EDF Innovation Lab
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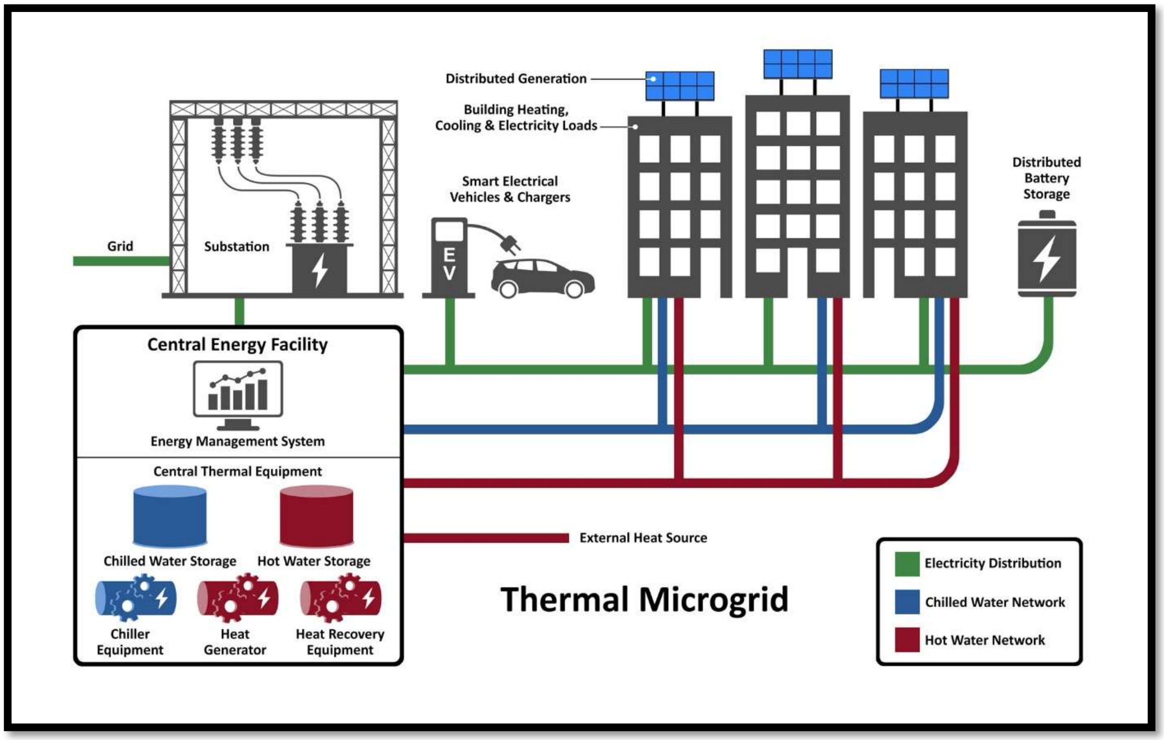
Thermal Microgrids: Technology, Economics and Opportunity



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About this Report

This report was completed as a part of a collaboration between EDF Innovation Lab, Stanford University and the City of Palo Alto Utilities for the project *Leveraging Experience from Stanford and EDF to Develop Information and Tools for Thermal Microgrid Feasibility Assessments*, funded by the American Public Power Association (APPA) Demonstration of Energy & Efficiency Developments (DEED) program. The project objective is to provide information and tools to support municipal utilities in evaluating the feasibility of deploying thermal microgrids. Deliverables of the project include i) a white paper describing the technology, economics and market of thermal microgrids and comparing them to alternatives (this report); ii) a case study report describing the Stanford Energy System Innovations (SESI) project, in which their campus-wide cogeneration system was transformed into to renewable electricity powered heat recovery with low temperature hot water distribution; iii) a suite of tools for assessing technical and economic feasibility; and iv) two municipal case studies applying the tools to carry out feasibility assessments.

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The authors are responsible for the final content and any mistakes.

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List of Acronyms

Acronym	Term
AMI	Advanced Metering Infrastructure
APPA	American Public Power Association
BAU	Business as Usual
BTU	British Thermal Unit
CCA	Community Choice Aggregation
CCF	Centum Cubic Feet
CCHP	Combined Cooling, Heat and Power
CHC	Combined Heat and Cooling
CHP	Combined Heat and Power
DEED Program	Demonstration of Energy & Efficiency Development Program
DER	Distributed Energy Resource
DG	Distributed Generation
DHC	District Heating and Cooling
DOE	Department of Energy
DR	Demand Response
EIA	Energy Information Administration
ETS	Energy Transfer Station
GHG	Greenhouse Gas
GIS	Geographic Information System
GJ	Gigajoule
GW	Gigawatt
GWh	Gigawatt-hour
HHV	Higher Heat Value
HP	Heat Pump
HRC	Heat Recovery Chiller
HVAC	Heating, Ventilation, and Air Conditioning
IDEA	International District Energy Association

Acronym	Term
IEA	International Energy Agency
IOU	Investor Owned Utility
IRR	Internal Rate of Return
kW	Kilowatt
kWh	Kilowatt-hour
LCA	Life cycle assessment
LCOE	Levelized Cost of Electricity
MES	Multi-Energy System
MMBTU	Million British Thermal Units
MW	Megawatt
MWh	Megawatt-hour
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
O&M	Operations and Maintenance
POU	Publicly Owned Utility
PV	Photovoltaic
PVC	Present Value Cost
SESI	Stanford Energy System Innovations
SHP	Separate Heat and Power
SPV	Special Purpose Vehicle
TWh	Terawatt-hour
UNEP	United Nations Environment Programme

Executive Summary

Addressing global climate change is the single greatest environmental challenge and opportunity faced by humankind. Energy provided for transportation, agriculture, industry, and buildings has enabled the vast advancement of humanity, yet the way humankind is producing, managing and using energy is threatening its very long-term existence. This report provides information about energy usage specifically in the buildings sector, and outlines a practical pathway for providing energy to buildings in a sustainable and economic way. The report includes information on a case study of how this has already been implemented at scale, as well as providing tools to help others evaluate such systems for their buildings.

Based on multiple studies carried out across the energy community in numerous countries, the emerging practical and scalable pathway to sustainable building energy supply is the combination of electrification and clean energy, following economic and sustained application of energy efficiency efforts. This conclusion is driven by the relative techno-economic feasibility of decarbonizing the generation of electricity as opposed to the use of renewable natural gas or transitioning to non-carbon fuels such as hydrogen. Power and cooling of buildings, when electricity-based, is readily made sustainable upon decarbonizing the electricity source. Heating and hot water, on the other hand, is predominantly supplied by fossil fuel such as natural gas. Decarbonization heating and hot water therefore requires a switch to a different, non-fossil fuel powered equipment.

Building electrification, however, need not rely on electric resistance appliances alone: electric-powered heat pumps can help catalyze this technological transformation. Electric heat pump appliances are commercially available and even more efficient than electric resistance and natural gas appliances, which unlocks the technological and economic transition to an all-electric system for building energy supply. Furthermore, heat pumps are flexible in that they can be used both to harvest waste heat from existing building cooling processes (heat recovery) as well as extract heat from ground, water, or air sources to augment heat recovery when needed in winter when waste heat alone is insufficient to meet building heating and hot water needs.

Discussions of building electrification and supporting policies have been gaining traction, yet the primary focus is building-level appliance switch-out (i.e. switching from a natural gas to an electric water heater in a building). An alternative approach is to develop a decarbonized energy system that is optimized for a group of buildings. These district energy systems are networks of underground pipes carrying steam, hot, or cold water used to heat and cool buildings. District energy has many advantages compared to building-level alternatives, including economies of scale from aggregating a collection of loads from numerous buildings; waste heat recovery technologies that are not available or efficient at a building-level scale; and, load and resource diversity that enable optimized central equipment sizing and resultant enhanced efficiency. Deploying heat pumps via a district energy system, adding thermal energy storage, and using advanced energy management programs can increase the efficiency and system resiliency, and lower the cost of electrification such that it becomes the least cost alternative for long term building energy supply. Collectively these components can be thought of as a thermal energy microgrid, much in the same way the combination of on-site renewable electricity, electricity storage, and electric vehicles can be thought of as an electric microgrid. The concept of electric microgrids has gained much attention as of late, yet given that two thirds of total energy use in buildings is thermal while electricity is but one-third, greater attention should be focused on the opportunity.

This white paper explores district-scale electrification incorporating both electricity and thermal (heating and cooling) services via so-called thermal microgrids as a technical pathway for decarbonization. Stanford University's campus energy system is the inspiration of the thermal microgrid approached and used throughout the white paper to illustrate its potential for achieving environmental, economic and other requirements for local energy systems.

1. Introduction & Background

Addressing global climate change is the single greatest challenge and opportunity faced by humankind. The energy sector in specific must play a decisive role in enabling the successful transition to a decarbonized economy, given that energy generation and usage contributes disproportionately to historic and current global greenhouse gas (GHG) emissions. Within the U.S., buildings are responsible for approximately 40% of all energy usage and a third of emissions, a significant portion of which is from appliances burning natural gas and other carbon-based fuels for heating and cooking[1]. The continued use of carbon-based fuels in buildings is not sustainable unless either supplanted by sustainable biogas sources or coupled with carbon capture and storage (CCS). However, both biogas and CCS are more expensive, less efficient, and impractical at scale compared to electrification combined with clean electricity[2]. Therefore, substantial fuel switching in the building sector from fossil fuel to electricity - also called electrification - combined with continued electricity decarbonization and energy efficiency are required to achieve science-based GHG emissions reductions targets[3]. These are also the conclusions of the international energy community as shown in references cited throughout the report.

Discussions of building electrification and supporting policies have been gaining traction in some regions[4], yet the primary focus is building-level appliance switch-out (i.e. switching from a natural gas to an electric water heater in a building). However, with increasing energy efficiency practices reducing building heating and cooling loads, it may be increasingly difficult to size equipment appropriately. One could alternatively take a district approach and develop a decarbonized energy system that is optimized for a group of buildings. In fact, in 2013, the United Nations Environment Program (UNEP) surveyed low-carbon cities worldwide to understand key factors for their success in achieving zero or low GHG emissions targets and increased integration of energy efficiency and renewable energy, and district energy was identified as a best practice approach for providing a local, affordable and low-carbon energy supply[5]. District energy systems are networks of underground pipes carrying steam or hot/cold water used to heat and cool buildings. Historically, district energy development accelerated in the late twentieth century to achieve higher primary energy efficiency when the systems relied on volatile, imported fossil fuels, and to combat urban air pollution from open coal fires and oil-fired boilers. District energy systems have many advantages compared to building-level alternatives, including economies of scale from aggregating a collection of loads from dozens of buildings; waste heat recovery technologies that are not available or efficient at a building-level scale; and, load and resource diversity that enable optimized central equipment sizing and resultant enhanced efficiency.

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[1] U.S. Energy Information Agency; U.S. Environmental Protection Agency's "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2015"

[2] California's Energy Future: The View to 2050, California Council on Science and Technology, May 2011; Williams, J.H. et. Al., The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity, Science, Volume 335, January 6, 2012; Pathways to Deep Decarbonization, Deep Decarbonization Pathways Project; Southern California Edison's The Clean Power and Electrification Pathway Realizing California's Environmental Goals (Nov 2017).

[3] Ibid.

[4] E.g. California

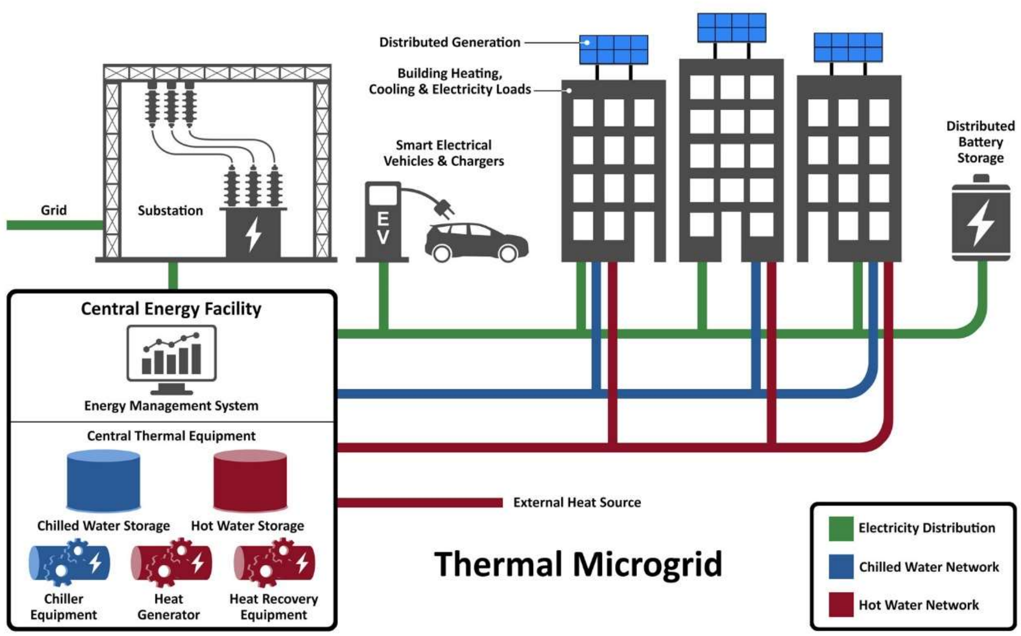
[5] United Nations Environment Programme, District Energy in Cities - Unlocking the Potential of Energy Efficiency and Renewable Energy (2015)

This white paper explores district-level electrification incorporating both electricity and thermal (heating and cooling) services via so-called thermal microgrids as a technical pathway for decarbonization. The objective of this white paper is to address the following questions.

- What is a "thermal microgrid"?
- What are the advantages and disadvantages of thermal microgrids compared to alternatives?
- What are the costs, GHG emissions impacts and water usage requirements compared to alternatives?
- What are the primary feasibility drivers?
- What is the potential of this technology in the U.S.?
- What business model structures could a municipal utility use for delivering thermal services via a thermal microgrid?

1.1 What is a "Thermal Microgrid"?

Figure 1: Illustration of a thermal microgrid



We define a thermal microgrid as follows.

> *A thermal microgrid utilizes energy efficiency; renewable electricity powered heat recovery; thermal storage; and, advanced analytics and controls to provide co-optimized power and thermal services to a group of interconnected and controllable energy loads within a defined boundary.*

The concept is illustrated in Figure 1. The term *microgrid* is used to emphasize benefits associated with traditional electricity-focused microgrids, such as local renewable energy utilization, enhanced community resilience and reliability, systems-optimized control and dispatch of the collection of loads and resources, and ability to meet critical loads during larger grid disturbances. The adjective *thermal* is added to denote that the microgrid also incorporates thermal services such as hot water, steam, and/or chilled water, in addition to electricity. Similar concepts have been introduced in prior studies, leading to a variety of other terminology, such as *energy district*, *multi-energy system*, *renewable district energy*, *multi-energy microgrid*, *energy microgrids*, *smart energy system*, and, most significantly, *4th generation district heating*[6].

The hallmark of a thermal microgrid is the utilization of renewable electricity powered waste heat recovery as the cornerstone of the system design, enabled by low-temperature district heating networks and low energy buildings. At its heart, it is district scale electrification. This new category of district energy systems is inspired by Stanford's recent transformation of their cogeneration system to a thermal microgrid, called Stanford Energy Systems Innovation (SESI)[7]. Burning fossil fuels in traditional district energy systems (e.g. combined heat and power) is replaced in thermal microgrids by advanced heat recovery utilizing heat pumps powered by renewable energy generation, either on-site or from grid-supply.

Table 1: Common energy system architectures

Non-District Energy Systems	• **Building-Level** refers to an energy system configuration where buildings use electricity and/or gas to power on-site appliances for heating and cooling needs.
District Energy Systems	• **Separate Heat and Power (SHP, District Heating or District Cooling)** is a heat or cooling network that provides thermal services independently from the generation, management and provision of power. • **Combined Heat and Cooling (CHC)** is the use of a centralized system to simultaneously provide heat and cooling services for a district. • **Combined Heat and Power (CHP or cogeneration)** is the use of a centralized plant to simultaneously generate electricity and heat for a district. • **Combined Cooling, Heat, and Power (CCHP or trigeneration)** is the simultaneous generation of electricity, heat and cooling for a district.

Most regions of the U.S. rely on building-level energy systems (Table 1, top). However, district energy systems are widespread across Europe and Asia, in addition to being prevalent in certain applications in the U.S., including specifically the central business districts of major cities, hospitals, university and corporate campuses, and military bases. There are several possible district energy system architectures, as outlined and defined in the bottom of Table 1. Traditional district energy in the U.S. uses fossil fuels as the main heating source and steam as the energy carrier. More recently, natural gas has emerged as a preferred fuel source given its availability, price, and reduced emissions, and hot

[6] Henrik Lund, Sven Werner, Robin Wiltshire, Svend Svendsen, Jan Eric Thorsen, Frede Hvelplund, Brian Vad Mathiesen, "4th Generation District Heating (4GDH) Integrating smart thermal grids into future sustainable energy systems", Energy 68 (2014) p1.

[7] https://sustainable.stanford.edu/campus-action/stanford-energy-system-innovations-sesi

water is increasingly used as the energy carrier in place of steam. Heat distributed to buildings can be used for space and water heating, or it can be processed by an absorption chiller to be converted to chilled water for cooling.

The primary district energy system architectures represent traditional architectures largely developed with fossil-fuel fired technologies. Thermal microgrids could fall under Combined Heat and Cooling (CHC) or Combined Cooling, Heat and Power (CCHP), depending on whether there is significant renewable energy supply located on-site (CCHP) or sited remotely from utility-scale plants (CHC)[8]. Although there need not be power generation on-site, the power system is not separate and independent from the thermal network: there is substantial coordination and optimization between electricity usage and the thermal networks, primarily via centralized thermal storage, leading to enhanced opportunities for efficiency gains. For instance, thermal storage incorporated into SESI enables over 20% more waste heat recovery from the overlap in heating and cooling needs across campus. Moreover, thermal storage incorporated into a central energy facility design enables electricity load shifting from on-peak to off-peak periods, enhances reliability and resilience by being able to continue to provide thermal services during grid disturbances, reduces the installed chiller capacity requirements, and aids in the integration of local, variable renewable energy generation. None of these benefits can be realized with building-level systems or any energy system configuration where the operation of the electricity and thermal networks are largely decoupled.

Please see section 2 for greater detail of the description of the technologies underlying thermal microgrids and alternatives.

1.2 Recent Trends Driving Interest in Thermal Microgrids

Industry experts and prominent academics cite the “three D’s” as the primary drivers behind the current energy system transformation: decentralization, decarbonization and digitization[9].

- **Decentralization**. The traditional paradigm of centralized power generation is being up-ended with the rise of customers and communities opting to take greater control over their energy production, management and use. Increasing adoption of behind-the-meter solar, smart thermostats and other building energy management devices enabled by exponentially decreasing costs and novel business/financing structures[10] combined with capacity and reliability considerations of the transmission grid are leading to a new, decentralized grid paradigm. Currently, distributed solar generation is estimated to reach 140 gigawatts (GW) by 2040, up from only 2 GW in 2010[11].

- **Decarbonization**. Local and state governments across the U.S. have adopted climate goals and corresponding energy policies and regulations to promote decarbonization of the energy

[8]Traditional CHP and CCHP systems combust fossil fuel in an integrated process to generates electricity and heat simultaneously. In this white paper, CHP and CCHP need not refer to an integrated thermal process, but simply to co-locating power generation within the thermal microgrid boundaries and integrating it into the overarching system optimization, management and control.

[9] https://energy.stanford.edu/from-directors/nurturing-innovation-during-strategic-inflection-point-global-energy

[10] E.g. third-party ownership models for rooftop solar (lease and power purchase agreements)

[11] https://www.eia.gov/outlooks/aeo/pdf/0383(2017).pdf

sector. Prominent policies include, for instance, renewable portfolio standards, incentives for distributed renewables deployment, and cap-and-trade programs for GHG emissions. These collective policies have supported renewables deployment, such that in 2016, renewables have grown to make up two thirds of all electricity capacity additions[12].

- **Digitization**. Currently, nearly half of U.S. electricity customers have advanced metering infrastructure (AMI) (aka *smart meters*) - the backbone of the smart grid transformation - which represents a doubling of AMI deployment since 2010[13]. More generally, the increased deployment of low-cost sensors, advanced control technologies, and artificial intelligence is fundamentally changing every facet of the energy sector, from home thermostats to utility rate-making.

The same three drivers behind the larger energy system transformation are ultimately responsible for driving interest in thermal microgrids, which are a decentralized technical pathway for achieving deep decarbonization enabled by advanced digital capabilities.

1.3 Goals and Objectives for Local Energy System Development

As referenced above, there are several considerations for local energy system deployment, and stakeholders must first identify and prioritize goals to evaluate a thermal microgrid versus an alternative energy system. The following are the most typically cited categories of goals, many of which are interrelated. Once goals are identified, stakeholders then identify objectives used to achieve each goal, which may be qualitative and/or quantitative. The goals and objectives are prioritized based on the community's shared priorities and values, taking into account the relative trade-offs between each.

- **Economics**. Energy and thermal services costs are a primary concern for all stakeholders. Thermal microgrids leverage economies of scale and enhanced efficiency to reduce costs, as does any district energy approach. The efficiency gains through advanced heat recovery improves the economics further. An economic assessment of a local energy system is typically evaluated using present value costs of the system over the lifetime, which can be compared across a variety of different system designs incorporating both electricity and thermal services.

- **Reliability and resiliency**. Communities that are prone to natural disasters and/or that have customers with critical loads may identify reliability and resiliency as a system design goal. Thermal microgrids incorporate distributed energy and storage and advanced analytics and controls, which enables detection and ride-through of local grid disturbances. Thermal microgrids, like CHP[14], can be used to enhance reliability and resiliency.

- **Reliance on fossil fuels**. The reliance of an energy system on fossil fuels has price risk implications, in addition to environmental ones. Historically, price shocks of imported fossil fuels have resulted in reduced rate stability. Although domestic production of natural gas through fracking has resulted in low prices for multiple years, the lifetime of an energy system can be up to 40 years. Natural gas prices over this period are uncertain. Price risk volatility can

[12] https://www.eia.gov/todayinenergy/detail.php?id=25172
[13] https://www.eia.gov/electricity/data/eia861/
[14] http://www1.eere.energy.gov/manufacturing/distributedenergy/pdfs/chp_for_reliability_guidance.pdf

be mitigated by transitioning to advanced waste heat recovery and renewable energy in the thermal microgrid design.

- **Environmental impact**. Minimizing the environmental impact of the energy system is another key goal of cities, campuses, and utilities driven by community preferences for renewables and action on climate change. Thermal microgrids are highly efficient because of their use of advanced waste heat recovery and renewable energy, enabling them to achieve environmental outcomes not possible on a building-level scale at comparable costs or at a district scale utilizing fossil fuel based systems. GHG emissions, local particulate matter and indoor air quality are the most common focus areas, all of which are improved using thermal microgrids.

- **Water usage**. Especially in drought-prone regions, water usage is a key consideration of the energy system design, due to both financial impact and availability of a scarce resource. Leveraging advanced waste heat recovery using heat pumps in the thermal microgrid design reduces water usage, because the waste heat that is recovered would in most cases be discharged using evaporative cooling towers.

- **System flexibility**. Given that energy systems can have a lifetime of up to 40 years, the ability of the energy system to meet future community needs and do so in a way that minimizes the prospect of stranded assets is another key consideration, especially in regions experiencing significant growth. Thermal microgrids can source electricity and heat using several types of technologies, allowing a community flexibility to optimize supply over the long lifetime of the system.

- **Local economic development**. As opposed to utility-scale power generation sited in remote areas of the state used to power building-level equipment, thermal microgrids incorporate central energy facilities (e.g. heat pumps, thermal storage) sited locally, which grant the opportunity for local workforce and business development.

- **Local control**. Another key goal of developing a local energy system is also simply for the community to have local control.

As discussed under each category above, thermal microgrids rank favorable in each category.

1.4 Summary of Opportunity

Given the transformation of the energy sector driven by the "three D's" (section 1.2), now is the time to explore the role of thermal microgrids for achieving clean, affordable and reliable energy systems to serve communities. Public power is uniquely positioned to lead the exploration and development of thermal microgrids, for several reasons. First, municipal electric utilities considering a prospective thermal microgrid are in an informed position to evaluate and act on trade-offs and synergies with other public sector utilities. Municipalities often have several public-owned utilities in addition to electric power, such as wastewater and potable water systems. These additional systems/services can be utilized for heat recovery and exchange in the thermal microgrid, as discussed in greater detail in section 2.2. Similarly, electric and thermal utility services can achieve cost savings through coordinating trenching. A waste heat recovery based system will obviate the need for a local cooling tower, and the associated health risks (e.g. Legionnaires' disease). A municipal electric utility can assess these trade-offs and synergies to maximize the cost-effectiveness across the provision of utility services to the community. Second, the thermal microgrid, like an electric-only microgrid, is embedded in the larger grid. Public power can standardize interconnection procedures and develop innovative policies and rate structures that harness the value in the flexible and controllable load. Third, the success of local energy system deployment hinges on the ability to navigate complex, multi-stakeholder processes to achieve community goals. Public power agencies have decades - in some cases over a century - of experience serving their communities by leading energy infrastructure deployment, making them ideal entities for steering thermal microgrid development. Fourth, historically, municipal utilities across the U.S. have shown leadership on environmental issues. Direct accountability to the communities they serve enables public power more flexibility in prioritizing non-economic goals of the local energy system (e.g. environmental impact), compared to for-profit utility business models. For all the above reasons, there is arguably no better institution than public power to lead thermal microgrid exploration.

2. Technology Description

As described in the prior section, a *thermal microgrid* utilizes a combination of energy efficiency, thermal storage, and renewable energy powered waste heat recovery or other renewable heat supply to provide co-optimized power and thermal services to a group of interconnected and controllable energy loads within a defined boundary. A thermal microgrid therefore includes several categories of technologies, including:

- one or more **heat and cooling sources**, including **thermal storage**;
- one or more **power generation systems**[15], from clean energy, either located on-site or remotely;
- a **thermal network** of pipelines - including both supply and return – running from the central energy facility to the buildings; and
- **building interconnection equipment** to couple the thermal network to the heating and cooling systems located at the customer site.

Thermal microgrids, like other district energy systems, provide significant flexibility since several technology options are available for most of these functions, and indeed heat and electricity supply sources may be swapped out over time given changes in policies and technology costs and performance. Ultimately, the combination of technologies selected for the final system design depend on the scale of the project, local resource availability, and special performance characteristics, among other factors, and must be analyzed on a case-by-case basis.

The following three sections provide an overview of technology options incorporated into a thermal microgrid, divided into three categories: central equipment, thermal network, and building interconnection equipment. The fourth and final section considers the various energy system architectures (Table 1) and the resultant range of estimated systems efficiency, emissions, and water usage one can expect given available technology choices compared to conventional alternatives.

2.1 Central Equipment

2.1.1 Heat Sources

The viability of a district energy system hinges on availability of a low-cost heat source. Heat can be generated or recovered from a variety of sources, either as single output process or in conjunction with power (e.g. CHP). The historical choice for heat production is a thermal power station or a dedicated CHP plant. In the framework of achieving deep decarbonization, however, there are multiple renewable/recovered heat sources that can deliver high-temperature (high grade) heat. Others can provide low-temperature (low grade) heat and then be used in conjunction with heat pumps to achieve a higher output temperature. Table 2 describes a variety of renewable/recovered heat sources that can be leveraged for a thermal microgrid, categorized by high-grade and low-grade heat.

[15] Background information on renewable electricity generation systems are not addressed in this report.

Table 2: Possible waste and renewable heat sources, categorized as either high-grade or low-grade heat

High Grade Heat	• **Waste Heat Recovery from Industrial Processes (200-1,800 °F).** Waste heat from industrial processes is commonly available, varying in temperature from extremely hot process industry flue gases down to lower temperature refrigeration exhaust. This heat source is often used in large-scale district energy systems, or for more localized systems when combined with other heat sources. • **Deep Geothermal (150-350 °F).** Recovering geothermal heat requires deep boring into the ground. Boring costs are substantial and can make this renewable energy source cost-prohibitive depending on specifics of the site. Yet when economically feasible, deep geothermal offers a renewable heat source for base load needs. • **Waste Heat Recovery from Municipal Waste Incineration (130-300 °F).** The combustion of municipal waste to provide electricity and/or heating (aka *waste-to-energy*) has been practiced in Europe for many years. Waste incineration occurs continuously throughout the year, making this a base load heat source. • **Biomass (130-300 °F).** Biomass can be used as fuel for large boilers or for CHP plants, a common choice for district energy systems. Sources of biomass include wood chips, clean construction and demolition lumber, yard waste, tree trimmings and multiple forms of agricultural waste such as oat hulls, etc. Biomass can also be used within existing fossil-fueled boilers as a co-firing to reduce emissions. • **Solar Thermal (175-275 °F).** Using solar energy as a heat source for district energy systems was traditionally considered infeasible on a year-round basis and utilized only for seasonal heat. Now by integrating thermal storage capacity, solar thermal energy is viable at almost any latitude for many countries. The solar energy can either augment existing heat sources in a thermal network, or feed a stand-alone system incorporating thermal storage to provide thermal heating year-round.
Low Grade Heat	• **Waste Heat Recovery from Building Cooling Process (50-80 °F)**. Stanford's state-of-the-art system uses the overlap in heating and cooling needs by capturing waste heat from the cooling network return pipe. The overlap in thermal needs leading to opportunity for waste heat recovery has been found to be a robust phenomenon across climate zones and building uses, and should be the first heat recovery source to be pursued given the same heat pump equipment can be used for both heating and cooling needs to capture this opportunity[16]. • **Waste Heat Recovery from Municipal Wastewater (50-80 °F).** Sewage is a heat source that is available in almost every community. A few degrees of heat can be extracted before or after sewage treatment. In the former case, the heat source is, of course, contaminated. In the latter case, the process is post-sanitation, but source temperature is significantly lower. • **Shallow Geothermal (50-80 °F)**. Shallow geothermal (aka *geoexchange*) is the recovery of heat from within several yards of the earth's surface, where the temperature remains relatively constant. Shallow geothermal as a heat source is becoming increasingly common for district energy systems. • **Other Waste Heat Recovery Opportunities**. There are a variety of other sources of waste heat, a largely untapped potential energy source, including high heat loads from data centers and air- and water-source heat.

[16] See the SESI case study companion deliverable for more information.

Incorporating multiple heat sources is a standard strategy to improve overall energy system efficiency and increase the penetration of renewable heat sources. Choosing the heat source or sources that are best suited for a local energy system depends upon local resources, climate, system design parameters, source temperature, and customers' thermal needs, among other factors.

2.1.2 Cooling Sources

District cooling has potential to help overcome challenges in the cooling sector[17] compared to a building-level cooling approach, while providing multiple additional benefits as described in section 1.3. Conventionally, large commercial customers have electric chillers on-site, which use electricity and a refrigeration cycle to produce cooling. District cooling schemes similarly incorporate chiller equipment in a central plant to produce chilled water. Other cooling source options include the efficient use of renewable electricity in large heat recovery chillers (water-to-water heat pumps), the combination of absorption heat pumps/chillers with a heat source such as those listed in the prior section, or natural cooling (aka *free cooling*) from surface water when considered to not be an environmental concern. Table 3 shows the primary cooling sources used in district energy systems.

Table 3: Cooling sources

- **Heat Recovery Chillers (HRCs) in a Heat Network.** As illustrated by SESI, cooling can be produced from a heat network using large HRCs located at a central plant.
- **Absorption Heat Pumps/Chillers with a Heat Source.** A heat source can be used to produce chilled water using absorption heat pumps/chillers, either located at the building site or at a central plant. Alternatively, a centralized trigeneration system utilizing similar equipment can produce a separate cold supply to serve a district, in addition to power and heat.
- **Surface Water (40-75 °F).** Also known as hydrothermal, lakes, rivers and oceans can be used as cooling source or as a heat sink. Some systems use surface water not just as a cooling source, but in a combined scheme to prepare or provide potable water supply, such as Toronto District Cooling. When the source temperature is not sufficiently low to directly feed the thermal network, a chiller is used to reduce the temperature.

2.1.3 Thermal Storage

Thermal storage is a key technology for enabling optimized system operation of a thermal microgrid. Thermal storage systems incorporated into the overall energy system design can increase the amount of heat recovery potential that can be economically exploited, enable electricity load shifting from on-peak to off-peak periods, enhance reliability and resilience by being able to continue to provide service during grid disturbances, and reduce the chiller capacity requirements. To achieve these use cases, the storage system is charged and discharged daily based on results from system-wide optimization. Chilled water is the most common form of cool storage, although ice or ice slurry could also be used. Hot storage is simply hot water, although hot storage is less common in the U.S. compared to Europe.

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[17] For instance, in large swaths of the U.S., the system peaks of the electricity grid are driven by AC load, and some building cooling needs are increasing given growth of computer and server use, which are heat generators.

2.2 Thermal Network

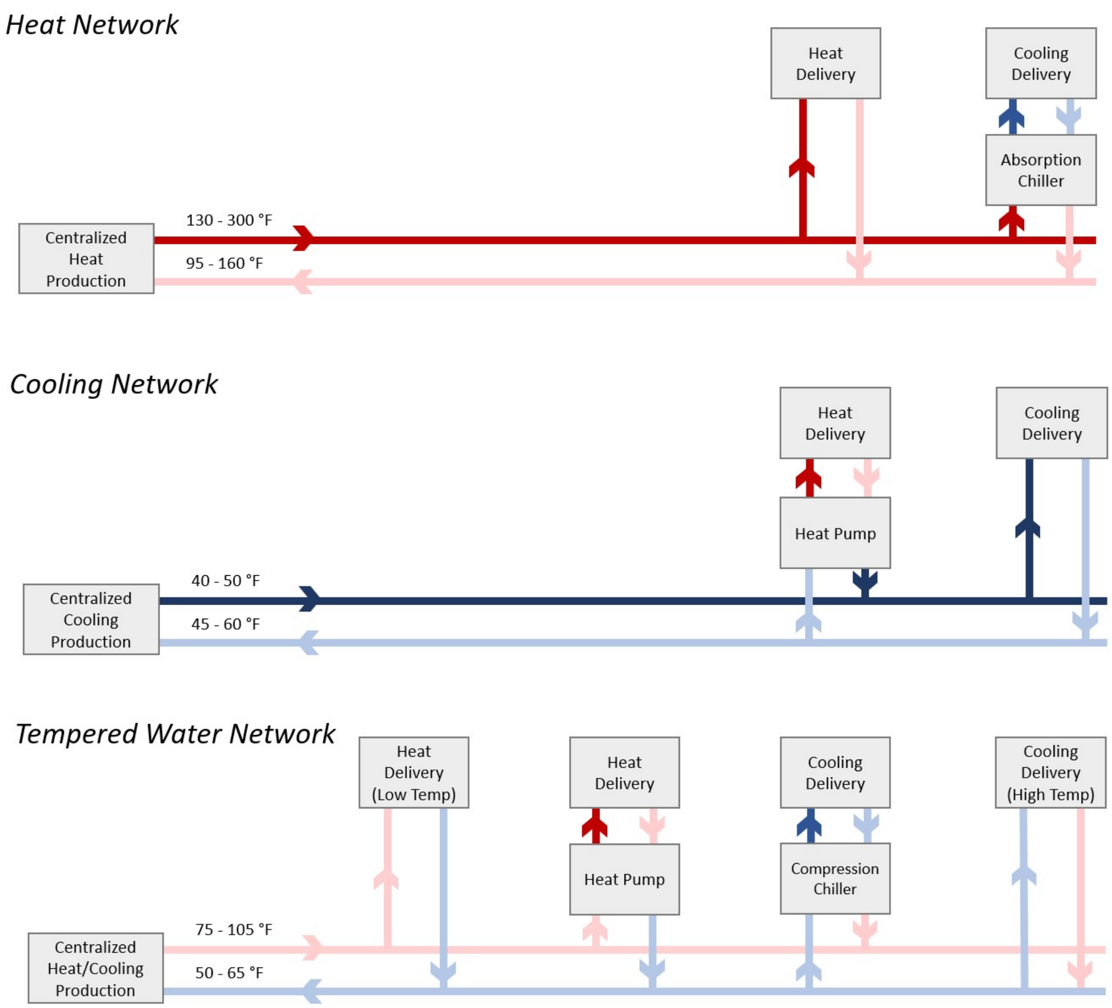
The *thermal network* is the distribution network of pipes, energy transfer stations, valves and controls to deliver steam, hot water or chilled water from a central energy facility to end customers. Each service in a thermal network consists of a pair of pipes: the *supply* that carries water or steam from the central energy facility to end customers, and the *return* that carries water or steam/condensate back from the end customers to the central energy facility. A district energy approach to serving a community will have an advantage over a building-level approach whenever the cost savings of the energy source and central equipment compared to conventional building-level systems is greater than the capital costs of the distribution network. Therefore, design choices of the thermal network and resultant costs and savings play a significant role in overall district energy system cost-effectiveness. Figure 2 illustrates the three types of thermal networks.

- A **heat network** directly provides the required heat supply to the buildings. A heat network can also provide cooling at the building via on-site absorption chillers.
- A **cooling network** directly supplies the required cooling supply to the buildings. It can also provide heat at the building via on-site heat pumps.
- A **tempered water system**, often referred to as an anergy network in Europe, provides heat or cooling supply directly to the building, whenever the temperature level of the demand is compatible with the network temperature.

The thermal needs of users are primarily domestic hot water and space heating and cooling. In a thermal network, heat transfer is quantified by the flow and temperature difference (*delta T*) between the water in the supply and the return.

Analogous to an electricity grid, a thermal network has a network operator that directly controls the outgoing water temperature and typically opens and closes circulation valves at the delivery points to regulate flow based on building needs throughout the thermal network. The network operator ensures that all customer needs are met, including those at the furthest customers at the end of the network. The return loop temperature is not controlled directly, but is a result of the operating scheme. The return temperature in a heat network is usually kept as low as possible: just high enough to ensure thermal needs of all customers are met, but not higher, so as to maximize overall system efficiency by reducing thermal losses from transportation through the pipes and minimizing pumping energy. Incorporating multiple heat sources can help facilitate operating the thermal network with a low return temperature, to improve efficiency and increase renewable energy penetration. For instance, the renewable heat source could supply 60-80% of peak demand, and comparatively low-cost backup units could be incorporated into the system design to be used as reinforcement during the rarely-occurring peak hours.

Figure 2: Schematic view of three thermal networks: heat, cooling, and tempered water networks[18]



2.2.1 Integrating Heat Supply into the Thermal Network

Most heat sources are only available at limited temperature levels, as indicated in Table 2 (section 2.1.1) and Table 3 (section 2.1.2). The methodology for integrating heat sources into the network supply is determined by the temperature difference between the heat source and the supply and return temperatures of the thermal network. The three cases are as follows.

- When the heat source temperature is higher than the thermal network supply temperature, the heat source can directly feed the thermal network in the supply loop.

[18] Translated and adapted from: Loic Quiquerez, "Décarboner le système énergétique à l'aide des réseaux de chaleur: état des lieux et scénarios prospectifs pour le canton de Genève", PhD Thesis, 2017.

- When the heat source temperature is in between the supply and return temperatures, the heat source can directly feed the thermal network in the return loop.

- When the heat source temperature is lower than the return temperature of the network, the heat source cannot directly feed the thermal network, and heat pumps are necessary to bring the temperature up to the required level.

2.2.2 Thermal Network Piping

There are a variety of materials available for thermal network piping, the selection of which will depend on the energy system architecture (Table 1), thermal network architecture (Figure 2), energy carrier, supply and delivery temperatures, desired flow rate, the local environment, materials costs, installation costs, and anticipated lifetime, among other factors. For hot water distribution systems, the most common piping material is steel with one to several inches of polyurethane insulation and a water vapor jacket applied around the pipe (aka *pre-insulated steel pipes*). For chilled water systems, steel or ductile iron piping has been used historically, although high density polyethylene is increasingly common. When steel pipes are used, they are typically coupled with a leak detection system to enable timely identification of leaks before they result in corrosion and damage. Chilled water piping can be pre-insulated, coated for corrosion protection, or left bare. The up-front and installation costs for pre-insulated piping of a chilled water distribution network are significantly more expensive compared to non-insulated piping. Therefore, a detailed thermal analysis is carried out for a chilled water distribution network to weigh the costs and benefits of insulation for a specific system. The three most important factors that will determine the distribution losses in the thermal network are 1) the thermal conductivity of the piping material, 2) the thermal conductivity of the surrounding soil, and 3) the temperature difference between the fluid and the surrounding soil. Additional factors that impact distribution losses include the pipe diameter, flow velocity, depth of the piping, and distance between buried supply and return piping.

2.3 Building Interconnection Equipment

The thermal network can interconnect with customer buildings in two ways.

- **Direct Connection**. The district energy system’s supply (i.e. steam, hot water or chilled water) is directly pumped through the customer’s building heating and cooling equipment (e.g. radiators).

- **Indirect Connection**. The district energy system is coupled to the building via heat exchangers used to transfer heat between the supply and the customer’s building system, keeping the supply isolated from the building heating and cooling system.

The customer building interconnection may be referred to as an *energy transfer station* (ETS). Most district heating systems use indirect connections, while most district cooling systems use direct connection due to the relatively small differential temperatures in chilled water systems. Major determinants of whether to use a direct or indirect connection include the system supply pressure at the building, current building equipment, and building height. Direct connections have the advantage of requiring less space, lower maintenance costs, and lowest return temperatures, maximizing the “delta T” between the supply and return leading to overall higher system efficiency and cost-effectiveness. However, they require increased power consumption to maintain sufficient pressure at the building interconnection points, make leak detection more challenging, and reduce reliability overall. When the pressure difference does not allow a direct connection, an indirect connection is used. Indirect connections are advantageous in that they provide compatibility for building interconnections with any district energy system pressure and temperature.

Controls are installed at the interconnection points to limit the maximum flow rate and keep the thermal network in balance. In addition to controls, heat meters and isolation valves and filters are also installed for billing and equipment protection, respectively.

2.4 Building Heating and Cooling Equipment

Although technically outside of the purview of the district energy system owner and operator, customers' building heating and cooling equipment must be compatible to interconnect and receive thermal services. The building system should be sized to meet peak demand, and no more: an oversized building heating system results in oversizing the entire thermal network to meet customers' needs. Of particular importance is the operating temperature of the building's heating systems: the building supply temperature must be lower than the thermal network supply temperature, and the building's supply and return temperature should be adjusted to reduce the return temperature as much as possible. The more critical design criterion is the building return water temperature – this should be driven as low as possible for maximum system efficiency.

2.5 Energy System Performance

A generalized comparison of energy system performance evaluated based on energy efficiency, emissions, and water usage can be challenging, given that a variety of local conditions will ultimately impact the actual system viability. Nonetheless, here we provide a simplified, high-level evaluation of performance of two energy system architectures, SHP and CHC[19]. To carry out the comparison, we assume a common fuel (natural gas) and make the following assumptions.

- Electricity consumption from the grid is provided by a new natural gas fired combined cycle power plant with a 52% efficiency[20].
- District heating is from new natural gas fired equipment with an 85% efficiency on a higher heating value (HHV) basis.
- District cooling from new chiller and cooling towers has an efficiency of 0.5KW/ton.
- Heat recovery chillers have an efficiency of 1.5KW/ton.

We compare SHP to a CHC system powered from grid electricity, by evaluating how much natural gas is required to provide one ton of chilling and 17,100 BTU of heating. Given the above assumptions, the total required using SHP is 23,339 BTU. This is compared to the total from CHC is 9,845 BTU. Therefore, CHC would use 57% less natural gas than SHP, and consequently result in a commensurate amount of GHG reductions. Limiting the use of evaporative cooling towers to reject waste heat further reduces water usage in the CHC design, of particular significance in drought-prone regions of the country.

[19] This section is paraphrased from the SESI case study companion deliverable, included here for completeness.
[20] *Thermal Efficiency of Gas-Fired Generation in California: 2015 Update*, California Energy Commission.

3. Overview of Project Economics

The deployment of a thermal microgrid is a major infrastructure project that incorporates substantial fixed project costs, along with ongoing electricity/fuel and operations and maintenance costs. However, in addition to the system design maximizing efficiency resulting in cost-effectiveness, the project may also lead to additional significant offsets: costs that would need to be incurred if maintaining the existing energy system, such as expensive electric distribution system upgrades. The subsections below outline and describe the typical project cost categories for thermal microgrids.

3.1 Primary Fixed Costs

Fixed costs for a thermal microgrid - or many district energy system configurations - can easily run in the hundreds of millions of dollars, potentially making up half of the total system costs over the anticipated lifetime, with the balance being made up by operations and maintenance (O&M), electricity, and fuel. The primary categories of infrastructure costs for thermal microgrids are as follows[21].

3.1.1 Central Equipment Costs

Thermal microgrids have central equipment that includes, for instance, heat sources, heat pumps, chillers and thermal storage. Depending on the energy sources used, the specific fixed costs in production capacity and unit variable costs related to the production of a unit heat and be very different from one system to another. Centralized renewable electricity generation equipment located on-site, such as distributed solar PV, may also be incorporated into the system design.

3.1.2 Thermal Network and Building Interconnection Costs

Distribution occurs via the thermal network, which consists of underground pipes, energy transfer stations, pumps and controls carrying steam or hot/chilled water, as described in section 2.2. With regard to costs, the key parameter is linear thermal density, or the amount of heat/cooling distributed annually per linear foot of the thermal network. Unit thermal network costs are inversely proportional to linear thermal density. Explained another way, the largely fixed costs of the distribution network and customer connections can be shared across more units of thermal service when the customer load is denser, resulting in a more cost-effective system. Building interconnection costs can be many multiples of the thermal network itself and vary depending on building type and corresponding thermal load.

It is worth noting that even if the per unit costs of delivering thermal services is higher in low-density areas, district energy can still be cost-competitive, especially if/when the heat sources are cheap and distribution losses are minimized. Furthermore, on the other extreme, high-density urban centers can present their own set of challenges, since thermal network installation can be complicated and expensive in crowded underground space.

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[21] Cost estimates based on the European market can be found in United Nations Environment Program's 2015 report, "District Energy in Cities - Unlocking the Potential of Energy Efficiency and Renewable Energy".

3.2 Primary Ongoing Costs

The two largest sources of ongoing costs are O&M and electricity/fuel, which are approximately proportional to units of energy sold[22]. O&M costs consist of maintaining the central energy facility equipment, in addition to any building interconnection equipment. The thermal network itself requires little maintenance and has an expected lifetime much longer than the central equipment. Supply equipment can be switched out one or more times while maintaining the same distribution network. O&M can comprise up to a fifth of the total costs over the system lifetime, depending on the energy system architecture and other system design choices.

Electricity and fuel are the other main source of ongoing costs. Depending on the energy system architecture, supply sources, and climate, among other factors, electricity and fuel of a new energy system can make up half of the total lifetime system costs. Thermal microgrids are designed around renewable electricity powered heat recovery; therefore, electricity costs can be substantial and fossil fuel sources are minimized, used only for capacity serving peaking and backup needs.

3.3 Other Costs

Although Section 3.1 and 3.2 cover the primary up-front and ongoing costs for a thermal microgrid, there are many other costs that are material, including the following.

- **Project development costs**. Often starting multiple years prior to breaking ground, feasibility studies, detailed engineering designs, and permitting and planning applications require substantial resources to carry out.
- **Customer acquisition**. For a new local energy system development, it can take significant time and resources to acquire a set of core customers to form the anchor loads for the system. To encourage building owners to subscribe for thermal services, some district energy developments under-recover fixed costs in the early years of the system lifetime.
- **Metering, billing, customer service and administration**. Like any utility service, a district energy system operator must meter, bill, respond to customers, and operate in accordance with municipal, state and federal laws and regulations. A portion of these costs - specifically billing, customer service and administration costs - may be shared across multiple utility services. Heat metering equipment costs are often already accounted for under building interconnection costs.

3.4 Synergies with Other Utility Services & Customer Needs

As discussed in section 1.4, public power is in a unique position to lead in the development of district energy systems because of their ability to identify and capitalize on cost savings across multiple utility services. Coordinating infrastructure projects for the thermal network and electricity grid is one major example of this. As described above, thermal networks are underground networks. Trenching and pipe installation for the thermal network could be coordinated and combined with installing (new development) or undergrounding (existing development) the electricity distribution system. Power lines and supply and return piping can be arranged in such a way to mitigate any potential negative impacts of elevated temperatures on the power lines. Insulating foam boards can also be added

[22] O&M is also often expressed in terms of percent capital costs.

around the power lines if they must be within close proximity to the thermal network. Combining the installation of piping and installing/undergrounding power lines can result in substantial savings for communities. These potential savings should be taken into account in the evaluation of cost-effectiveness of the various local energy system options. Similarly, deploying a thermal microgrid can help delay or avoid major infrastructure investments in the electric distribution system for neighborhoods undergoing new development or major redevelopment accompanied by a substantial increase in electricity demand.

In addition to coordinating costs across utility services, there are also customer considerations that can be factored into whether a district energy system architecture is preferable over a building-level system. Having a district energy system reduces on-site capital expenditures required of customers. For Austin Energy, for instance, the primary motivation for exploring a central cooling plant was to reduce development costs for new buildings in a brownfield redevelopment area. The district cooling system precluded the need for chiller equipment installed in the new buildings, an offset to customer-financed capital projects. Although these costs would have been incurred by the customer, as opposed to the utility, customer preferences nonetheless play a significant role in determining the preferred local energy system design.

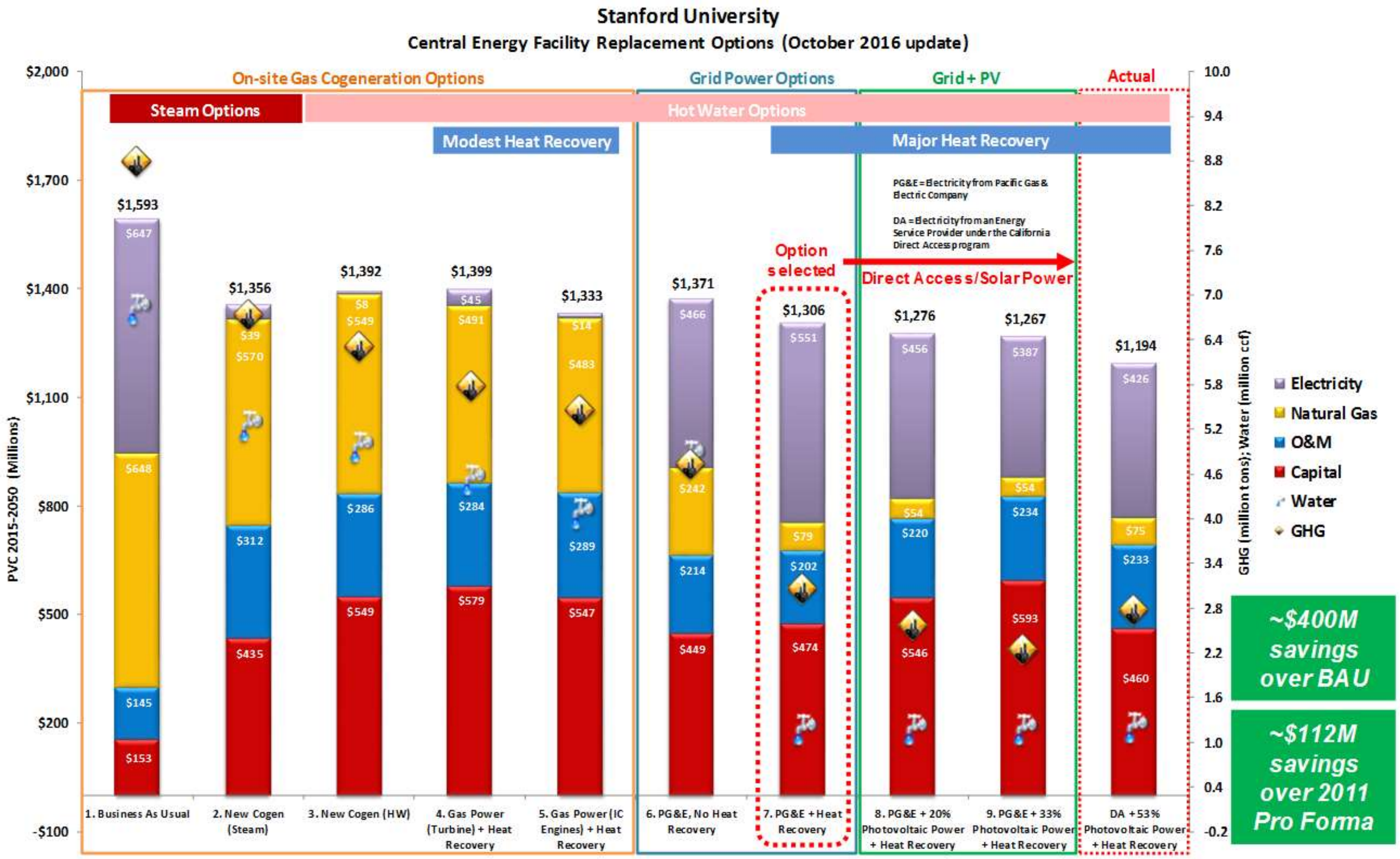
3.5 Comparison of Project Economics Across System Design

Prior to deciding on a specific system design, one must compare the project economics to alternatives, such as CCHP, CHP, SHP, and a building-level system. Furthermore, there also may be several different design variations within each of the aforementioned categories. A *business as usual* (BAU) system design is defined as a continuation of the existing energy system and used as a baseline for comparison. Section 4 (next section) describes techno-economic feasibility assessments, which aid in arriving at the subset of system design options that are sufficiently promising for more detailed evaluation.

As with any major infrastructure project, a variety of methodologies can be used to carry out the economic assessment. The methodology used in this report is to calculate the present value of projected cash flows. Standard project finance inputs such as discount rate, project lifetime, cost input estimates, cost of debt, etc. are all incorporated into the assessment. Sensitivity analyses can be used to determine to what extent the results change given changes in input assumptions. When assessing project economics, it is also critical to accurately capture all costs and benefits of each system including potential offsets, such as those described in section 3.4.

For illustration, Figure 3 summarizes the results of the economic assessment of multiple central energy replacement options, duplicated here from the SESI Case Study. Along the horizontal axis are all system design options considered, categorized by power source (on-site gas cogeneration, grid power, grid power plus solar), heat network (steam or hot water), and level of heat recovery (none, modest heat recovery, and major heat recovery). On the left vertical axis is present value costs in millions over the anticipated 35-year system lifetime (2015-2050). Costs are broken down by four sources: electricity, natural gas, O&M, and capital. Water usage and GHG emissions are plotted along the right vertical access to reflect the environmental impact of each system design option. Figure 3 is specific to Stanford's detailed evaluation of replacement options for their 1987 cogeneration plant (BAU). However, the relative trends between energy system design options are transferable to other locations.

Figure 3: Stanford's central energy facility replacement options



4. Feasibility Assessment

The progression of district energy system design can be categorized into four stages, as shown in Table 4. As a project advances through each stage, the number of system design options under consideration narrows, estimates of project costs are refined, and project risk declines.

Table 4: Stages of a district energy project

1. Pre-Feasibility	● This is the initial stage of assessment when all system design options are under consideration. Pre-feasibility assessments are typically carried out several years in advance of the beginning of project construction and require minimal input. Tools for pre-feasibility assessments may be referred to as *screening tools*.
2. Feasibility	● The second stage is the feasibility assessment. The category of models to determine whether a given system design is technically and economically feasible subject to the operational constraints of component technologies and other physical limitations of the system operation fall within the general category of *techno-economic feasibility models*. More detailed input data is required at this stage in the assessment, such as hourly heating and cooling loads and long-term forecasts for electricity and fuel prices. The outcome of a feasibility assessment may be expressed in a chart such as that shown in Figure 3. At the end of this stage, stakeholders decide on the final energy system architecture and have estimates for equipment sizing.
3. Engineering Design	● The next stage is detailed engineering design of the identified system architecture, and refined costing.
4. Request for Bids	● The final step of the project is issuing a request for bids. At this stage, all aspects of system design are finalized.

This white paper focuses on models and methodologies that fall within the first two stages: pre-feasibility and feasibility. Given promising results from results of these two stages, additional time and resources can be devoted to carry out a more detailed technical and financial assessments. Please note that a companion deliverable of this four-part APPA-funded project catalogues and describes pre-feasibility and feasibility tools for thermal microgrids. Discussion of specific tools and their capabilities is reserved for that deliverable, scheduled to be released in Summer 2018.

Prior to beginning any modeling work, stakeholders should determine a prioritized list of goals, such that a subset of system design concepts can be evaluated via a pre-feasibility assessment. As discussed in section 1.3, a community may have a variety of goals for its local energy system. One goal could be, for instance, reducing GHG emissions by 40% by 2030, which a thermal microgrid would be instrumental in helping to achieve. Stanford's goals were to minimize GHGs and energy and water usage within reasonable cost, for instance.

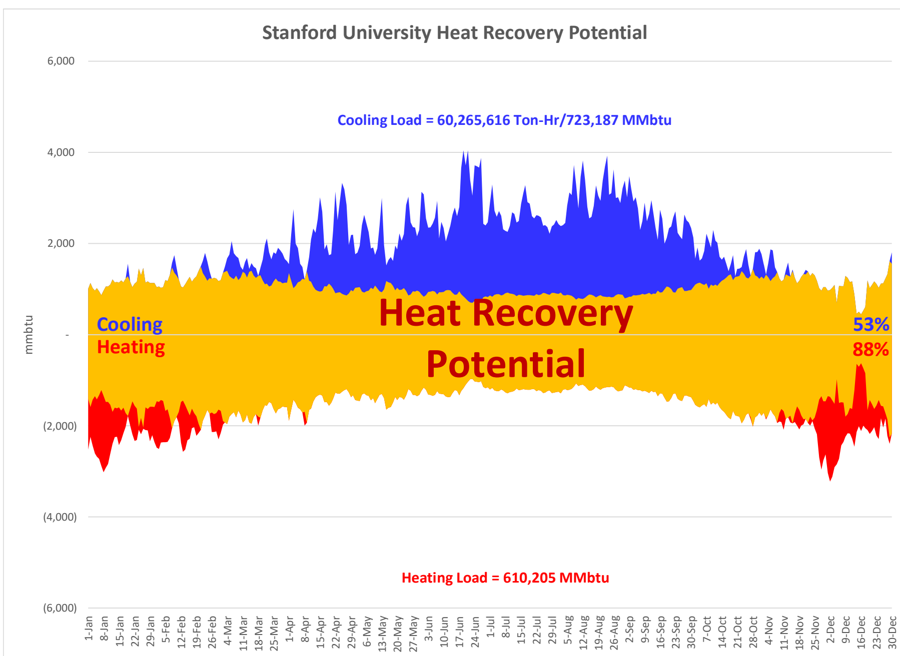
Also prior to the pre-feasibility assessment, the boundary must be defined within which the local energy system will serve customers. Multiple geographic boundaries could be evaluated, adjusted iteratively throughout the design phase. For the case of Stanford, the geographic region of interest included the university campus.

4.1 Pre-Feasibility Assessment for Thermal Microgrid Design

A common component to any feasibility assessment is collecting the heating and cooling loads of all buildings within the district, or, if historical data is unavailable, modeling the loads using building energy modeling tools. Calculating hourly heating and cooling loads is needed to determine the overlap in heating and cooling needs and the resultant waste heat recovery potential. Significant waste heat recovery potential warrant further investigation into the feasibility of a thermal microgrid.

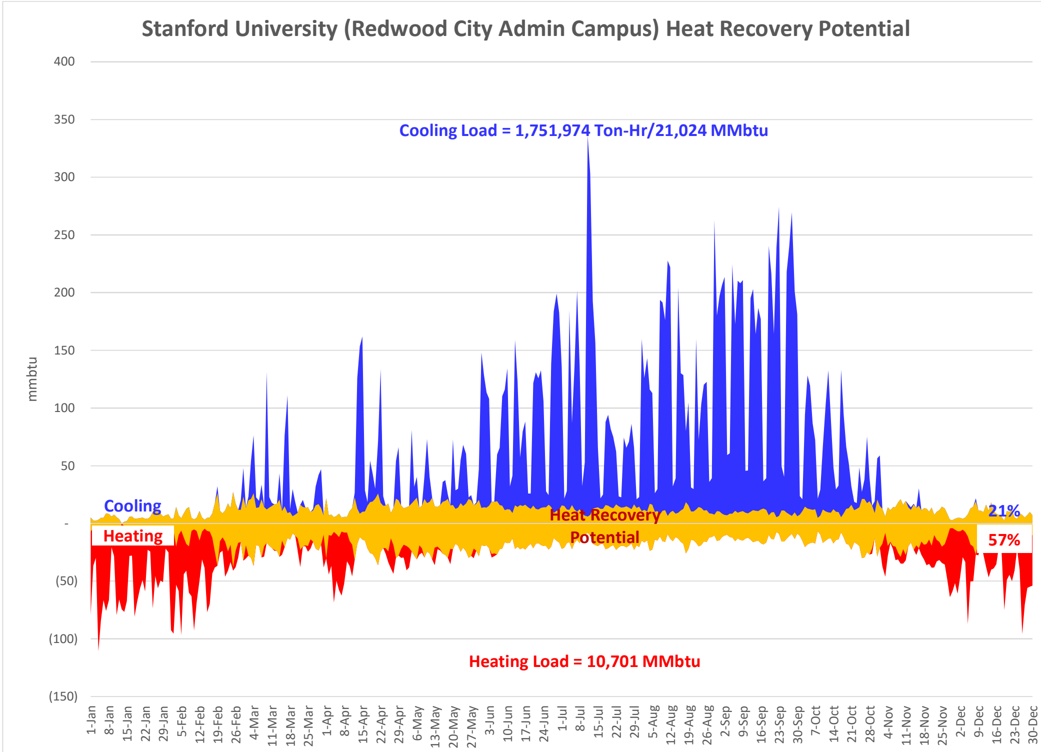
Figure 4 shows the historical hourly heating and cooling loads for Stanford campus over a calendar year. This figure accounts for hot and cold storage in the calculation of heat recovery potential. In addition to Stanford, substantial opportunity for waste heat recovery is observed in other regions, as shown in Figure 5. As shown on each figure, even in significantly different climate zones and on non-research university campuses, the potential for waste heat recovery is substantial. Stanford's administrative campus is currently under construction and utilizes a SESI system design[23].

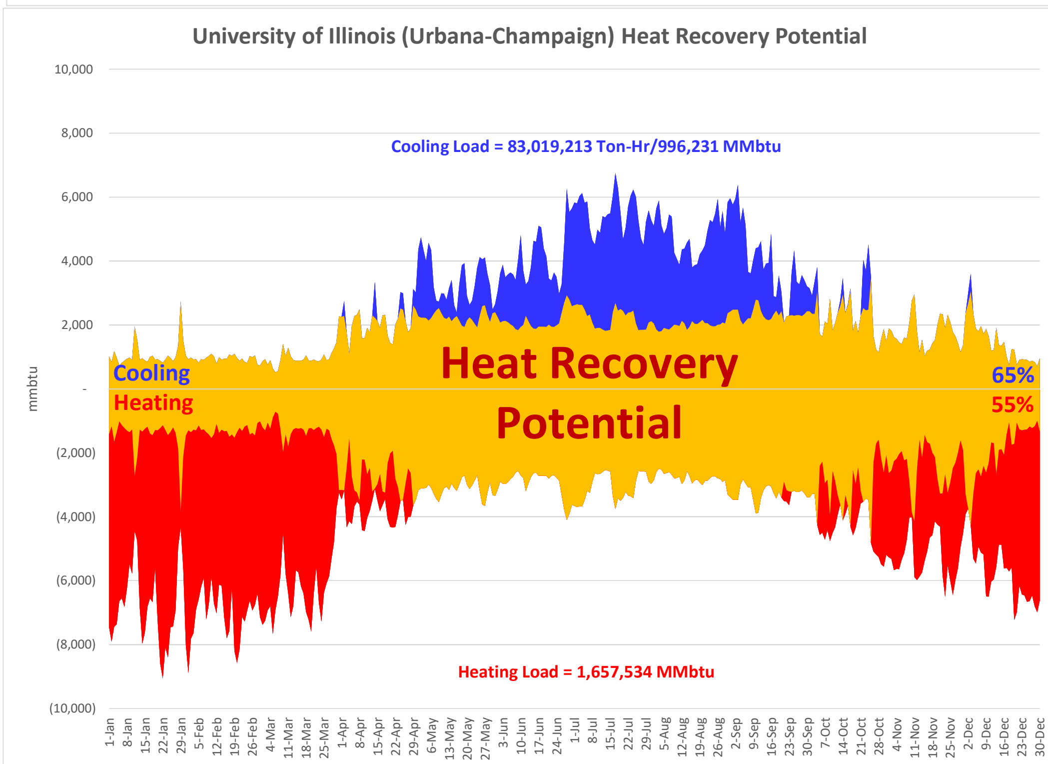
Figure 4: Stanford's campus-wide hourly heating and cooling needs over a year, indicating heat recovery potential for a system incorporating hot and cold thermal storage

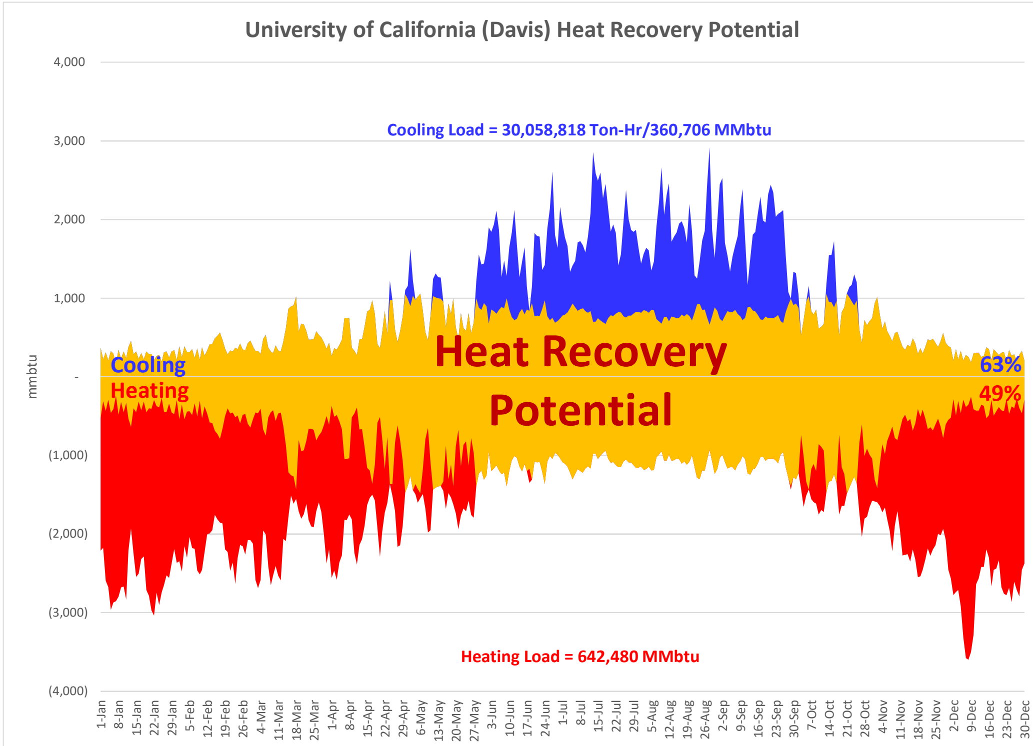


[23] https://redwoodcity.stanford.edu/

Figure 5: District hourly heating and cooling needs over a year for Stanford's Redwood City administrative campus (top), University of Illinois Urbana Champaign (middle), and University of California Davis.







When building waste heat recovery potential is minimal given low coincident cooling needs, the system design can incorporate supplemental heat sources, such as renewable heat recovery from the ground, surface water, or air, or other described above (Table 2). In addition to thermal microgrid system design options, building-level design options and traditional district energy system architecture (i.e. CHP) could also be evaluated simultaneously for comparison purposes.

Note that these diagrams depict the maximum overlap of heating and cooling that could be considered. Conditions such as density of load, difficulty of thermal grid installation and other constraints may limit the number of buildings can be economically connected to the thermal grid.

4.2 Methodology for Techno-Economic Feasibility Assessment

Upon narrowing the system options after the pre-feasibility assessment, the next stage is determining project feasibility. The basic methodology is as follows. Examples from Stanford's energy system transformation are included for illustrative purposes. Note that some of the data will already have been collected for the pre-feasibility assessment.

1. **Gather input data**. There are three main categories of input data.

    a. *Heating and cooling load profiles*. The energy system must be designed to meet the heating and cooling needs of the region over the system lifetime. As such, heating and cooling load profiles are a key input to the model. Building loads vary depending on the specific building use (hospital, office building, etc.), time-of-day, season, and building age, among other factors. The higher the load data resolution (temporal and spatial), the more confidence one can have in the results of the feasibility assessment, but the more onerous the study. Two features of the load profile are the base load (minimum level of demand) and the peak load (maximum demand), which are often expressed on an hourly basis and are critical for determining appropriate system design and sizing. If historical load data is unavailable, one can estimate the heating and cooling load profiles using building simulation models or by making rough assumptions based on square footage, climate zone, building use, etc. Irrespective of whether historical data is available, one must consider anticipated *future* energy consumption and development over the project lifetime, which can be decades. Figure 4 (above) shows Stanford's hourly heating and cooling over a calendar year, in addition to the heat recovery potential.

b. *Electricity, fuel and emissions price forecasts*. Forecasts for electricity, fuel and emission prices are key inputs to the model, especially to compare to baseline system designs. Often multiple forecasts are used to identify a range of potential outcomes.

c. *Technology characteristics*. If it is not already integrated into the model, information about component technologies incorporated into the system design must be provided as inputs, such as lifetime, rated capacity, operational constraints, capital cost, fixed and variable operations and maintenance costs, efficiency and emissions rate. Technology information may be included in libraries already integrated with the modeling tool.

d. *Other*. In addition to the primary data categories, the user may provide other inputs such as discount rate, financing costs, and any specific stakeholder objectives identified (e.g. a GHG emissions cap).

2. **Run techno-economic feasibility model**. Using the input data gathered in the prior step, run the model for all system designs of interest. Output of a model run may include present value cost (PVC), GHG emissions, and water usage. Financial output could be framed in terms of cost-effectiveness from a customer, utility, and/or societal perspective. Results from Stanford's are shown in Figure 3 (above).

3. **Iterate through steps 1-4, modifying design choices, input assumptions, and objectives**. Depending on the outcome of the model runs, one may wish to evaluate modifications to the initial geographic region, system designs and other input assumptions. In this respect, the techno-economic feasibility assessment is an iterative process that may lead to alternative design options that were not originally considered.

4.3 Key Feasibility Drivers

The primary feasibility drivers of a thermal microgrid compared to a building-level system design are the following.

- **Load density**. The primary feasibility driver of a district energy system is the density of heating and cooling needs within the geographic region of interest. Heating and cooling networks are more localized than electric networks. Furthermore, the thermal network is a major source of project costs: the closer the buildings and the denser the load, the more cost-efficient the thermal network will be. The International Energy Agency (IEA) estimates that a region can be served economically with district energy if the heating load density is at least 0.93 kWh per square foot or the linear heat demand is at least 9,146 kWh per foot[24].

- **Cost of heating and cooling supply**. The cost of source heat is another primary feasibility driver. Advanced heat recovery enables low cost source heat for a thermal microgrid design. In addition to waste heat recovery from the building cooling process as in the Stanford energy system design, other renewable and waste heat recovery opportunities include data centers, industry, and air-, water- or ground-source heat, for instsance.

- **Load diversity**. Sizing each individual building for its annual peak demand is inherently more expensive than sizing a collection of buildings with load diversity. Especially with increasingly ambitious energy efficiency targets for buildings, the problem of sizing will become increasingly challenging. Advanced communications and controls to operate the resources and loads of the thermal microgrid can capitalize on load diversity and further enhance efficiency gains. Even though university campuses can capitalize on their high load diversity given different building uses, even aggregating loads of the same use (e.g. single family residential) can provide benefits. Load diversity, nonetheless, can be considered a key feasibility driver.

- **Implementation Difficulty.** The ease and relative cost of the implementation of the thermal network to connect the buildings is another key consideration and feasibility drive**.**

[24] District Heating and Cooling, Frederiksen and Werner (2013).

5. Assessment of Potential in the U.S.

Although a comprehensive quantitative study of the potential of thermal microgrids in the U.S. is beyond the scope of this white paper, we can provide insight on the potential based on existing literature, and technology and policy trends. Many types of state and federal energy and environmental regulations would serve to promote thermal microgrids and their energy efficient, cost-effective approach to decarbonization, including a carbon tax, a cap-and-trade program, energy efficiency targets, and local air quality standards. As referenced in prior sections, there are several non-technical barriers that could significantly inhibit thermal microgrid deployment, such as the following.

- **General familiarity with district energy and advanced waste heat recovery** in the U.S. is lower relative to Europe and Asia, given the lower incidence rate of projects. Additional effort is required for stakeholder education – especially policy makers and the public – to ensure thermal microgrids are considered alongside other options for decarbonization.

- **Parts of the value chain for district energy are under-developed in the U.S.**, resulting in too few vendors to create a competitive market. Furthermore, thermal microgrid systems such as Stanford's are an emerging system design on the global stage, meaning expertise with this system type is even more scarce. Government policies to support upstream development of the value chain could help spur efficient market development.

- **Complex, multi-stakeholder processes** for energy infrastructure development can be a major inhibitor to district energy deployment. Active engagement of stakeholders and consideration and responsiveness to concerns will aid in navigating the project development process.

- **Securing the large initial investment** required for capital outlay is another challenge. Sticking points for potential investors include depreciation duration, access to finance, and potential financial risk given uncertainties in the final rates, actual building load, and energy market evolution (policy and regulations), for instance.

- **Timing of building equipment replacement** in existing developments, unless advanced building retrofits are considered, is a critical practical factor in district energy deployment and of primary importance to potential customers. The development of the thermal network could potentially be timed, such that it is developed in phases, matching natural replacement times of buildings.

- **Space constraints** for siting and hosting central energy equipment for district energy can also be a challenge in some areas. Regions with sufficient thermal density are more likely to encounter space constraints.

- **Customer acquisition** can be another challenge, given factors such as negative perceptions about reliance on long-term contracts for heat supply. Although on the customer side, these downsides are counterbalanced by consumer convenience of not having responsibility for boilers and fuel purchases.

- **Project replicability** is another barrier. Unlike with CHP, where there are now several packaged system options available in a variety of system sizes, thermal microgrids have not reached that state of maturity. Standardization would allow for streamlined installation and maintenance and lower overall project risk.

- **Economic and policy uncertainties over the long project lifetime** are also a barrier. The world is rapidly changing, making long-term investment decisions, such as energy infrastructure development, more challenging.

As mentioned above, carrying out a comprehensive potential assessment for thermal microgrids across the U.S. is a complex undertaking beyond the scope of this white paper. However, it is the subject of ongoing R&D activity. Please see Appendix B for general background on energy technology potential assessments and application to thermal microgrids.

6. Utility Business Models for Thermal Services

District energy systems, like electricity and gas networks, are natural monopolies. There are multiple design choices for utility business model for thermal services, which are largely similar to the options available for municipal electric utilities. The subsections below identify and describe some of the primary business model design considerations.

6.1 Ownership & Governance Structure

There are multiple ownership and governance structures for municipal utilities that can be utilized for thermal services, just as they are used for electric utilities. Each structure has strengths and weaknesses, and the best ownership and governance structure for a specific system will depend on the community's desired amount of control, investment, and risk, as well as the overarching local energy system goals and objectives. Whatever business model is chosen, it should ensure that all stakeholders achieve financial benefits from the development of a district energy system, including the investors, owners, operators, end customers and municipalities.

Four common business models for district energy systems are as follows.

- **Enterprise fund and operational department within a university or local government**. Municipal utilities that exist within a municipal government or university typically establish themselves as an enterprise fund and an operational department within the organization. The City of Palo Alto's Utilities Department and Stanford's SESI are both established in this way. The governance structure of the department is the same as the larger organization. For instance, a city council will act as the governing body for the municipal utility. Utility directors are granted authority by the governing body to make procurement decisions within approved limits. Procurement exceeding this authority or decisions with important policy implications may require the full review and approval of the governing body.

- **Special district independent from existing local governments**. The second option is to establish a special district - typically referred to as a municipal utility district in this context - that is organizationally independent from established municipal and county governments and is governed by its own set of elected or nominated board members. The sole purposes of the district would be to develop, own and operate the utility, and the governing board is defined upon creation, contingent upon constraints in the enabling state legislation.

- **Community-owned non-profit cooperative**. Third, a municipality can form a private, wholly community-owned non-profit cooperative, where customers (owners) have indirect representation for selecting the board. This model is common in Europe.

- **Community-owned limited liability corporation**. The fourth option is to form a private, wholly-owned subsidiary, with a board comprised of representatives of local building owners, local electric utilities and municipalities. This is typically achieved using a special purpose vehicle (SPV). Although structured as a for-profit entity, municipalities often own stakes in the company. District Energy St. Paul has this ownership and governance approach. In Germany, utility services are commonly provided by *stadtwerke*, which typically are structured as a limited liability, for-profit entity majority-owned and therefore controlled by a municipality[25].

There are also a variety of other public-private partnership structures that could be used, such as joint ventures and concession models[26]. Moreover, a completely privately owned, for-profit corporation could develop, own and operate a thermal microgrid. However, the downside of this model is that a for-profit entity has a higher cost of capital and they do not incorporate community-driven governance approaches that may be needed to make the project a success. Furthermore, such a project must comply with zoning, environmental, health and safety requirements. Navigating compliance with such laws and regulations requires cooperation with local agencies. Therefore, most successful district energy business models incorporate the public sector in some way.

Advisory commissions comprised of industry experts from within the community may be established and leveraged to provide an additional layer of review and stakeholder feedback that could be incorporated into any of the organizational structures described above.

6.2 Metering & Rate Structures

Thermal microgrid systems that serve multiple customers must incorporate metering equipment to measure customer-level energy usage, so that accurate billing can be carried out for all entities within the service territory. For systems that cover a region with existing electric utility accounts, the existing electrical metering equipment should be sufficient for accurate billing for electric service. However, submetering equipment at the building level may be desired. State or local regulations may dictate what rates may be charged in the submetering context. For instance, in California, the same rate as the local utility must be used for electricity charged to tenants.

The thermal services provided by the local energy system will require separate, dedicated metering infrastructure. Furthermore, the metering equipment and approach will be dependent upon the medium of delivery: water vs. steam. For water-based systems, the focus of this report, a simple approach is to install a single meter at the building for each network for measuring supply and return water temperature. The temperature differential can then be used to determine the amount of heat delivered to the building, which is used to charge the customer. This same approach can be applied for both the chilling and the heating loops. Of course, this is only one approach for metering thermal services. An alternative is charging based on square footage or an engineering estimate of energy needs. Ultimately, the community and the governing board must decide on appropriate cost-recovery mechanisms for their energy system, compliant with local, state and federal regulations.

For heating, cooling, and hot water consumption, charging based on square footage or estimation of usage, based on common engineering standards, may be the easiest and most straight forward option. The electrical equivalent to this is "master metering", where the public utilities commission designates baseline quantities of electricity for the average residential customer's reasonable energy needs[27]. This

[25] See for instance Munich's stadtwerke, Stadtwerke München GmbH: swm.de (English option)

[26] For more case studies of district energy systems with various ownership and governance structures, please see the IEA Technology Collaboration Programme on District Heating and Cooling including Combined Heat and Power, Governance Models and Strategic Decision-Making Processes for Deploying Thermal Grids.

[27] Please note that this approach is only appropriate when the functional use and occupancy time of all spaces is similar. If vast differences exist, various factors must be applied to higher load spaces to account for greater heating and cooling consumption.

same type of metric may need to be developed for district-scale heating and cooling. Metering the water flow is another option, though this can be costly and problematic.

7. Conclusions, Outlook & Next Steps

The “three D’s” -- decentralization, decarbonization and digitalization -- are driving the transformation of the energy sector, and concurrently encouraging consideration of efficient district electrification as a technology pathway for achieving clean, affordable and reliable energy systems to serve communities. There are several non-technical challenges to market uptake, as described in this report. Nonetheless, they are not insurmountable, and public power in particularly is in a unique position to overcome them.

Further evaluation of the market potential and the transferability of thermal microgrids across climate zones and community circumstances is needed, while comprehensive evaluation of technology pathways for decarbonization and resultant policy formulation at the state and local levels are both still in formative stages. This white paper is the deliverable for Part 1 of a four-part APPA-funded project, *Leveraging Experience from Stanford and EDF to Develop Information and Tools for Thermal Microgrid Feasibility Assessments*. The following companion deliverables are either completed or in development, with anticipated publication dates included in parentheses.

- Part 2: Case study describing the Stanford Energy System Innovations (SESI) project, in which their campus-wide cogen system was transformed into to renewable electricity powered heat recovery with low temperature hot water distribution. (Early 2018)
- Part 3: A compilation of tools for assessing technical and economic feasibility of thermal microgrids. (Summer 2018)
- Part 4: Case studies applying the tools to carry out techno-economic feasibility assessments of regions within municipal utility service territories. (Fall 2018)

Please see Appendix A for additional further reading.

Appendix A. Further Reading

The following on-line references provide additional information on district energy project development and its role in achieving deep decarbonization.

- *Community Energy: Planning, Development and Delivery*, IDEA (2010). This free guide was developed to help land use planners and prospective project developers "understand and create or influence energy maps [...] and other information for use in master plans or development plans; gain an understanding of energy use in buildings and developments; recognize where there are opportunities for district energy projects, and understand the value of incorporating thermal energy considerations in planning efforts; translate energy opportunities into financially viable and deliverable, sustainable projects; [and] understand the stages of developing an energy project and who is involved in each."

- *District Energy in Cities: Unlocking the Potential of Energy Efficiency and Renewable Energy*. UNEP (2015). This report: "identifies modern district energy as the most effective approach for many cities to transition to sustainable heating and cooling, by improving energy efficiency and enabling higher shares of renewables. Countries such as Denmark have made modern district energy the cornerstone of their energy policy to reach their goal of 100 percent renewable energy, and, similarly, other countries, such as China, are exploring synergies between high levels of wind production and district heating.

  Locally appropriate policies are required to harness the multiple benefits of district energy systems, lower upfront costs and reduce financial risk for investors. This publication is one of the first reports to provide concrete policy, finance and technology best-practice recommendations on addressing the heating and cooling sectors in cities through energy efficiency improvements and the integration of renewables, both of which are central to the energy transition. These recommendations have been developed in collaboration with 45 champion cities, all of which use district energy, with 11 of them using it to achieve 100 per cent renewables or carbon-neutral targets."

The following recent textbooks can provide more detailed technical information for interested readers.

- *District Heating and Cooling*, Svend Frederiksen and Sven Werner (2013).
- *Advanced District Heating and Cooling (DHC) Systems*, Edited by R. Wiltshire (2016).

Appendix B. Energy Technology Potential Assessment

B.1 Introduction to Technology Potential Assessments

Energy technology potential assessments are customarily divided into four stages[28]. First, *resource potential* is the energy content of the resource after accounting for any theoretical physical potential and constraints. Second, *technical potential* is the market size of a technology after considering resource potential and all technical limitations and constraints, such as technology efficiencies, land-use constraints, or topological constraints to arrive. Third, *economic potential* takes the technical potential and accounts for projected costs and benefits such as technology and fuel costs to arrive at the level of technology deployment that is economically viable (i.e. cost-effective). Fourth, the *market potential* is an estimate of the ultimate, realistically achievable market size, using the technical potential and accounting for all remaining factors affecting deployment, such as policies and regulations, consumer behavior, and competing products. At each stage of the assessment from resource potential to market potential, the estimated market size decreases, often considerably. The potential for an energy generation technology is calculated in terms of megawatts capacity, or megawatts capacity thermal equivalent for a district energy system such as a thermal microgrid. Table 5 illustrates the stages of a potential assessment using rooftop solar PV as an example.

Table 5: Illustration of energy technology potential assessment for rooftop solar PV in the U.S.

Resource Potential	• Resource potential is the average annual solar energy reaching building rooftops in the U.S. This value could be estimated, for instance, using location-based solar irradiance data from the National Oceanic and Atmospheric Association (NOAA) meteorological stations and satellite imagery analysis for building roof footprints.
Technical Potential	• Technical potential is the average annual solar electricity that could be generated if solar PV was installed on all suitable rooftops, which can be estimated, for instance, using geographic information systems (GIS) analysis to calculate the solar suitable area of rooftops after eliminating surfaces that are too steeply sloped, poorly oriented, shaded, cluttered with rooftop equipment, or otherwise unable to accommodate solar panels. The calculation accounts for solar PV panel and inverter efficiencies to estimate output.
Economic Potential	• Economic potential is the fraction of technical potential that is cost-effective, which occurs when the total value created from system (i.e. bill savings) exceeds the system costs (solar PV panels, inverters, permitting, maintenance, etc.) over the system lifetime.

[28] See, for instance, NREL's page on renewable energy potential assessments: https://www.nrel.gov/gis/re-potential.html.

Market Potential	• Market potential is the estimated achievable adoption of rooftop solar PV, which uses the economic potential as an input and accounts for regulations and policies to support rooftop solar PV adoption (e.g. streamlined permitting), demographic data, consumer behavior, and comparison to competition (e.g. grid supply).

B.2 Application to Thermal Microgrids

The technical potential of thermal microgrids is the market size based on the technology's ability to meet end-customer energy needs. The technical potential for thermal microgrids can be divided into two parts: i) meeting the additional electricity load from electrification using carbon-free electricity, and ii) meeting the thermal needs of a site by converting the on-site building energy equipment from an existing fossil-fuel based system to a thermal microgrid leveraging advanced waste heat recovery. Regarding the former, using rough approximation, switching natural gas to electricity would result in an additional annual usage of 2,300 TWh[29]. This additional electricity load must be met by decarbonized electricity supply. The National Renewable Energy Laboratory (NREL) carried out an extensive GIS-based analysis to calculate the technical generation potential of several renewable energy technologies in the U.S. The result was hundreds of thousands of TWh of technical potential across the U.S.[30]. Although the study does not go so far as to consider technical feasibility of renewable energy integration, given a variety of renewable energy technologies were evaluated in the NREL study, with different hourly, daily and seasonal production profiles, and that the resultant technical potential is many orders of magnitude greater than the very rough anticipation of need from building electrification, one can safely assume there is sufficient renewable energy generation technical potential to accommodate electrification of the building sector, whether by districts or by a building-level approach. This general conclusion is consistent with regional and national decarbonization studies, all of which indicate that decarbonization is not limited by technical potential of clean energy supply[31].

Given the above result, the technical potential is limited by feasibility of deploying the thermal network and the potential for renewable or waste heat recovery. Technical potential for the technology can be expressed in terms of system capacity in gigawatts thermal equivalent to meet the thermal needs of the study region, or for district heating potential exclusively, petajoules. A rigorous technical potential assessment would account for technical performance and limitations of on-site energy efficiency measures, thermal storage technologies, central and distributed heat recovery equipment, and

[29] Annual U.S. natural gas usage in 2016 in the commercial and residential sectors totaled 7,450,000 million cubic feet (U.S. EIA). Using the 2016 annual average heat content of natural gas of 1,037 BTU per cubic foot (U.S. EIA), this equates to approximately 7,700 million MMBTU. As an approximation, we assume all natural gas used in the residential and commercial sectors is used for space and water heating. Using rough approximation, switching natural gas to electricity would result in an additional annual usage of 2,300 TWh, using 3,412 BTU per kWh and assuming the appliance efficiency of each are equivalent. For reference, annual U.S. electricity sales in 2016 totaled 3,762 TWh.
[30] A. Lopez et al., U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis, NREL/TP-6A20-51946, July 2012.
[31] See footnote 2.

topological or system constraints of the heating and cooling networks. Carrying out a calculation of the technical potential would incorporate the following steps[32].

1. Select regions where the density of thermal load exceeds a specified threshold that makes thermal microgrids – and the development of a thermal network in a district energy system more generally – viable. As mentioned above, a region may be suitable for district energy if the heating load density is at least 0.93 kWh per square foot or the linear heat demand is at least 9,146 kWh per foot[33]. This can be used as a floor for load density in the technical potential assessment. In all other regions with insufficient thermal density, building-level electrification is a more suitable decarbonization pathway.
2. Model the hourly heating and cooling needs of the collection of buildings within each region that has sufficiently high thermal density. Thanks in part to the Open Government movement, an increasing amount of data is published by cities and states, including GIS data sets of land zoning (e.g. residential, commercial) and building information (e.g. number of floors, square footage, age). These data can be combined with other data sources (e.g. weather, census data, satellite imagery) and advanced analytics such as machine learning algorithms to model thermal loads quickly across large potential markets.
3. Estimate thermal microgrid potential in terms of megawatts capacity thermal equivalent needed to meet thermal loads of each region, calculated taking into consideration the overlap in heating and cooling loads; ground-, water-, and air-source heat recovery opportunities; hot and cold thermal storage; and, advanced analytics and controls. If a site has multiple thermal requirements (i.e. chilled and hot water), the thermal microgrid can be sized to meet the largest of the loads. This results in the total technical potential.

The technical potential is a necessary input for estimating a realistically achievable market size.

Economic and market potential builds on the technical potential by taking into account all other considerations to reach an ultimate estimated market size. Economic potential includes costs and benefits of deploying technically feasible systems. As mentioned previously, a district energy approach is generally economically advantageous if the cost savings from centralized versus building-level energy equipment is larger than the substantial costs of developing the thermal network. Furthermore, the cost-effectiveness of the distribution network is dependent upon the thermal density of customer demand, where the denser the load, the more cost-effective the service. Inputs for estimating the economic potential would include all the cost categories identified in section 3 over the system lifetime, which are compared to a baseline system design to determine cost-effectiveness. A comprehensive study of the potential of thermal microgrids in the U.S. is beyond the scope of this white paper, but the subject of ongoing R&D activity.

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[32] See the following reference, for instance, for a technical potential study of district heating in the U.S.: Gils, H.C., et.al. "GIS-Based Assessment of the District Heating Potential in the USA." Energy 58 (2013): 318–29

[33] District Heating and Cooling, Frederiksen and Werner (2013).