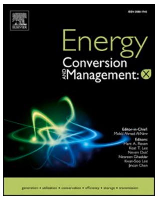
Energy Conversion and Management: X 24 (2024) 100726

Contents lists available at ScienceDirect

Energy Conversion and Management: X

journal homepage: www.sciencedirect.com/journal/energy-conversion-and-management-x



Review

Decarbonized district energy systems: Past review and future projections

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ARTICLE INFO

Keywords:
District energy system
Thermal energy network
District heating and cooling
Decarbonized
Heat pump

ABSTRACT

A significant portion of building energy usage globally goes toward space heating and cooling, and whether using individual building systems or district systems, those loads are often met with carbon-based sources. As we shift to decarbonize the electrical grid, we must also consider how to best decarbonize our heating and cooling loads in a way that aligns well with a renewable electrical grid. District energy systems (DES) distribute thermal energy to buildings in a community using shared resources and infrastructure. Unlike other decarbonized solutions, DES has the potential to reduce strain on the electrical grid and integrate renewable thermal sources and waste heat. This review will focus on current technology for decarbonizing DES and will discuss important design considerations as well as a qualitative comparison to individual systems.

A DES consists primarily of energy sources and storage, a distribution network, heat conversion, and user loads (such as buildings). We classify heating and cooling sources as constant, variable, or dispatchable, and review carbon-free options. The design of a DES depends on multiple factors including the nature of the energy sources, the loads to meet, central or distributed plant design, and the potential need for redundancy and resilience. We review design decisions including what sources and loads to connect, what distribution network design to implement, and the modeling and control of DES, and consider how to best integrate with a fully renewable electrical grid. Currently, DES designs are unique for each installation and require tailoring for each site. Due to the large number of distributed components, controls are important for DES, both at a component and system level. Future trends to consider include rising cooling demand loads, winter electrical peak load, conversion of traditional DES to state-of-the-art decarbonized systems, and the changing costs and economics of DES.

Introduction

Conventional district heating and cooling systems, characterized by centralized boilers for hot water or steam and electric-based chillers for chilled water, have substantial site and source carbon emissions. In the past few decades, these systems have undergone improvements to reduce energy consumption and incorporate more sources of available waste heat. To meet the global carbon emissions goals, the majority of countries have committed to achieving carbon neutrality by 2050, with the United States planning a 50 % reduction in emissions by 2030 [1]. To reach these goals, the decarbonization of our heating and cooling sector must be hastily and fully realized.

As of 2020, commercial and residential building energy consumption contributed 40 % of the United States' primary energy consumption, 73 % of electricity use, and 29 % of economy-wide emissions [2]. Of this, 53 % of energy used by residential homes in the United States went into space heating, cooling, water heating, and refrigeration [3], while heating and cooling of buildings accounted for more than half of the European Union's energy consumption in 2020 [4]. The dependence on fossil fuels to meet building loads must be reduced or removed to eliminate this source of greenhouse gas (GHG) emissions. One common solution for decarbonizing a single building is to electrify the heating and cooling infrastructure via individual air-source or geothermal heat pumps. However, even when the electrical source is fully decarbonized, electrifying all buildings will significantly increase electrical demand and may add to the mismatch of generation and demand at all timescales. For example, Buonocore et al. [5] showed that winter electrical peaking loads may exceed summer peaks in a foreseen scenario called the "falcon curve", a significant change from the current summer electrical peak loads. Therefore, a completely decarbonized heating and cooling system will need to consider how to meet summer and winter loads without relying on fossil fuel-generated electricity. While a fully renewable electrical grid is critical in reaching these decarbonization goals, this paper will assume that a future renewable grid is possible and instead focus on meeting heating and cooling demands in a way that aligns with a renewable electrical grid.

Utilizing advanced district heating and cooling systems may be one

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https://doi.org/10.1016/j.ecmx.2024.100726
Received 29 May 2024; Received in revised form 22 September 2024; Accepted 23 September 2024

Acronyms

1G	first generation
2G	second generation
3G	third generation
4G	fourth generation
5G	fifth generation
AC	air conditioning
CHP	combined heat and power
COP	coefficient of performance
DES	district energy system
DHC	district heating and cooling
ETS	energy transfer station
GHG	greenhouse gas
HP	heat pump
LCOE	levelized cost of energy
NREL	National Renewable Energy Laboratory
PV	photovoltaic
RE	renewable energy
TEN	thermal energy network
UBEM	urban building energy modeling

way to help reach a decarbonized solution, without straining the electrical grid with winter peaking. Historically, district heating systems delivered steam or hot water from a centralized plant to users, meeting building heating loads in an efficient manner. Often, the heat was generated from industrial processes or combined heat and power plants (CHP) where waste heat from the combustion of fossil fuels was then utilized by the district heating system. Even in areas with functioning district systems, as the power sector decarbonizes, many CHP plants will be phased out over time and newer decarbonized solutions will need to be considered. Over time, improvements to the district technology have reduced water temperatures and employed more modular construction to improve efficiency and reduce costs. Current district systems may also include cooling as part of the same system or in a parallel system, thus forming a district heating and cooling system. As designs have become more variable and bidirectional heat flow occurs, we feel the term district energy system (DES) more accurately reflects these systems that meet buildings' heating and cooling loads. For this reason, DES will be used throughout the paper.

A generalized comparison of different heating and cooling topologies is shown in Fig. 1 for individual building heating and cooling, traditional district heating and cooling, and decarbonized DES. Energy sources can come in the form of electrical sources which run equipment such as air conditioners or heat pumps, fossil fuel resources that may be combusted on-site in a furnace, or thermal sources which may be used directly or coupled with a heat pump to increase/decrease the temperature to the desired operating temperature. Uniquely, state-of-the-art DES now include storage for thermal energy dispatch, while individual systems or traditional districts often used little to no explicit thermal storage to meet user loads because they could rely on the electrical grid and fossil fuel infrastructure for the flexibility needed to adapt to changing demand. Additionally, as new components such as thermal storage or low-grade heat are added to the DES, the design and operation of the district becomes more complex and becomes more critical to achieving high performance.

DES could be designed to meet multiple performance goals including minimal capital cost, minimal consumer cost, improved resilience, or more recently, minimal emissions. In this review, we will focus on systems where the entire network is designed to reduce GHG emissions such as carbon dioxide (including fugitive emissions). Therefore, it is assumed that with a future electrical grid, the electricity used to operate the DES including heat pumps, circulation pumps, and controls will come from carbon-free sources. Decarbonizing both the emissions on-site and requiring that the electricity come from carbon-free sources results in decarbonized scope 1 and 2 emissions for these systems. Note that reducing GHG emissions overall is also a goal, which means additional work should be done to reduce refrigerant leakage from heat pumps and other emissions within the DES.

The potential to reduce emissions by utilizing a DES has already been demonstrated. Stanford University switched from gas-fired CHP to electricity-driven heat recovery chillers and reduced GHG emissions by 65 % [6,7]. The Colorado Mesa University and Ball State University systems (see Table 1) reduced fossil fuel emissions from heating and cooling by 75 % and 19 %, respectively [8,9].

In the residential sector, converting current heating systems to heat pumps reduces carbon emissions in most states, accounting for electricity production emissions [10]. However, more research is needed to understand the impacts of decarbonizing an entire district and to consider how decarbonization affects both the in-home emissions along with the energy source emissions and regional electrical grid. The environmental impacts of installing single home geothermal heat pump

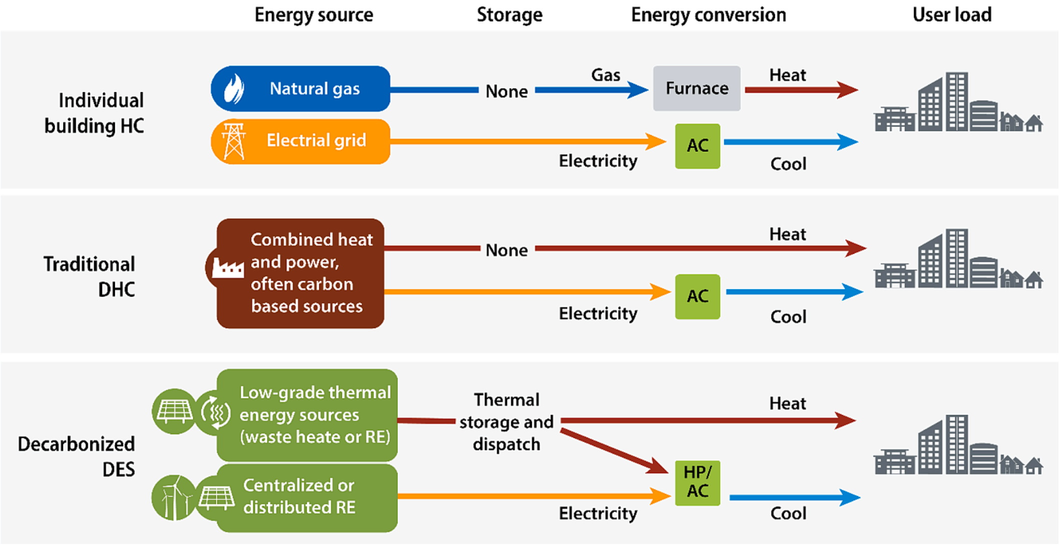

Fig. 1. Overview of energy use to meet building loads for individual building heating and cooling (HC), traditional district heating and cooling (DHC), and decarbonized DES including the use of heat pumps (HP) and air conditioners (AC).

Table 1

Selection of DES, mainly in North America, with novel decarbonized system aspects. Includes year installed (or upgraded), system type, storage, and thermal sources (with a focus on unique or decarbonized sources).

Site	Installed (or upgraded) Year	System Type	Thermal Source or Storage	Thermal Conversion	References
Colorado Mesa University. Colorado, USA	2008	5G DES, one pipe loop, ambient temp	471 boreholes, 91–152 m deep. Cooling towers, irrigation HX	heat pumps at users	[8,19,22,23]
Mjinwater. Herleen, NL	2013	5G DES, two pipes, bidirectional flow	flooded mine as open-loop thermal storage	heat pumps at or near users	[24–26]
Whisper Valley “GeoGrid.” Texas, USA	2017	5G DES, ambient temperature	237 boreholes at 107 m deep distributed along loop. Cooling tower	heat pumps at users	[27–29]
Eversource networked geothermal pilot. Massachusetts, USA	2023	5G DES, one pipe, ambient temperature	88 boreholes at 170–215 m deep	heat pumps at users	[30,31]
Drake Landing Solar Community. Alberta, CA	2007	4G DES, two pipes	144 boreholes at 35 m deep. 240 m^3 hot water storage. Distributed solar thermal collectors	heat exchangers at users	[32]
Cornell University. New York, USA	2000	3G DES	lake-source cooling, heating via traditional sources (CHP)	heat exchangers at users	[33]
Ball State University. Indiana, USA	2012	3G DES, three pipes	3,600 boreholes at 122 m deep. Centralized heat recovery chillers	heat exchangers at users	[9,34]

(GHP) systems is well characterized and can be managed with proper planning and design [11]. Again, the district-level environment impacts need to be further studied to ensure that the location of heat sources and installation of the distribution network still have a net benefit to the environment.

There is still a lack of research and demonstrations of decarbonized DES in the United States. Historically, DES have been more common in Europe than in North America. Most DES examples in the United States are on college campuses or densely populated urban areas, totaling around 660 systems [12]. Few, if any, of these systems can be counted as fully decarbonized. While previous articles have reviewed 5G DES installations [13], or focused on modeling and control [14], the focus of this review will instead be on minimizing grid impacts through decarbonized DES. This review will consider types of components, importance of design, and current state of modeling tools to evaluate design options under the growing demand of these systems.

This paper will review the current technology for decarbonizing DES along with important components and design considerations for implementing an effective system. First, current technology and major components of DES are reviewed in Section “Current technology”, including a comparison of different decarbonization options, followed by a breakdown of the major heating and cooling sources in Section “Carbon-free heating and cooling sources” classified by dispatchability. Then Section “Design of district energy systems” reviews how to use those components for a real design and what should be considered in the design process. Finally, Section “Future trends and predictions” discusses future trends for decarbonized DES.

Current technology

The current standard in the literature for discussing changes to district heating and cooling systems over time is to use “generations,” where progressive generations increase system efficiency as new technologies are adopted. Based on previous definitions from Buffa et al. [13] and Lund et al. [15], the authors have chosen to define the district generations herein as:

- First-generation (1G) district heating used steam as the heat carrier.
- Second-generation (2G) district heating used pressurized hot water with temperatures over 100 °C as the heat carrier.
- Third-generation (3G) district heating uses lower temperature pressurized water with temperatures below 100 °C as the heat carrier. It also utilizes prefabricated and pre-insulated pipes.
- Fourth-generation (4G) district heating (and cooling) utilizes water as close to the required user operating temperature as possible as the heat carrier. The water is used directly for heating and cooling in buildings. The low temperature of the system allows for utilization of some low-grade heat.
- Fifth-generation (5G) district heating and cooling (or DES) uses ambient temperature water (10°–25 °C) as the heat carrier. The system temperature is too low for direct heating (though it may be suitable for direct cooling in some cases) and instead requires a heat pump at the end user to meet loads. This system integrates heating and cooling loads into one combined system and easily integrates low-grade waste heat.

While the exact definitions vary, and there is ongoing discussion about the distinction between fourth-generation and fifth-generation systems (discussed further in [16]), the definitions outlined above will be used throughout our review. Fig. 2 shows a graphical representation of the generations through time, efficiencies, and technologies. The image is adapted from [15] and adds in a new generation of DES defined as Ambient, along with cooling temperature ranges for 4G and 5G. The efficiency axis shows the overall potential system efficiency and is meant to be a qualitative metric.

Note that the inclusion of cooling systems is a more recent advancement. District cooling using chilled water for direct use may be used in tandem (as a separate system) with any of the above district heating systems, but district cooling generally started with 4G systems. Only for 5G systems are heating and cooling intertwined in the same system (typically as part of the same supply). Many previous systems have been in areas dominated by heating; expanding DES into new areas often requires meeting mixed heating and cooling loads or even cooling-dominated loads.

Modern 4G and 5G systems

Modern systems being installed today are mostly 4G and 5G systems. Fig. 3 illustrates two example commercial applications of DES, one with a four-pipe 4G system and one with a one-pipe 5G system. Earlier generation systems (such as 3G) may continue to be relevant during this transition phase as decarbonized solutions by utilizing high-temperature heat pumps or high-temperature renewable heat resources such as high-temperature geothermal resources. However, this paper will focus mainly on the 4G and 5G systems. Also, the move to 5G systems is ideal in climates with mixed heating and cooling loads resulting in a central loop temperature that is regulated by the varying demand.

These new state-of-the-art 4G and 5G systems have a few important features. There is a shift to electrify the system, reducing or removing the centralized plant and instead increasing district pumping energy and

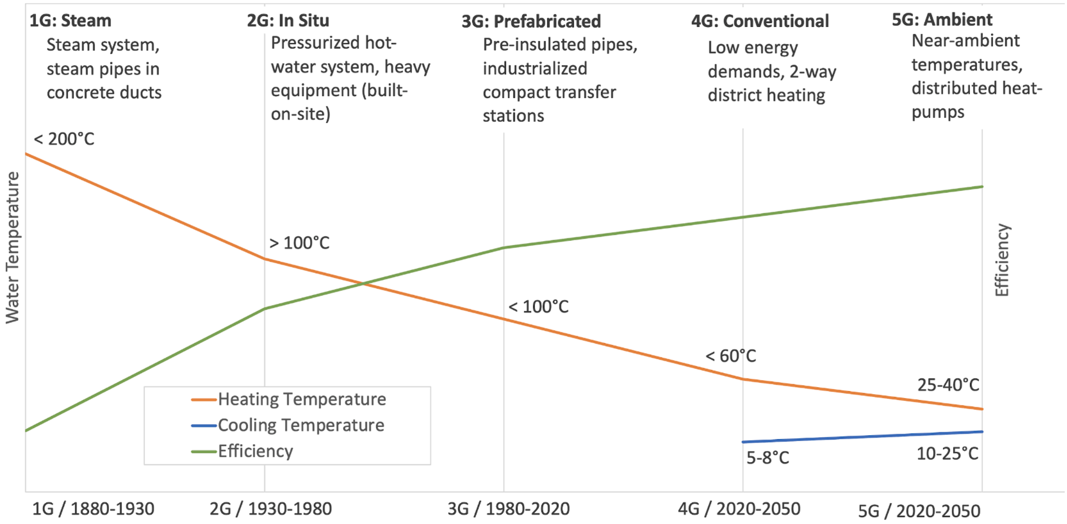

Fig. 2. Temperature and efficiency of various generations of district energy systems (adapted from [15])

end user electricity usage (i.e., the building's energy consumption). Additionally, these are "smart systems," where 4G is specifically defined as a smart thermal grid [15]. These systems are designed to interface with high-efficiency, weatherized buildings [17].

Another important aspect of 4G and 5G systems is the potential of bidirectional flow of energy, whereby users in the district are able to both consume heat from the system or produce heat to the system [13]. These users who both produce and consume heat are called "prosumers." As such, these systems are sometimes called "thermal energy networks." In Fig. 3b, users interface with the thermal loop via heat exchangers or heat pumps and move heat to and from the loop.

If the heating and cooling loads on the system are not balanced annually, a central plant may be needed to balance the system [17]. Systems without balanced heating and cooling loads may struggle to meet building demand and may use a higher amount of auxiliary energy, as seen in Suurstoffi demonstration [18]. At the Colorado Mesa University DES, a key to success was deciding to connect multiple buildings to the same loop so that some of the heating and cooling loads could balance out. Diverse building loads may see benefits from simultaneous heating and cooling loads as well as spreading out the timing of peak thermal load. These diverse loads spread out the electricity demand and reduced monthly peak demand charges [19]. Thus, whether or not these new DES are preferred over individual heating and cooling depends on the density and diversity of the loads [17].

For 5G systems, which operate with the loop at "ambient" temperature, additional considerations are required. Due to the moderate temperature in the loop and low temperature differentials, 5G DES require larger pipes and pumps to accommodate increased flow rates to meet the load [20], and may incur higher capital cost to switch over the building systems to heat pumps [13]. The 5G systems, as defined herein, always require a heat pump for heating and may require a heat pump for cooling or may utilize "free cooling" via heat exchangers, cooling towers, or economizers (i.e., the ability to bypass energy systems when the desired temperatures for cooling are already present). These advanced systems have many potential advantages including full electrification, improved efficiency compared to air-source heat pumps, seasonal heat storage options, and the balancing of simultaneous heating and cooling loads from different building [13].

Example DES installations

The first 1G district heating system in the United States was installed in the 1890s in Boise, Idaho, United States and ran on geothermal heat to produce steam [21]. Since then, installations of district energy systems in the United States have continued, though there are fewer and generally smaller installations in North America as compared to Europe [21]. Looking to more modern systems, Colorado Mesa University in the United States and Mijnwater in the Netherlands are two of the first documented examples of full-scale 5G DES installations. Oh and Beckers assessed five case studies in the United States that all used geothermal heat pump-based DES [22], considering both centralized and decentralized systems.

A sampling of installations that demonstrate important technology for a future fully decarbonized DES is shown in Table 1, with a focus on North America. More information about these systems can be found in the attached references.

The 5G installations can be differentiated from the 4G and 3G installation based on the thermal conversion technology, where 5G requires a heat pump at the end users while 4G and 3G can use different types of heat exchangers to directly utilize the heating or cooling.

The two 3G systems listed in Table 1, Cornell University and Ball State University, show examples of decarbonizing or reducing energy use to generate heating and cooling streams while still utilizing older distribution technology. The Cornell system uses lake-water cooling to generate cold streams for cooling across campus. At Ball State University, large borehole fields combined with heat recovery chillers were used to replace the original boilers and chillers to create hot and cold water streams that are then used in the district. These systems demonstrate how retrofitting a 3G system can be one way to reach decarbonization goals, although conversion to a 4G or 5G system commonly increase overall system efficiency and reduce energy consumption.

Comparing options for decarbonizing heating and cooling

State-of-the-art DES still share many components with earlier generations including central and distributed plant components (e.g., heating and cooling sources, thermal energy storage, pumps), distribution components (e.g., heat exchangers, additional thermal storage, distribution pumps), energy sources (e.g., electricity, natural gas), and energy transfer station components (e.g., heat exchangers, load distribution pumps, supplementary heating and cooling). District systems can also be compared against individual systems such as individual air-source heat pumps (ASHP) or geothermal heat pumps (GHP) for decarbonizing buildings.

State-of-the-art DES (4G and 5G) are compared against early generation DES (1G) and individual electrified options (ASHP and GHP) in

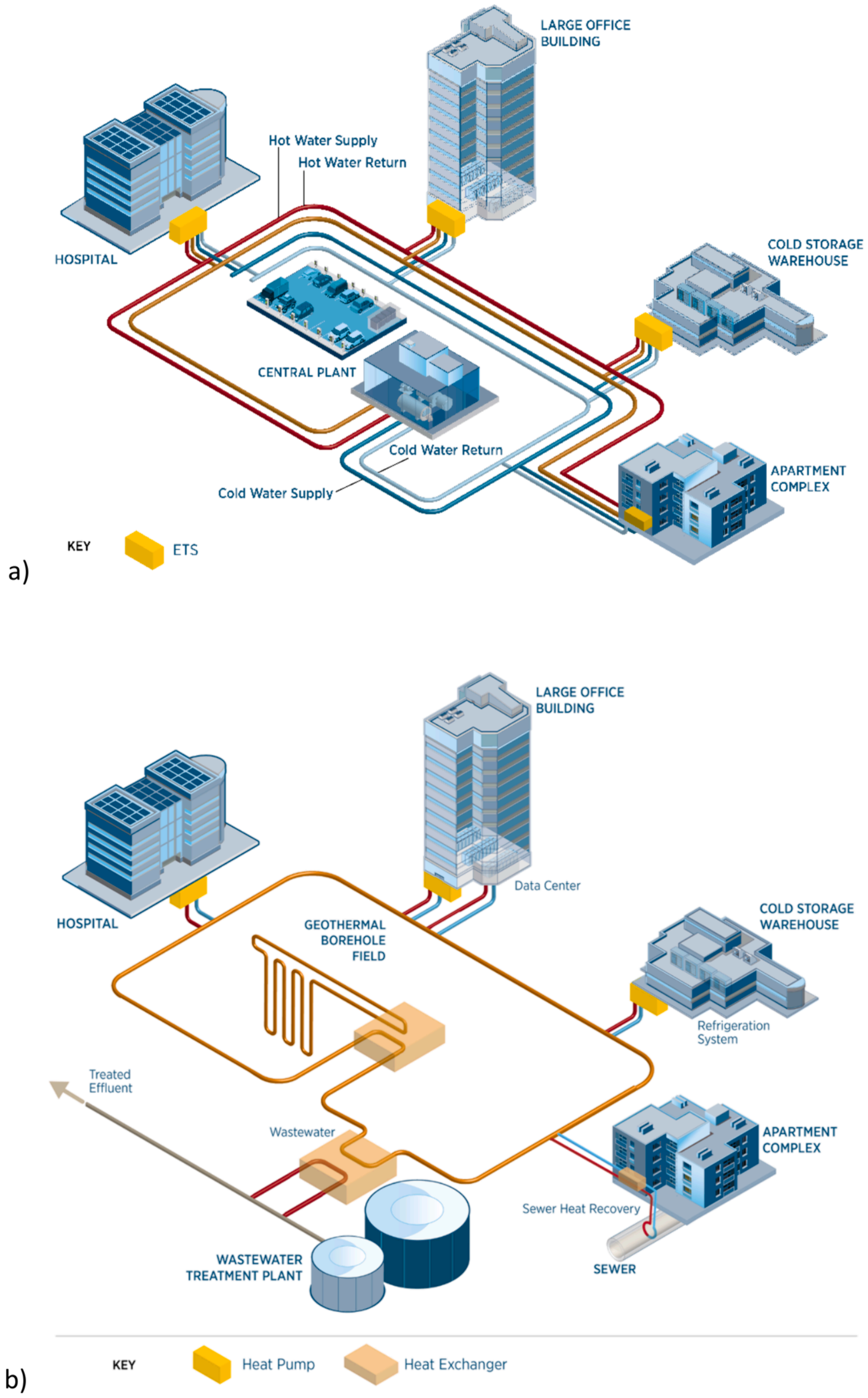

Fig. 3. Example commercial application of a) a four-pipe 4G DES providing hot and cold water supply to each building via an energy transfer station (ETS), and b) a one-pipe 5G DES illustrating heat sources of wastewater, data center, sewer water, and refrigeration, as well as storage in a geothermal borehole field and connection to building loads via heat pumps. *Graphics by Marjorie Schott, NREL.*

Table 2
Comparing heating and cooling technologies benefits and drawbacks for achieving decarbonized heating and cooling.[1]

	Individual ASHP	Individual GHP	1G DES	4G DES	5G DES
Benefits					
Removing scope 1 emissions (on-site emissions)	++	++		+	++
Utilization of waste heat				++	+++
Modularity	+++	+++		+	++
Thermal storage potential			+	+++	++
Integrating renewable thermal sources		+	+	+++	++
Shaping electric demand profiles		+		++	+++
Integrating renewable electrical sources	++	++	+	++	+++
Efficiency	+	++		++	+++
Drawbacks					
Complexity of design		–	–	– –	– – –
Capital investment[2]		– –	– – –	– –	– – –
Operations & maintenance	–	–	– – –	– –	– –

[1] Empty spaces denote the category is either not applicable or that technology is considered the baseline. The other technologies can then be considered as better "+" or worse "-" than the blank technology.

[2] Capital investment is for new system installations.

Table 2, looking at relative benefits ("+") or drawbacks ("−") of each technology. The comparison includes 1G DES (steam systems) for comparison because steam systems are still installed in many locations including institutions, campuses, and downtown areas. Note that these comparisons reflect the authors' interpretation.

Most of the compared technologies remove scope 1 emissions, thus aiding in decarbonizing heating and cooling loads. Notably, 1G DES (and sometimes 4G DES) tend to generate their heating via fossil fuels. However, these technologies vary significantly in their design, cost, and integration.

DES provide more flexibility for decarbonizing scope 2 emissions than individual systems. 4G and 5G DES can integrate waste heat, rather than producing heat, and all DES have some ability to integrate thermal storage or renewable thermal sources. Thermal sources are further discussed in Section "Carbon-free heating and cooling sources". Modern DES also provide options for shaping electrical demand profiles, not just by the use of thermal storage but also by sharing energy across the network [35]. The potential changes in electrical demand profiles may make it easier to integrate these technologies with a fully renewable electrical grid, discussed further in Section "Interaction with electrical grid".

The modern DES (4G and 5G) are more modular than previous generations, but individual systems are still the most modular and allow for easily changing a single home's heating and cooling system. 5G systems have some advantages for modularity over other DES as they can more cost effectively leverage a meshed grid network (discussed in Section "Distribution network") and distributed thermal sources can be added over time at different thermal loop locations.

Despite their many benefits, DES are complex and expensive to install and operate, compared to individual systems. Future costs and financing options will be discussed further in Sections "Future costs" and "Future financing options".

Carbon-free heating and cooling sources

The heating and cooling sources for a DES have historically needed to be high-temperature heating or low-temperature cooling streams, but as new systems lower the operating temperatures and approach ambient conditions, more sources can be added to a DES to balance the loads. Additionally, as districts decarbonize and make use of less dispatchable resources, a greater diversity of energy sources may help stabilize temperatures in a DES. An overview summary of the types of decarbonized resources available for input into a DES is given in Table 3. The types or options for each resource are listed. Thermal sources are roughly categorized here such that high-temperature thermal energy (∼>60 °C) can provide high-temperature direct heating, medium-temperature (∼40°–60 °C) can provide direct heating in low-energy buildings, and low-temperature (∼<40 °C) may require a heat pump for heating or cooling uses. Note that mass flow rates are also important for determining which thermal resources can be used.

The thermal sources for heating and cooling (or heat sources and sinks) are generalized into time-based categories below that may be important for operation of a DES. Dispatchable sources are generally able to be controlled up or down at will, constant sources provide generally the same thermal source over time, and variable sources may change in thermal production over time (though that variation may be predictable) outside of the operator's control.

Dispatchable sources

Dispatchable sources are important for controlling the DES loop temperatures. However, they have traditionally been powered either directly or indirectly by carbon-based power sources. Thus, it will be important to continue to investigate heat-powered sources and carbon-free electrically powered sources to provide stable control for decarbonized DES.

Combined heat and power

Traditional DES often used combined heat and power (CHP) plants as the heat source [15,37], because combustion processes for power generation often create a large amount of high-quality, high-temperature waste heat that can be utilized. While these CHP plants are typically run on fossil fuels, there may continue to be carbon-free options such as nuclear or renewable options such as biomass.

Electric-powered sources

Electric-powered heating and cooling sources such as heat pumps and chillers can be part of a decarbonized DES when powered directly by carbon-free energy or when connected into a carbon-free electrical grid. Renewable energy generation that provides this carbon-free energy may be centralized (part of electrical grid) or distributed (as considered in [50]) such as localized photovoltaic (PV) panels on individual houses.

Table 3
Summary of sources for decarbonized district heating and cooling.

Heat/Cool Source	Timing	Energy	Citations
CHP (nuclear, biomass, etc.)	Dispatchable	Electrical and high-temp	[15,36,37]
Shallow, vertical, or horizontal geothermal heat exchanger	Constant	Low-temp or heat storage	[38]
Deep geothermal	Constant	High-temp	[21,39]
Solar thermal	Variable	Medium-temp	[32]
Photovoltaic-thermal	Variable	Electrical and thermal	[40–42]
Natural thermal reservoirs (lake, river, ocean, etc.)	Constant	Low-temp or cooling	[33,43,44]
Waste heat	Variable	Medium or low-temp	[45–49,120]
Heat-powered cooling (absorption chiller)	Dispatchable	Cooling	
Electric-powered sources (heat pump, chiller)	Dispatchable	Heating and cooling	

In the context of a DES, heat pumps can either be located at a centralized plant to adjust the temperature of the distribution loops or at the end user to meet building heating and cooling loads. On the building side, Fig. 4 shows a simple schematic of how a heat pump is used for heating and cooling, interfacing between the building and thermal network. Note that a key feature of a heat pump is that for every unit of electricity put in, more than one unit of heat is moved; thus, it has an efficiency or coefficient of performance (COP) that is greater than one.

However, there are some limitations to heat pump use. Heat pumps can produce a wide range of temperatures, but generally are designed to produce low- and medium-temperature heating. While air-source heat pumps have historically had limitations based on ambient air temperature (but have improved significantly in the last decade), water-source heat pumps used in DES (Fig. 4) do not interface with outdoor air and thus only see the milder temperature of the thermal loop fluid. The COP of these heat pumps is still best when the loop is at a more moderate temperature (5°–30 °C), and the COP reduces at more extreme loop temperatures. Refrigerants used in heat pumps have changed over time both to increase the range of operating temperatures and reduce the global warming potential. However, refrigerant leakage is still a potential issue, and the potential global warming effect should be considered.

If carbon-free electricity is available, a centralized plant can power central or booster heat pumps to adjust the thermal loop temperatures (as employed by Ball State [34]). Vapor compression chillers, heat recovery chillers (used by the Stanford system [7]), or cooling towers (used by the Colorado Mesa system [19]) may provide cooling for the system. Heat pumps are being installed in Esbjerg, Denmark to decarbonize the heating sector by replacing a coal-fired heat system; the heat pumps will be run on wind energy to charge thermal energy storage, helping to balance the electrical grid if needed [51,52].

Heat-powered sources

Additional heat can be used to run absorption or adsorption chillers for cooling. Solar thermal has been investigated in conjunction with absorption chillers [53,54]. The pairing of solar power and cooling works well because of their temporal alignment: when there is high solar thermal energy, there is a high need for cooling [41]. Additionally, surplus heat in the district heating system (for example, from CHP) could help run absorption chillers in summer when there is less heating and more cooling demand [55,56].

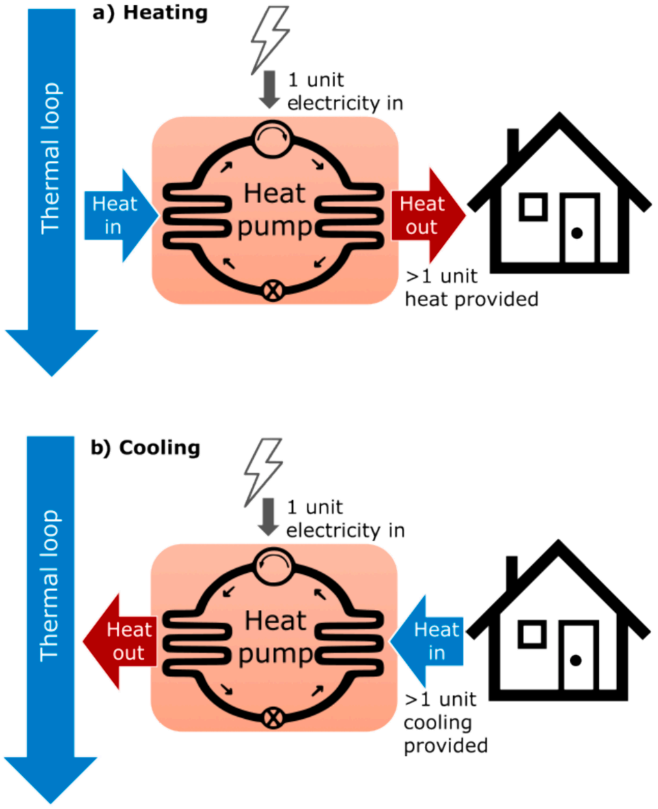

Fig. 4. Heat pump diagram in a) heating mode, and b) cooling mode.

Constant sources

Constant sources are able to provide nearly continuous heating or cooling, with little variation over time. These sources act like baseload generation on the electrical grid and provide continuous support to the DES.

Geothermal

There are multiple options for utilizing geothermal resources in DES, as shown in Fig. 5, including low-temperature closed-loop systems and high-temperature open-loop systems. Historically, high-temperature hydrothermal geothermal has been used to generate high-temperature steam from deep wells [21]. The availability and affordability of hydrothermal geothermal resources is dependent upon subsurface properties and drilling costs but can be competitive with carbon-based sources [39].

Shallow geothermal systems such as horizontal ground or vertical borehole heat exchangers do not require as specific subsurface properties as hydrothermal systems and thus can be sited more broadly. These closed-loop systems, also known as “geo-exchange,” can be used to generate consistent low-temperature energy sources by exchanging heat with the ground [57,58]. Additionally, for ambient temperature systems without insulation, the DES thermal loop itself will exchange heat with the ground and act as a large horizontal ground heat exchanger [38]. Depending on the depth of pipe and the ground temperatures, the loop could be a significant thermal source. Warmer ground temperatures were found by Quirosa et al. to improve system results with an ambient loop [59].

The application of geothermal in 4G/5G DES may also be in the form of long-duration energy storage, discussed further in Section “Storage”.

Natural thermal reservoirs

Natural low-temperature thermal reservoirs such as lakes, rivers, seas, and underground reservoirs provide a large source for constant temperature heat exchange. Sea water cooling was investigated in Hong Kong and found to use less electricity compared to standard systems [43]. The Cornell University system (detailed in Table 1) utilizes a lake-source cooling system via heat exchange with water from the bottom of a nearby lake [33]. Lake-source cooling for DES was investigated throughout Europe by [44]. Natural thermal reservoirs tend to be used for low-temperature heat or cooling.

Variable sources

Variable heat sources fluctuate over time, though their fluctuations may be predictable like the daily cycling of solar power or the increased waste heat production in the summertime. These sources are particularly useful for DES when paired with thermal storage.

Solar thermal

Solar energy can be used to heat water or other heat transfer fluids (e.g., glycol). Simple solar collectors can be used to generate hot water for heating, as is done at the Drake Landing Solar Community [32], or to supplement a larger DES [60]. Solar thermal is often combined with seasonal thermal storage [32,61], though the land area needed could be a constraint [62]. Concentrating solar thermal can also be used to generate higher temperatures, though more often solar thermal is used to generate medium-temperature heat.

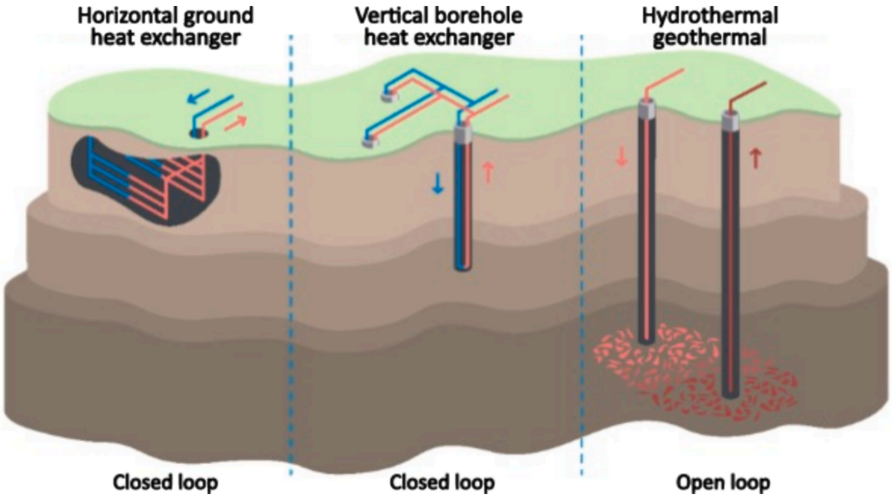

Fig. 5. Common types of geothermal systems used for district heating and cooling: shallow horizontal or vertical heat exchanger and deep hydrothermal. Adapted from [38].

Solar PV panels can be combined with thermal collection systems to generate both electricity and thermal energy [40–42]. These hybrid photovoltaic-thermal (PV-T) systems generate electricity and then cool the panels, collecting the thermal energy. Advances in this technology include compound parabolic concentrator PV with solar thermal from [53].

Waste heat

Unlike high-temperature systems, 4G and 5G systems operate at lower temperatures and can thus utilize waste heat from a large variety of sources. Availability of these sources increase as loop temperatures decrease, and waste heat sources are particularly useful for 5G systems to balance the ambient temperature loop. Depending on the temperature and quality, waste heat may also be useful for direct-use heating application, but more often it is used for low-temperature heat.

Large producers of heat include data centers, industrial processes, and commercial refrigeration. Additionally, wastewater treatment or sewage heat exchange has been leveraged as a heat source [63]. The timing of heat generation and heat demand must be considered for use of waste heat, and energy storage may be required to make effective use of it [48]. Data centers and wastewater treatment plants have fairly constant heat rejection and thus may be the most useful for adding heat to a district system [47], though the variation in wastewater output temperatures may make wastewater more difficult to use [49]. Prosumers (users who both consume heat and reject heat to the system) can also provide significant waste heat from refrigeration, commercial buildings heating or cooling, and even general residential cooling.

Electrical energy storage technologies, including compressed air energy storage and pumped thermal energy storage, generate large amounts of waste heat during operation. These electrical storage technologies can therefore be seen as thermal sources for DES while acting as electrical storage for the grid. Compressed air energy storage systems have been investigated in conjunction with district heating, where waste heat from compression can be sold to a district heating system as an additional revenue stream [64,65]. Some pumped thermal energy storage systems, including the CHEST system [66,67], are being designed for integration with district heating systems and thus are able to interface with both the electrical and heating networks.

Storage

Energy storage technologies for DES are discussed below, including the most common forms of energy storage for DES: water tanks for short-term storage and geothermal boreholes for long-term storage.

Geothermal energy storage is most common as either vertical boreholes or horizontal ground heat exchangers (illustrated in Fig. 5). Borehole thermal storage (BTES) has been investigated in many studies including [46,59,61,68–71] and used in installations including [19,28,32,34]. Boreholes may have a coaxial or U-tube setup [72]. Additionally, aquifer thermal energy storage (ATES) is another form of long-duration subsurface storage which injects and recovers water from the subsurface, but with no net water extraction [73]. Borehole storage and aquifer storage both work well for space constrained high-density areas but are highly dependent on the subsurface properties [74]. Additional comparison of thermal storage technologies for DES is provided by Sadeghi et al. [75] and Fry et al. [76].

For short-term storage, water tanks are used to hold hot or cold water [74]. Water tank storage acts as an important buffer between the system and other long-duration storage options because it can provide heat quickly at a high rate [32]. For longer duration water storage, pit storage can be used for up to seasonal storage [62,73]. Ice storage is also commonly utilized in buildings for short-term storage [77]. Other forms of storage for higher temperature or higher density storage are being investigated, including new salt compositions for molten salt storage [78] and latent heat or phase change materials [74].

In addition to the traditional forms of thermal storage, "virtual storage" within the thermal inertia of the loop, the buildings connected to the loop, or the building's thermal mass can provide a large additional source of storage [7,79,80]. The distribution pipe temperatures can be allowed to shift up or down to store energy [50]. Quirosa et al. modeled the use of heat pumps run on excess solar power to store heating or cooling energy in the thermal loop [50,81]. They found that the loop could act as short-term energy storage and that the ability to store thermal energy on the loop might help make less dense loops more worthwhile where they would otherwise be too costly.

Design of district energy systems

The approach to the design of DES depends on multiple factors including the nature of the energy sources, the existing loads on the electrical grid, the loads to meet, central or distributed plant design, the distribution network, control characteristics, and the redundancy and resilience needs. While Sections "Current technology" and "Carbon-free heating and cooling sources" focused on current technology and components for a decarbonized system, this section will describe some important considerations for installing operational systems. Key topics for designing and deploying 4G- and 5G-based DES will be discussed. The finality of this section will briefly describe the role of modeling in the design of DES.

While the major components and technology for modern DES are not novel, the design of an efficient and cohesive system is still an ongoing topic of research. The complexity and uniqueness of each DES results in the need for a cohesive and experienced design team. Currently, there are no such things as a combination central plant, distribution system, and energy transfer station connections “in a box.” Further, the energy systems on the load side of the DES may not contain adequate equipment to leverage the supplied energy (either no water support or mismatch in temperatures or mass flow limitations). The consequence is a complex engineered system to provide users with the heating and cooling energy needed to meet the required loads. These design considerations need to be assessed within the context of a DES master plan [82].

Interaction with electrical grid

DES relying heavily on electrically-driven sources (such as heat pumps and electric boilers) run the risk of significantly increasing load on the electrical grid, but also have an opportunity for beneficial relationship with the electrical grid. Considering this interaction with the electrical grid is an important part of planning and designing a DES with the goal of decarbonization.

The energy storage technologies discussed in Section “Storage” can be used to shift when to use electricity in a DES and help balance the electrical grid. For example, when there is excess renewable energy on the electrical grid, thermal storage systems can be charged with electrically-powered sources (for diurnal storage up to seasonal storage). Thermal storage can later be discharged to the DES to meet loads and reduce demand on the electrical grid. Many of these forms of energy storage (such as thermal loop inertia, aquifer thermal storage, and implicit building thermal mass) only work or make sense on a district-scale rather than an individual-scale, so the biggest benefits may be seen when district systems are used.

There have been multiple studies looking into this interaction between the electrical grid and DES. Barberis et al. [83] investigated using excess electricity from a smart grid to charge thermal storage with heat pumps and avoid later peaks in thermal load. As discussed earlier, running heat pumps on excess solar power to charge storage has also been investigated [50,81]. However, there is still limited research into the larger grid impacts of DES including the potential to reduce peak loads and transmission build out as buildings and the grid decarbonize.

There may be additional passive benefits of DES. Liu et al. [84] found that converting existing HVAC systems to individual geothermal heat pumps resulted in significant load reduction on the grid, reduced energy prices, reduced transmission requirements, and reduced emissions. Utilizing a networked system of geothermal heat pumps via a 5G DES is likely to have equal or greater reductions in load on the grid, before even considering active use of energy storage.

Energy sources and load analysis

While there is a wide variety of energy sources (described in Section “Carbon-free heating and cooling sources”) that are available to communities interested in deploying a DES, design of a DES requires careful selection of those energy sources. During the design of the DES, it is important to evaluate the local availability of any potential energy sources and designed accordingly [85]. For example, if a high-temperature geothermal source is available, then it is important to locate and design the central plant (if required) accordingly. Additionally, designing a decarbonized system requires the exclusion of carbon-based energy sources such as natural gas for heating or electricity generated from coal. The lack of inherent dispatchability in a decarbonized system may pose an additional challenge to the design, and the energy sources will need to be chosen carefully to ensure a carbon-free system that still meets user needs robustly.

In addition to sources, the heating and cooling loads in the district must be understood and carefully selected, which is often conducted with a load analysis. A load analysis studies the energy consumption of individual buildings and groups of buildings. The load analysis is a critical step in the design of a DES as it allows engineers to understand the current and future energy demands of the system, which is essential for sizing the central plant components and distribution systems [86]. Current energy demands are often collected from historical data and include multiple years of data, if possible, to account for different weather conditions over the DES lifetime. Future energy profiles should consider expansion of the DES including designing for modularity as loads change over time as buildings are added, re-commissioned, or decommissioned. If the design is for a brownfield, then it is important to consider any proposed improvements to the existing buildings.

In cases where the building load profiles indicate diurnal or seasonal swings, then strategies for managing the peak loads need to be considered, including adding additional cooling and/or heating sources or thermal energy storage [49]. In cases where there are more loads than expected capacity, then a topology optimization can be conducted to determine which buildings should be connected based on diversity, distances, and costs [87].

Additionally, lessons from studying and modeling DES could be applied to other fields, such as city planning, to build a better city block for use with DES, for example designing mixed-use communities with diverse heating and cooling loads [26].

Distribution network

The design of the distribution network needs to consider many variables including distances between the energy transfer station (ETS) and central plant (if any), the number of pipes, pipe diameters, pumping stations, temperatures, topologies, geographic constraints, resilience and redundancy considerations, and many others. The ETS is the connection between the distribution loop and the served load, and can include a combination of valves, heat exchanges, and, in 5G systems, a water-to-water heat pump or water-to-air heat pump. The distribution network is composed of pipes carrying heat transfer fluid (usually water, propylene glycol, or a mixture [38,88,89]). The choice of heat transfer fluid must balance trade-offs (based on the site’s location) of freezing point, viscosity, and specific heat along with local climate to find the ideal mixture composition. The number of pipes can vary based on system design from 1, 2, 3, or 4 [13], as seen in the examples in Table 1. The use of one pipe in a loop is also known as a “reservoir network” [20].

While most 5G systems can accommodate bidirectional *heat* flow due to their low working temperatures, they may have unidirectional or bidirectional heat transfer *fluid* flow and open-loop or closed-loop systems [13]. Traditionally, flow on a distribution network is unidirectional with a clear separation of supply and return piping, or two-phase single-pipe for steam supply and return. As heating and cooling sources are now being distributed around the network, the use of bidirectional flow should be considered with a few advisements. Flow control and thermal management need to be carefully designed. Verhoeven and Boesten demonstrated the use of cluster connections to the backbone distribution network [25,26]. The cluster connections provide a buffer for bidirectional flow and seasonal storage, which is technically a form of hydraulic isolation. Bidirectional systems need to be monitored more closely and will have higher investment costs due to additional sensors, controls, and commissioning needed to minimize pressure variations. Regardless, bidirectional flow systems should be carefully considered due to a potential increased overall energy efficiency benefit.

One factor to consider is to whether there is a need to hydraulically isolate the district and load. Buffa et al. noted that in multiple jurisdictions, the legal requirement is to hydraulically isolate the load from the DES [13]. Additionally, hydraulic isolation can aid in the hydronic balancing of the system with hybrid piping [90]. However, hydraulic isolation increases pressure losses and introduces added cost and complexity to the system. The choice of hydraulic isolation needs to be evaluated by an engineer, but the addition of hydraulic isolation may facilitate the integration of diverse energy sources, allowing for more flexibility and sustainability in distribution networks.

For thermal loop distribution, von Rhein et al. described the complexities of various network topologies including radial, mesh, and ring grids in terms of cost and resilience [91]. Fig. 6 shows an example of three different distribution designs. In a radial grid, everything stems from the DES central plant, the ring grid provides a loop for redundancy, and the meshed grid allows for multiple layers of redundancy. Also note that each line in the diagram can represent a single pipe or multiple pipes.

Based on some of the considerations outlined above, the choice between radial, ring, and meshed grids should consider the following:

- **Load Density and Distribution**: As discussed in the section on loads, the density and distribution of heating and cooling loads within the service area play a fundamental role in grid design. Radial grids, featuring a single heat source connected to a network of pipelines, are suitable for relatively low-density areas with a single heat source. In contrast, mesh and ring grids are better suited for high-density areas, as they allow for multiple interconnections, ensuring even heat distribution and redundancy. Arguably, as DES systems expand over time, they will inevitably become a ring or meshed grid, with added complexity.
- **Redundancy and Reliability**: Reliability is a key factor in distribution network design. Mesh and ring grids excel in this aspect. Mesh grids offer multiple paths for heat transfer, reducing the impact of outages or maintenance, while ring grids provide a continuous loop that can maintain service even when certain sections are offline. Radial grids, by contrast, may suffer more significant disruptions if the central heat source or pipeline experiences a problem.
- **Expansion and Scalability**: Consideration must be given to future expansion and scalability. Mesh and ring grids can be more easily extended by adding new connections, making them suitable for growing urban areas. Radial grids may require significant reconfiguration when expanding the network.
- **Investment and Operating Costs**: The initial investment and operating costs are key factors when designing and extending distribution networks. Radial grids are generally less complex and may have lower upfront costs. However, mesh and ring grids may offer operational cost savings due to improved efficiency and reliability over the long term.
- **Energy Source Diversity**: The type and diversity of energy sources used in the DES can influence grid choice. Mesh and ring grids are more flexible in accommodating multiple heat sources, such as combined heat and power plants, geothermal, or waste heat. Radial grids are typically designed around a single heat source, which is becoming less common.
- **Energy Efficiency**: Mesh and ring grids are known for their energy efficiency, as they can optimize heat flow and reduce heat losses. Radial grids, being simpler, may be less efficient in the distribution of heat.

Ultimately, the choice between mesh, radial, and ring grids should be made based on the specific requirements of the district heating system, including size, reliability, redundancy needs, and the long-term energy strategy, as these factors significantly influence the network's efficiency and effectiveness in meeting the community's heating demands.

Controls

A decarbonized DES utilizing 4G or 5G system architecture provides many opportunities for system control, although implementing system-level control may be complex. The system-level structure must integrate a series of controls on each component: demand-side, thermal sources, energy storage, and circulation pumps.

Component control

Some of the major components that the system operator can control include:

- **Thermal sources and sinks**: As described in Section "Carbon-free heating and cooling sources", thermal sources and sinks may provide opportunities for dispatching heat to or from the system (thus providing heating or cooling), and a given DES may include multiple thermal sources. For example, the control system may decide between utilizing a borehole field versus turning on central heat pumps.
- **Energy storage**: The control system can utilize thermal storage to balance the system over time. The controls system may make use of both physical storage systems as well as "virtual" storage in building inertia and loop inertia [93].
- **Circulation pumps**: Circulation pumps may be distributed or centralized, and constant or variable speed. Some circulation systems may use "passive" control, whereby the fluid is only moved by the heat pumps themselves, or "active" control, where centralized pumps move the fluid [38]. Pumping for 5G systems requires additional considerations. The single-pipe reservoir networks need a well-designed controller to minimize pumping cost [20], which may otherwise be high due to the large size of the pipe and low thermal energy in the fluid. The hydraulic system can be complicated and, if not well-designed, may consume a large amount of energy [18].

Control implementation

System operators face some unique control challenges for DES. While DES with centralized plants can focus on control and dispatch from one location, DES with distributed or decentralized architecture have the

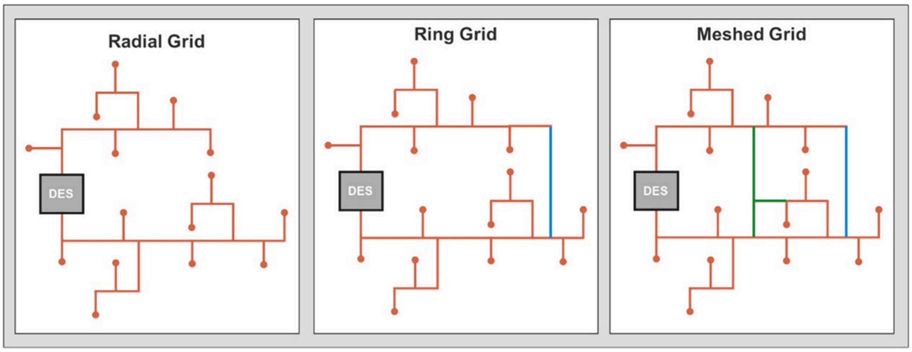

Fig. 6. Diagram demonstrating the differences between radial, ring, and meshed grids (. adapted from [92])

added complexity of controlling disparate system components to cumulatively meet loads with available energy resources. Implemented control systems may involve a centralized operator adjusting all components or more individual stand-alone control of each component.

Additionally, the demand-side controls at the ETS or within connected buildings will likely be inaccessible to the system operators. Users will determine building comfort set points and interact with the thermal loop accordingly. Thus, the control system needs to keep the energy system stable and be able to meet user loads, with little to no control over the timing and demand of loads.

District system controls may be used to meet different objectives and their operation and decisions will look different depending on the objective. For example, goals may include reducing carbon intensity of the electricity used by the system, reducing energy usage, reducing peak thermal demand, reducing capital cost of local equipment, or evenly distributing heating and cooling amongst users. The importance of the metric of choice was demonstrated by Brunt et al., who found that when comparing a 3G district system and a new 5G system, the better option depended on the metric: traditional had a lower levelized cost of energy (LCOE), while 5G had a lower levelized cost of carbon [94]. A study by Quirosa et al. found that the optimal system design varied depending on the objective: integrating renewable energy or maximizing savings [50].

As DES become more distributed and shift to fully decarbonized systems, energy storage will play an increasingly important role. By utilizing hot and cold storage, operators can shift demand temporally, reduce maximum demand load (and cost), and potentially shift to times of low-carbon electricity production [7]. Thus, control of storage is key to decarbonizing heating and cooling without putting additional strain on the electrical grid. Li et al. found that water tanks for short-term storage and geothermal boreholes for long-term storage were both able to reduce energy bills by helping with the mismatch between supply and demand and reducing peak load [46].

Modeling

Depending on the design phase of the building and district energy system, the type of modeling required may differ. The model level of detail or level of development [95,96] can map to the required details needed for building and district energy modeling. The most critical decisions on energy, GHG emissions, and cost occur during the predesign/conceptual or schematic design phase of the design process [97]. Depending on the design phase and how quickly the decision needs to be considered, the model can be accomplished in a spreadsheet, with a simple Python-based script, leveraging whole building energy modeling (8760 h-based simulation), or a more involved equation-based program with detailed transients for control decisions. The progression from spreadsheet to physics-based or equation-based solvers follow the design process as more building and site level information is collected, and more detailed specifications are determined.

Modeling tools that are “bottom-up” and rely on first principles are more specifically termed urban building energy modeling [98]. Reyna et al. outlined an urban building energy modeling (UBEM) taxonomy for four categories: portfolio (of buildings), district, weather, and system [99]. A tool-based evaluation was completed by Allegrini et al. [100] including a detailed breakdown of 24 technologies. The analysis showed how many tools are available and that only a few tools create detailed models of district parts: TRNSYS, EnergyPRO, and NetSim. Since Allegrini’s paper, there have been advances with more recent district-based modeling tools including URBANopt DES (leveraging components in the Modelica Building Library) [101], and more recent reviews by Sola et al. [102]. Xu et al. [103] reviewed the current state of UBEM tools and characterized UBEM level of details for modeling based on five categories: input data and representation of buildings, DES components, outdoor environment, user behavior and mobility, and validation and licensing. These categories should be considered by mechanical design firms looking to model district energy systems. Note that most of the DES modeling software and model reviews focus on building modeling and district design, with less detail on modeling and characterizing thermal sources.

In order to scale DES installations to the level required to meet climate goals, modeling must be more tightly integrated into the design process. Modeling is valuable as it allows for assessment of designs and component sizing without expensive demonstration projects. It also allows for optimization of controls systems on a virtual DES, potentially with a digital twin of a real system before implementation of new control systems in real life. As such, models may need to capture different components of the system depending on their goals, such as user loads, thermal inertia of the system, and heat sources. There are multiple tools that can help practitioners answer difficult design and operational questions. For example, if a practitioner is looking to size thermal energy storage of an already known load, then a detailed physics-based model with representative control algorithms of the district is probably not needed; however, if dispatching strategies of thermal energy storage is desired, then a model in TRNSYS or libraries built with the open-source language Modelica is probably warranted.

Thus, realizing a complicated control system typically requires modeling and measuring the system. Presently at many US-based design firms, detailed district modeling is often done in the commercial software TRNSYS (used by the Drake Landing [32] and Eversource installations) or using the programming language Modelica with specific component libraries such as the Modelica Buildings Library [104] and AixLib [105]. As with many modeling tools, the modeling engines often have user interfaces built on top to enable easy data ingestion and analysis results viewing. For example URBANopt and URBANopt DES make use of the OpenStudio/EnergyPlus engine [106,107] and the Modelica programming language, respectively [101]. URBANopt DES utilizes the GeoJSON to Modelica Translator to convert input files into a Modelica model for a DES [108] and takes the building loads from the results of OpenStudio/EnergyPlus. The Modelica Buildings Library project has continued adding feature-rich components, enabling more advanced simulations of district connected systems [109,110]. To enable improved modeling for controls, metamodels have also been used to find a middle ground between low and high fidelity models [111].

The need for bespoke models is often required, and researchers will write their own models such as [50,112,113], which may be useful for capturing more complex fluid dynamics such as the difference in propagation speeds between pressure and temperature in the loop. Future models need to flexibly capture new and different heat sources as those are very location specific. Additionally, there is a need for user-friendly, open-source models that are more accessible to communities considering installing a DES.

Future trends and predictions

DES have been a staple for meeting energy demands in urban districts, campuses, and institutions for decades. Based on recent trends, it is expected that the demand for DES will only increase as the United States and the world progress toward higher urban energy efficiency and decarbonization of the built environment. The complex nature of decarbonized DES means that additional research on energy sources, design, controls, and operation will need to continue as more installations are installed and more lessons are learned. A few future trends we expect to influence DES are listed below.

Changing heating and cooling loads

As DES expand over time, new loads are added or removed, and building loads change, it is expected that the system operation may change. Future changes in heating and cooling loads are expected to be driven by climate change, energy efficiency improvements, expanding demand for conditioned floor space, re-programming of building types (e.g., office buildings adapted to be multifamily) and income growth, in addition to global effects of climate change [114,115]. The trends seen in Fig. 7 from [115] are also predicted in [114], where heating demand is expected to decrease in many northern countries, while cooling demand is expected to increase significantly in many developing regions. Applying different climate change predictions to buildings models in Hong Kong area showed that current cooling systems may be undersized for future cooling loads [116]. The use of future typical meteorological year (FTMY) design data should be used to inform current district energy system designs to help mitigate the climate-based impact on future loads [117].

When comparing different types of DES, Yichi et al. found that while 4G DES is the most economical option in the current energy landscape, 5G DES becomes the best solution in some future scenarios as demand changes due to climate change, renewable energy pricing, and building renovations [118].

In addition, conversion from fossil fuel-based heating to individual (or grouped) heat pumps is expected to significantly increase the winter peak electrical loads, known as the "falcon curve" [5]. However, a well-controlled DES with sufficient thermal storage may be able to reduce these electrical loads. Luc et al. [119] showed that load shifting of a small district heating system could result in 40 % to 50 % of a load shift during peak periods using a schedule-based approach.

Transition from existing systems

Transitioning between DES generations is complicated and often occurs in parallel with a campus or district master plan update. For example, it is common for United States' university campuses to have steam loops providing energy to some portions of the campus while other portions of campus use more efficient hot water. Each transition requires a significant engineering (re)evaluation to determine which buildings will be migrated to the newer DES and which ones will be added or removed. Universities and institutions (hospitals, large corporations, military installations) have the advantage of master planning and common facility managers to influence the selection of the building systems that will interconnect with the DES. Districts composed of many independent users have an extra challenge to convince everyone of the adoption and reliability of the DES, as well as determining the energy provider (thermal utility, energy services company, or private operator), metering infrastructure, and cost structures.

Challenges aside, one major benefit for an urban district of DES over other decarbonization strategies for heating and cooling is the synergy with existing utilities (both gas and electric). The "gas to geo" transition would see natural gas pipelines in the street replaced with thermal loop pipes and the utility structure of natural gas supply and metering applied to managing a DES. This conversion of an existing utility would enable utilization of much of the same workforce (e.g., drillers and pipelayers) and would also allow for equity benefits of distributed capital costs. The new thermal energy utility could equitably distribute capital costs for installing a DES across all users and over the long lifetime of a project, thus making the decarbonization of heating and cooling more affordable for each consumer.

Future costs

A future decarbonized electrical grid with increased renewable energy production and phasing out of fossil fuel production will affect future decarbonized DES. A decarbonized grid will result in changes to electricity prices and may increase price variability. Traditional DES utilizing fossil fuels for boilers and CHP plants will need to find alternative heat sources, and the availability and type of heat resources will be a driving factor for costs. And if carbon pricing is implemented widely to encourage decarbonization, the economics of a DES will change.

Current and future system installation costs will affect when and where DES are economical to implement. The high capital cost of switching to heat pumps at each end user makes the LCOE of 5G systems prohibitively high in many cases [94]. Capital costs could be decreased by reducing heat pump costs or focusing on newer homes that may be constructed as heat-pump-ready. There is a large benefit from greenfield construction, where the thermal loop can go underground as other utilities and roads are being installed [29], as was implemented at Whisper Valley in Texas.

Operations and maintenance costs need to be considered as systems are transitioned. Not only will the distributed heat pumps require occasional maintenance, the workforce to maintain these systems needs to be grown from existing trade groups. Facilities managers and maintenance personal need to be ready to maintain the newer 5G systems, or there is a risk of regressing back to individually connected buildings.

Lastly, as existing single building-based equipment (roof top units, air handling units, boilers, chillers) approach end-of-life, it is important to plan for a viable decarbonized replacement. These forward looking decarbonization plans in existing buildings, central utility plants, and campuses can help unlock future funding for projects by preventing last minute like-for-like replacement of systems. Often, building equipment is run to failure which requires immediate replacements; having a system-by-system decarbonization plan in place can prevent "carbon lock-in" for the life of the like-for-like equipment and put the replacement funding towards a decarbonized system instead.

Future financing options

Commercial success of a DES deployment/development will depend on the financing and market structure used. The financing structure is complex due to the combination of providing a thermal energy stream (at varying temperatures) to users coupled with electricity usage via circulation pump and/or heat pumps. The predominate and best financing structure for the future is still to be determined with future increasing deployment, but three generalized, projected models are outlined below with their potential benefits and drawbacks.

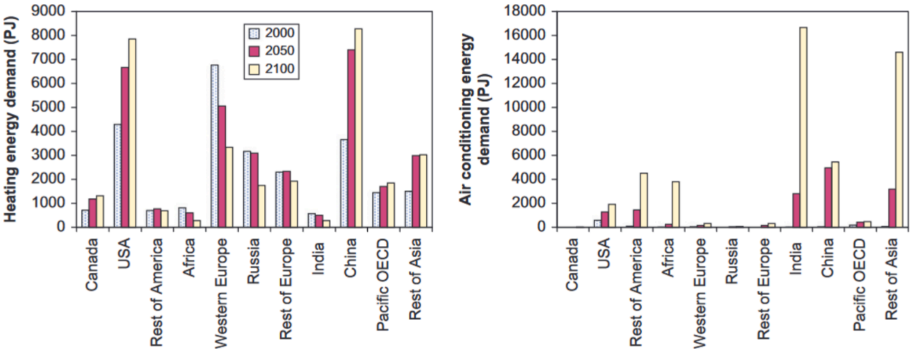

Fig. 7. Future heating and cooling (air conditioning energy) trends from [115].

- Municipal model:
  - o Capital cost is handled by local municipality, similar to an electrical co-op structure.
  - o Benefits from being local and may have access to community-owned assets such as water and wastewater, which can be useful heat sources.
  - o Highly dependent on local income levels and tax revenue and may see large variability in what resources are available.
- Project finance model:
  - o Capital costs are covered using the same financing model as is used for electrical power plants and renewable energy projects by securing an income stream and payback structure.
  - o Will likely trend toward efficient, low-cost, and low-energy designs.
  - o Will target worthwhile heat sources and buildings with quick paybacks, which may leave some customers and areas excluded.
  - o May not plan for residual natural gas infrastructure fixed costs, which may then fall to a smaller number of customers still on the gas system.
- Utility model:
  - o Capital costs are financed and distributed over a large customer base over many years. Utilities have experience with profitable operation based on these large upfront capital cost investments in infrastructure.
  - o Can plan for long-term transition away from natural gas without leaving stranded assets or a small number of customers supporting a large amount of fixed infrastructure costs.
  - o Significant differences between publicly owned utilities versus investor-owned utilities.

The market structure remains unclear at this point. Multiple values streams will need to be considered including thermal energy and electricity usage. Thermal markets are one potential option, although additional research will be needed to determine how they should be structured and regulated.

Conclusions

Herein, this paper reviewed the state-of-the-art DES technologies for achieving decarbonized heating and cooling loads, and discussed important design considerations for a decarbonized DES. A DES consists primarily of energy sources and storage, distribution network, heat conversion, and user loads. The user loads, or demand side, were not examined in detail here, as this paper focused on district systems. Designing and operating a decarbonized DES requires careful consideration of the energy input to the system to ensure that both the heat and electricity come from carbon-free sources.

Decarbonizing heating and cooling loads is a critical step toward achieving zero-carbon emissions. Unlike other decarbonized solutions such as individual electrified sources, correctly designed and commissioned DES may reduce strain on a renewable electrical grid. District solutions were compared against individual decarbonization solutions in terms of relative benefits and drawbacks, and generally DES perform well with use of carbon-free thermal sources such as waste heat and renewable sources as well as shaping demand profiles but may be complex and costly. There are unique challenges and opportunities with decarbonized DES including a lack of inherent dispatchability and storage found in the natural gas infrastructure, a need for complex controls, a requirement for a renewable electrical grid, and an opportunity for increased resilience and redundancy in the DES.

This paper reviewed the generations of district heating and cooling technologies and then focused on 4G and 5G technology. The shift toward low-temperature, high-efficiency 4G and 5G systems has made decarbonization of heating and cooling more manageable. Building loads, thermal storage, and waste heat sources can act as prosumers and exchange thermal energy bidirectionally within the district. Heat for the network can come from a variety of sources including more centralized CHP, geothermal, solar thermal, and heat pumps, as well as more distributed sources such as waste heat and prosumers. Thermal storage options for these systems include short-term water tank storage and seasonal borehole energy storage, among others.

The thermal sources and loads to connect to a system must be chosen carefully, and systems should take advantage of any available carbon-free heat sources as each design will be unique to a given location. The importance of a good initial design for these systems must be emphasized; designs should account for future flexibility, options for modularity, and potential changes in loads from the beginning. Designers may need to be creative about what heat sources/sinks are integrated in order to keep system costs low. Conscious design choices can reduce electricity demand and emissions and create a more resilient and lower cost system that performs better. Modeling and control of these DES are critical, especially for efficient operation of the new 4G and 5G installations with more distributed heat sources. If designed and operated well, a DES may have a beneficial relationship with a renewable electrical grid including shifting electrical loads to reduce peaks or charging storage at times of low electrical demand. Future trends to consider include the rising cooling demand loads, winter electrical peak load, conversion of traditional DES to start-of-the-art decarbonized systems, and the changing costs and economics of DES.

Based on the findings of this review paper, there seems to be sufficient research on the components that would go into a decarbonized DES (renewable electricity, heat pumps, heat sources, distribution network, etc.), but research into the integrated system modeling, design, and operation is still ongoing. It is suggested that research continue on electric grid impacts since current research has mostly focused on individual GHP impacts and extrapolated to DES impacts. Lower temperature resources are beginning to be utilized, but additional work is needed to identify and utilize low-temperature resources. Controls will need to evolve to handle decentralized systems, complex network topologies, and bidirectional flow. Finally, this review assumes that a future electrical grid will provide carbon-free electricity which requires continued research to realize.

CRediT authorship contribution statement

Juliet G. Simpson: Writing – original draft, Conceptualization. **Nicholas Long:** Writing – original draft, Conceptualization. **Guangdong Zhu:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided in part by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Industrial Efficiency and Decarbonization Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S.

Government purposes.

The authors would like to acknowledge the input and support from Amy Allen, Nathan Moore, Matt Mitchell, Amanda Kolker, and Josh McTigue at NREL, the NREL Communications team, and the Home Energy Efficiency Team (HEET).

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