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A thermodynamic analysis of a novel bidirectional district heating and cooling network

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A R T I C L E I N F O

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We evaluate an ambient, bidirectional thermal network, which uses a single circuit for both district heating and cooling. When in net more cooling is needed than heating, the system circulates from a central plant in one direction. When more heating is needed, the system circulates in the opposite direction. A large benefit of this design is that buildings can recover waste heat from each other directly.

We analyze the thermodynamic performance of the bidirectional system. Because the bidirectional system represents the state-of-the-art in design for district systems, its peak energy efficiency represents an upper bound on the thermal performance of any district heating and cooling system. However, because any network has mechanical and thermal distribution losses, we develop a diversity criterion to understand when the bidirectional system may be a more energy-efficient alternative to modern individual-building systems. We show that a simple model of a low-density, high-distribution loss network is more efficient than aggregated individual buildings if there is at least 1 unit of cooling energy per 5.7 units of simultaneous heating energy (or vice versa). We apply this criterion to reference building profiles in three cities to look for promising clusters.

1. Introduction

Over 54% of people worldwide live in urban environments [1]. As such, large city infrastructure projects have potential to affect progress toward sustainability goals. District heating and cooling (DHC) systems are often touted as a useful tool for meeting these goals. In their 2015 City Energy Efficiency Scorecard, the American Council for an Energy Efficient Economy gives cities sustainability "points" for the presence or intention to support district systems, regardless of quality [2]. District systems are not inherently more efficient than their individual alternatives. Depending on technology generation, maintenance, thermal load density in space, and thermal load diversity between heating and cooling in time, the efficiency can vary immensely. Determining the optimal levels of density and diversity, and projecting where such levels will exist in the coming decades, are ongoing topics of research [3]. In planning for large-scale city retrofits, as well as new installations that can last decades, it is crucial to understand how the best, modern district systems compare energetically to the best, modern individual building systems. Here we attempt to do that.

1.1. History of DHC systems

Lund et al. divide the history of district heating into four generations [4]. The original systems were built in the late 1800s and distributed steam primarily to remove the risk of boiler explosions from individual residences. Many of these systems still exist and visibly leak extensively. While not necessarily efficient by modern standards, these systems still provide a range of benefits over individually supplied systems. First, economies of scale can enable investment in more sophisticated systems than any individual building owner could afford or justify. This can include utilization of operationally-intensive systems such as biomass, combined heat and power, or thermal storage [5,6]. The centralization of equipment and control can also ease the maintenance burden at each individual building and free up space previously used for heating, ventilation, and air-conditioning (HVAC) equipment [6].

The second generation is characterized by pressurized liquid water instead of steam, typically still over 100 °C [4]. Using liquid reduces thermal losses in the distribution network and improves the efficiency of the building-side heat coils. It also enables easier integration with sources of waste heat, such as in combined heat

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Nomenclature

COP	Coefficient of Performance
DHC	District heating & cooling
div	Diversity of a district system
HX	Heat exchanger
$\dot{Q}$	Heat flow rate [W]
T	Temperature [K]
$\dot{W}$	Work flow rate [W]
η	Efficiency

and power plants. Heat recuperation is also possible between buildings on the system, allowing for benefits from complementarity, when buildings have simultaneous opposite needs for heating and cooling. In Seattle, the waste heat from a Westin Building data center will heat the new nearby Amazon offices, saving about four GWh/year [7]. Relative to the earlier generation steam systems, lower temperatures here make thermal storage systems more efficient due to reduced heat transfer losses. However, the system still has to be sized for the anticipated loads and is not easily expanded or retrofitted to include additional buildings beyond initial design capacity.

As the district water temperature decreases below 100 °C, integration with solar thermal and ground-source heat exchange becomes more efficient. This additional fuel flexibility marks third generation systems and can provide both CO_2 reduction and resiliency benefits to the network. There are new opportunities for aggregated demand response to minimize peak electric loads and/or balance integration of intermittent renewables on the electric grid.

The newest, 4th generation, systems are often called “ambient” for supplying water near room (or mild outdoor) temperature. Some of these systems even forgo distribution line insulation because the thermal losses are so low [8]. At such low temperature lifts, electric heat pumps and chillers become very efficient and can be used to boost temperatures up and down at either a central plant or the individual buildings. These networks typically serve energy-efficient buildings so that the heating coil sizes are still reasonable despite the small temperature differences between the district ambient water and the internal heating and cooling systems. The ability to modulate temperature at each building means that the district no longer has to be temperature-controlled for the worst building.

1.2. Bidirectional DHC systems

Historically all DHC systems have been “unidirectional”, meaning that the water in each pipe segment only flows in one direction. Separate circuits are needed for heating and cooling. In this paper we refer to a “bidirectional distribution” system as one in which the water in each pipe segment can flow in alternating directions, depending on the net thermal fluxes on the system. In this case, there is a single network for both district heating and cooling. As shown in Fig. 1, the network can either receive or donate heat locally. This thermal distribution system functions much like the electrical grid, which can convey energy both from a centralized generator to a consumer and back from a rooftop PV into the grid. A significant additional benefit of this design is the capacity for waste-heat recovery at each building. In the case where buildings can meet each other's loads, no flow rate is required through the central plant. The Swiss Competence Center for Energy Research is actively building and monitoring such bidirectional systems [8,9].

Fig. 1 shows an example schematic of a bidirectional system.[1] In net heating mode, the plant guarantees delivery of water between 12 and 20 °C and in net cooling mode, between 8 and 16 °C. The near-ambient temperatures maximize efficiency of the building-side heat pumps. Unlike central DHC, the bidirectional system need not be operated to serve the lowest and highest temperature needs. Rather, each individual building is equipped with heat pumps so that it can modulate its own chilled and hot water loops up or down in temperature from the main network. The system has the benefit of being modular, such that more buildings and generators can be added in time.

Exergy is a measure of the potential of a resource to do work and is the absolute efficiency benchmark imposed by physics. It combines the first and second laws of thermodynamics to account for both energy quantity and quality. An exergy analysis comparing the bidirectional system to a unidirectional 4th generation heating system with the same end loads found that the bidirectional system had 1.6× the exergy efficiency of the unidirectional system [8]. These numbers were calculated for both a theoretical model as well as an ongoing full-scale demonstration site. This is an active area of research and there remain both practical problems, such as managing complicated hydraulics, and strategic questions, such as how well this bidirectional system translates to different locations and different energy load profiles [10].

However, with the option to use individual heat pumps and chillers, it is possible that the added expense and complication of a coordinated district among multiple owners crossing public property is not a huge benefit. Here we explore the extremes of high and low diversity and density to ask when and why bidirectional systems thermodynamically outperform modern individual building alternatives.

The remainder of the paper is structured as follows: Section 2 presents the methodology and introduces the system architectures that will be used in two model problems: the first theoretical and the second more applied, discussed in Sections 3 and 4, respectively. Section 5 has conclusions and next steps in moving from a thermodynamic assessment to a practical system implementation.

2. Methodology

The purpose of this paper is to compare the thermodynamic performance of modern individual and district thermal systems for differing load diversities and densities. We will identify the overall system efficiencies, as well as the sources of inefficiency in each sub-process. Understanding these losses can indicate where and how changes to the system could lead to efficiency gains, and therefore fuel savings. To do this we will use exergy analysis. Exergy allows for direct comparison between systems with different types of energy flows. While all of the energy systems in this study are electric, often district systems incorporate a range of resources, which can be appropriately-valued thermodynamically using exergy.

2.1. System architectures

Both the individual and district systems are designed for buildings with near-ambient space heating and cooling. This allows for the use of low-lift electric heat pumps and chillers. For ease of

[1] Other research papers analyzing similar ring networks exist, but don't tend to refer to them as “bidirectional”. This is because they use a two-pipe system: one for heating and one for cooling.