BEYOND 2020 – World Sustainable Built Environment conference IOP Publishing
IOP Conf. Series: Earth and Environmental Science **588** (2020) 022054 doi:10.1088/1755-1315/588/2/022054

A topology optimization framework to facilitate adoption of advanced district thermal energy systems

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Abstract. Advanced district thermal energy systems, which circulate water at temperatures near ambient conditions, and facilitate the utilization of waste heat and renewable thermal sources, can lower the carbon-intensity of urban districts, advancing the U.N. Sustainable Development Goals. Optimization of the network topology — the selection of the best subset of buildings and the best network to connect them, to minimize life cycle cost — can increase adoption of these system in appropriate applications. The potential "solution space" of the topology optimization problem grows factorially with the number of buildings in the district, motivating the consideration of a design heuristic. In this study, a heuristic for the network selection was evaluated with an exhaustive search, for a prototypical four-building district. For the prototypical district considered, the heuristic was effective in selecting an optimal network topology. Additionally, it was found that, in this case, the selection of the subset of buildings was more influential on the life cycle cost than the selection of the network topology. This work is part of a larger effort to develop a topology optimization framework for district thermal energy systems, which is anticipated to address barriers to adoption of ambient-temperature systems.

1. Introduction

The global trend towards urbanization and the urgency of addressing climate change require addressing the energy- and carbon-intensity of the built environment in cities [1]. Advanced district thermal energy systems, which circulate water at near-ambient temperatures, can leverage the density and diversity of load in urban districts and facilitate the use of renewable thermal resources and waste heat, reducing reliance on fossil fuels, and advancing the U.N. Sustainable Development Goals for Sustainable Cities and Communities, Affordable and Clean Energy, and Climate Action [1].

However, the high infrastructure cost and extensive planning effort required by district thermal energy systems hinder their adoption, motivating the consideration of new approaches [2]. This study is part of a larger effort seeking to address these challenges through development of a topology optimization framework for district thermal energy systems. The topology optimization framework seeks to minimize the life cycle cost associated with meeting the space conditioning requirements of a new or existing district, through answering the questions, "Which subset of buildings, if any, should be connected to a district thermal energy system, and by what thermal network should that subset be connected?" The size of the search space associated with this topology optimization problem grows factorially with the number of buildings considered. For example, for a district of 10 buildings, considering all potential subsets of the group of buildings, and all the potential networks by which they could be connected represents a number of potential configurations on the order of 10^{16}. This motivates the consideration of a heuristic to address the selection of the network by which a given set of buildings should be connected.

In this work, a graph theoretical interpretation is applied to the topology optimization problem. District thermal energy system network topologies are represented as "undirected graphs." An undirected graph comprises a set of vertices, or nodes, and a set of edges (unordered pairs of nodes) [3]. A graph can be represented by an *adjacency matrix,* $\boldsymbol{A}$, in which an element $A_{i,j} = 1$ if there exists an edge between nodes i and j and 0 otherwise. A graph in which there exists a path between each and every pair of nodes is considered a *connected graph.* A path that starts and ends at the same node, and passes through at least three distinct nodes is a *cycle* [3]. A *spanning tree* is a connected graph without cycles, and the spanning tree with the least total edge length is considered the minimal spanning tree. In this context, a network corresponding to the minimal spanning tree will connect a given set of buildings with the least infrastructure cost. However, the minimal spanning tree network may not necessarily minimize energy-related costs, since additional thermal connections could potentially improve the efficiency of the network. In this study, the selection of the minimal spanning tree (MST) as the network to connect a given subset of buildings is evaluated as a heuristic for the topology optimization problem, and will be referred to as the "MST heuristic."

This study and the larger effort focus on applications to fifth generation district heating and cooling (5GDHC) systems. 5GDHC systems circulate water at temperatures near ambient conditions (typically in the range of 15–25 °C) and leverage water-source heat pumps at the connected buildings to further temper the water [4] either for heating or cooling. This study considers a 5GDHC system in a two-pipe configuration, with bi-directional mass flow permitted. A centralized heat pump maintains the network temperature within a desired range. Buildings are connected in parallel to the thermal network. An energy transfer station (ETS) serves as the interface between each connected building and the district thermal network. The ETS consists of a heat pump, heat exchanger, and a circulation pump. Based on the nature of the building's thermal load, water will be drawn from the network's "cool pipe" or "warm pipe" by the circulation pump. The moderate system temperatures allow individual buildings to add or reject heat to the network in a manner that offsets the load on centralized supply equipment, and would facilitate integration of waste heat and renewable thermal sources such as solar thermal and geothermal [2]. The use of electrically-driven heat pumps as the primary equipment, facilitated by the moderate system temperatures, is compatible with decarbonization of source energy, advancing targets in the U.N. Sustainable Development Goals for substantially increasing the share of renewable energy in the global energy mix [1]. Reducing the carbon intensity of space conditioning at the district scale, which can be accomplished through leveraging 5GDHC systems, represents a scalable approach for lowering carbon emissions, advancing targets in the U.N. Sustainable Development Goals for reducing the per capita adverse environmental impact of cities [5].

With opportunities for buildings to exchange heat synergistically through the thermal network, 5GDHC systems motivate consideration of more complex network topologies, including ring and meshed configurations. Conventional district thermal energy systems are generally configured with radial networks. Examples of these network types are shown in Figure 1. Past studies addressing topology optimization for district thermal energy systems have primarily focused on heating-only systems, and a limited set of network configurations. The work of [7]

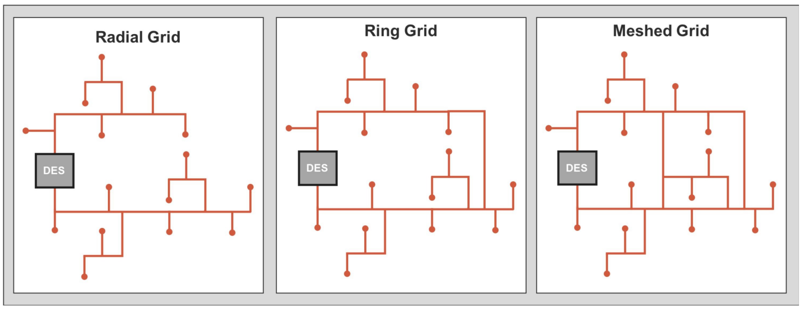

Figure 1. Grid topologies for district thermal energy systems, courtesy of [6].

solved an optimization problem for the network topology of a district heating system, including the location of the central plant, and pipe diameters, to minimize life cycle cost. The authors constrained the potential network topologies to exclude ring or meshed configurations, and the connection of each building to the district network was imposed as a boundary condition. Simplified building load profiles based on "time slices" were used. The authors approached the problem with genetic algorithms, and concluded that the relative locations of the buildings, the thermal load, and pressure and temperature requirements for the network significantly influenced the optimal topology.

The work of [8] optimized the network topology, pipe diameter, and supply and return temperatures of a district heating network for minimal life cycle cost. They cast the problem into three-sub problems, which they approached with linear and non-linear programming. The authors considered several scenarios of building locations and loads, and concluded that the optimal topology configuration was not readily generalizable.

A study by [9] performed topology optimization for a district heating and cooling network and compared the outcomes based on two different objective functions: capital cost and life cycle cost. The authors constrained the problem such that only radial and ring topologies were considered, and that the connection status of each building was a boundary condition. With analysis of a study case, the authors concluded that differences in pumping energy and heat loss through the networks led to different solutions associated with the two objective functions, highlighting the importance of topology optimization. The authors of [9] called for future work in the area of topology optimization for district thermal energy systems to address more flexibility in the network configurations, and higher-fidelity load profiles.

This study, and the larger effort to which it contributes, addresses this need and offers a departure from past work, by considering the full space of potential network configurations, the option for buildings to be served by independent systems, and by leveraging high-fidelity building load profiles. 5GDHC systems, with bi-directional thermal and mass flow, offer greater potential rewards from topology optimization than conventional district thermal energy systems, and pose a more challenging problem, with the larger solution space of network configurations.

Design of a district thermal energy system typically begins with a feasibility assessment in which potential system types and technologies are identified, and parcels in a geographically-defined district are screened for suitability to connect to a district energy system, based on their current or expected base thermal loads, proximity to a potential central plant, and regulatory and economic factors. District thermal energy systems in the U.S. are often developed through a design-bid-build contractual structure, or built, owned, and operated by a third party [10]. Traditionally, design of district thermal energy systems has treated building loads as deterministic. However, the emergence of net-zero energy and other low-energy districts has motivated consideration of more integrated design approaches [11]. The development of the topology optimization framework addresses a need identified by [2] for "advanced energy system analysis tools of coherent systems" to enable the use of advanced district thermal energy systems in the context of increased penetration of renewable electricity generation.

2. Methodology

In this study, an exhaustive search was performed to evaluate the MST heuristic for a prototypical urban district consisting of three multi-family buildings and a hospital. All possible networks that could serve a district consisting of four buildings and a central plant were analyzed, constituting 908 different cases. This topology optimization problem seeks to minimize a cost function representing the life cycle cost of piping infrastructure for the district thermal energy system, and the energy required to meet the HVAC loads of all buildings in the district, whether or not they are served by the 5GDHC system. The cost function considered also accounts for a potential future price on carbon in the United States, based on a scenario outlined in [12]. The cost function is based on that implemented by [6] and is formulated as follows:

$$\begin{aligned} &\min_{\mathbf{A}} C_{pipes} + C_{elec}UPV_{elec}(E_{de} + \sum_{i=1}^{n} E_{be,i}) + C_{gas}UPV_{gas}\sum_{j=1}^{n} E_{bg,j} \\ &+ \sum_{t=1}^{20} m_{CO2}(t)C_{CO2}(t)UPV_{CO2} \end{aligned} \tag{1}$$

subject to:
(1) If there exists a pipe directly thermally connecting building i and building j, $A_{i,j} = 1$. Otherwise, $A_{i,j} = 0$.
(2) If building i is served by the district thermal energy system, there exists a path from the central plant to node i.

$\mathbf{A}\ \epsilon\ R^{(n+1)\ \mathrm{x}\ (n+1)}$: adjacency matrix describing the thermal network

C_{pipes} : Cost of pipes and trenching

C_{elec}: Electricity cost rate

C_{gas}: Natural gas cost rate

$E_{be,i}$: Annual electric consumption for HVAC at building i

E_{de}: Annual electric consumption for district energy systems, including primary equipment and distribution pumps

$E_{bg,j}$: Annual natural gas consumption for HVAC at building j

UPV_{elec}: Uniform present value factor for electricity, accounting for projected escalation in rates

UPV_{gas}: Uniform present value factor for natural gas, accounting for projected escalation in rates

$m_{CO2}(t)$: Annual CO2 emissions, accounting for projections of reduced carbon intensity of electricity

$C_{CO2}(t)$: Cost associated with CO2 emissions in a given year, per projections under a scenario by NIST

UPV_{CO2}: Uniform present value factor associated with carbon pricing

The twenty-year time horizon used for calculating the life cycle cost is consistent with that used in [6] for evaluation of a 5GDHC system. Note that a graph representing a network for a district with n buildings will have $n+1$ nodes, as one node of the graph corresponds to the central plant.

An energy model of the 5GDHC system, implemented in Modelica, was used to evaluate the energy consumption terms in the cost function. The underlying energy model was developed and documented in [6]. Modelica is a "non-proprietary, object-oriented, equation-based language to conveniently model complex physical systems," such as systems containing mechanical, electronic, hydraulic, and thermal components [13]. The load side of the energy model was adapted to represent the prototypical urban district under consideration in this study. Building types to be included in the district were selected based on an evaluation of thermal load diversity, using a metric defined by [14]. This metric captures the extent to which simultaneous heating and cooling loads are present in the district, which enhance the potential for buildings to recover and reject heat synergistically , improving the exergetic efficiency of 5GDHC systems at the district level. The combination of buildings selected for this study, three multi-family buildings and one hospital, yield a value of the thermal load diversity metric of 0.63, exceeding the threshold of 0.60 identified by [14], for 5GDHC systems to exceed distributed building-level HVAC systems in exergetic efficiency. This study expands on previous work performed by the authors, which analyzed the spanning-tree scenarios only, for a prototypical district with less thermal load diversity present, documented in a manuscript currently under review [15].

In the energy model of the 5GDHC system, building thermal load profiles were represented with data-driven metamodels, developed with the Metamodeling Framework documented in [16]. This is consistent with the approach taken by [6]. The use of metamodels to represent building loads, in comparison with full-order physics-based models, improves the simulation efficiency of the 5GDHC model, and the Metamodeling Framework has been demonstrated to represent building thermal load profiles accurately [16]. Under the Framework, a data set based on the U.S. DOE prototype building energy models for the applicable building types is used to train the metamodels [16]. The Framework offers several model types, and random forest models were selected in this study, based on their accuracy, and the computational efficiency of building the models [16]. Each building has two associated thermal load profiles: one for the case in which the building is connected to the 5GDHC system, and one for the case in which the building is served by independent systems.

Separate training data sets are used to generate metamodels for the "connected" and "independent" cases, i.e., when a building is connected to a district energy system or when it is served by its own dedicated building energy systems. The applicable DOE prototype building models are used, with a parameter sweep, to generate the training data set for the "independent" case. For the "connected" case, the HVAC systems of the prototype building models are modified to use water-source heat pumps. Table 1 shows the characteristics of the prototypical multi-family and hospital buildings represented in this study.

The analysis was performed using weather data for Golden, Colorado. Natural gas and electricity rates obtained from the U.S. Energy Information Administration for Colorado in 2017 [17], and unit costs for pipes and trenching ($500/meter) from [6] were used in this study. The four hypothetical buildings and a district thermal energy system central plant were "placed" on a block in Golden, Colorado, for purposes of calculating pipe lengths.

3. Results and Discussion

In order to evaluate the MST heuristic, the life cycle cost associated with each MST network was compared to the costs associated with the other possible networks connecting the same subset of buildings. For each of the fifteen possible subsets, the MST network resulted in either the minimal life cycle cost, or a life cycle cost that was within a negligible margin (1%) of the minimum. This is summarized in Figure 2, which shows the ratio of the life cycle cost of a given scenario to the life cycle cost of the MST for the same subset of buildings, as a function of the

Table 1. Characteristics of prototypical buildings considered in study.

Building Type	Floor Area(m^2)	Baseline HVAC System Type	Baseline EUI ($\frac{MJ}{m^2}$)
Multi-family	3,134	Packaged units with DX cooling and gas heating	436
Hospital	22,436	Variable-air volume with hot water reheat	924

total pipe length, with scenarios color-coded based on the nature of the buildings connected to the network. Scenarios that represent an MST are depicted with stars, and for these scenarios the value of the ratio is naturally 1.0. (Note that for clarity, only scenarios with a total pipe length under 100 m are shown, which encompasses all MSTs.)

In this case study, the life cycle cost (LCC) of a particular scenario was more influenced by the selection of the subset of buildings than the network by which they were connected. Figure 3 shows life cycle cost as a function of the total pipe length associated with each scenario, with the scenarios grouped by the nature of the buildings connected to the network. As shown in Figure 3, for the scenarios consisting of two or three connected buildings, the inclusion of the prototypical hospital building in the network resulted in a significantly higher LCC, due to the high heating load associated with this building, and the high cost of meeting that load with electricity as opposed to natural gas. (Note that in Figure 3, a representative sample of the datapoints with four buildings connected is shown, due to the large number of scenarios.)

Figure 4 shows a disaggregation of the LCC by component (energy, carbon, and infrastructure) for a randomly selected subset of the topology scenarios. Consistent with the subset represented in Figure 4, among all scenarios, the fraction of the life cycle cost attributable to energy costs ranges from 82% to 88%, the fraction attributable to carbon costs from 10% to 17%, and the fraction attributable to infrastructure does not exceed 2% . This dominance of costs related to energy and carbon (which is also proportional to the energy consumption) is attributable to the magnitude of the thermal loads of the prototypical buildings considered. The infrastructure costs are a function of the spatial locations of the buildings. Note that the nature of this disaggregation is not expected to extend to districts with buildings with lower energy use intensity, or lower spatial density, in which cases, the infrastructure costs would be expected to be more significant proportionately.

The small fraction of the LCC that is attributable to infrastructure costs in the scenarios resulting from this case study explains the lack of sensitivity of the LCC to the network by which the subset of buildings is connected. The selection of the network influences LCC through the infrastructure cost component, as well as through thermal interactions that influence the energy consumption of the network. Given the dominance of energy-related costs in the LCC, and the higher costs of electricity relative to gas per unit of delivered energy, a sensitivity analysis was performed for the electricity cost value. The multiplier applied to the electricity cost was a proxy for a multiplier on the ratio between the electric and gas rates per unit of delivered energy. The results of this analysis are shown in Figure 5, for two different values of a ratio (R_{ele}) by which the base case electric rate was multiplied, R_{ele}=0.75, and R_{ele}=0.5.

As shown in Figure 5, the maximum and median values of the life cycle cost are reduced with the reduction in electric rates, and as a result, the range of values is also reduced. This shows that a reduction in the ratio of electricity to natural gas rates per unit of delivered energy would

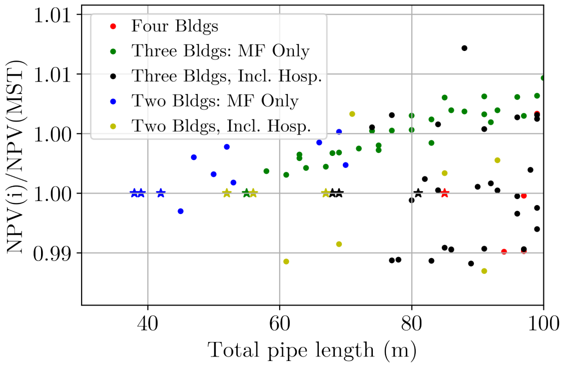

Figure 2. Ratio of life cycle cost to life cycle cost of MST as a function of pipe length for topology scenarios.

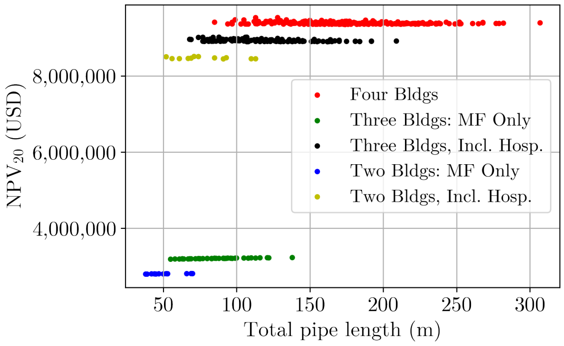

Figure 3. LCC as a function of pipe length for topology scenarios.

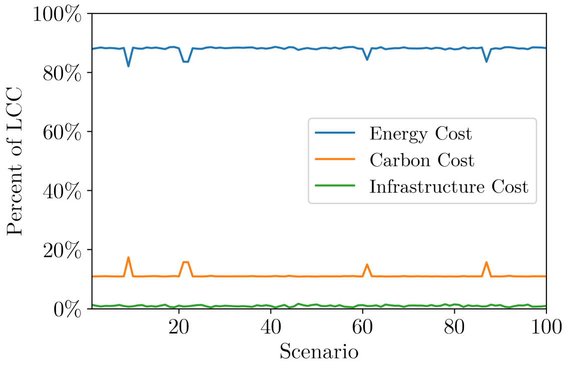

Figure 4. Disaggregation of life cycle cost by component for selected topology scenarios.

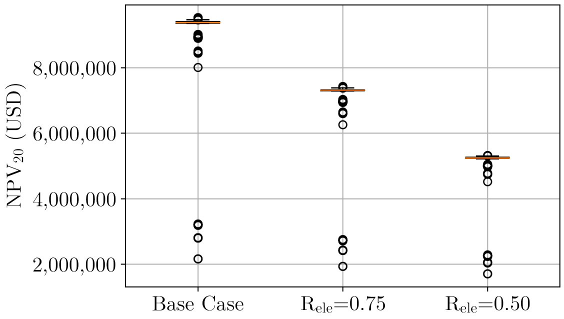

Figure 5. Box and whisker plot showing the range of life cycle costs for all scenarios, for the base case and for two cases with a multiplier (R_{ele}) applied to the electricity rates.

reduce the bifurcation of solutions shown in Figure 3, corresponding to the presence or absence of the prototypical hospital building in the network. (In the cases considered in the electric rate sensitivity analysis, the minimum values remain approximately the same, as they correspond to cases in which the largest heating load, associated with the hospital, is not connected to the district thermal energy system, and is thus served with natural gas.) This suggests that a reduction in electricity rates relative to natural gas rates could contribute to a greater influence of the network selection, as opposed to the subset of buildings served, on life cycle cost. A shift in building HVAC energy use in the “independent” systems case from natural gas to electricity, as would occur if building heating systems were electrified, would also be expected to increase the influence of the network selection for this reason.

4. Conclusion

This study demonstrated that, for the prototypical urban district considered, with a relatively high degree of thermal load diversity, the MST heuristic is effective in selecting the “best” network by which to connect a given subset of buildings. In this study, due to the relatively high magnitude of the thermal loads present at each building, the selection of a network was relatively unimportant in influencing LCC relative to the selection of the subset of buildings. The results of this study support the inclusion of the MST heuristic in the proposed topology optimization framework. In the future, the MST heuristic will be evaluated for a larger prototypical district, with the integration of a waste heat source, and the robustness of the MST heuristic will be evaluated through Monte Carlo analysis of high-level parameters in the cost function. Future work could also potentially characterize the relative importance of the two elements of the topology optimization problem with a load diversity metric. Further development of the topology optimization framework will include implementation of an optimization algorithm for selection of the subset of buildings to connect to the network. Particle swarm optimization and other meta-heuristic algorithms will be considered, as they are compatible with the use of the Modelica simulation as a function evaluator. It is anticipated that the topology optimization framework, when complete, will result in a useful tool for planners, consultants, and engineers that can expand adoption of advanced district thermal energy systems in appropriate applications, supporting progress towards the U.N. Sustainable Development Goals.

Acknowledgments

This work was authored in part 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 by the Building Technologies Office and the Advanced Manufacturing Office. 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.

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