Modeling district heating and cooling systems with URBANopt, GeoJSON to Modelica Translator, and the Modelica Buildings Library

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Abstract

The URBANopt project has successfully leveraged OpenStudio/EnergyPlus to model buildings and electrical systems at an urban scale; however, URBANopt has lacked the ability to model district thermal energy systems until recently. This paper will present the modeling infrastructure that was developed specifically for the analysis of district heating and cooling systems, and how it is integrated into the existing URBANopt framework.

The paper also discusses the development of new models added to the Modelica Buildings Library to model various district energy system components including loads, energy transfer stations (ETS), distribution networks, and central plants. The paper describes how different building loads can be modeled including time series, TEASER reduced-order models, or Spawn of EnergyPlus models. URBANopt District Energy Systems allows the user to switch between the various configurations.

Key Innovations

- URBANopt District Energy System adds the ability to run models of district energy systems using templated systems
- The ability to quickly model loads connected to a district system using Spawn of EnergyPlus, time series models, or reduced order models
- New functionality to export loads from URBANopt's OpenStudio simulations into a district energy system analysis using Modelica

Practical Implications

The presented open-source toolchain allows automating the workflow for authoring, running and analyzing district energy models.

Introduction

In recent years, there has been an emphasis on evaluating buildings in a district context to leverage the diversity of building loads to reduce energy consumption, integrate renewable energy sources, and to flatten the overall district demand curve. Several software tools have been developed to help achieve these objectives and one of them is the URBANopt software development kit (URBANopt SDK) (Kontar et al., 2020; Macumber et al., 2016; Polly et al., 2016). URBANopt SDK has been developed over the last half decade and focuses on

providing users with backend analysis capabilities leveraging OpenStudio (Guglielmetti et al., 2011) to provide detailed physics-based building energy models. URBANopt SDK enables connection through file-based data exchange to other analysis engines. We leveraged this capability to expand URBANopt SDK to analyze district heating and cooling (DHC) systems, using Modelica models for the system simulation.

Use of Modelica allowed for more comprehensive modeling of DHC systems by including pressure-driven flow and its impact on pump energy and controllability, dynamically varying water temperatures in the distribution network, detailed control algorithms, and greater flexibility with district energy system architectures. This portion of the project is termed URBANopt District Energy Systems (URBANopt DES) and encompasses two major modeling components: 1) The Modelica Building Library, and 2) a Python-based GeoJSON to Modelica Translator (GMT). The intention of the GMT is to provide quick access to the major types of district energy systems, namely steam systems (first generation) and low temperature systems (fourth generation). However, at the time of this writing, only fourth-generation systems are enabled. We will discuss these two components and conclude with an example workflow which generates a complete DHC model in Modelica using the results of URBANopt SDK run with OpenStudio.

Finally, the use case of the URBANopt DES project is to provide an open-source library where practitioners can easily screen DHC system options during the early phase of a project. However, URBANopt DES can also be used in later phases of projects by allowing the user to generate a Modelica package of an entire DHC model that can then be customized using any of the Modelica-based editors (e.g., Dymola, IMPACT, OpenModelica, etc.).

Background

District energy systems in the United States have long been undervalued as the trend towards electricity generation using central power pushed electricity generating plants from city centers (Meeker et al., 1985). The lack of district heating caused localized buildings to provide their own heating (in the form of steam or hot water) as needed. However, in the last several decades, many campuses (colleges, industrial, office complexes)

have implemented centralized hydronic heating and cooling systems.

The value of DHC systems has changed over time with a revitalized interest in DHC to help jurisdictions reach aggressive climate goals by reducing energy consumption, increasing penetration of renewables, and achieving significant reduction of greenhouse gas (GHG) emissions (Reyna et al., 2018). In the context of increased renewable generation, electrification of heating equipment is planned to replace combustion processes which offers reductions in greenhouse gas emissions; however, the time-value emissions of electricity need to be considered as higher electricity consumption using conventional thermal power plants typically results in higher GHG emissions. Increased renewables will make this issue more problematic, and many solutions will be needed to shift the peak energy consumption in buildings. The use of DHC may help solve this problem by providing 1) thermal energy storage (either through existing fluid capacity or district-based thermal energy storage), 2) the connection of diversely loaded buildings onto a network to reduce overall peak demand, 3) the ability to capture additional waste heat, and 4) the integration of combined heat and power (CHP).

Lund et al. (Lund et al., 2014) describes four generations of DHC. A brief overview of the major trends between the different generations shows that, as the generations increase, heat is distributed at lower temperatures and the energy efficiency increases. First generation (1G) systems are steam-based, and fourth generation (4G) systems have heating water temperatures below 70°C, while some novel very low-temperature systems use near-ambient temperature water with distributed water-to-water heat pumps or heat recovery chillers in the Energy Transfer Station (ETS). These systems can integrate newer waste heat resources such as heat rejected from wastewater treatment plants, refrigeration processes, and data center cooling systems.

Few, if any, urban building energy modeling (UBEM) tools that handle conventional, state-of-the-current, and nascent DHC systems exist. These tools need to handle the building physics, distribution networks, energy transfer station components, and the complex central plant configurations and controls. Several integrated urban building energy modeling tools exist with varying levels of accuracy at the defined system boundaries (which we define as the building loads, energy transfer station, distribution network, and the central plant).

Some existing projects that provide integrated UBEM include CitySim (Emmanuel & Jérôme, 2015), Virtual Pulse (Heidarinejad et al., 2015), CityBES (Hong et al., 2016), and umi (Reinhart et al., 2013). These tools vary from modeling the building loads with reduced order models to detailed physics-based models, as well as having varying degrees of user interfaces, and central plant modeling. In general, there are only a few commonly used simulation engines for modeling the energy consumption in district systems, which include

TRNSYS (A. Klein et al., 1976), EnergyPlus (DOE, 2018), IDA/ICE (Björsell et al., 1999) or reduced order models (ROMs). The focus of this paper is on extensions to the URBANopt SDK project, which will be discussed in more detail in subsequent sections.

URBANopt SDK is designed to be a backend tool where third parties can develop custom user interfaces and extensions to support their respective use cases. URBANopt SDK has been integrated with OpenDSS for grid modeling, REopt for evaluation of renewable energy integration, and Reference Network Modeling (RNM) (Mateo Domingo et al., 2011) for large-scale electric distribution planning. The extensions are connected using a data exchange paradigm using OpenStudio Measures (Roth et al., 2016) to send the results of detailed building energy models to the tools' required inputs. These connections are flexible as the Ruby programming language is used to transform the data as needed. URBANopt SDK uses GeoJSON (Butler et al., 2008) as the main file format for the urban context. This file contains the building footprint data, building characteristics, piping layouts, electric layouts, central plant locations, and other geospatially defined parameters.

Motivation

Modern district thermal energy systems, operating at more moderate temperatures and coupling heating and cooling, have the potential to leverage the density and diversity of thermal loads in urban areas to significantly reduce energy use intensity, and further reduce carbon emissions through their compatibility with electrification of heating equipment (Allegrini et al., 2015; Connolly et al., 2014). The benefits of those systems are mainly driven by the gains in the Second Law efficiency and the heat recovery opportunities that they yield. A proper assessment of those gains and of their trade-offs (higher pumping energy due to lower delta-T) requires tighter integration of the buildings, energy transfer stations, and distribution networks, and thus more refined modeling capability, than that provided by existing tools which calculate thermal loads of individual buildings, and loads at the district level that are typically met. Electrification of heating also motivates consideration of interactions between thermal and electrical loads to mitigate increases in peak demand and requirements for larger electrical infrastructure. The characteristics of near-ambient temperature systems also motivates consideration of network configurations beyond the typical ring or radial networks used by earlier generations of district thermal energy systems. The "search space" of potential network configurations can quickly become intractable for manual comparison of scenarios (Allen et al., 2020).

Modelica has been increasingly used for building and district energy simulation, see for example IEA EBC Annex 60 (Wetter & van Treeck, 2017) and IBPSA Project 1 (Wetter et al., 2019), as it allows flexible

modeling of system architectures, controls, and simulation of actual pressure distribution and its associated pump energy. The Modelica Buildings Library (MBL) (Wetter et al., 2014) contains building components used specifically for building and district energy and control systems. These components range from pipes to heat pumps and detailed room models to reduced order models. A more recent development combines EnergyPlus' envelope model with MBL's HVAC models in a project called Spawn of EnergyPlus (Wetter et al., 2020).

Implementation

The implementation of URBANopt DES required the implementation of a data layer, an application layer, and updates to the building models in Modelica. For the application layer, we developed a new Python package called the GeoJSON to Modelica Translator (GMT) to assemble a fully functional district energy system based on the inputs from the data layer. The GMT was built with a top-down approach; that is, the GMT focused on the use case as seen from the end user (e.g., mechanical engineer, urban designer, etc.). The GMT's design includes four DHC categories including the building loads (loads), distribution network (network), energy transfer stations (ETS), and central plants (plants).

The GMT application requires two data files and various Modelica template files. Figure 1 shows how a GeoJSON file, and a system parameter file can be read into the GMT application to set values in the templated Modelica models. The result is a fully functional Modelica package which includes the resulting Modelica models and references to models in the MBL.
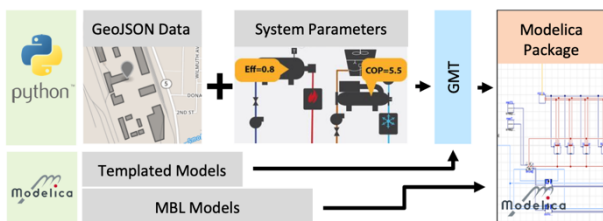

Figure 1: Workflow to generate Modelica.

Modelica Buildings Library

We leverage the MBL as a core component of URBANopt DES; however, several additions are being made to the MBL to allow easy assembly of DHC systems using the GMT. This is to either streamline the modeling workflow or to enable modeling various technologies used in DHC applications. These new developments and their documentation are accessible under the package Experimental.DHC[1] and are briefly described hereunder.

A set of base classes provides a fixed interface for the different system components to be connected, namely the central plant, the distribution network, the energy transfer station, and ultimately the building and the terminal unit serving the load. Fixed interfaces allow for easy

redeclaration of each component that supports straightforward modeling and analysis of various system options.

Distribution networks are modeled using a scalable component that can connect an arbitrary number of ETSs to the main pipe. Two-pipe and one-pipe configurations are supported for parallel and series connections, respectively. The pressure drop relationship with the flow rate transitions from quadratic to linear as the flow regime transitions from turbulent to laminar. The flow resistance is initially computed based on the physical characteristics of the pipe material, and sizing parameters that can be either provided by the user or computed at initialization based on the nominal pressure drop ratio to the pipe length. The heat transport delay can be accounted for using a dynamic plug flow pipe model (Heijde, 2017).

The main limitation pertains to the computation of the heat loss to the ground and other pipes in case of underground distribution systems, for which a model is currently under development.

A package was developed to model various energy transfer station layouts and controls, including steam to water heat exchangers and direct and indirect consumer connections to chilled water and heating water service. The control valve models allow for specifying a fixed flow resistance—representing a balancing valve—in series with a variable flow resistance—representing the modulating valve. The two flow resistances are lumped to avoid an algebraic loop when solving for the pressure drop. A preprocessing routine for automatic hydronic balancing is planned for development. We also integrated models of decentralized heat recovery chillers or heat pumps for simultaneous heating and cooling in novel very low-temperature DHC systems.

A package for combined heat and power generation is being developed. It already covers combustion-based CHP plants (so-called "topping cycle") following the modeling principles from the work of Beausoleil-Morrison et al., 2007. The next planned addition to the package addresses the modeling of CHP systems based on heat recovery (so-called "bottoming cycle"), for instance with a two-phase Rankine cycle.

A package of models representing the building loads is under development. Here the modeling focus is twofold. First, that development allows interoperability with different types of building load models, from simple time series to detailed EnergyPlus envelope models (using the MBL built-in Spawn coupling capabilities described in Wetter et al., 2020). Secondly, pertaining to the building mechanical systems, a linear scaling of the simulation time with the number of connected loads is achieved through a tailored modeling approach of the in-building distribution system where a few lumped equations are used to represent the mass flow rate and pressure drop variation with the terminal valve demand, for a variety of

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[1] https://github.com/lbl-srg/modelica-buildings, SHA: 7badd8a68

typical hydronic configurations and controls that the user can select from.

We developed several example models illustrating the use of this modeling framework to represent different generations of DHC systems. For instance, a model of a very low-temperature DHC system with a central geothermal borefield and a sewage heat recovery system is available. Although some of these examples are still mainly generated by manually instantiating and connecting the MBL components, the URBANopt SDK toolchain will ultimately provide a programmatic workflow to achieve the same result. This is described in the next section.

GeoJSON and System Parameter Data

Figure 1 shows how the MBL models in conjunction with additional data generate a full Modelica package. These data come from GeoJSON, the system parameter file, and templated Modelica files.

The GeoJSON has a defined schema; however, the *properties* section of the GeoJSON is a freeform field. We used the same *properties* structure as URBANopt SDK. This section provides the geospatial data of the buildings and districts (e.g., building footprints, building types, heights, physical locations of district components, etc.). The system parameter file is a JSON-based file providing the configuration of the DHC system (e.g., building load model types, weather file locations, boiler efficiencies, etc.). The system parameter file contains the same DHC categories as the GMT: building loads, ETSs, network topology, and central plants. The GMT is needed to programmatically set the various system level components of the DHC system and to allow for flexible modeling of different component options (e.g., the GMT allows the modeling of building loads using Spawn, reduced order models and time series).

The underlying functionality of the GMT is the templated Modelica models and the referenced MBL models. The Modelica models are templatized using Python's Jinja2 framework (Ronacher, 2008). These templating-based approaches are common in other projects including CoTeTo (Nytsch-Geusen et al., n.d.) and TEASER (Remmen et al., 2018). The templatization requires updating the concrete Modelica components and adding variable strings that could be easily replaced with the values from the system parameter file. The templated Modelica files are saved with new file extensions *.mot* and *.mopt* files for Modelica template and Modelica partial template, respectively. Note that conventional Modelica files have *.mo* extensions. An example of the template would be a system parameter file specifying the effectiveness of the indirect ETS's heat exchanger as 90%, which the GMT will extract from the system parameter file and set into the *CoolingIndirect.mot* file and save the resulting file into the appropriate folder as *CoolingIndirect.mo*. Note that this approach ultimately creates copies of the Modelica files that may already be stored in the MBL, which can be useful if the templated version provides more flexibility but may also require

updates to the template when the underlying MBL component is updated.

The result of the GMT is a Modelica package that can be opened with any Modelica-compliant tool for inspection, editing and simulation. This package includes folders for the building loads, ETSs, distribution networks, and central plants. Each folder can have multiple subfolders and contains all the resources needed to run the simulations (e.g., weather files, load files, etc.). The project has been tested with JModelica, OPTIMICA, and Dymola.

The architecture of the GMT is a rigid structure between the building loads, ETSs, distribution network, and the central plant. Figure 2 shows an example of how the different components can connect to each other. The rigidity of the connections is across the DHC categories (e.g., building loads vs. ETS) and not within a DHC category—meaning that new building loads can be added assuming that the *interface* is the same for the existing building loads.
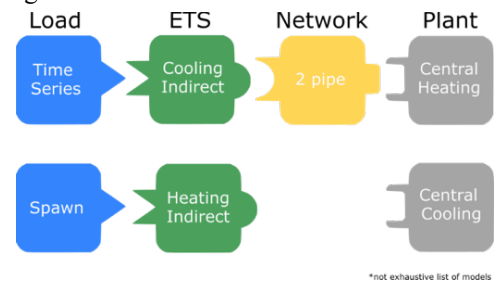

Figure 2: GMT connections.

The updates to the MBL described above provided the partial models and the GMT provides the concrete implementations of the various components.

GMT Application Package

The GMT contains four categories of DHC components, and each category contains representative Python files for managing both the connections, data, and references to templated Modelica files. These include the *building loads*, *energy transfer stations*, *distribution network*, and the *central plants*. The structure of the GMT allows for multiple implementations of components within the same category as long as the interface is the same. These four categories as implemented in the GMT will be discussed below.

Building Loads: The building loads within the GMT contain four different component models, 1) reduced order models using TEASER, 2) Spawn of EnergyPlus, 3) time series using loads in Watts, and 4) time series using mass flow rate and temperature. This was the first set of components developed and it provided the initial architecture of the GMT. Specifically, it demonstrated the need for the GMT to have multiple abstractions of component models based on the desired level of fidelity to be modeled.

TEASER (Remmen et al., 2018) was used for the development of the reduced order models to calculate the coefficients of the already available reduced order models

in the MBL based on a few high-level characteristics of the building types. TEASER saves the resulting models into its own Modelica package structure which the GMT leveraged; however, this required the development of the Modelica Builder in conjunction with the GMT (Long & Summer, 2020). The Modelica Builder provides an abstract syntax tree (AST) of loaded Modelica (.*mo)* files allowing users to programmatically parse, manipulate (update connections, add components, update component parameter values, etc.), and save resulting files. This was needed in order to update the results of TEASER to conform to the requirements of the building load component as defined by the GMT and underlying MBL partial models.

Time series-based models can be represented in power (watts) or as required mass flow rates and supply and return temperatures on the building side of the DHC system.

Energy Transfer Stations: The GMT implements the ETS as the interface between the district (distribution side) and the thermal energy user (building side). Currently, the GMT has templatized two different ETSs for conventional water-based district networks: an indirect connection and a direct connection. The indirect connection allows hydronic separation from the main district thermal loop using a heat exchanger and is the default in the GMT. As discussed above, a system parameter file is used to override key input variables that a typical user would want to configure such as the nominal heat exchanger effectiveness, pressure drops, supply or return temperature set points, and other controller options.

Distribution Network: The GMT does not require the underlying Modelica models to be templatized. However, the GMT is structured to allow for a graph-based connection of nodes to be used in the near future. This will enable dynamic generation of varying network configurations, which could be leveraged for purposes of network topology optimization. Network topology optimization has been shown to have the potential to deliver reductions in life cycle cost and energy use intensity for very low-temperature systems (Allen, Henze, et al., 2021).

Central Plants: We have implemented two central plant templates in the GMT, one for heating and one for cooling. The cooling central plant consists of two water to water chillers, two primary only variable speed chilled water pumps, two cooling towers, and two cooling water pumps. While the heating central plant consists of two heating water boilers and two primary only variable speed heating water pumps

The templated Modelica components vary slightly from the MBL versions allowing for the control system and sequence of operation to depend on a lead/lag concept, where the chillers/boilers staging tracks the current cooling/heating loads respectively. The primary variable

speed pumps track a differential pressure signal from the remote hydronic connection. The central plants have implemented a modulated bypass valve on the decoupler line to maintain the circulation of the cooling/heating units' minimum flow rate. As with the other components, several system parameter variables have been abstracted out of the models to allow for user configuration without the need for Modelica expertise. These parameters include design nominal heating/cooling flow rates, pump pressure heads, nominal temperature differences, hydronic circuits pressure drops, and others.

URBANopt SDK Integration

A typical user of URBANopt DES is not expected to manually construct a GeoJSON file and/or the system parameter file; therefore, it was imperative that there exists an URBANopt DES entry point from existing software (i.e., URBANopt SDK). The integration between the URBANopt SDK and URBANopt DES facilitates representing building thermal loads with time series data for required mass flow rates, and supply and return temperatures. An OpenStudio measure was developed to extract these data from OpenStudio outputs, and with post-processing in Python, the time series was configured as a boundary condition for the Modelica model of a district thermal energy system (Allen, Long, et al., 2021). This configuration allows the modeling of building-level hydronic HVAC systems in OpenStudio as a time series representation of the thermal loads needed to meet required space conditions which will be served by the DHC system, extending the flexibility of the GMT. Note that this approach requires the modeling of a hydronic HVAC system at the building level. An alternative time series load representation leverages thermal (heating and cooling) load values directly. Time series load profiles have been extracted from the OpenStudio's Standards prototype models (Roth, 2016) for all combinations of building vintage and location, with a few exceptions for load profiles that could not be generated. The prototype building models represent characteristics of common commercial and multi-family building types, with customization available for different vintages and locations to reflect different applicable energy code requirements. The generated load profiles are available in an open-source GitHub repository[2]. This approach facilitates consideration of loads from underlying building models without hydronic HVAC systems, with the caveat that the replacement of an air-based system with a hydronic system could alter the load observed by the district thermal energy system at the point of connection with the building. This approach may be well-suited to a high-level analysis of an existing building model that has not yet been configured with a hydronic HVAC system, but instead is served by an air-based system. The load profiles generated from the prototype buildings are based on the assumption that the load was

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[2] https://github.com/urbanopt/openstudio-prototype-loads

met in each timestep, and account for sensible loads only, and do not include ventilation loads. Heating and cooling loads for each zone (for multi-zone buildings) were summed separately.

The GMT includes a Command Line Interface (CLI) for users to interact with the functionality provided. Once a user has run EnergyPlus simulations using the URBANopt SDK to generate the building loads (at a user defined simulation timestep), the GMT CLI allows a user to automatically create a system parameters file from the output of the SDK simulations. The system parameters file includes default values and values from the SDK via the two OpenStudio measures mentioned above:

- *export_time_series_modelica* creates a CSV file containing temperatures and mass flow rates at the demand outlet and inlet nodes of hot water and chilled water loops. These values represent the load on a connection to a district thermal energy system.
- *export_modelica_loads* creates both CSV and *.mos* files containing heating, cooling, and hot water loads for use in the Modelica model.

The system parameter file and the URBANopt SDK FeatureFile, which describes the buildings and their locations, are combined with weather and other SDK output files to become the inputs used by the GMT to build and run a Modelica model to simulate the entire DHC system. The workflow is shown below in Figure 3.
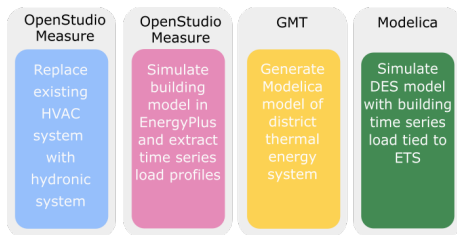

Figure 3: URBANopt DES Workflow.

GMT Example Model Development

The GMT is designed to provide flexibility and diverse representations of building loads and district thermal energy models. We created a fully connected DHC system with time series loads from OpenStudio's large office prototype building. The DHC model consists of heating and cooling central plants and two buildings connected to the district distribution network via indirect ETS. The building thermal load is represented by a time series file of the DOE large office prototype building. The large office prototype building contains office, support, and data center spaces. The main areas of the building, excluding the data center, are conditioned by hot water and chilled water loops, and served by an on-site chiller and boiler. purposes of representing a district heating system, the data center spaces were not of interest, and load profiles were extracted from the hot water and chilled water loops at the "point of connection" to the primary equipment, to emulate an alternative scenario in which the buildings were served by a district thermal energy system.

Figure 4 shows the fully assembled DHC system as it is exported from the GMT. As mentioned, the building loads are exported from the OpenStudio simulations showing how URBANopt SDK and URBANopt DES can synergistically function.
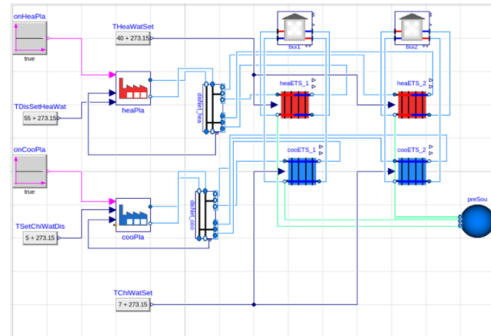

Figure 4: Combined heating and cooling thermal district energy system model.

This use case is meant to demonstrate the overall DHC configuration but does not provide a full picture of flexibility related to the building thermal loads side such as implementation with TEASER and/or Spawn of EnergyPlus. Figure 5 shows calculated heat flow across the cooling and heating ETS for three days as reported by Modelica. The data are in agreement with *Building-1*'s OpenStudio time series loads. Note that in Figure 5, the building load and rate of heat delivered (or rejected) by the ETS are defined with opposite magnitudes. Finally, more examples and use cases of th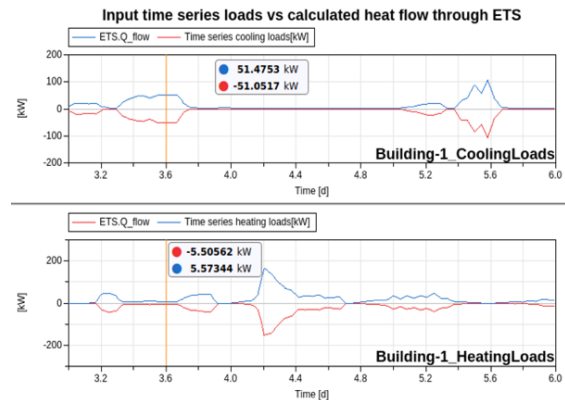is project can be seen in the project's example repository (https://github.com/urbanopt/geojson-modelica-translator-examples).

Figure 5: Building-1 heating and cooling loads.

Conclusion and Future Work

The adoption of district heating and cooling systems in the United States has lagged other countries for various reasons, one of which is the ability to easily demonstrate the benefits of such systems using adequate modeling frameworks. We developed a new application as part of the broader URBANopt project focused on analyzing DHC systems with high fidelity and providing flexibility using a new Python package called the GeoJSON to Modelica Translator. Many new Modelica-based components were developed and added to the MBL and

are leveraged in the GMT. We hope that the development of these libraries and packages will alleviate some of the barriers to modeling DHC and help facilitate adoption.

URBANopt DES is a work in progress with an initial focus on fourth generation systems and first generation and very low-temperature systems being developed and added to the GMT soon. There are, of course, limitations and future work that need to be discussed.

First, the GMT has several abstractions, and the code needs to be better structured to remove redundancies as well as incompatible configurations.

Second, more flexibility is needed around providing pumping system options in the GMT. Currently, if a user wants to implement a custom solution, then the user must use the GMT to export the Modelica package and then update the package using their editor of choice. This process limits the "high-level" configuration options.

Third, the interfacing between DHC categories (e.g., between a time series load and heating indirect ETS) are rigidly defined using specific Modelica code. This means for every new interfacing of DHC categories, the GMT must include a new set of particular Modelica files.

Fourth, due to the GMT's templating system, users are limited in what values inside of the generated models they can modify. For example, in the time series load model, users can provide a file path to their own file containing loads for the model, but they cannot configure the heating or cooling water temperature at inlet and outlet ports. Related to this issue is the limitation where users can only customize the model files used by the DHC (e.g., time series load model) and cannot configure any of the Modelica code generated inside of the actual district model code itself (where all of the models are instantiated and connected) without editing the Modelica files directly in an editor.

Lastly, the tool does not cleanly organize visual components of the generated DHC, including component icons and connectors, which would be useful when viewing the models in visual Modelica editors.

The URBANopt DES project has shown that modeling DHC systems with high fidelity and integrating the workflows with existing building energy modeling software is achievable.

Acknowledgement

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