Development of Prototypical District-Scale Models

Preprint

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Development of Prototypical District-Scale Models

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Abstract

The United States has set the climate goal to achieve net zero greenhouse gas emissions by 2050. District-scale solutions, which include campus- and neighborhood-scale opportunities for energy and emissions savings, can be investigated and implemented to help accelerate decarbonization and progress toward this goal. However, there is currently a lack of district-scale models of buildings and community energy systems that can be used to evaluate potential district-scale technologies and strategies across a range of representative community types. This initial work aims to define and develop prototype district models that can be adapted to support the planning, design, and operation of buildings and energy systems in districts considering the complexity and interactions of diverse building loads, weather impacts, distributed energy resources (e.g., PV, EV, electric and thermal energy storage), electric and thermal grid systems, and pricing signals. An overall workflow for developing these prototype district models is established. Stakeholders and potential users of the prototype district models provided technical feedback. The specifications of the selected high-priority districts were defined and documented in a scorecard format. An example prototype district model was implemented with the URBANopt™ platform workflows. A case study was performed to demonstrate the model application.

Highlights

- Technical feedback from stakeholders is helping guide the prioritization, definition, and development of prototype district models.
- Stakeholder feedback indicates the greatest interest in mixed-use districts of existing commercial and residential buildings.
- Specifications of four prototype districts were defined and an example model was implemented in the URBANopt platform workflows.
- A case study was conducted to demonstrate the application of prototype district models.

Introduction

The United States has set the climate goal of net zero greenhouse gas emissions by 2050 (White House, 2021). Residential and commercial buildings, which currently represent about 39% of U.S. primary energy use (U.S. Energy Information Administration, 2022), are a key sector for which solutions need to be developed and implemented to achieve broader goals. While the efficient design of individual newly constructed buildings and upgrades to individual existing buildings are key strategies, it is also important to research and implement district-scale solutions for decarbonization of groups of buildings and community energy systems together. For the purposes of this work, the term "districts" generally refers to the scales of tens to hundreds (in some cases several thousands) of buildings that are typically co-located, often aligning with the scale of city blocks or neighborhoods, communities, campuses, etc. District-scale approaches are useful for scaling and accelerating decarbonization efforts, and also present unique opportunities for additional energy, emissions, and cost savings compared to an individual building-by-building approach (Olgyay et al., 2020; Pless et al., 2020).

Currently there are various sources of prototype energy models for individual building types (e.g., offices, retail, multifamily, data centers) (Sun et al., 2021; U.S. Department of Energy, 2022), but to our knowledge there are no widely accessible and utilized prototype district models that provide detailed and transparent descriptions of buildings and energy systems that can be adopted by users. To fill this gap, we are focused on developing prototype district models that provide detailed and transparent descriptions of buildings and energy systems.

Unlike a simple aggregation of multiple prototype building models for individual buildings, prototype district models should instead consider the building characteristic variations (e.g., new/existing, commercial/residential, size, occupancy rate), inter-building connections (e.g., shading, radiation), and the interactions between various energy systems (e.g., PV, EV, storage). These factors all influence the energy use and emissions of a district, and as a result, influence the applicability and effectiveness of technologies and strategies. Prototype district models should be representative of district types commonly found in the United States so that they may serve as a baseline foundation for applications such as technology evaluation, informing policy decisions, and benchmarking. More specifically, prototype district models can help to identify potential trade-offs and synergies between different district-scale technologies and strategies, and provide insights into the most efficient and cost-effective approaches for achieving climate goals. Prototype district models can also be used to evaluate from a technical perspective the impact of different potential policy interventions, such as incentives, regulations, and taxes, on energy use and emissions at the district scale, which can help inform decision-making and policy development. Benchmarking is another potential application for prototype district models, where districts with similar characteristics (e.g., building type and vintage combinations, population density, district energy system type) may compare with the prototype to identify possible improvement opportunities.

To address the lack of prototype district models, it is critical to first understand what types of prototype district models are most needed by industry and communities, and then explore how prototype district models can be developed and used to simulate and evaluate district-scale technologies and strategies to reduce building energy use, decrease carbon emissions, and improve resilience.

URBANopt (Urban Renewable Building And Neighborhood optimization) is an EnergyPlus™- and OpenStudio®-based simulation platform aimed at district- and campus-scale thermal and electrical analysis for community and urban district energy modeling (Kontar et al., 2020; Polly et al., 2016). URBANopt is a software development kit (SDK)—a collection of open-source modules focused on underlying analytics for a variety of multi-building design and analysis use cases (NREL, 2023). Commercial software developers can use and customize URBANopt modules to help implement the desired workflows for their end-user tools. Researchers can use the SDK to create customized workflows to perform specific modeling tasks (NREL, 2023). Because of the development capability and flexibility, alignment with targeted audiences/users/applications, and open-source nature, URBANopt is adopted as the platform to implement the prototype district models.

Method

Figure 1 illustrates the overall workflow of the prototype district model development. First, technical feedback was gathered from stakeholders, including industry, government, and academia, about use cases and corresponding needs for the types of districts and their characteristics. This feedback informed the prioritization, definition, and development of prototype district models. Second, specifications of the selected high-priority districts were defined by conducting literature reviews and gathering statistical data from a number of example cities. These specifications describe the characteristics of the prototype districts, which serve as the input assumptions for the prototype district models. Details of the technical feedback and specifications are discussed in the next section. Third, the prototype district models will be developed and implemented in the URBANopt workflow based on the defined specifications. In this paper, we will introduce the first example district model that the team has developed. Lastly, the example prototype district model was tested via a case study that investigated the effectiveness of several technologies toward load flexibility in different climate zones. The simulation results were analyzed and illustrated to demonstrate the potential benefits of the prototype district models. The implementation and case study are presented in the "Implementation and case study" section.

Specifications definition

Technical feedback from stakeholders

A set of technical questions was designed to gather technical feedback from relevant stakeholders to learn about their needs for district-scale use cases. For example, the value propositions of the prototype district models were explored by asking stakeholders to select and rank the most important use cases. The types of districts were prioritized based on stakeholders' feedback on several aspects: (1) use types, e.g., residential, commercial, mixed-use, university/corporate campuses, medical campuses, shopping/entertainment centers; (2) current state of district community, e.g., new development on previously undeveloped land, revitalization or re-development on previously developed land, retrofits and infill new construction in existing district, retrofits without new construction in existing district; (3) scale, i.e. number of buildings in the district; and (4) terrain, e.g., urban, suburban, rural.

Stakeholders included researchers, consulting firms, AEC (architecture, engineering, and construction) companies, software developers, government agencies (federal/state/city), industry organizations, and community-based organizations. We received technical feedback from 26 stakeholders, covering the 7 stakeholder categories as shown in Figure 2. Based on the results, we summarized the characteristics of high-demand prototype district types: (1) Existing district retrofit and new district design were both in high demand, with the former slightly more demanded than the latter. For existing district retrofit, a combination of retrofits and new construction infill were more demanded than pure retrofit or revitalization. A popular use case of prototype districts was studying potential impact of a technology or approach across different district types. (2) Mixed-use districts of commercial and residential were the most demanded in terms of use types, compared with other use types such as residential-only, commercial-only, university/corporate campuses, and medical campuses. (3) For scale, districts with 10 to 100 buildings were predominantly demanded. (4) For terrain, districts in urban areas were predominantly demanded.

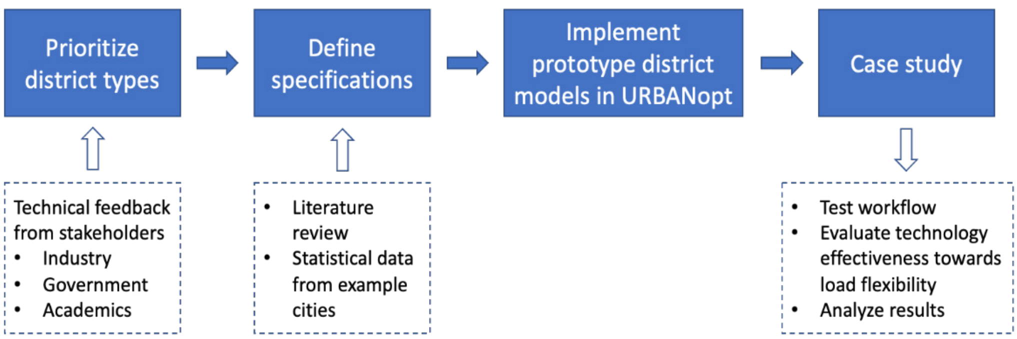

Figure 1. Overall workflow of developing prototype district-scale models.

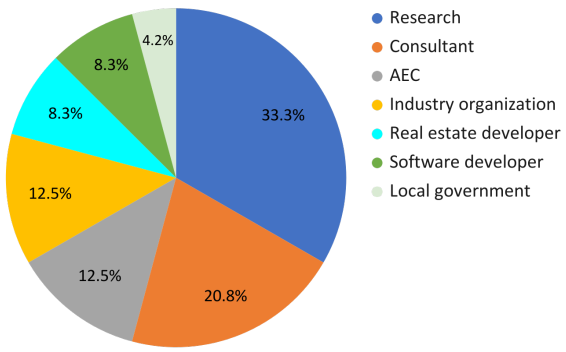

Figure 2. Categories and breakdown of stakeholders who provided technical feedback.

In summary, a mixed-use district with 10 to 100 commercial and residential buildings located in urban areas was of the highest interest amongst the stakeholders who provided technical feedback. Existing district retrofit and new district design were both of high demand, with the former being slightly more demanded. Feedback was also provided regarding the most important types of technologies to consider for district-scale evaluation. The results showed that district-scale technologies (e.g., district thermal energy systems and waste-heat recovery, microgrids, and community-scale solar systems) were more demanded for the prototype district models than building-scale distributed energy resources (e.g., rooftop PV, behind-the-meter stationary batteries, and energy storage), while both of them were substantially more demanded than individual building technologies (e.g., building HVAC, envelope, water heating). Thoughts were also shared regarding how the prototype district definitions could support broader diversity, equity, and inclusion objectives, which is a critical extended topic to study in the future.

Scorecard development

Selection of representative districts

The purpose of the Prototype District Scorecard is to define and gather district characteristics for district energy modeling with URBANopt. This first draft of the scorecard covers districts categorized into four types: Urban Core, Urban Edge, Suburban, and Rural districts. Characteristics of the districts were gathered from 11 U.S. regions. More district types and more cities may be included in future versions of the scorecard. The 11 regions are in the surrounding area near New York NY, Los Angeles CA, Chicago IL, Houston TX, Phoenix AZ, Philadelphia PA, Dallas TX, San Francisco CA, Seattle WA, Denver CO, and Portland OR. These are the U.S. cities with the highest population density. For each of the 11 regions, 4 specific areas within and surrounding the cities were selected using the Public Use Microdata Areas (PUMA) defined by the U.S. Census Bureau. As per the U.S. Census Bureau, PUMAs are non-overlapping statistical geographic regions containing no fewer than 100,000 people (United States Census Bureau, 2020).

For the Urban Core, the densest puma was selected with the tallest buildings. Urban Edge was selected where density begins to drop off. The Suburban district was less dense and had more detached housing. Rural was even less dense but still in an area where there was some development. The primary characteristics gathered were a mix of building types, vintage, and number of stories all by building floor area. The density of building floor area (square footage per acre) was also gathered. The next section describes the process of sampling building characteristics for these cities.

Sampling of data

The End-Use Load Profiles for the U.S. Building Stock project (National Renewable Energy Laboratory, 2022a) provide publicly available data sets of the U.S. commercial and residential building energy use for different building types. These profiles are available through the ResStock™ (National Renewable Energy Laboratory, 2022b) and ComStock™ (National Renewable Energy Laboratory, 2022c) tools for the residential and commercial building stock respectively, at the granularity level of a PUMA. The underlying building models, and model inputs sourced from CBECS (Commercial Buildings Energy Consumption Survey), DEER (Database for Energy Efficiency Resources), ASHRAE, and other data sources are also publicly available for both commercial and residential buildings. The team leveraged these model inputs to sample building characteristics and create the Prototype District Scorecard for the PUMAs identified previously. The following building characteristics were obtained: building type, square feet, number of stories, and building construction year or vintage.

The model inputs are defined for each unique building model within ComStock and ResStock input databases, and have a weight or "associated frequency" specified. The weight times the square feet of the unique model determines the total area for the model and corresponding building characteristics within the U.S. building stock. The building characteristics for the selected PUMAs were filtered and multiplied by the weight. The ComStock and ResStock building characteristics were then combined and the percentage square feet distribution for the building characteristic was determined. The percent square feet distributions for building characteristics for all district types and across all 11 cities were obtained in this manner. To determine the representative characteristics, the results for each district type were averaged across the 11 cities, shown in Figure 3.

While PUMAs represent thousands of buildings and more than 100,000 people, URBANopt prototype district models are likely to be a small area within a PUMA representing tens to hundreds of buildings. In some cases, knowing that density and building type mix within a PUMA is not the same throughout the PUMA, in some cases visual observation of a specific area was used to adjust the mix of building types and number of stories for a subset of a PUMA that would match the size appropriate for a prototype district model.

A part of the scorecard is shown below:

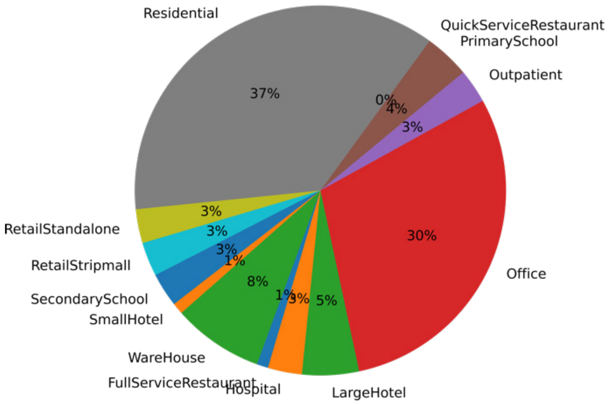

Figure 3. Building Type Distribution by floor area (sq. ft.) for Urban Edge District.

Implementation and case study

The defined specifications serve as the major input assumptions for prototype district models. The specific layouts of the prototype districts were not defined by the scorecards. To instantiate the prototype models, currently we use the modified geometries from existing districts as a starting point. In the future, it may be possible to implement the capabilities to allow users to generate the geometries with high-level inputs or from scratch as they want.

To demonstrate how the prototype specifications are applied and used to generate prototype district models, an example prototype district model of the Urban Edge type was developed based on an actual neighborhood located in ASHRAE Climate Zone 3B and was modified according to the scorecard specifications. The layout is illustrated in Figure 4.

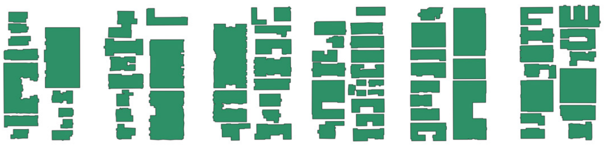

Figure 4. Example district layout for Urban Edge type of districts.

There are a total of 77 buildings in the example district. The distributions of the building types and the vintages for the example district are illustrated in Figure 5.

The example district model was developed using the URBANopt platform workflows, and was released with an open-source license on GitHub (Goldwasser et al., 2023). The model can be used as an input feature file for many existing URBANopt workflows. A case study was performed as a demonstration use case.

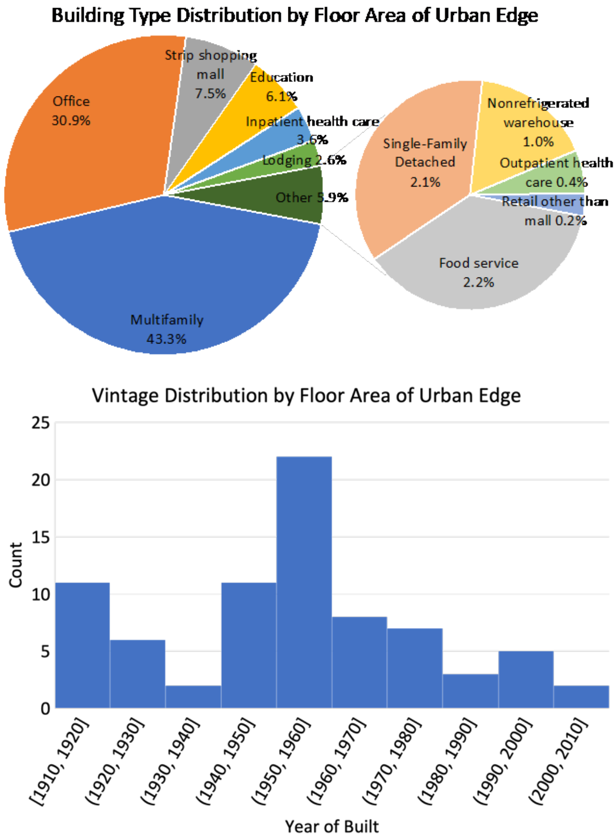

Figure 5. Urban Edge Prototype District: building type (upper) and vintage distribution (lower).

The case study aims to investigate the load flexibility of the group of buildings in the district considering their load diversity and varying operational characteristics. It compared the baseline scenario and the load flexibility scenario for the whole district. URBANopt generated the baseline models following the DOE commercial reference buildings and the IECC residential standard for the corresponding year built in the example prototype district (Charan et al., 2021). In the load flexibility scenario, three measures were chosen and applied to the baseline models: 1) reducing the electric equipment loads during the peak hours in summer; 2) adjusting heating and cooling set points during the peak hours in the heating and cooling seasons, respectively; and 3) adding a chilled water storage tank to the existing chilled water loop to discharge it during the peak hours and recharge it during the night.

A new "weather sweep" feature was also implemented in URBANopt, which takes the district feature file to run with weather files from different climate zones and automatically adjusts the building energy efficiency levels and HVAC system types based on the building energy standards defined for the climate zones (leveraging underlying OpenStudio workflows). The baseline and load flexibility scenarios were also tested through the weather sweep feature to illustrate the different effects of the load flexibility measures in several different climates. Table 1 shows the selected locations for the TMY3 weather files from six major U.S. climate zones.

Table 1. Selected six climate zones for the case study.

Climate Zone	Type	City
2A	Hot, Humid	Tampa, FL
3A	Warm, Humid	Atlanta, GA
3B	Warm, Dry	El Paso, TX
4A	Mild, Humid	New York City, NY
5B	Cold, Dry	Aurora, CO
6B	Cold, Dry	Great Falls, MT

Hourly electric load profiles were generated from the EnergyPlus simulations of individual building models and were aggregated at the district level. Table 2 shows the peak load of the year and the time of occurrence for the two scenarios. The peak load was reduced by 264 to 783 kW for different climate zones, and for some climate zones, the peak time shifted to different days.

Figure 6 plots the monthly averaged daily load profile for the warmest climate zone 2A and the coolest climate zone 6B. The load shedding effects were most significant for the hot climate during the summer months due to the electricity used to meet the cooling load. While the space heating was mostly by natural gas, the load reduction during the winter was not obvious.

Apart from the peak load reduction, the energy consumption for heating, cooling, and electric equipment was also reduced due to wider thermostat set points and lower electric load density. However, the electricity used by pumps was increased by 2% to 23% due to the additional water loop brought by the chilled water storage tanks. See Figure 7 for an example of the end-use breakdown comparison for the two scenarios. There was also a minor increase in the energy consumption by fans, which might be because of the larger airflow required after the peak hours to compensate for the unmet cooling/heating load due to the thermostat adjustment.

Table 2. Peak load change comparison across climate zones.

Climate Zone	Baseline Peak Time	Baseline Peak Load (kW)	Load Flexibility Peak Time	Load Flexibility Peak Load (kW)	Peak Load Reduction (%)
2A	07-21 16:00	9,377	07-18 15:00	8,594	8.4
3A	07-07 16:00	8,962	07-07 15:00	8,299	7.4
3B	06-02 16:00	8,869	06-15 15:00	8,569	3.4
4A	06-19 12:00	8,423	06-19 12:00	8,128	3.5
5B	06-26 16:00	7,993	06-26 15:00	7,729	3.3
6B	07-17 16:00	7,509	07-17 14:00	6,976	7.1

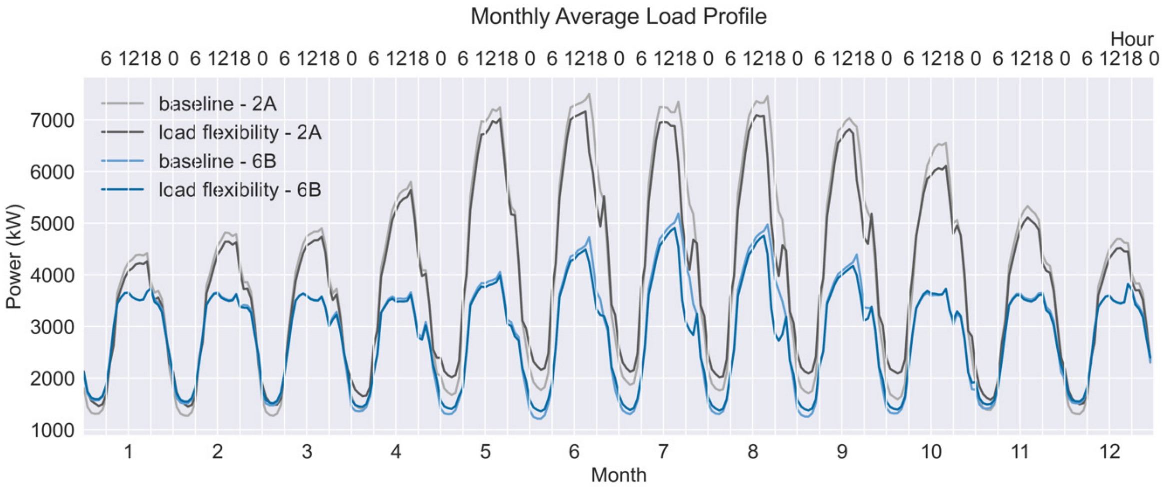

Figure 6. Monthly averaged daily electric load profile of the district for climate zone 2A and 6B.

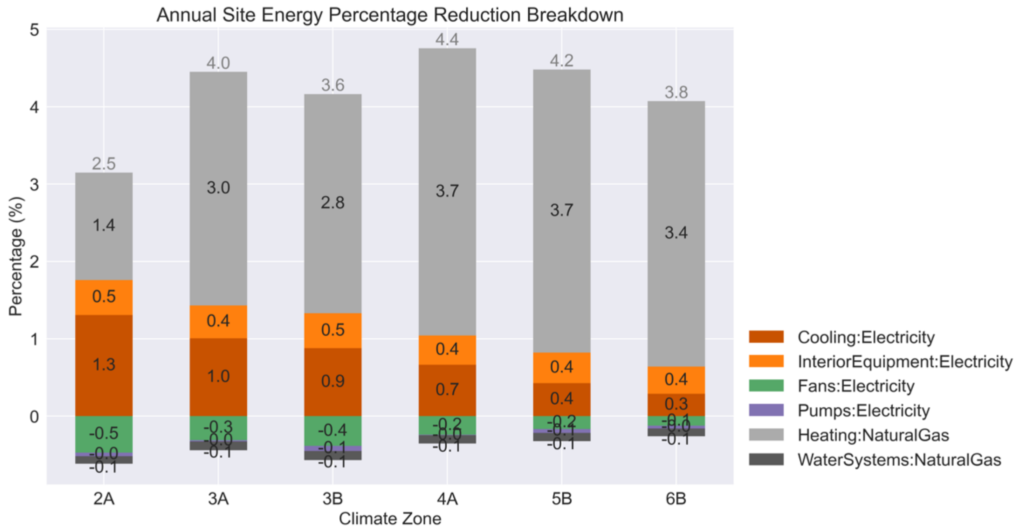

Figure 7. Annual site energy percentage reductions by different end-use categories across climate zones. Negative values represent increase; the values on top are the total net reduction percentages.

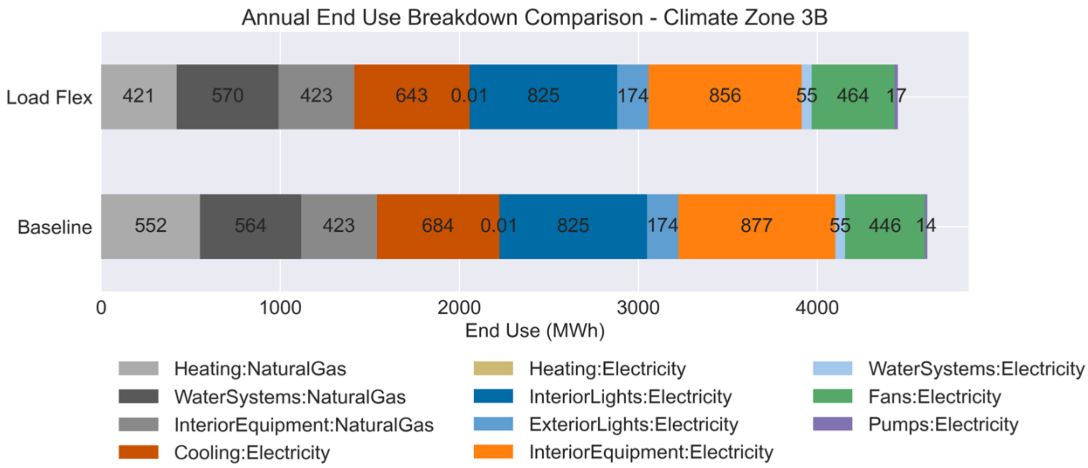

Figure 8. Annual site energy end-use breakdown for climate zone 3B.

While the primary objectives of the measures analyzed were to reduce consumption during peak periods and to shift the timing of loads (load flexibility), Figure 8 and Table 3 show the site energy consumption reductions by the load flexibility scenario across the six climate zones. Overall, the energy use was reduced in all climate zones and the natural gas for space heating was the category that saved the most energy.

Table 3. Annual total energy consumption savings across climate zones.

Climate Zone	2A	3A	3B	4A	5B	6B
Electricity Savings (MWh)	57	54	41	44	32	29
Electricity Savings Percentage (%)	1.6	1.8	1.3	1.6	1.2	1.1
Natural Gas Savings (MWh)	60	143	126	199	188	197
Natural Gas Savings Percentage (%)	5.3	7.5	8.2	7.2	7.1	5.8

Conclusion

In this work, we proposed the development of prototype district models to simulate and evaluate district-scale technologies and strategies for reducing energy use, carbon emissions, and improving resilience in the built environment. We gathered technical feedback from a variety of stakeholders, which informed prioritizing the types of districts for development. According to stakeholders' feedback, we identified that a mixed-use district with 10 to 100 commercial and residential buildings located in urban areas was of the highest interest; existing district retrofit and new district design were both of high demand, with the former being slightly more demanded.

Four district types were prioritized and selected for scorecard development. We referred to literature and statistical data from a number of example cities as the foundation for defining the prototype district specifications. The key modeling assumptions were documented in the form of a scorecard. An example prototype district model for one district type (Urban Edge) was implemented in the URBANopt platform workflows and was released open-source on GitHub for public use.

We used the example model to conduct a case study to demonstrate the model application. The case study evaluates the effectiveness of several technologies toward load flexibility in different climate zones for a particular type/configuration of district. The results show that the implemented technologies can help reduce the peak load, especially in the summer of the hot climate zone, due to the large cooling load. Some of the technologies reduce the energy use while shedding the load, while the water storage tank shifts load but at the expense of increased energy consumption. The case study also demonstrates the use case and value of the prototype district model to evaluate technologies at the community level across different climate zones. With other scenarios implemented in URBANopt, the use case is not limited to load flexibility, but could be expanded to include energy efficiency, carbon emission impacts, etc.

Potential future work includes continuous development of the prioritized district types, increased building characteristic and operational variability across buildings in a district, field validation of the developed prototype district models with real districts, improvement of usability and flexibility of the prototype district models to facilitate industry adoption, and model expansion to include social aspects such as addressing diversity, equity, and inclusion objectives.

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