Energy Modelling Methodology for Community Masterplanning

ABSTRACT

Net-zero energy is an influential idea in guiding the building stock towards renewable energy resources. Increasingly, this target is scaled to entire communities which may include dozens of buildings in each new development phase. Although building energy modelling processes and codes have been well developed to guide decision making, there is a lack of methodologies for community integrated energy masterplanning. The problem is further complicated by the availability of district systems which better harvest and store on-site renewable energy. In response to these challenges, this paper contributes an energy modelling methodology which helps energy masterplanners determine trade-offs between building energy saving measures and district system design. Furthermore, this paper shows that it is possible to mitigate electrical and thermal peaks of a net-zero energy community using minimal district equipment. The methodology is demonstrated using a cold-climate case-study with both significant heating/cooling loads and solar energy resources.

Keywords: energy planning, district energy, net-zero energy, resiliency, energy model

INTRODUCTION

An increasingly adopted building performance target is net-zero energy (NZE), or the reduction of building energy use sufficiently such that renewable energy generation can meet the remaining on-site energy demands during a typical meteorological year (DOE, 2015). ASHRAE directly supports the development of tools and methodologies that facilitate the design of net-zero energy buildings and communities (ASHRAE, 2008). NZE is influential since it is a measurable goal and a guiding principle in transitioning the building sector towards renewable energy supplies. The NZE target is typically sought after for buildings, however there are compelling reasons to also consider a community-scale target.

Community energy systems offer several distinct advantages over building solutions in achieving NZE: (i) the target is easier to achieve since energy deficiencies in larger buildings can be offset by on-site energy generation and storage, (ii) renewable energy resources can be better collected and stored, leading to higher solar utilization fractions (Sibbitt et al., 2012), (iii) existing or emerging 'plug-and-play' technologies can be integrated with building or district systems aiding the NZE goal without disrupting building operations, and (iv) it prioritizes peak management strategies between buildings rather than treating the grid as an infinite source and sink of electricity.

Achieving community-scale NZE requires an energy masterplan (EMP). EMPs develop realizable targets to reduce carbon footprints, energy use intensity, and operational costs while improving the resiliency of a portfolio of buildings. To support EMP practitioners, energy modelling methodologies are required which quantify integrated design strategies. Similar to building energy modelling studies, EMPs consider conservation, efficiency and generation strategies to reduce or offset energy use. However, as an added complexity, community integrated energy modelling studies must identify optimal outcomes which include energy use reductions in buildings and peak mitigation opportunities using district system technologies. Methodologies which simplify information extraction from this highly-coupled problem are desired.

LITERATURE REVIEW

The literature supporting urban-scale energy modelling is rapidly growing. As of 2017, ASHRAE has introduced six paper sessions at annual conferences focusing on urban-scale modelling. The nature of previous contributions is highly diverse relating to topics such as urban micro-climates, model calibration, and expedited model creation. As such, the scope of reviewed papers in this section is reduced to urban energy modelling aiming to quantify energy saving measures in a significant retrofit or new build scenarios which best represent the goals of this paper.

A few principles regarding EMP formation have been previously outlined in literature. Zhivov et al. (2014) suggested energy masterplanners should focus on reducing energy use first, followed by the optimization of district system configurations. However, other researchers have demonstrated that energy saving measures have diminishing returns, meaning that there is an inflection point where on-site renewable energy generation is more cost-effective than energy use reductions in buildings (Norton and Christensen, 2008). Case et al. (2015) proposed a tool which scales smoothly from energy masterplanning to facility level design. Strasser (2015) suggested that by combining building energy saving measures with district systems, primary energy demand could be reduced by up to 70% for an Austrian case-study. Bucking and Cotton (2015) proposed a preliminary modelling methodology focused on buildings in a community setting using net-energy use and life-cycle cost objective functions.

There is some evidence that low-energy buildings should affect how district systems are designed. Morvaj et al. (2015) found that district design approaches for low energy buildings should concentrate more on district cooling and renewable energy integration. This differed from reference district systems used for typical buildings. Similarly, Harb et al. (2015) found that using low temperature combined heat and power systems with heat pumps could reduce carbon emission by 33%. Lauster et al. (2015) suggested partial differential equation solvers could reduce the computational demands of solving urban scale problems.

Several software tools are undergoing active development to conduct and support urban energy studies. LBNL CityBES (2017) is a web-based tool that provides building energy modelling to support district energy programs. Bentley-UBEM (2017) combines site recording techniques such as photogrammetry with building information models to enable virtual communities, cities and campuses. Nouvel et al. (2015) suggested a standardizable data exchange format for urban energy models using a data structure called CityGML.

When energy masterplanning, the search for integrated solutions includes a vast number of design possibilities each with multi-variate performance indicators. This literature review suggests that the research community is actively progressing towards comprehensive urban energy modelling tools and methodologies. What is still needed is a highly detail building energy model coupled with district energy systems to help determine whether it is advantageous to reduce energy loads in a building or meet those loads using thermal storage and shared district equipment. This paper aims to fulfill this niche application.

The focus of present research is largely on carbon and energy use reduction. This ignores the power management challenges found in low-energy buildings. This is particularly omnipresent in NZE buildings where peak renewable generation often does not coincide with peak demand leading to power management issues. As a first-step towards solving this problem, this paper describes a modelling methodology for evaluating design trade-offs between reducing energy use in buildings and the selection of district technology which better harvests energy on-site and meets a defined load. The particular challenge this methodology aims to solve is identifying the optimal balance of energy saving measures in buildings versus out-sourcing loads to localized district systems.

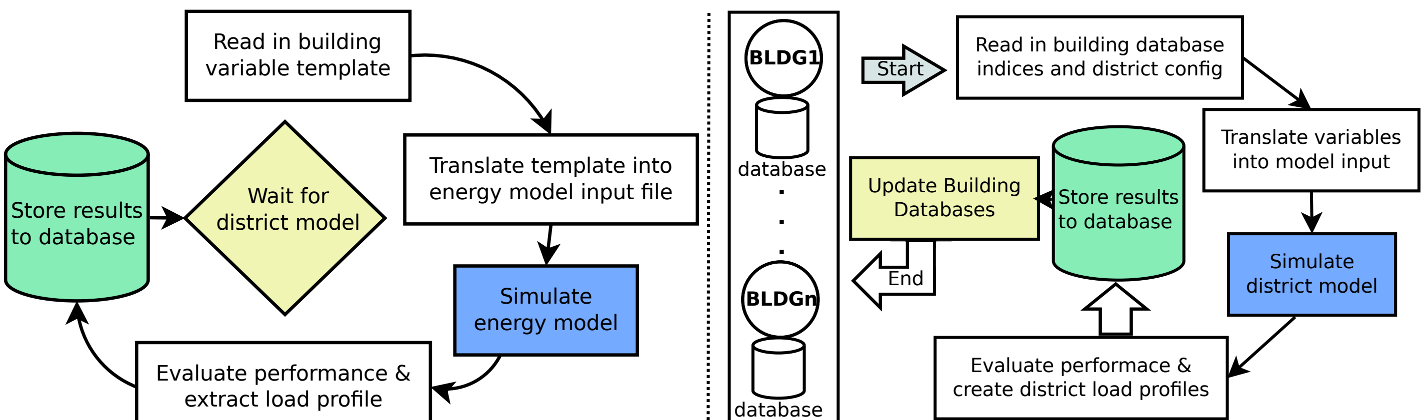
METHODOLOGY

Developing energy models for NZE communities presents several challenges: (i) integrated design at the community level requires navigation of many interconnected trade-offs, (ii) various technologies, both in buildings and district systems, require implementation within a common model to evaluate trade-offs and interactions between them, (iii) sub-hourly energy load profiles are required to evaluate peak management implications of energy conservation, efficiency and generation measures, (iv) achieving NZE targets is difficult above certain building heights using present technology and additional generation technologies may be needed to achieve an energy balance (O'Brien et al., 2010), and (v) energy model creation is a time intensive process that is required for each building archetype and shape. Since developing one detailed building energy model can take almost one hundred hours, creating a community energy model is a major undertaking.

A methodology is described which addresses these challenges. The approach is presented starting with model creation and integration followed by energy and district models. The case-study is shown before the model as aspects of the methodology require it for background knowledge.

Model Integration

The energy modelling methodology is divided into a building and district model, see Figure 1.



(a) Building Model Methodology (Step 1) (b) District Model Methodology (Step 2)

Figure 1: Energy modelling methodology

The energy model, shown in Figure 1, translates simplified input variables into a detailed energy model. Each unique set of variables has its own energy model with performance indicators determined via simulation. Load profiles are generated by post-processing simulation results. Results are stored into database entries post simulation.

Similarly, a district model, shown in Figure 1, accepts building load profiles as inputs and evaluates the performance of a district configuration resulting in an output load profile to be met by a utility company. Indices to building databases are used to combine load profiles together into thermal and electrical meters to be met by a district system. After each district system performance evaluation, building databases are updated such that individual building representations have a record of how they performed as part of a district system.

Case Study

Figure 2 shows the masterplan considered as a case-study. Three building archetypes are modelled in this paper: a multi-residential building, commercial office and townhouse archetypes. The buildings are mixed use and have been setup to include technologies which represent ASHRAE 90.1-2010 (ASHRAE, 2010) energy codes and an improved design which is near net-zero energy.

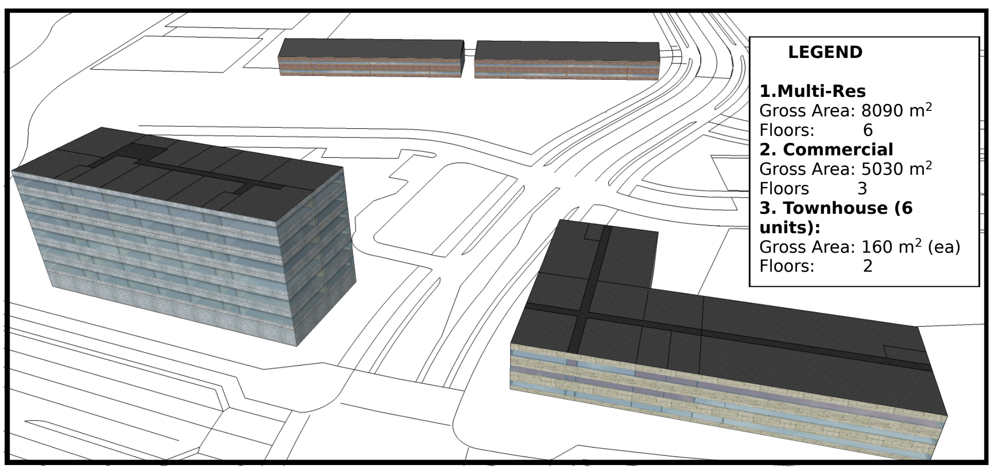


Figure 2: Masterplan and building renderings of phase one.

Energy Models

A combination of tools were used to create energy models for various buildings types: (i) OpenStudio for drawing geometry and window positions (NREL, 2014); (ii) WINDOWS for specifying glazing spectral properties (LBNL, 2014b); (iii) THERM for specifying envelope properties (LBNL, 2014a); (iv) EnergyPlus for energy performance simulation (DOE, 2014); and (v) a custom scripting process for technology implementation and modelling best-practices.

A customized scripting process deployed a programmatic approach to assign EnergyPlus objects and technologies required to achieve NZE in a cold-climate to each zone or envelope/glazing surface in the energy model. The time savings were significant and less error-prone than text file manipulations. Renewable energy generation was considered integrated into vertical façades and roof surfaces using building integrated PV (BIPV). Additional PV generation could also be installed on ground mounted racks and parking structures. The modelling process is further described in Bucking and Cotton (2015).

Equation 1 evaluated the performance of each building permutation using energy use intensity. This equation is important as it quantifies a building achieves a renewable energy balance.

$$f(\mathbf{x}) = (E_{heat} + E_{cool} + E_{DHW} + E_{elec} - E_{PV})/A_{bldg} \quad (1)$$

where: $\mathbf{x} = (x_1, x_2, \cdots, x_N)^T$ is a design variable vector as described in Tables 1–2, $f(\mathbf{x})$ is the equivalent annual net-energy use intensity (EUI) of the building, $E_{heat,cool}$ is the equivalent annual heating and cooling load of the building, E_{DHW} the equivalent domestic hot-water (DHW) energy use, E_{elec} is the gross annual electricity use in lighting, appliances and plug-loads, E_{PV} is the electricity generated by BIPV, and A_{bldg} is the gross building area. All values are taken from an EnergyPlus simulation. NZE is achieved when $f(\mathbf{x}) = 0$ implying an annual renewable energy balance and a building is net-positive energy if $f(\mathbf{x}) < 0$.

Table 1 shows the decision variables considered for the townhouse units described in Figure 2. Each of the six townhouses shown in the masterplan was allowed a unique set of decision variables.

Table 1: Sample of Influential Model Variables for Townhouses

Variable	Description	Units	Start	Stop
aspect	Aspect ratio (south facing width to depth ratio)	–	0.7	2.2
azi	Building orientation/azimuth	degrees	-45	45
wall_ins	Effective resistance of wall insulation	m^2K/W	3.5	13.0
		ft^2 °F-h/Btu	20	74
ceil_ins	Effective resistance of ceiling insulation	m^2K/W	5.6	15.0
		ft^2 °F-h/Btu	31	85
base_ins	Effective resistance of basement wall insulation	m^2K/W	0.0	7.0
		ft^2 °F-h/Btu	0	40
slab_ins	Effective resistance of slab insulation	m^2K/W	0.0	2.3
		ft^2 °F-h/Btu	0	13
infil	Natural infiltration rate	ACH	0.025	0.179
occ_loads	Occupant loads (percent of Canadian average consumption) (Armstrong et al., 2009)	% CAD_{avg}	50	80
ovr_south	Width of Southern Window Overhangs	m	0.00	0.45
		ft	0.00	1.5
pv_area	Percent of PV area on roof	%	0	90
pv_eff	PV efficiency	%	12	15
roof_slope	South facing roof/PV slope	degrees	30	47
wwr_s	Percent of window to wall ratio, south (also N,E,W)	%	5	80
GT_s	Glazing type, south (also N,E,W)	–	1	4
FT	Window Framing Types (1:Wood, 2:Vinyl)	–	1	2
zone_mix	Air circulation rate between thermal zones	L/s	0	400
		cfm	0	850

Table 2 shows the decision variables considered for the multi-residential and office building. District heating systems, if required, provided heating and hot-water services. As a mechanical system option, heat pumps could lift or drop water temperatures using a circulated water loop present in the office and multi-residential building. Water-source and variable refrigerant flow heat pumps were considered as potential mechanical solutions. The district loop provided water at a temperature of 15 °C (59 °F) during the winter and 30 °C (86 °F) during the summer months. This heat delivered to buildings was treated as a load that a district model must meet.

Table 2: Sample of Influential Model Variables for Office and Multi-Residential Building

Variable	Description	Units	Start	Stop
infil	Infiltration through walls: percentage compared to reference	%	75	100
lpd	Lighting power density: percentage compared to reference	%	50	100
eleceq	Electrical equipment power density: percentage compared to reference	%	50	100
azi	Building orientation relative to south	degrees	-39.4	45
base_ins	Basement insulation	m^2K/W	0.18	7.04
		ft^2 °F-h/Btu	1	40
ceil_ins	Ceiling insulation	m^2K/W	3.52	11.40
		ft^2 °F-h/Btu	20	65
wall_ins	Wall insulation	m^2K/W	3.52	10.57
		ft^2 °F-h/Btu	20	60
wintyp_n	Window type north [1: Double Glz low-e. 2: Triple Glz Low-e]. Also variables for east, west, south.	–	1	2
wwr_s	Window to wall percentage south	%	10	80
wwr_n	Window to wall percentage north. Also variables for east, west	%	10	50
use_doas	Use a Dedicated Outdoor Air System for ventilation control	bool	0	1
hvac_sys	HVAC system (Commercial) [1: VAVelec. 2. FCU, 3: BaseBoard 4: VRF]	–	1	4
hvac_sys	HVAC system (MultiRes) [1: PTAC 2: BaseBoard 3: FCU 4: VRF 5: VRFdist 6. PTHP 7. WSHP 8. WSHPdist]	–	1	8
dhw_sys	DHW system [1: DHW NG Plant. 2: DHW HP Plant]	–	1	2
pvbal_sc	Ballasted PV space scaling factor	–	0.1	2.5
pvbal_ang	Ballasted PV angle	degrees	0	35
pvfrac_s	PV percentage on south. Also variables for east, west, roof	%	0	80
pvfrac_a	PV parking lot array area	m^2	0	400
		ft^2	0	4306
blind_type	Blind shading type [1: ExteriorShading; 2: InteriorShading]	%	1	2
dhw_ld	Percent of DHW energy use relative to reference	%	60	100
use_nv	Use natural ventilation for night cooling	bool	0	1

abbrev: Variable Air Volume (VAV), Fan-coil Unit (FCU), Variable Refrigeration Flow (VRF), Packaged Terminal AC (PTAC), Packaged Terminal Heat-Pump (PTHP), Water Source HP (WSHP)

Building design parameters were represented using a vector, see below. Parameters shown in this representation refer to those described in Tables 1–2.

$$\overbrace{\text{“}\underbrace{1.3}_{\text{aspect}}\ \underbrace{8.93}_{\text{wall\_ins}}\ \underbrace{5.60}_{\text{ceil\_ins}}\ \dots\text{”}}^{\text{Vector Representation}} \tag{2}$$

EnergyPlus results were reported using metered comma separated files. Metered outputs for electrical and gas consumption were stored in a database entry for each model instantiation so that after a building's performance was evaluated, the annual performance and sub-hourly meter files could be accessed via a database query. This eliminated the need for future resimulation. The combined meter files for several buildings was required as an input for the district model as shown in Figure 1.

District Energy Model

The district energy model required the sum of sub-hourly building energy meters as an input load profile. This input was created using the sum of each individual building meter file output. Specifically, four meters inputs were necessary: building district heating, gross electric demand, PV generation and natural gas consumption. Figure 3 describes the technologies considered in the district model.

The district energy model allowed for the export and import of electricity to and from a hypothetical smart grid. Electricity was generated on-site using PV panels or a combined heat and power system (CHP). This model assumed electricity could be exported to the smart grid from buildings using BIPV, discharged from batteries or generated from district infrastructure. The heat from CHP systems could be used immediately or stored for later usage using thermal storage. As specified by the manufacturer, CHP units had a 30% electrical efficiency and a 60% thermal efficiency for a combined peak unit efficiency of 90% (Capstone, 2016).

Thermal storage and electrical batteries were modelled using an ideal energy balance approach. This allowed for the auto-sizing of storage components

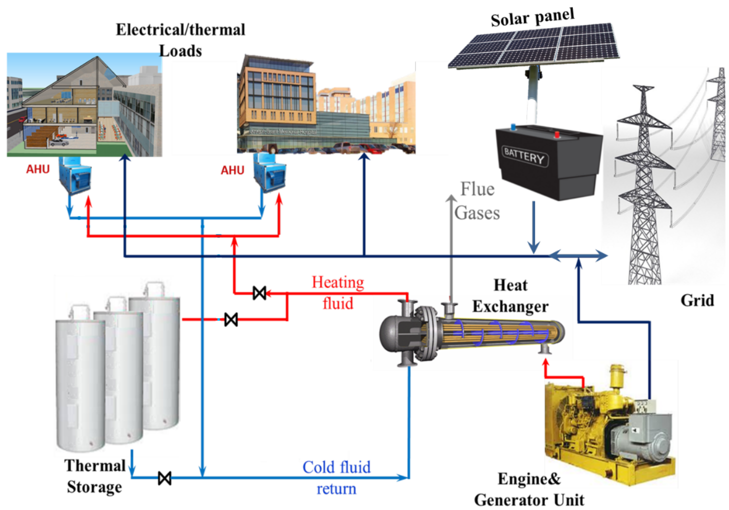


Figure 3: District energy model schematic. Lines connecting PV panels/battery and CHP to buildings indicate electricity transmission. Lines connecting CHP unit to air handling units (AHU) and storage indicate thermal energy transferred.

without requiring manufacturer specifications for a particular component with unique charge/discharge characteristics. The thermal storage model assumed water was stored above its freezing and below its boiling point. The sizing of batteries and thermal storage was determined based on peak annual utilization. Electric batteries had a 95% draw and charge efficiency. Although these models are purely theoretical constructs, they estimate how well thermal and electrical storage can aid in mitigating peaks. The modelling approach ensured that storage started and finished with the same charge to equalize technology comparisons.

With respect to thermal transportation, a two-pipe loop was assumed to move only pre-heated water. As presently implemented, the model assumes the buildings are located in close vicinity such that the pipe losses with respect to distance are not directly modelled. Although the approach could be expanded to include chilled water using an absorption chiller and four-pipes distribution, this was not considered due to the reliance on heat pumps in the energy models.

District models were controlled using one of five strategies:

1. District heating demands (if existent) are met using a 80% efficient hot-water boiler

2. CHP was sized to meet instantaneous heating demands. CHP generated electricity that was used instantly. No thermal/electrical storage.

3. CHP was controlled to meet seasonal thermal demands by utilizing thermal storage. CHP was operated to shed peak electrical loads using the method shown in Figure 4. No electric batteries. CHP was operated to shed electric peaks using the method shown in Figure 4. No electric batteries.

4. CHP was sized to meet instantaneous heating demands. CHP and PV electricity was stored in batteries. Stored electricity was used if there was demand in the future timestep.

5. CHP was sized to meet instantaneous heating demands. CHP and PV electricity was stored in batteries. Batteries were controlled to shed peak loads using the method shown in Figure 4.

Figure 4 shows a load duration curve for balancing electrical loads as used for control options 3 and 5. Traditionally, load duration curves determine how often and when peak loads occur. For the purpose of this paper, load duration curves determined how much on-site generation could be stored and strategically used to shed peaks at an optimal power level over a given year, see Figure 4. Note the shape of the load duration curve was unique for each community permutation.

An iterative solution was required to choose an exact balance point as load duration curves ignored the temporal representation of peaks in meter files which was needed to size batteries and thermal storage.

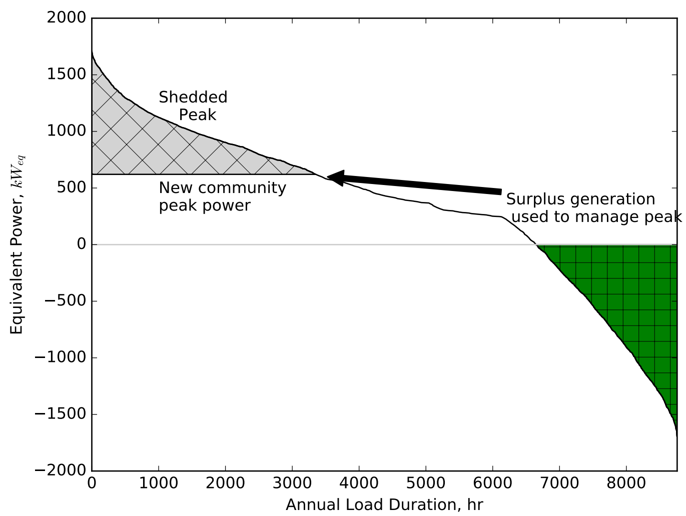


Figure 4: Peak load management controller for district modes 3 and 5. Negative power implies net-generation.

Equation 3 evaluated the district model performance. This equation has two terms: the average power of net-electricity and natural gas used (in equivalent units) plus the square root of mean square error. Note the performance of a district system depends strongly on the load profiles provided by the building models.

$$g(\mathbf{x}) = P_{avg} + \sqrt{\frac{\sum(P_i - P_{avg})^2}{N}} \tag{3}$$

where: $\mathbf{x} = (x_1, x_2, \cdots, x_N)^T$ defined the district configuration and building indices, see Equation 4; $g(\mathbf{x})$ is the district performance function; P_{avg} is the district average equivalent power; P_i is the instantaneous district equivalent power; and

N is the number of load profile timesteps.

The added term in Equation 3 is a sum of squares which penalizes peaks with the square of their distance from the average power discerning positive and negative distances of the peak from the average signal. Adding the average equivalent power ensures that district configurations with the lowest average power are preferred. Note this added term is equivalent to adding a standard deviation of signal to the community average power.

The district performance function, shown in Equation 3, is an important deviation from the annual EUI performance function used for buildings shown in Equation 1. If annual energy use was used to rank district system performance, results at the building and district scales would be identical and therefore redundant, ignoring the peak management challenges of the problem. Therefore, the goal of the district model was to effectively balance load profiles provided by the building models. Whereas the goal was of building models was to reduce annual energy use. Using both energy and peak mitigation indicators ensured the most interesting solutions were identified.

Community details were represented using vectors with database indices pointing to a building model performance evaluation. This simplified community representations allowed for the querying of building load profile data from a database without energy model resimulation. Thus, a combinatorial approach represented buildings using the following representation:

$$\overbrace{\text{“}\ \underbrace{\#20}_{\text{bldg1}}\ \ \underbrace{\#100}_{\text{bldg2}}\ \ldots\ \underbrace{\#50}_{\text{bldgN}}\ \ \underbrace{1}_{\text{district\_mode}}\ \text{”}}^{\text{Vector Representation}} \tag{4}$$

The identifiers shown in the representation are linked to the building energy model using the primary key from the simulation database. Since there are eight buildings in the masterplan, there are eight unique databases where building energy simulation results are stored. The variable 'district_mode' represents which combination of technologies and control strategy was used as described in the district model section.

RESULTS AND DISCUSSION

Table 3 shows several trial runs for different community masterplans. The weighted EUI refers to Equation 1 except it uses the total equivalent net-energy use for all buildings divided by the total gross floor area. The average equivalent power refers to Equation 3. This table shows that the average power of a community can differ by orders of magnitude if the optimal combination of energy use measures with sufficient on-site energy generation and thermal/battery storage charging strategies are used. An average power less than zero implies that the combination of buildings with the district system can disconnect, or island, at any point in the year if a micro-grid is present. Islandable communities are realistic as proven by several micro-grid demonstration projects both in the US and Japan (Berkeley Microgrid Lab, 2017; Smart Electric Power Alliance, 2015). These successes suggest that power reductions shown in Table 3 are feasible.

Table 3 shows that non-optimal district options still provided a significant opportunity to reduce peak loads. This table also demonstrates that decreasing EUI is not directly correlated with decreasing equivalent power. This is important as EUI is still primarily used to report community energy performance in literature. The proposed methodology offers a more holistic approach and factors in load swings/imbalances into performance calculations.

Table 3: Weighted Energy Use Intensity Versus Average Equivalent Power

Trial Number	District Option	Weighted EUI (kWh_{eq}/m^2)	Weighted EUI ($kBtu/ft^2$)	Average Power (kW_{eq})
1	4	63.7	20.2	931
2	2	65.0	20.6	780
3	1	37.1	11.8	770
4	3	58.5	18.6	336
5	5	45.6	14.5	157
6	3	68.6	21.7	26
7	5	45.3	14.4	2

Figure 5 shows the convergence characteristics of coupling building and district models using a search algorithm. This Figure suggests that an iterative design approach is required to explore trade-offs between lowering building energy use and minimizing peaks via district systems. A box-whisker plot shows the limits, quantiles and district performance as outlined by Equation 3. Superimposed is a convergence plot which shows the relative frequencies of a particular district model's performance occurring in the set.

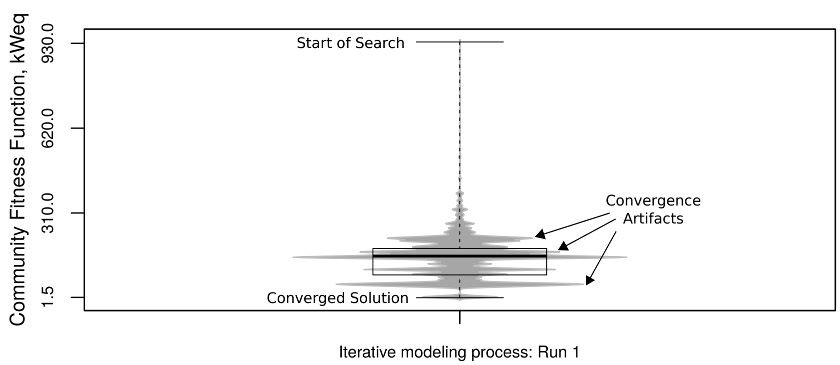


Figure 5: Convergence characteristics of integrated building and district model

The pre-convergence artifacts, shown in Figure 5, occurred because globally optimal solutions were not identifiable until building EUI was sufficiently reduced to lower the community average power. Thus, an iterative approach between lower EUI and managing peaks loads is recommended. To achieve the results shown in Figure 5, roughly 50 iterations were required for the problem to converge. Regardless, the combination of low energy buildings with district systems allowed for better load and generation management.

A search algorithm identified several interesting community design strategies. Consistently, building orientations were diversified, deviating from an exact south facing orientation as suggested by single building optimization solution sets. This is contrary to a building-centric energy modelling results that prefers south facing for improved passive solar gains. The decision to diversify orientation also varied the temporal occurrence of both heating/cooling peaks and when BIPV peak generation occurred. For district infrastructure and control, both modes 4 and 5 were dominant, implying that battery storage is an essential piece in balancing loads between buildings. Thermal storage mode 3 offered a few scenarios that reduced the community average power to approximately 20 kW_{eq} representing a low-cost solution to balancing loads without using more expensive battery storage.

CONCLUSION AND FUTURE WORK

This paper proposed an energy modelling methodology which helps communities achieve NZE while balancing peak loads using a district energy system. These outcomes could aid in improving the energy resiliency of buildings and make micro-grids a more achievable option in future NZE communities. A key outcome of the paper is an energy modelling methodology which identifies technological solutions aiding in flattening and reducing district loads to a near net-zero point for a cold-climate case-study.

Future work can be summarized as follows: (i) couple the proposed energy modelling methodology with an optimization/parametric analysis tool, (ii) conduct an uncertainty and sensitivity analyses on the energy model to identify significant model parameters, (iii) calibrate energy models to measured building meter data, (iv) add advanced district system configurations such as geothermal borehole storage and ice-storage, (v) consider the proximity of buildings to district resources, (vi) incorporate measured weather data to evaluate the robustness of proposed community solutions, and (vii) implement additional predictive control strategies for peak management.

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