Designing for Zero Energy and Zero Carbon on a Multi-Building Scale using URBANopt

Preprint

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ABSTRACT

Groundbreaking efforts are necessary to mitigate contributors increasing impacts of climate change. In parallel to inventing pioneering clean energy technologies it is even more fundamental to rethink designing energy systems within a singular facility and collectively to function as a district. Facilities should not be continuously passive by just consuming; there is a need to shift to perform more dynamically. Designing for zero energy and zero carbon on a multi-building scale can uncover opportunities for building energy efficiency, decarbonization, demand flexibility, and resiliency that are not accessible at an individual building scale. This approach can be challenging without innovative tools to evaluate the multitude of possibilities. As an investigated result, we highlight the use of a campus-scale energy modeling platform – URBANopt™ – for the expansion of the National Renewable Energy Laboratory's (NREL's) South Table Mountain campus in Golden, Colorado. Programmatic growth included the design of three new all-electric, zero-energy, and zero-carbon, mixed used buildings (a combination of research laboratories and office space). This investigation is critical to NREL reaching net-zero emissions for its operational footprint, which will occur in phases over the next decade. Leveraging URBANopt's capabilities, we evaluate 1) high-performance building energy efficiency and decarbonization measures, 2) 4th generation district heating and cooling (4th GDHC) systems, 3) optimized onsite generation and energy storage assets that meet zero-energy and zero-carbon targets at minimum life-cycle costs, and 4) cost-optimal distributed energy technology mixes, dispatch strategies, and associated capacities that increase resiliency to grid outages. This work demonstrates the use and capabilities of URBANopt through a real-world case study on a multi-building scale, reveals the challenges and opportunities of zero energy and zero carbon targets, and offers key strategies that future designers can consider in their pursuit of a decarbonized built environment.

Introduction

Reduction of emission production as well as net zero energy (NZE) and net zero carbon (NZC) design have become more prominent priorities for buildings industry research (Steven Nadel, 2019) (Nadel, 2020). Many energy researchers and designers have shifted the focus of high-performance and/or zero energy/carbon targets from the building-scale to the community/district-scale to unlock enhanced energy efficiency and renewable energy approaches and opportunities (Pless et al. 2020). This paradigm shift has resulted in increased need for multi-building energy evaluation tools to support and inform design alternatives, and to evaluate the ample array of available and emerging building-level and district-scale technologies to achieve a project's cost, energy, and carbon saving performance targets. One recently developed tool is URBANopt (El Kontar, 2020), (Ben Polly, 2016), with unique capabilities that leverage high-fidelity simulations of buildings, community-scale systems, distributed energy resources, and the associated interactions with local distribution-level electric infrastructure. URBANopt has been successful at evaluating and informing numerous high-performance community-scale design projects (Meyer, et al., 2021) (Houssainy, et al., 2020), (Jing Wang, 2022), and this paper highlights an additional case study with unique project circumstances for future users to reference in their projects. This work illuminates the capabilities of the URBANopt tool to design and evaluate NZE and NZC districts. We use URBANopt to create a district, evaluate energy efficient design for the district, test the performance of a 4th GDHC system, and finally, evaluate the system size and components for economic viability, resiliency, or ability to achieve NZE and NZC operation.

URBANopt Background

URBANopt building model articulator

The open source URBANopt software development kit (SDK) builds on the U.S. Department of Energy's state-of-the-art building-level EnergyPlus™ and OpenStudio® analysis platforms and enables community-level energy analysis and optimization. URBANopt manages automated model creation, simulation, and results aggregation utilizing high-level information such as building footprint, type, vintage, number of floors, etc. Each building model is generated using these high-level URBANopt inputs, and fully detailed using modeling assumptions from ASHRAE 90.1 standards, OS-HPXML, or CPUC's Database of Energy Efficiency Resources (DEER).

URBANopt DES module

District energy systems have been leveraged for hundreds of years to move energy (typically waste heat from industrial processes) to effectively maintain comfort in neighboring buildings; however, modeling the potential and effectiveness of these systems has been a challenge due to complexity. The URBANopt DES workflow aims to make DES analysis more approachable in hopes of encouraging DES adoption through better evaluation of new systems or upgrades/expansions of in situ systems. The URBANopt DES workflow includes a GeoJSON to Modelica Translator (GMT) to enable the analysis of DES systems (Hinkelman, 2021).

The GeoJSON to Modelica Translator (GMT) is a one-way trip from GeoJSON in combination with a well-defined instance of the system parameters schema to a Modelica package that can support multiple buildings loads, energy transfer stations, thermal distribution networks, and central plants. The URBANopt DES workflow will eventually support multiple paths to build up district heating and cooling system topologies; however, the initial implementation is limited to 1GDH and 4GDHC (URBANopt).

The URBANopt DES workflow is motivated by the need to easily evaluate district energy systems. The goal is to eventually cover the various generations of heating and cooling systems. Moving towards 5GDHC systems can help electrify heating through heat pump-based systems, improve efficiencies, enable energy recovery across buildings (heating buildings with the heat rejected by cooling other buildings, and vice versa), and create greater utilization of waste-heat sources and sinks (by reducing the distribution loop temperature).

URBANopt-REopt module

In addition to its building energy modeling capabilities, at the hourly and end-use level, analysis of cost-optimal distributed energy resource (DER) asset mixes and dispatch strategies can be performed using URBANopt's built-in integrations with NREL's REopt^{TM} tool. REopt^{TM} is an open-source tool that enables optimization of dispatch for distributed generation (PV, wind, and combined heat and power), and storage (electrical and thermal), with financial and resiliency objectives (S. Mishra, et al., 2021). REopt^{TM} leverages a mixed-integer linear program to determine the optimal economic size of PV, wind, and storage subject to a site's characteristics and user-defined resiliency and economic constraints. REopt solves a series of simultaneous equations to find the system sizes and dispatch strategies that minimize the site's life cycle cost of energy to the building or district owner. REopt recommends hourly DER dispatch strategies (including battery storage charging/discharging by PV or the power grid, PV serving building loads, and grid serving load) according to the provided electricity rate structure to size generation and storage equipment to maximize the Net Present Value (NPV) of the assets over their life cycle (S. Mishra, et al., 2021).

This paper describes a preliminary zero energy feasibility design assessment for three new research buildings to be located on the east side of NREL's South Table Mountain (STM) campus. The three new buildings are planned to comprise a mixture of 100% electric laboratory and office spaces. The assessment was conducted using URBANopt following these steps:

(1) Outlined strategies to reach at least 30% energy efficiency savings over ASHRAE 90.1 2019 standard assumptions to achieve high-efficiency electric operation of the buildings.
(2) Analyzed the performance of a 4th GDHC system for the three new buildings.
(3) Evaluated optimal distributed energy resource assets and dispatch strategies that result in NZE, and NZC status at minimum LCC.
(4) Investigated four scenarios with added resiliency to grid outages and presented the optimal DER capacity, dispatch operations, and costs that would otherwise be required to reliably survive grid outages while meeting critical building loads.

Methods

Our analysis workflow is outlined in Figure 1. We begin by generating URBANopt articulated building energy models based on ASHRAE 90.1 2019 standards assumptions using high-level input parameters. We then calibrate the building models using additional information that reflects anticipated building design characteristics, such as ventilation rates, occupancy space types, and operational/occupancy schedules. The tuned building models are used to assess energy efficiency measures and mechanical system options that minimize energy usage. We aim to achieve at least 30% site energy savings (over ASHRAE 90.1 2019 standard assumptions). The high efficiency building model scenarios are then used to optimize distributed energy resource assets to achieve zero energy status. Lastly, two DER asset optimizations are considered: the first scenario considers a purely financial optimization objective that aims to achieve zero energy status at minimum LCC, and the second scenario aims to achieve zero energy at minimum LCC while also surviving a predefined grid outage for added resiliency.

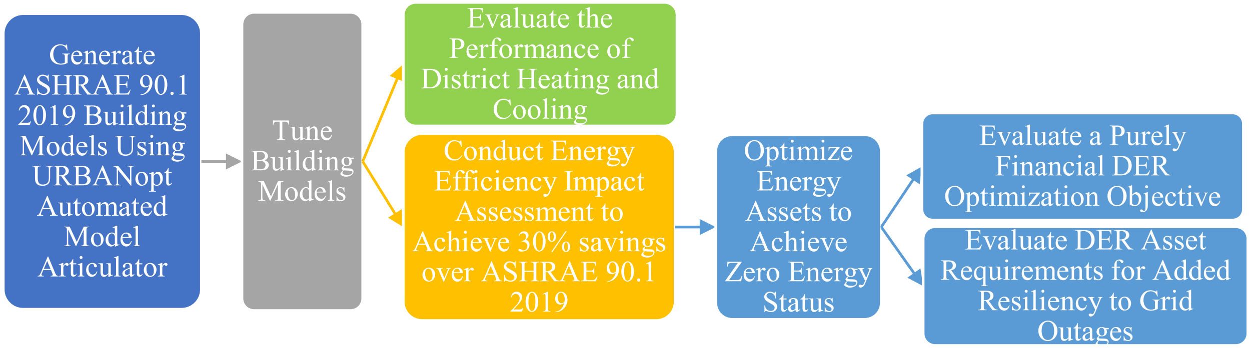

Figure 1: Zero energy feasibility analysis workflow using URBANopt

Building Model Articulation

URBANopt's core GeoJSON input file, containing high-level building characteristic information (e.g., building occupancy types, number of stories, etc.), was developed by manually tracing open street map footprints for the three new buildings and assigning appropriate predefined building design characteristic parameters. A visual of the GeoJSON building footprints is shown in Figure 2, and the associated high-level building input parameters are outlined in Table 1.

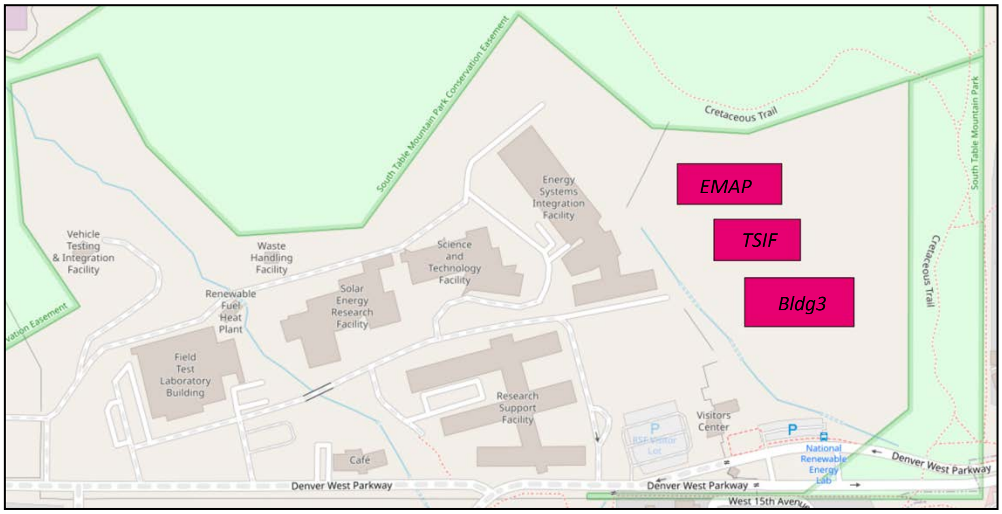

Figure 2: A visual of the URBANopt GeoJSON file containing building footprints and high-level building characteristics

Table 1: High-level building characteristic inputs used by URBANopt to articulate the building models

Building Name	Building Floorspace (ft^2)	Number of Stories	Percent Office	Percent Lab	Building Standard Assumptions	Heating Fuel Type
EMAPS[1]	95k	2	42%	58%	90.1 2019	NG
TSIF[2]	80k	2	33%	67%	90.1 2019	NG
Bldg3	120k	2	50%	50%	90.1 2019	NG

Each building model is generated using the URBANopt inputs and fully detailed using modeling assumptions from ASHRAE 90.1 2019 building standards[3]. The fully detailed 3D extruded geometry of the building model for EMAPS is shown in Figure 3. The baseline VAV system model was chosen to reflect system type 7 (VAV with hot water reheat) per the performance rating method in Appendix G of ASHRAE 90.1 2019.

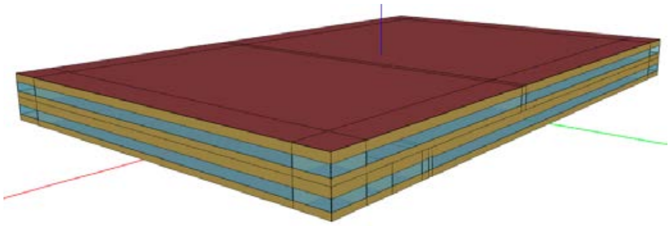

Figure 3: URBANopt articulated 3D geometry of the two-story EMAPS building model

Model customization and tuning

The URBANopt articulated models were tuned to reflect anticipated building design characteristics. Model tuning was composed of adjustments to default ventilation rates, occupancy space types, and operational/occupancy schedules. Laboratory space type ventilation rates were specified to meet NREL's ESH&Q standards and minimum ANSI/ASHRAE 90.1/62.1 2019 standards. Minimum outdoor air ventilation was adjusted to always meet 10 CFM/person and 1 CFM/ft2 across the baseline and proposed models. Default data center space types from URBANopt's articulated office models were removed, given large-scale computing needs will be met by cloud resources and/or NREL's central data center. Lastly, 2019 whole-building measured 15-min electricity time series data for NREL's RSF, RSF2, and ESIF were used to inform and specify the operational schedules for EMAPS, TSIF, and Bldg3 respectively. This includes adjustments to occupancy, lighting, and electric equipment schedules. The building operations start/stop time probability distributions of RSF, RSF2, and ESIF are shown in Figure 4 and the associated mean start/stop time values and mapping to the campus expansion models are summarized in Table 2 (Carlo Bianchi, 2020). Additional realism in the models is established by

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[1] Energy Materials and Processing at Scale (EMAPS) Laboratory Building

[2] Transportation Systems Integration Facility (TSIF)

[3] See the OpenStudio standards assumptions using the following link: https://github.com/NREL/openstudio-standards/tree/master/docs/scorecards, for a complete breakdown of all assumptions used to build the energy models.

introducing diversities in modeled loads, which is reflected by the variations in start/stop times of the building model schedules.

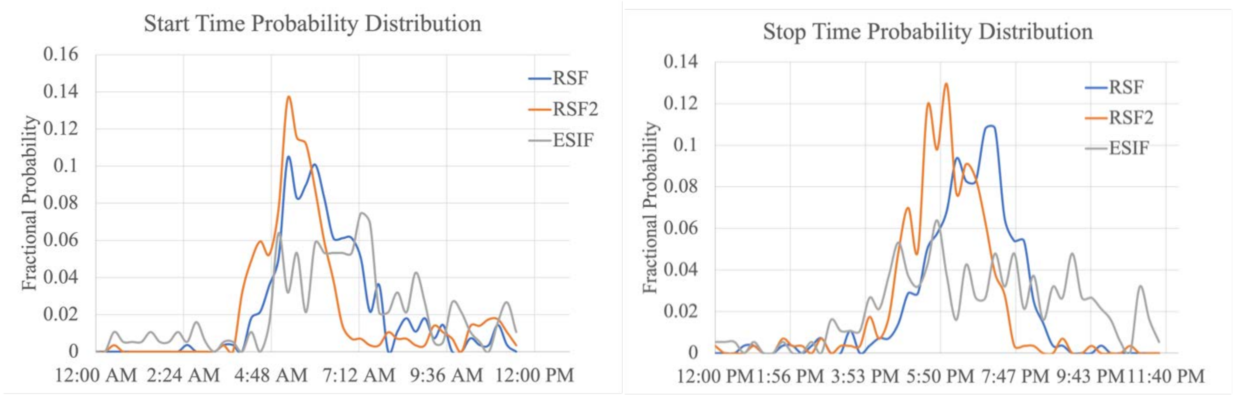

Figure 4: Probability distributions for start/stop times for RSF, RSF2, and ESIF based on 15min measured electricity data from 2019

Table 2: Calculated mean start/stop times for RSF, RSF2, and ESIF used to inform schedules for EMAPS, TSIF, and Bldg3 models, respectively.

Building	Mean Start	Mean Stop	Mapping
RSF	6:15am	6:30pm	EMAPS
RSF2	6am	6pm	TSIF
ESIF	6:45am	6:45pm	Bldg3

Energy Efficiency Assessment

The list of energy efficiency measures and HVAC options that were evaluated for each modeled building is shown below:

1- Optimal building orientation
2- Optimal window-to-wall ratio (WWR)
3- Increased exterior wall R-value
4- Adjustments to equipment power densities (EPD)
5- Adjustments to lighting power densities (LPD)
6- Energy recovery ventilation (ERV)
7- Heat pump water heater (HPWH)
8- HVAC
    a. Dedicated outdoor air system (DOAS), chiller, and air-source heat pump
    b. DOAS, and ground-source heat pump (GSHP)

District Heating and Cooling

For district modeling, the three buildings are connected to a central boiler and a central chiller. The boiler produces hot water at 55C and the chiller produces chilled water at 5C. The hot water and the chilled water are then sent to individual buildings to provide heating and cooling. The chiller is modeled using DOE2 chiller model and the boiler uses a simplified general model that has an efficiency of 0.8.

Distributed Energy System Optimization

The analysis and the calculated system size are highly affected by the financial and technical assumptions used in the optimization. Table 7 provides a summary of the assumptions used in this analysis. These values are mostly compatible with the default values provided by REopt. It should be noted that the assumptions used for this work are generalized and do not represent the financial details and contract specification in use by NREL.

Table 3: REopt assumptions

Financial assumptions	Study period	25 years
	Discount rate	8.3 %
	Electricity cost escalation rate	2.3 %
	Operation and Maintenance cost escalation rate	2.5 %
PV generation assumptions	PV system cost ($/KW)	$1600
	Tilt (deg)	40^{o}
	System losses (%)	14 %
	DC to AC size ratio	1.2
Storage and resiliency assumptions	Battery round trip efficiency	97 %
	Minimum state of charge (SOC)	20 %
	Initial state of charge (SOC)	50 %
	Resilience critical load factor	50 %

Results and Discussion

The results and discussions of this work follow the analysis workflow described in Figure 1. We discuss the impact of energy efficiency measures on the loads of the buildings and prescribe design guidelines to achieve 30% site energy use reduction compared to ASHRAE 90.1 2019 standard assumptions. We also evaluate the performance of a 4th GDHC system to meet baseline heating and cooling loads (to isolate the impact of a district configuration on energy consumption). Finally, we calculate the optimized array size and battery capacity for four different DER scenarios.

The normalized annual energy consumption of each building model as a function of building orientation (0^{o} reflects the orientation shown in Figure 2), and as a function of WWR is shown in Figure 5.

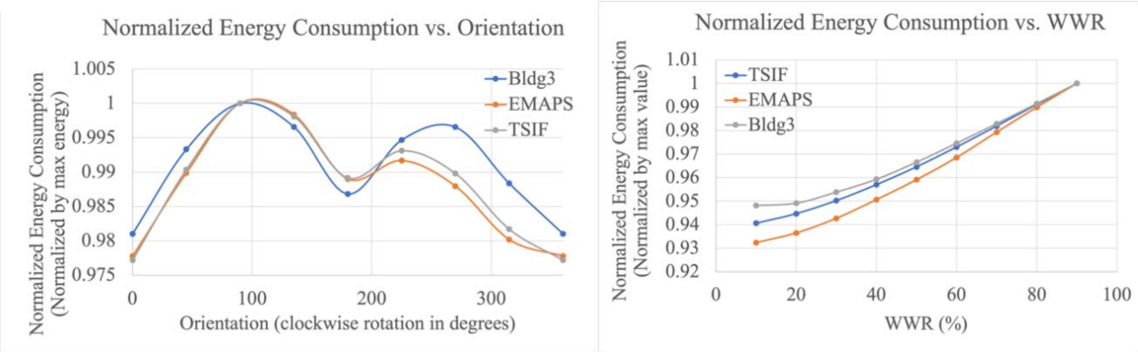

Figure 5: Normalized annual energy consumption of each building model as a function of building orientation [left] and window-to-wall ratio (WWR) [right]

Per the performance rating method in appendix G of ASHRAE 90.1 2019, the average energy consumption across all orientations of Figure 5 [left] was used as the baseline, and energy efficiency savings associated with building rotations to 0° were claimed. Moreover, WWR's of 15% were selected and savings over the ASHRAE 90.1 baseline WWR of ~40% were claimed. Equipment power densities (EPD's) and lighting power densities (LPD's) for all office spaces were reduced to $0.35 W/ft^2$ and $0.63 W/ft^2$, respectively, which reflects RSF power densities.

The incremental impact of energy efficiency and HVAC measures, listed in the method section (Energy Efficiency Assessment), on the whole-building energy consumption of each building is summarized in Figure 6. As shown in Figure 6, optimal building orientation results in 1% annual whole-building site energy savings across all three modeled buildings. Optimal building WWR results in 1.2%-1.7% in annual energy savings, and high efficiency EPD's in office spaces results in 3%-3.8%. Converting gas fueled water heaters to heat pump water heaters results in 0.7%-0.9% in annual site energy savings. 21.1%-25.3% energy efficiency savings are attributed to replacing VAVs with DOAS/chiller/HP systems across all three buildings. ERV's have a substantial impact on energy savings, with 11%-12.1% improvement over the baseline. As depicted in Figure 6, EPD and LPD impacts are greater in buildings with more office space i.e., Bldg3>EMAPS>TSIF. Similar trends are observed for HPWH's and heat pumps, given the larger predicted space heating loads associated with buildings with more office spaces compared to laboratory spaces. ERVs have a marginally higher impact in buildings with more lab space, and GSHP resulted in marginal savings over air-source HPs. In the appendix, three tables associated with each modeled building are provided with incremental energy savings by fuel type across the investigated energy efficiency measures. Note that each energy efficiency measure was added incrementally in the analysis, therefore the interactive effects of the energy efficiency measures are considered. In addition, the impact of HVAC system alternatives was also added incrementally to Figure 6, and the associated detailed tables in the appendix.

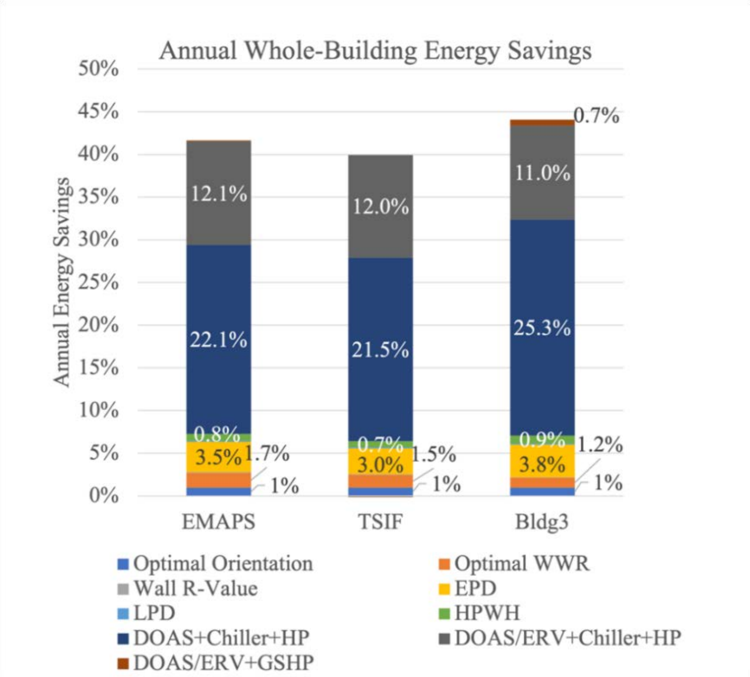

Figure 6: Annual whole-building energy savings as a function of incremental energy efficiency

measures and HVAC options

A high-level comparison of the proposed high efficiency model energy use intensities (EUI's) for EMAPS, TSIF and Bldg3 is shown in Figure 7. Figure 7 also includes the measured EUI's for RSF (excluding the data center) and ESIF (excluding the high-performance computing energy consumption) and ENERGY STAR portfolio manager for comparison. The proposed high efficiency modeled EUI's for EMAPS, TSIF, and Bldg3 are correlated with percentage of lab space (outlined in Table 1) and lies between RSF – a pure office building – and ESIF - a mix of office and laboratory space occupancy types.

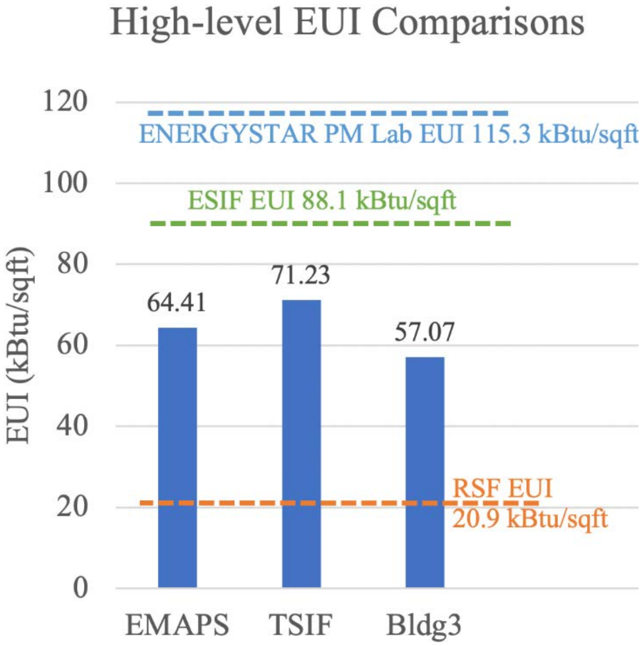

Figure 7: EUI comparison of the proposed high efficiency models and measured RSF, ESIF, and ENERGYSTAR Portfolio Manager EUI's.

DES Analysis

In Figure 8, we compare the annual heating and cooling power inputs for the DES case and the baseline case. For the baseline case, the orange dots include all three buildings' total consumption. In this particular comparison, DES results in lower power consumption for both heating and cooling. Specifically, the DES case saves 2.4% energy in heating operation and 9.7% energy in cooling operation. Even though the equipment efficiencies are the same for the baseline and DES cases, there are a number of other variables that determine overall energy consumption (tradeoffs between pump energy and compressor energy, lumped part load ratio versus part load ratios for individual building systems, equipment sizing, etc.), and whether or not a DES configuration saves energy will be situation specific. However, for the DES configuration we analyzed here (4th GDHC), we don't anticipate significant increases or decreases in energy efficiency between district and non-district system designs.

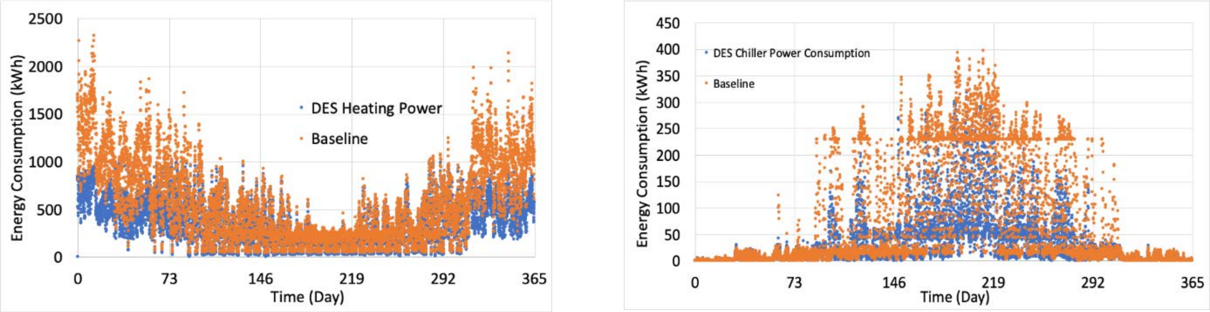

Figure 8: Annual power consumptions of boiler (left) and chiller (right) comparison between the DES case and the baseline case

REopt Analysis

This work uses the REopt web tool (through URBANopt's connection with REopt's Application Programming Interface or API) to evaluate the viability of PV generation and electric storage for financial, resiliency, and self-sufficiency objectives.

NREL uses the Primary General Service (Schedule PG) rate provided by Public Service Co of Colorado utility. The rate structure indicates that the energy charge is 0.00458 \$/kWh and demand charge is from 2PM - 5PM and is priced at 14.26 \$/kW during summer season (June – September) and 9.55 \$/kW during the rest of the year(OpenEI) (Colorado).

- This section evaluates the financial viability of installing PV and storage system to serve the three new buildings as a part of the east campus expansion project. The annual hourly load of these three buildings is evaluated in four different scenarios:
- Financial
  - The financial scenario is only limited by the utility rate structure. In other words, the economical optimum sizes of PV and storage are highly sensitive to the utility prices for energy and demand. And as shown above the inexpensive electricity at the location of the study makes larger generation and storage systems less financially attractive. In this case, the optimum system has storage capacity, which is charged using grid purchases, to reduce the demand charges during peak hours.
- Net zero energy/carbon
  - In the net zero energy scenario, we have limited the optimization by choosing a minimum size for the PV panels, that can support the electricity consumption of the district, and allowing for the optimizer to select the appropriate storage size that results in a less costly installation. We are comparing the electricity imports from the grid with the electricity exports to the grid as well as curtailment of PV. As of now, utility agreements will not allow for the buildings to be prosumers of electricity, which causes REopt to curtail some of the onsite generation (S. Mishra, et al., 2021). However, in a futuristic view of having the campus to be a prosumer, this curtailed potential will be harvested and we have included the curtailed values on NZE/NZC scenario. These buildings are fully electric;

therefore, a net zero design is considered a net zero carbon operation. (Paul A. Torcellini, 2020)

- Summer resiliency
    - In this scenario, the two-week outage starts July 1st. Due to higher solar irradiance the PV system size does not need to increase compared to the net zero scenario. However, a larger storage system is needed to ensure that the electricity needs of the buildings are met.
- Winter resiliency
    - In contrast with summer resiliency event, during the winter a larger PV array is needed in addition to a substantially larger battery storage system. This two-week event starts on February 1st and as seen in the graph the less available generation on February 5th and 6th is the main cause of this increase in the system size.

Table 4: REopt scenario summary table.

Scenario	Area needed (kft^2) [1]	PV size (MW)	Battery power (kW)	Normalized Battery capacity (kWh)	Net Present Value (NPV)
Financial	0	0	88	160	$30,223
Resiliency, 02/01 - 02/15	292	4.17	1378	12,153	-$6,550,221
Resiliency, 07/01 - 07/15	227	3.25	725	4380	-$2,707,670
Net Zero, financial	266	3.80	220	349	-$1,953,184

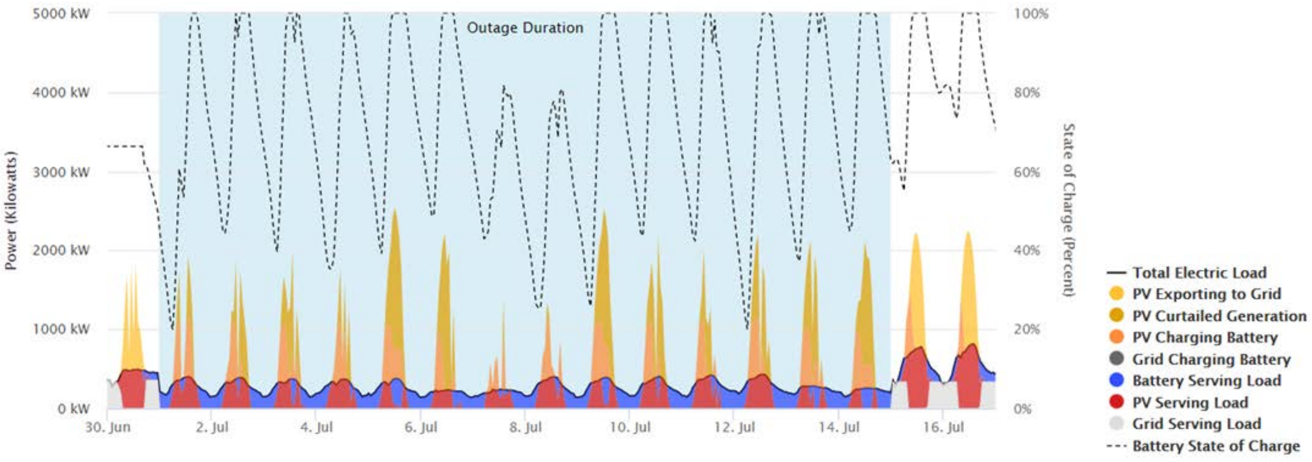

Figure 9: Summer resiliency power use and dispatch *(NREL)*

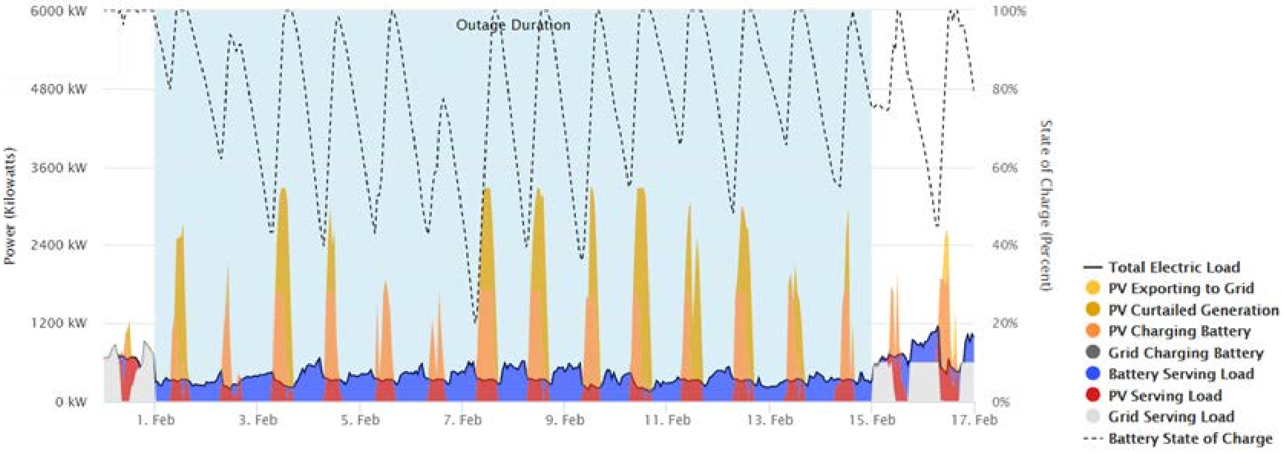

Figure 10: Winter resiliency power use and dispatch *(NREL)*

Table 6 summarizes all the scenarios with regard to their import, export, system sized and the net present value of the systems over a 25-year life cycle. The winter resiliency scenario requires a large storage system to be able to compensate for lower renewable production in cloudy days.

Conclusion

This work demonstrates some of the capabilities of the URBANopt tool in designing a net zero energy and net zero carbon districts. For this purpose, a case study of expanding the NREL east campus was selected. The evaluated campus expansion will include addition of three new buildings that include both office and lab spaces. Starting from the ASHRAE 90.1 2019 standard design as our baseline, we have investigated the impact of energy efficiency measures on the electric demand of the buildings. Also, we evaluated the performance of a 4GDHC system for the baseline to compare district's cooling and heating energy use with the aggregated use of the building-level equipment. Finally, we evaluated different scenarios of DER sizing to achieve resilient, NZE and financially optimum designs.

The design approach in our analysis prioritized maximum energy efficiency followed by on-site renewable energy utilization to achieve the net zero energy/carbon target. Energy efficiency improvements followed strategies from NREL's state-of-the art Research Support Facility (RSF), which included lighting, plug, and process load strategies that reflect natural daylighting utilization, advanced lighting controls, high efficiency equipment and smart power adapters that reduce "vampire" power usage. High efficiency lighting and equipment, well-insulated envelope, optimal building orientation, and optimized window-to-wall ratios achieved annual whole-building energy efficiency improvements of roughly ~5% over ASHRAE 90.1 2019 standards for all modeled buildings. Substantial whole-building annual energy efficiency savings were realized by swapping baseline building-level VAV systems with high efficiency air source and/or ground heat pump with DOAS solutions (roughly ~30% savings). Our modeling predictions indicate marginal energy savings improvements from air source to ground source heat pump systems; therefore, additional work is necessary to consider cost implications as an added attribute to better inform cost-optimal system selections.

We compared annual heating and cooling power consumptions from centralized DES systems with an individual baseline. The centralized DES concept shows marginally better efficiency in both heating and cooling operation, although performance is expected to be case specific. A 5th generation system with a single ambient (low temperature) distribution loop and distributed heat pumps would provide inherent efficiency benefits over both building-level solutions and the analyzed 4th generation system; such a system would reduce piping losses, enable energy sharing between buildings (for example, some buildings could be heated using the waste heat generated by cooling other buildings), and increase opportunities to harvest low-temperature waste heat sources. Future research is needed to quantify those savings.

This work conducted DER optimization for 4 scenarios. The electricity rate is one of the most important factors in the financial viability of onsite generation and storage of electricity. Achieving net-zero energy operation is more feasible if market mechanisms allow for export of excess electricity. Also, planning for resiliency require energy storage systems appropriately sized to the building load, and unreliability of the onsite generation source. It is important to note that with due to lower PV production during winter compared to summer months, the resiliency capacity needs are derived by winter peak and generation conditions.

In this work, we analyzed the NZE design of three fully electric buildings. Due to nonexistence of direct emission production, such as onsite combustion for heating, NZE design is also considered annual NZC. It is notable that, achieving carbon free operation is more challenging than NZC. For a carbon free design, we need (1) a large renewable generation and storage system that can support the buildings without reliance on the grid, or (2) only balancing the emission avoided, by selling excess renewable generation to the grid, and emission produced, by electricity purchases. Grid connected carbon free design will require adequate information regarding the grid average and marginal emission factors as well as ability to manage the load and storage in the district dynamically.

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Appendix

Table A-1: Incremental impacts of energy efficiency measures for EMAPS

EMAPS						
EE Measure (Incremental impact)	Total Energy Consumption (GJ)	Electricity Consumption (GJ)	Natural Gas Consumption (GJ)	Total Energy Savings	Electricity Savings	Gas Savings
Baseline	11093.60	5235.537	5858.071	0	0	0
Optimal Orientation	10983.77	5183.7	5800.07	1.0%	0.6%	1.4%
+ WWR	10790.28	5223.45	5566.84	2.7%	0.2%	5.0%
+ Wall R-Value	10780.81	5223.98	5556.83	2.8%	0.2%	5.1%
+ EPD	10392.41	4626.51	5765.9	6.3%	11.6%	1.6%
+ LPD	10375.33	4572.22	5803.11	6.5%	12.7%	0.9%
+ HPWH	10287.43	4617.65	5669.77	7.3%	11.8%	3.2%
+ DOAS + Chiller + HP	7830.72	7830.72	0	29.4%	-49.6%	100.0%
+ DOAS/ERV + Chiller + HP	6490.07	6490.07	0	41.5%	-24.0%	100.0%
+ DOAS/ERV + GSHP	6473.34	6473.34	0	41.6%	-23.6%	100.0%

Table A-2: Incremental energy efficiency impacts for TSIF

TSIF						
EE Measure (Incremental impact)	Total Energy Consumption (GJ)	Electricity Consumption (GJ)	Natural Gas Consumption (GJ)	Total Energy Savings	Electricity Savings	Gas Savings
Baseline	9989.7181	5085.562	4904.156	0	0	0
Optimal Orientation	9890.81	5035.21	4855.6	1.1%	0.8%	1.4%
+ WWR	9740.95	5089.21	4651.74	2.5%	-0.1%	5.1%
+ Wall R-Value	9734.21	5090.78	4643.42	2.6%	-0.1%	5.3%
+ EPD	9433.24	4621.17	4812.08	5.6%	9.1%	1.9%
+ LPD	9421.82	4577.68	4844.14	5.7%	10.0%	1.2%
+ HPWH	9346.94	4609.85	4737.09	6.4%	9.4%	3.4%
+ DOAS + Chiller + HP	7201.82	7201.82	0	27.9%	-41.6%	100.0%
+ DOAS/ERV + Chiller + HP	5999.34	5999.34	0	39.9%	-18.0%	100.0%
+ DOAS/ERV + GSHP	6039.46	6039.46	0	39.5%	-18.8%	100.0%

Table A-3: Incremental energy efficiency impacts for Bldg3

Bldg3						
EE Measure (Incremental impact)	Total Energy Consumption (GJ)	Electricity Consumption (GJ)	Natural Gas Consumption (GJ)	Total Energy Savings	Electricity Savings	Gas Savings
Baseline	12950.018	5802.46	7147.558	0	0	0
Optimal Orientation	12821.8	5745.01	7076.79	1.1%	0.6%	1.4%
+ WWR	12671.77	5821.45	6850.32	2.1%	-0.3%	4.2%
+ Wall R-Value	12667.36	5828.41	6838.95	2.2%	-0.4%	4.3%
+ EPD	12174.31	5007.6	7166.71	6.0%	13.7%	-0.3%
+ LPD	12155.05	4949.78	7205.27	6.1%	14.7%	-0.8%
+ HPWH	5	4993.67	7040.98	7.1%	13.9%	1.5%
+ DOAS + Chiller + HP	8758.39	8758.39	0	32.4%	-50.9%	100.0%
+ DOAS/ERV + Chiller + HP	7332.78	7332.78	0	43.4%	-26.4%	100.0%
+ DOAS/ERV + GSHP	7244.6	7244.6	0	44.1%	-24.9%	100.0%

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