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# Evaluating Energy Targets and Efficiency Measures in Multifamily Subtropical Buildings through Automated Simulation



Building operation accounts for a significant portion of global greenhouse gas emissions. Hawaii is committed to 100 percent clean energy by 2045. This study demonstrates a replicable process using early design phase energy modeling to reduce energy use in multifamily residential buildings in subtropical climates. The team simulated the design of air-conditioned buildings that can reduce annual energy use 29–61 percent compared to the International Energy Conservation Code, with an additional 10 percent savings if air conditioning is not used. The results inform the design of multifamily residential buildings by identifying building characteristics with the largest impact on energy use, energy cost, peak loads, and greenhouse gas emissions. The study demonstrates that generating 100 percent of annual site energy is possible using a combination of design measures and rooftop solar panels.

◁ Opening Figure. Honolulu, Hawaii's mild subtropical climate and planned new development present an opportunity to curb fossil fuel use through energy efficient building design and on-site renewable energy production. (Credit: Andrew Richard Hara)

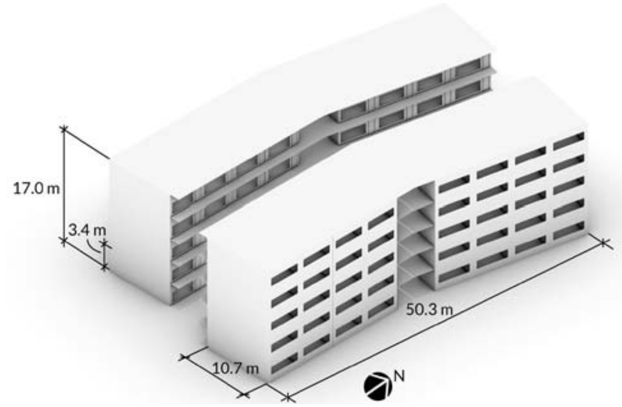
**Keywords:** Performance Simulations, Energy Studies, Sustainable Design

## Context

In 2018 the building and construction sector accounted for 36 percent of final energy use and 39 percent of energy- and process-related carbon dioxide ($CO_2$) emissions: more than either the transportation or industry sectors (IEA, UNEP 2019). Energy efficiency in buildings is a key low-cost component of Hawaii's commitment to achieve 100 percent clean energy by 2045 (Hawaii PUC 2018). Studies show that Hawaii's economic energy efficiency potential can exceed current intermediary goals of 30 percent, or 4,300 GWh, savings from energy efficiency by 2030, but that a business-as-usual approach to energy efficiency is not likely to achieve the 2030 Energy Efficiency Portfolio Standard goal (Hawaii PUC 2018; Larsen et al. 2018). In order for jurisdictions to meet energy and emission reduction goals, energy targets for performance in individual buildings for commercial and multifamily buildings are a useful tool (Carbonnier 2019). The AIA Code of Ethics and Professional Conduct requires setting ambitious performance goals for greenhouse gas emissions reduction with clients for each project (AIA 2020), yet building design professionals in Hawaii lack quantitative targets for building energy use intensity that surpass the required energy code to meet the State's clean energy goals. This research addresses that gap by demonstrating a replicable process to estimate a building's target energy use intensity (EUI) during the early phases of design.

The next step in meeting the State's energy efficiency goals is to identify design strategies that reduce energy use. Hawaii Energy, the energy efficiency program serving as Hawaii's Public Benefits Fee Administrator (Hawaii Energy n.d.(b)), and other stakeholders agree there is an "increased…customer need for informed partners in developing building-level energy plans that align with state and county level climate action plans" (Hawaii Energy 2018). In 2018, projects using energy modeling had approximately 25 percent greater reduction in predicted energy use intensity than non-modeled projects (AIA 2019b). Yet, only 41 percent of AIA member survey respondents (AIA 2019a) and about 50 percent of projects (AIA 2019b) use building performance simulation to improve energy performance. To reach a zero net carbon future, the AIA urges the design community to increase energy modeling in early design phases (AIA 2019b), but barriers to energy modeling, such as lack of dedicated budget or technical expertise, hinder its widespread use (Contoyannis and Wilson 2019). Recognizing that some building projects do not use design-phase energy modeling, this research project creates a resource for design teams that quantifies the relative energy savings from various energy efficiency measures for similar building projects.

In addition, this research establishes a range of target EUIs with the goal of guiding future design and construction while demonstrating a replicable process that constituents may adopt. Though not yet commonly applied, the National Renewable Energy Laboratory (NREL) zero energy design guide recommends the following standards: compare the EUIs of peer buildings; identify energy intensive building components; set an overall goal to achieve an EUI; and create an energy model very early in the design process (Torcellini et al. 2019). The next recommendation is to include energy goals identified in this analysis in the request for proposals and contract for building design and construction (Torcellini et al. 2019). Establishing a whole-building absolute target EUI, as opposed to targeted percent reductions compared to a baseline building, offers benefits including time saved in developing a baseline building model, a clear target, and an easier comparison to operational performance (Torcellini et al. 2019). An example application of a target EUI approach is the 2015 Commercial Seattle Energy Code which includes an alternative compliance path to establish a design EUI that requires validation during operation (Seattle Department of Construction & Inspections 2015). Similarly, the city of Boulder, Colorado is considering potential EUI design targets and outcome-based energy codes (Frankel and Carbonnier 2019).




△ Figure 1. Massing model of the multifamily buildings.

Energy efficiency reduces peak electrical demand, which in turn reduces requirements for generating capacity to serve peak load (Hawaii PUC 2018). As new demand charges and time-of-use rates are piloted, these reductions could affect utility bills. The Hawaii daily electricity demand curve peaks in the late afternoon and evening and does not coincide with the solar photovoltaic (PV) panel's maximum output from about 9 a.m. to 4 p.m. (Hawaii Energy 2018). Targeted energy efficiency and other strategies are "required to provide location-specific capacity deferral" (Hawaii Energy 2018). This research quantifies peak electrical demand reduction from various measures and calculates reduced demand with battery storage.

Capturing on-site renewable energy contributes to Hawaii's clean energy goals. This study assessed the potential for rooftop PV to generate a portion of the buildings' annual source energy or 100 percent of annual site energy. The study references source energy per the US Department of energy net-zero energy building definition (US DOE 2015). Site energy is referenced in the Living Building Challenge Energy Petal Intent (ILFI 2016); Zero Energy Certification (ILFI 2020); and Zero Code (Architecture 2030 n. d.). Taller buildings (over three or four stories) designed to International Energy Conservation Code 2015 code minimum and prescriptive requirements typically cannot generate 100 percent of annual site energy even if rooftop PV is maximized (International Code Council 2016).

*Building Typology and Climate*

Hawaii's significant demand for housing (SMS 2019), rapid building renovation, and planned construction in new Transit Oriented Development (TOD) areas make the multifamily residential building typology relevant to this study. The team simulated a conceptual design for two multifamily residential buildings on State-owned land in the Waipahu TOD area. The conceptual buildings' massing was one of multiple TOD proof-of-concept design studies on State-owned land conducted separately by the UH Community Design Center for the State of Hawaii Office of Planning (OP) in August 2019. The OP indicated if any of the designs were to move forward, the multifamily building seemed most likely. The research team identified an opportunity to demonstrate a new process for the OP: setting EUI targets early to include in future requests for proposals and demonstrating a replicable process utilized for other new State buildings. The conceptual massing for the two five-story buildings (not categorized as low-rise), each with a single loaded corridor or exterior walkway, were used in the energy simulations. Each building's length is 50.3 m (165 ft); width is 10.7 m (35 ft); floor-to-floor height is 3.4 m (11 ft); the long sides of the buildings face east and west due to the land parcel dimensions (Figure 1). There are forty one-bedroom dwelling units per building, each 60.4 $m^2$ (650 $ft^2$), and occupants are assumed to be primarily permanent.

Honolulu, Hawaii is located at 21°N latitude and is hot-humid, categorized as climate Zone 1A (moist category) in the IECC climate zone map (PNNL 2015). The Honolulu International Airport TMY3 weather data has zero heating degree days (HDD18.3°C) and 5527 cooling degree days (CDD10.0°C) (ASHRAE 2007). The winter design dry-bulb (99 percent) temperature is 17.1°C and the summer design dry-bulb and mean coincident wet-bulb temperature (2 percent) is 31.0/22.8°C (Grondzik and Kwok 2019). Given the cooling dominated climate, design strategies for indoor thermal comfort include dehumidification, sun shading of windows, mechanical cooling, natural ventilation cooling, and fan-forced ventilation cooling, listed in order of highest to lowest number of applicable annual hours (Milne 2020). Based on Honolulu TMY3 weather data, natural ventilation can provide thermally comfortable indoor conditions for approximately 51 percent of annual hours using the Adaptive Comfort Model in ASHRAE Standard 55-2010 (ASHRAE 2010).

## Methodology

*Setting Early Design Phase Energy Use Intensity Targets*

Demonstrating how to set energy goals prior to commencing energy modeling, the team compared the energy use intensities for peer buildings. Data sources included the Commercial Building Energy Consumption Survey (CBECS) (US EIA 2012), Energy Star (US EPA n. d.), and Hawaii Energy (Hawaii Energy n. d.(a)). The Residential Energy Consumption Survey (RECS) (US EIA 2015) was considered but cannot be clearly correlated to the multifamily buildings studied because it is focused on single-family homes. The team compared the EUIs of the Baseline model, peer buildings, and the New Buildings Institute's Zero Energy Commercial Building Targets report (Carbonnier 2019).

*Identifying Effective Energy Efficiency Measures*

The research used whole-building energy modeling to estimate relative differences in annual energy use and cost, peak cooling demand, peak electricity demand, and greenhouse gas emissions given various energy efficiency measures. The simulation engine EnergyPlus 8.9 (US DOE 2018) was used through the Rhino 6 (Robert McNeel & Associates 2019) software's Grasshopper plug-ins, Honeybee (Ladybug Tools 2019a) and Ironbug (Ladybug Tools 2019b), with the typical meteorological year (TMY3) weather file for Honolulu Airport.

First, the team created an energy model called the "IECC 2015 Baseline" that minimally complies with the Hawaii State Energy Code/International Energy Conservation Code (IECC) 2015 prescriptive requirements. Next, using the IECC 2015 Baseline as a starting point, the team worked with parametric modeling to evaluate energy efficiency measures in terms of their impact on EUI. A standard approach to this type of analysis may include modeling variables independently and then modeling a number of predetermined combinations of design inputs and comparing these scenarios to the baseline. A more holistic approach, used in this analysis, is to run parametric simulations with all of the possible combinations of design variables cross-referenced, creating a data set representing the whole range of possible performance outcomes. This approach requires running more simulations than the standard approach, but leveraging Ladybug (Ladybug Tools 2019a) and Ironbug (Ladybug Tools 2019b) allows the team to perform thousands of simulations automatically. A central script generated the combinations of energy efficiency measures, which ensured consistency between models. This method builds on previous frameworks that utilize parametric whole-building simulations to provide early-design guidance in residential buildings by modeling all possible design combinations' impacts on EUI (Samuelson et al. 2016). A limitation of this approach is the longer time required for the automated simulations to run.

Shown in Table 1 are all the major inputs used in energy simulations completed as part of the parametric analysis, including building envelope, ventilation, air conditioning, lighting, domestic hot water, and plug loads. The input categories were sorted into the IECC 2015 Baseline, Moderate Performance, and High Performance, with the Moderate- and High Performance values based on the NBI Multifamily Guide (NBI 2017) and professional experience. Those input categories were cross-referenced in the parametric simulation. For example, each of the three heating, ventilation, and air conditioning (HVAC) systems was simulated with all three glazing percentage options (lighting, plug load, solar heat gain, and shading ratio options)

**Table 1. Parametric Energy Model Inputs**

| Category | Variable | IECC 2015 Baseline | Moderate Performance | High Performance |
|---|---|---|---|---|
| **Envelope** | Orientation | 0° | 0° | 0° |
| | Mass | CMU concrete | CMU concrete | CMU concrete |
| | Insulation ($W/m^2$-°K) | U-0.44 wall, U-0.27 roof | U-0.31 wall, U-0.16 roof | U-0.31 wall, U-0.16 roof |
| | Window-to-wall ratio | 30% | 50% | 40% |
| | Shading ratio projection factor | None, includes walkway | 0.30 | 0.50 |
| | SHGC | 0.30 | 0.25 | 0.20 |
| | Glass U-value ($W/m^2$-°K) | 2.84, fixed | 2.84, fixed | 2.27 |
| | Infiltration Rate (ACH) | 0.29 | 0.12 | 0.013 |
| **Equipment** | Plug loads ($W/m^2$) | 4.31 | 4.31 | 2.15 |
| **HVAC System** | HVAC system—cooling | Split 11.2 EER | Split 14.1 EER, 19 SEER, 4.12 COP | Split 15.2 EER, 20.5 SEER, 4.45 COP |
| | HVAC system—ventilation | Naturally ventilated | Ventilation via split | Heat recovery ventilation via split |
| | Ventilation rate | Naturally ventilated | ASHRAE 62.1 & 62.2; 0.002 $m^3/s/p$; 0.0003 $m^3/s/m^2$ | ASHRAE 62.1 & 62.2 x 130%; 0.003 $m^3/s/p$; 0.004 $m^3/s/m^2$ |
| | HVAC sizing | Constant speed | Variable speed | Variable speed |
| | Programmable thermostat | Setback to 26.7°C 10pm–6am | Setback to 26.7°C 10pm–6am | Setback to 26.7°C 10pm–6am; off if < 30% occupied |
| **Domestic Hot Water** | | Gas boiler 80% efficiency | Air-source heat pump (HP) 2.0 COP | High Eff. Heat Pump (HEHP) 3.84 COP |
| | | | Solar thermal (ST) 60% fraction w/ electric backup | Heat Pump w/ Heat Recovery (HR) from AC |
| **Lighting** | Power Density ($W/m^2$) | 5.49 ASHRAE 2010 | 4.31 | 3.23 |
| | Lighting Control | None | None | None |
| **Other** | Solar Photovoltaic | None | None | Maximum 75% of roof space |
| | Solar Thermal | None | None | 60% solar fraction |
| | Battery Storage | None | None | 10% of peak load |



for a total of nine cross-referenced simulations. Grouping certain related values, such as thermal properties (U-value) for the opaque envelope components, reduced the number of total iterations. Variations to the mixed mode and building orientation were analyzed separately from the parametric analysis.

The parametric model envelope inputs included window-to-wall ratio, shading ratio, opaque envelope R-value, glazing U-value, solar heat gain coefficient, and infiltration rate (Table 1). The NBI Multifamily Guide (NBI 2017) provided the moderate- and high-performance envelope values, as well as the IECC 2015 Baseline and high-performance infiltration rates.

All occupancy inputs assumed half the residential units had two full-time occupants and half had one full-time occupant. The generic ASHRAE hotel occunpancy was used which assumes almost 100 percent occupancy from 10 p.m. to 7 a.m., about 30 percent occupancy from 9 a.m. to 5 p.m., and 40–85 percent occupancy in morning and evening.

The plug load inputs are based on professional experience designing multifamily buildings. A power density of 4.31 watts per square meter ($W/m^2$) is generally achievable with standard appliances located in the residential unit, while 2.15 $W/m^2$ requires selecting the best Energy Star rated appliances or limiting the number of major appliances in the unit.

**Table 2. Inputs for Combinations of Energy Efficiency Measures**

| | Combinations of Energy Efficiency Measures | | | |
|---|---|---|---|---|
| **Inputs** | **IECC 2015** | **Developer** | **Highest Performance 1** | **Highest Performance 2** |
| **WWR (%)** | 30 | 50 | 30 | 30 |
| **Shading Ratio** | 0 | 0 | 0.5 | 0.5 |
| **Opaque Envelope** | IECC | IECC | IECC | IECC |
| **Glazing U-value (W/m²-K)** | 2.84 | 2.84 | 2.84 | 2.84 |
| **SHGC** | 0.3 | 0.3 | 0.2 | 0.2 |
| **Lighting (W/m²)** | 5.49 | 4.31 | 3.23 | 3.23 |
| **Plug (W/m²)** | 4.31 | 2.15 | 2.15 | 2.15 |
| **Infiltration rate (ACH)** | 0.29 | 0.29 | 0.12 | 0.12 |
| **Ventilation** | Min. | Min. | Min. | Min. |
| **DHW** | Gas | HP | HR | HEHP |
| **HVAC** | Split System | High | High | No AC |

The HVAC inputs include four approaches: (1) IECC 2015 Baseline compliant split system with natural ventilation (EER 11.2); (2) higher performing (EER 14.1) readily available split systems with integrated ventilation, e.g., LG HSV5; (3) best available (EER 15.2) split systems with heat recovery ventilation, e.g., Mitsubishi MUY; and (4) full passive cooling and natural ventilation. Each case was modeled with a basic programmable thermostat allowing a nighttime setting of 26.7°C. The highest performance case includes a smart thermostat to turn off the HVAC system when occupancy is below 30 percent. For the completely passively cooled and naturally ventilated case, the windows were opened when the interior temperature reached 25.6°C, which is the set point recommended by Energy Star for residential cooling. The operable window area for the slider windows was 50 percent. The window opening area as a percentage of the floor area is 18.1 percent, a metric provided for comparison to the Hawaii energy code tropical amendment (Hawaii SEO 2016).

The domestic hot water inputs include five systems: (1) IECC 2015 baseline with a standard 80 percent efficient gas water heater; (2) air-source heat pump with a coefficient of performance (COP) of 2.0; (3) higher efficiency heat pump (HEHP) with COP over 3.8; (4) heat pump with heat recovery (HR) from the AC system condenser; (5) solar thermal (ST) system with electric backup. Since domestic hot water production (NBI 2017) and HVAC consume a large portion of the energy in residential buildings, the team tested four or five options each, rather than two options.

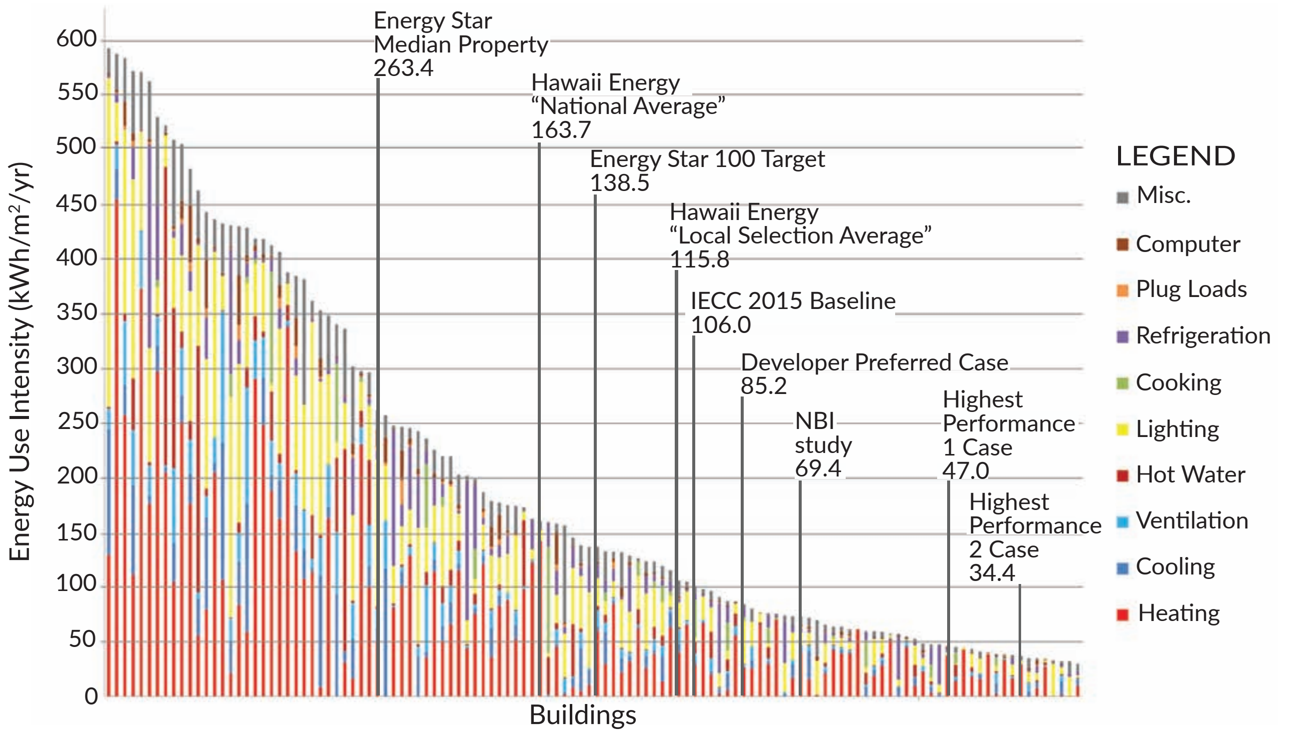
Electric lighting power density (LPD) inputs for the moderate case are selected for their similarity to the NBI Multifamily Guide requirement for a maximum LPD of 4.63 W/m$^2$ in common areas (NBI 2017). (The guide does not set an LPD requirement for inside residential units.) The energy models do not include daylight dimming or occupancy/vacancy lighting controls because they are not typical inside residential units.

*Testing Combinations of Energy Efficiency Measures*

Working from the complete data set created by the parametric energy models, the team identified selected combinations of variables by observing the design elements most impactful when modeled together. The metrics used to evaluate each combination include EUI, PV required to generate 100 percent of annual site energy, energy cost, and greenhouse gas emissions. Greenhouse gas emissions (GHG) for Hawaii in 2017 are 763.2 kg/MWh for electricity and 237.6 kg/MWh for gas (US EIA 2020).

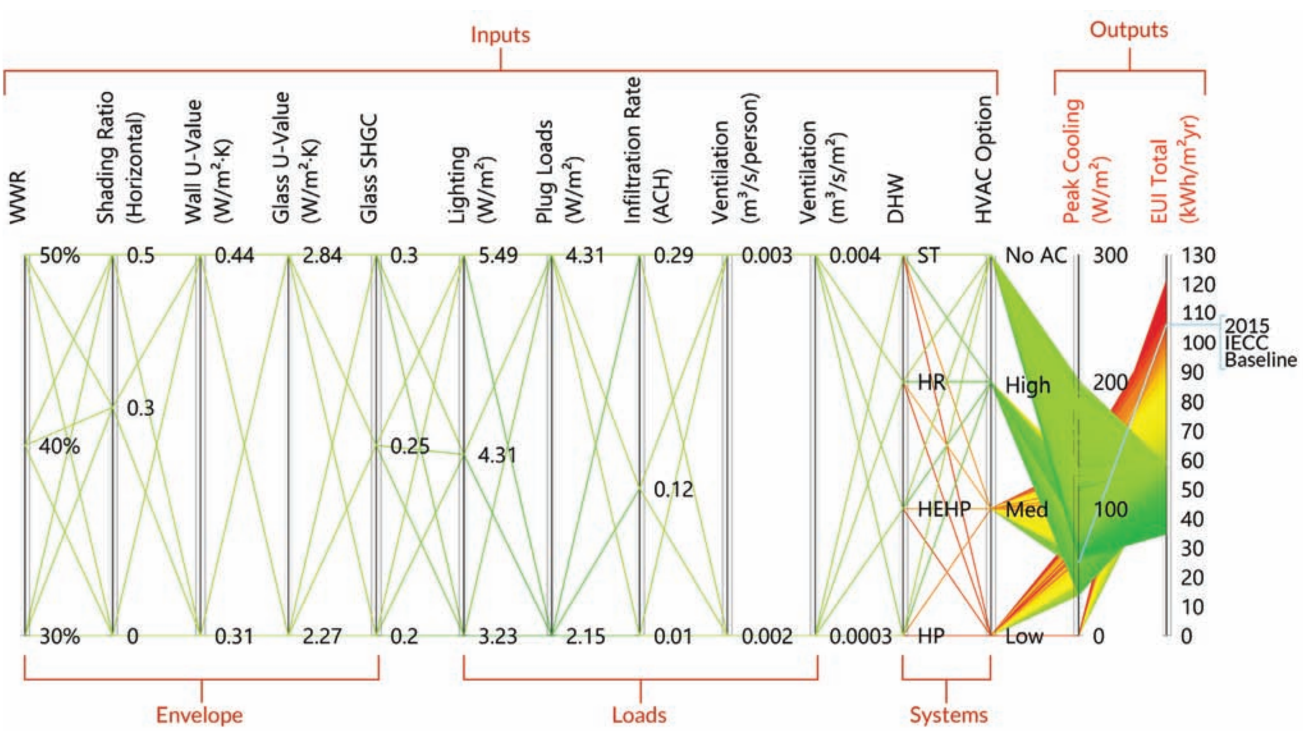
The following selected combinations of energy efficiency measures were used to establish a range of target EUIs to guide the future design and construction of the study buildings. The "Developer Preferred" combination included energy efficiency measures the team deemed likely employed if the State were to develop the building today; inputs were based on recommendations from the NBI Multifamily Guide and the team's professional experience designing high-performance buildings. The intent was to provide a specific EUI target more ambitious than code minimums but still considered reasonable by the State Office of Planning for inclusion in future building requirements. The Developer Preferred combination features a high window-to-wall ratio, no improvements to glazing solar heat gain coefficient, no external shading, code-minimum envelope insulation, high performing HVAC and DHW systems, and limited plug loads (Table 2).

The intent of the "Highest Performance" combinations (P.1, P.2) was to estimate the maximum technical potential (i.e., best performance achievable with current technology) to determine a feasible EUI, following the approach to develop Zero Energy Commercial Building Targets from the New Buildings Institute (Carbonnier 2019). The aggressive EUIs in the Highest Performance cases could inform multifamily EUI inputs in the Hawaii Clean Energy Initiative's future energy savings projections and target-setting as well as future potential energy codes that utilize EUI targets, such as in Seattle, WA or Boulder, CO (Carbonnier 2019). The Highest Performance combinations (P.1, P.2) include the most aggressive energy efficiency measures, including lower window-to-wall ratios, external shading, stringent solar heat gain coefficient, high performing HVAC




△ Figure 2. Energy use intensity for existing buildings in the CBECS with the benchmarks chosen for this project.






△ Figure 3. Parallel coordinates plot showing parametric analysis inputs and outputs.

and DHW systems, lower lighting power density, limited plug loads, and moderate infiltration rate (Table 2). The Highest Performance P.1 has mechanical cooling and ventilation whereas combination P.2 has no cooling and uses natural ventilation. Passive cooling (no mechanical cooling) is paired with the domestic hot water high efficiency heat pump (HEHP), rather than the heat recovery (HR) heat pump, given that there is no air conditioning system from which to recover heat.

*Mixed Mode Building and Orientation Simulations*

Given the potential for natural ventilation to satisfy adaptive thermal comfort criteria for approximately half of annual hours, it is important to quantify energy targets with mixed-mode building operation, which uses a combination of operable windows and mechanical cooling. Modifications to the IECC 2015 Baseline model to represent a mixed-mode building assume occupants close the windows and use mechanical cooling when the outdoor temperature goes above 25.6°C.

The whole-building energy model design cases have a fixed orientation, with long facades facing east and west, due to site constraints. A sensitivity analysis was conducted, rotating the fully conditioned IECC 2015 Baseline model by 90°, 180°, and 270°, both without shades and with horizontal overhangs that provide a 50 percent shading ratio between the height of the window and the shade projection.

*Potential to Generate 100 Percent of Annual Site Energy*

A net-zero energy building is an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy (US DOE 2015). The boundary for the simulated operational energy in this analysis is the building. The load/generation balance is calculated with no weighting factors (Sartori et al. 2012). The team found energy generation from a rooftop PV array insufficient for this five-story building to be zero net energy. Recognizing this, the team estimated and compared the sizes of rooftop PV arrays required to generate 100 percent of annual site energy, because other benchmarks reference site energy. First, the team determined the maximum building site EUI offset by installing a PV array on 75 percent of the total roof area, leaving room for maintenance access and other equipment. The team calculated and visualized the required area for a rooftop PV array to generate 100 percent of annual site energy for each of the combinations of energy efficiency measures (Figure 8). The PV electricity production estimated using the online tool, PV Watts version 6.1.3 (NREL n.d.), assumed a 16 percent PV efficiency, 14 percent system losses, 20° tilt, facing south.

*Potential for Shaving Peak Electrical Demand with Battery Storage*

The State of Hawaii recognizes energy storage will be a critical component of the 100% Clean Energy Target. To help understand how energy storage reduces the peak electrical load, the team identified a battery system that shed at least 10 percent of the building's estimated peak electrical demand. This 10 percent value reflects the LEEDv4 (USGBC 2019) demand response Energy and Atmosphere Credit (EAc4) threshold. The team estimated the total building electrical demand on an hourly basis for the IECC 2015 Baseline.

**Results**

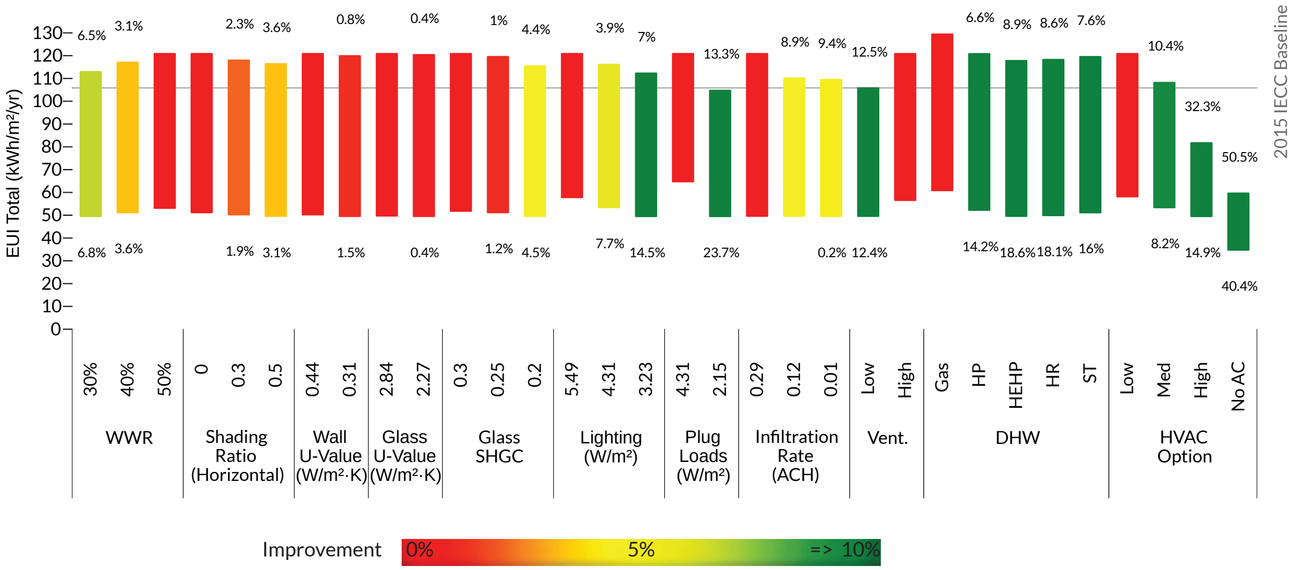
*Setting Early Design Phase Energy Use Intensity Targets*

To inform early design phase energy use intensity targets, the team examined the spectrum of energy performance for peer buildings and found the Hawaii Energy benchmarking studies more applicable than national energy benchmarks such as Energy Star because the Hawaii Energy studies (Hawaii Energy n.d.) include buildings with similar climates, and heating and cooling use. Figure 2 illustrates the EUI for the building data available in the CBECS with the benchmarks chosen for this project. The National Average and Local Selection Average (based on Hawaii Energy Data) is much lower than the CBECS buildings and the Energy Star Median Property, which could be because CBECS groups multifamily housing with dorms, hotels, and assisted living facilities. All fall under the "lodging" category and have higher occupied density for more hours of the year than a typical residential building reflected in the Hawaii Energy data. In addition, the CBECS Climate Zone 5 groups Hawaii, Alaska, California, Washington, and Oregon together.

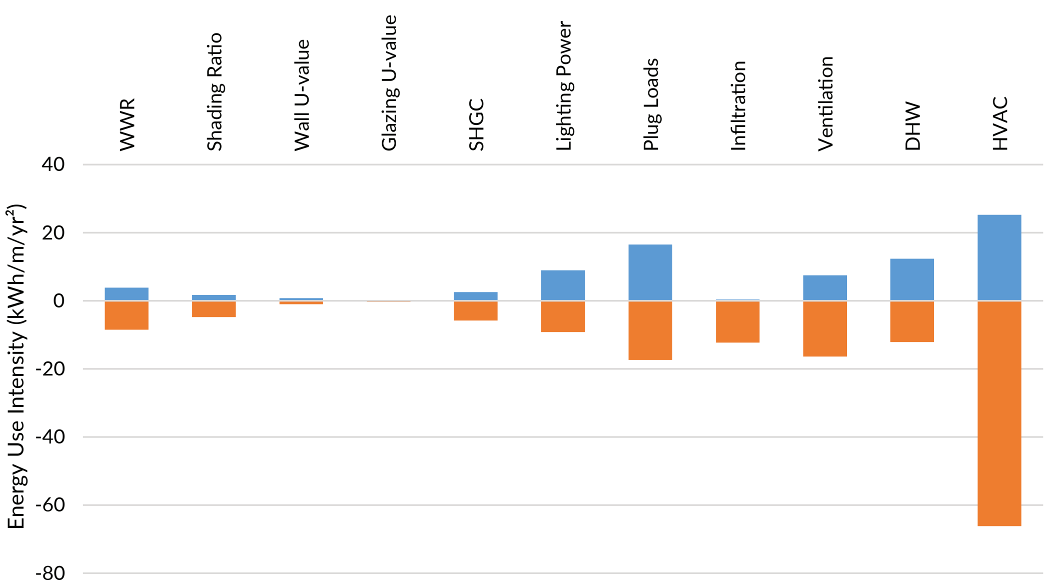
An IECC 2015 Baseline multifamily building was modeled with an EUI of 106.0 kWh/m$^2$/yr while Hawaii Energy found the "local selection average" of existing condo/multifamily buildings had an EUI of 115.8 kWh/m$^2$/yr. This indicates the EUI of new condo/multifamily buildings designed and built to the current energy code (2016) may only be about 8 percent lower than the average EUI of existing condo/multifamily developments in Hawaii. This modest savings indicates that driving building energy consumption down dramatically will involve more than code-minimum design. Design teams looking for energy targets may reference the study by the New Buildings Institute (NBI) which states that in Climate Zone 1A a zero-energy mid-rise apartment's EUI target is 69.4 kWh/m$^2$/yr (Carbonnier 2019), about 60 percent of the "local selection average."

*Identifying Effective Energy Efficiency Measures*

The IECC 2015 Baseline model with minimum prescriptive requirements resulted in an EUI of 106.0 kWh/m$^2$/yr. The annual energy consumption end uses include cooling energy/HVAC (41 percent); equipment (plug loads) (23 percent); lighting energy (18 percent); domestic hot water (14 percent); and elevators (4 percent). Similarly, the parametric analysis determined that air conditioning, occupant plug loads, ventilation requirements, domestic hot water, lighting, and window-to-wall ratio/glass performance are the biggest contributors to energy performance (from largest to smallest). Building orientation and shading also affect energy performance (~4 percent annual energy savings), however, insulation values of the windows and wall had a negligible impact on energy performance. Designers can significantly reduce energy use in air-conditioning, domestic hot water, and some lighting energy, while equipment and elevator energy use may be reduced through tenants' appliance selection, behavior, or tenant-owner agreements.




△ Figure 4. Energy use intensity sensitivity with single fixed variables.



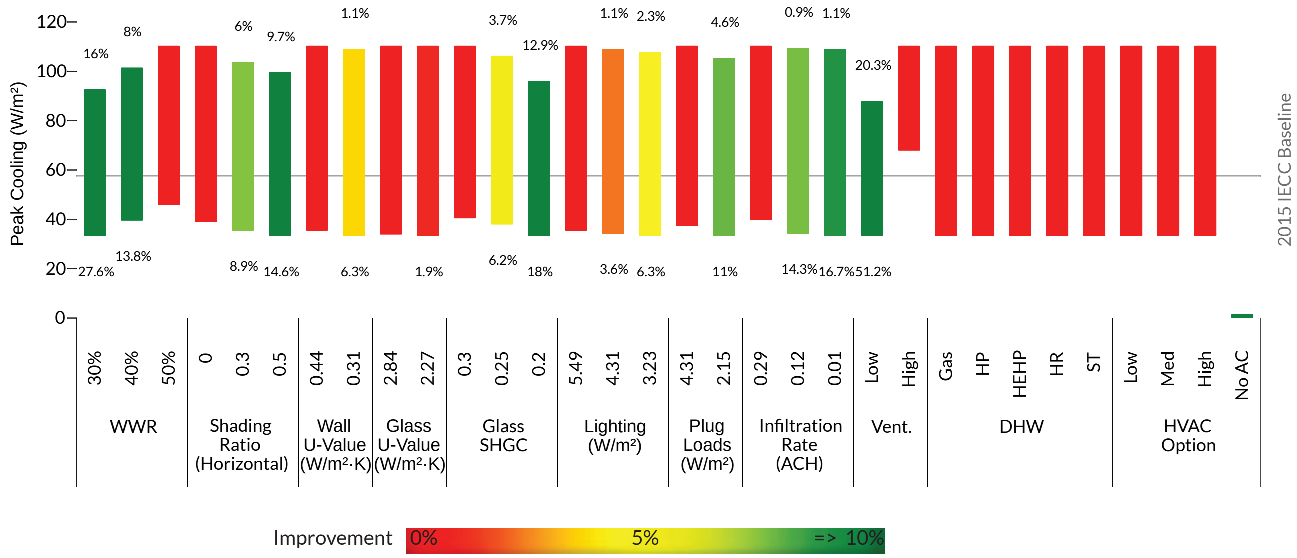

◁ Figure 5. Overall impact of window-to-wall ratio, shading ratio, wall U-value, glazing U-value, SHGC, lighting power density, plug loads, infiltration rate, ventilation, domestic hot water, and HVAC efficiency on EUI.



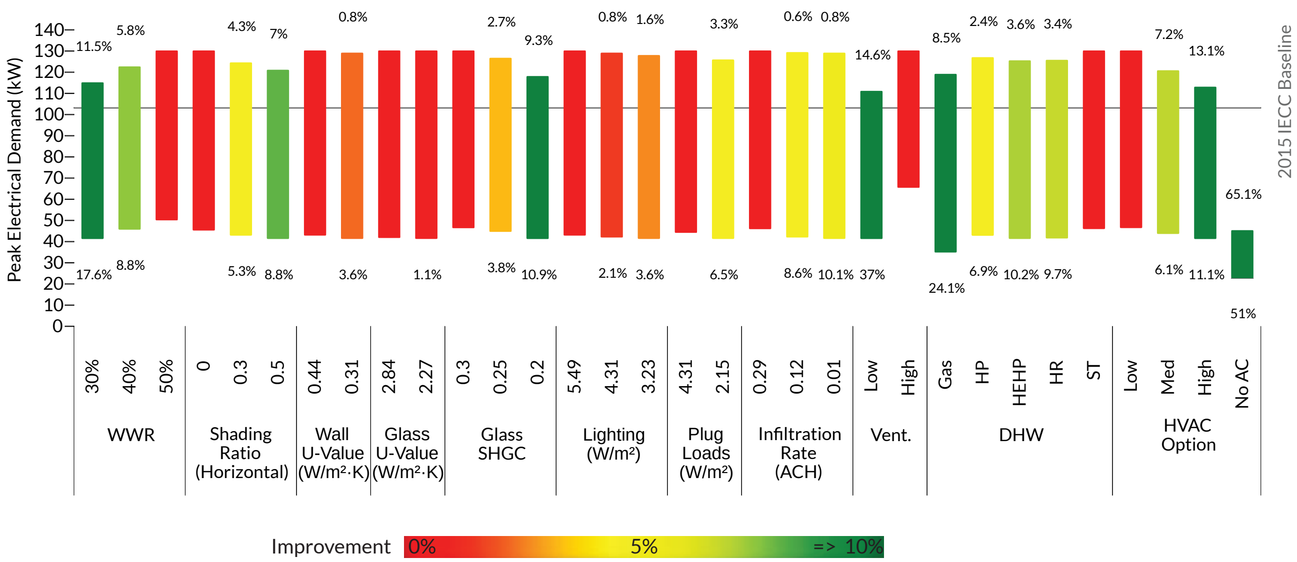
The inputs and outputs for the parametric analysis are visualized in the parallel coordinate plot (Figure 3). All simulations are represented by a line from the input variables on the left to the output metrics on the far right. The line colors indicate the relative performance of each iteration in terms of energy consumption, green being the least amount of annual energy (most efficient), and red the highest energy consumption. From this data set, it is apparent most of the highest energy consumption design combinations (red and orange colors) emanated from the low and medium efficiency HVAC systems. High performance features coupled with the high efficiency HVAC or passive cooling reduce EUI to about 47.3 kWh/m$^2$/yr and 34.7 kWh/m$^2$/yr, respectively.

Each bar in Figure 4 represents the range of energy (EUI) outcomes possible given a single fixed variable. The color indicates whether a given variable has a positive (e.g., low energy) or negative impact on energy performance based on whether it eliminates high performance options (low EUI), or eliminates the worst performing options. The following measures reduce EUI and are listed from greatest to least impact: reduced plug loads; ASHRAE standard ventilation rate; moderately reduced infiltration; efficient domestic hot water; lower lighting power densities; lower window-to-wall ratio; more stringent solar heat gain coefficient; and external shading.

Another way to understand the data is by looking at the total difference or delta of the lower energy and higher energy




△ Figure 6. Peak cooling demand with fixed single variables.




△ Figure 7. Peak electrical demand with fixed single variables.



result for each input (Figure 5). For instance, infiltration when coupled with high performance features (particularly a low energy HVAC system), has little impact on the total building performance. All infiltration options, when coupled with high performance features, result in an EUI of just over 47.3 kWh/m$^2$/yr. However, if linked to lower performance features, high infiltration can spike the EUI up to 119.9 kWh/m$^2$/yr, while low infiltration is at 110.4 kWh/m$^2$/yr or a delta of 9.5 kWh/m$^2$/yr.

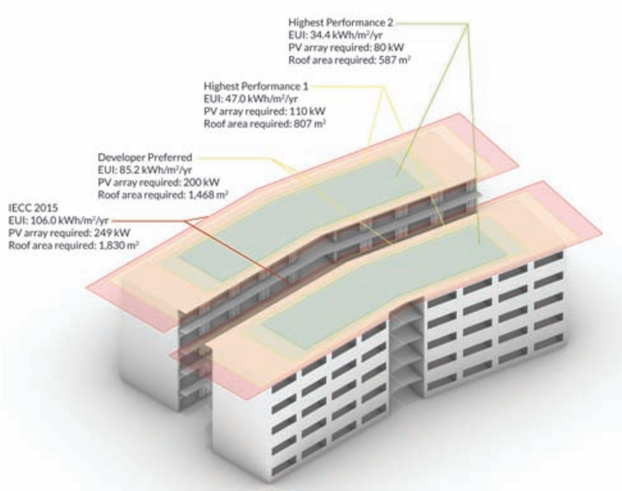
*Impact of Energy Efficiency Measures on Peak Cooling and Peak Electricity Demand*

The analysis in Figure 6 illustrates peak cooling demand can be reduced by using ASHRAE standard ventilation rates, building orientation with long north and south facades, lower window-to-wall ratio, a stringent solar heat gain coefficient, higher shading ratio, and reduced plug loads. In Figures 6 and 7, each bar represents the range of peak cooling or electrical demand outcomes possible given a single fixed variable. The color indicates whether a given variable has a positive impact (e.g., low peak demand) or a negative impact on peak cooling, based on whether it eliminates low demand or high demand scenarios from the solution set.

Peak electrical demand reduces by having no AC, high efficiency AC, minimum ventilation, lower window-to-wall ratio, higher shading ratio, and more stringent glazing solar heat gain coefficient (Figure 7). On-site battery storage shaves the

**Table 3. Results for Combinations of Energy Efficiency Measures**

| Combination | EUI (kWh/m²/yr) | PV Required for 100% site energy (kW) | Energy Cost (US$/yr.) | GHG Emissions (metric tons CO2e/yr) |
|---|---|---|---|---|
| **IECC 2015** | 106.0 | 249 | 107,000 | 300 |
| **Developer Preferred** | 85.2 | 200 | 93,800 | 248 |
| **Highest Performance 1** | 47.0 | 110 | 52,000 | 137 |
| **Highest Performance 2** | 34.4 | 80 | 38,000 | 100 |




△ Figure 8. Roof area required for PV to generate 100 percent of annual site energy for various combinations of energy efficiency measures.

peak electrical demand. Using a gas water heater also reduces peak electrical load but results in a higher annual EUI than the other domestic hot water options tested and would not meet clean energy goals. These peak electrical demand numbers represent electrical demand from the energy model, not necessarily sizing values for transformers or other electrical infrastructure.

*Varying Combinations of Energy Efficiency Measures*

Combining energy efficiency measures shows the potential for moderate or significant energy savings. The Developer Preferred combination indicates an estimated energy use intensity (EUI) of 85.2 kWh/m²/yr (Table 3). This demonstrates developers can select the often-desired high glazing percentage (without additional external shading costs) if paired with a high performing HVAC system and heat pump water heater. This combination still achieves a 19 percent improvement over the IECC 2015 Baseline, which includes a much less efficient gas boiler for domestic hot water.

The highest performing cases estimate this type of multifamily building can achieve at least an EUI of 47.3 kWh/m²/yr with full mechanical cooling, or 34.7 kWh/m²/yr without cooling. This is a 56 percent and 68 percent reduction, respectively, compared to the IECC 2015 Baseline (Table 3). These meet and exceed the NBI net-zero study EUI of 69.4 kWh/m²/yr (Carbonnier 2019).

*Mixed Mode Building and Orientation Simulations*

When the IECC 2015 Baseline changes to mixed-mode operation, the whole building EUI is reduced to approximately 88.3 kWh/m²/yr, 16 percent lower than the original IECC 2015 Baseline. This energy efficiency measure has low or no additional initial cost but may require occupant education. Designers may enable more frequent mixed mode operation by limiting heat gain (e.g., external shading or a stringent solar heat gain coefficient).

Rotating the IECC 2015 Baseline so that long facades face north and south achieves a 4 percent energy savings and 19 percent peak cooling savings (3 percent energy and 16 percent peak with shades). Climate-appropriate building orientation is a long-term design decision that commonly has low or no initial cost, but can provide significant energy and peak cooling savings, and should be informed by early design phase energy studies.

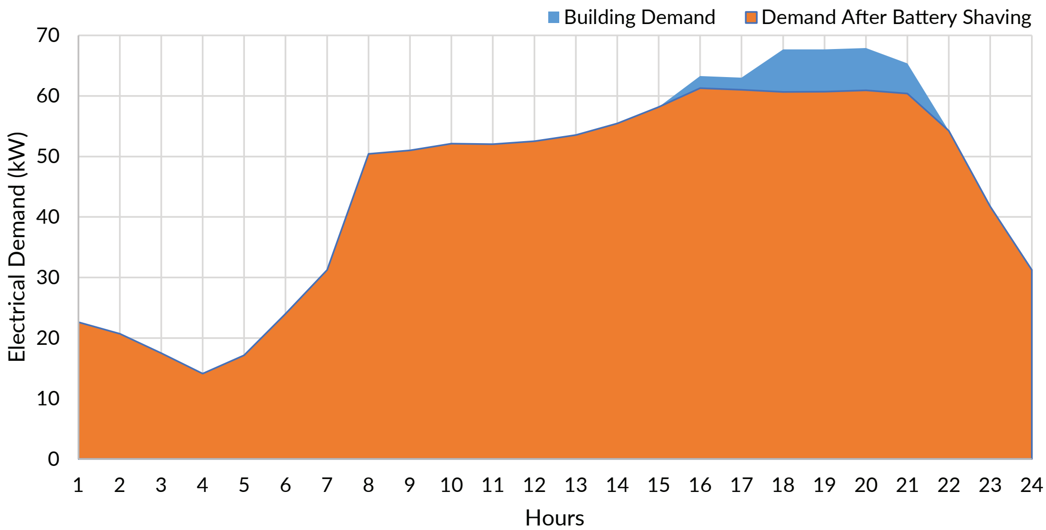
*Potential to Generate 100 Percent of Annual Site Energy*

Electricity generated by rooftop PV cannot offset the annual source energy use for any of the simulated combinations, but can offset the Highest Performance P.1 and P.2 combinations' site energy use. To achieve net-zero source energy, the Highest Performance P.1 combination requires a 363-kW PV system that does not fit on the roof. The Highest Performance P.1 combination has a source EUI of 155.1 kWh/m2/yr, based on an Oahu electricity generation site-to-source ratio of 3.3; this is 3.3 times the site energy measured at the building site for the island of Oahu (HEI 2018). Given the available rooftop area, a 145-kW PV system can offset the annual site energy use if each building's maximum EUI is approximately 63.1 kWh/m²/yr. Figure 8 illustrates the roof area required to generate 100 percent of annual site energy for each of the combinations of energy efficiency measures. The Highest Performance P.1 and P.2 combinations can generate 100 percent of annual site energy with PV on the available rooftop area.

*Potential for Shaving Peak Electrical Demand with Battery Storage*

The IECC 2015 Baseline annual peak demand is around 87 kW, with typical summer and autumn daily peaks just under 70 kW. Daily peak demand consistently occurs in the late afternoon when the solar gain drives AC energy use and in the early evening when many residents are home.

Figure 9 shows hourly electrical demand on the autumn equinox for the IECC 2015 Baseline and the effect of a 50-kWh battery system. When the battery discharges electricity during the high load hours, it reduces the peak demand by roughly 10 kW. This is more than a 10 percent reduction in peak demand and would meet the LEEDv4 EAc4 Demand Response credit




◁ Figure 9. Electrical demand and peak demand shaving with battery storage for the IECC 2015 Baseline on the autumn equinox.

threshold. A 50-kWh battery system is comparable to 10 Tesla Powerwalls (the maximum number offered in a single residential Powerwall system).

## Conclusion

This research presents new quantified information to significantly reduce energy use, greenhouse gas emissions, and peak electrical load in multifamily buildings in subtropical climates. The parametric analysis showed air-conditioning, occupant plug loads, and ventilation requirements are the biggest contributors to energy performance (Figure 5). Peak cooling demand can be reduced by using ASHRAE standard ventilation rates, building orientation with long north and south facades, lower window-to-wall ratio, stringent solar heat gain coefficient, higher shading ratio, and reduced plug loads (Figure 6). Reducing peak electrical demand means having no AC, high efficiency AC, minimum ventilation, lower window-to-wall ratio, higher shading ratio, and more stringent glazing solar heat gain coefficient (Figure 7). The analysis established a range of target EUIs, from 34.7 to 85.2 kWh/m$^2$/yr, achieving a 68 percent or 19 percent reduction, respectively, compared to the IECC 2015 Baseline. In order to be designed for net-zero source energy, the combination of energy efficiency measures designated "High Performance" require a 363-kW PV system larger than fits on the roof, whereas the Highest Performance P.1 and P.2 combinations as tested generate 100 percent of annual site energy on the available rooftop area. This research demonstrates that the High-Performance combinations relying on mixed mode or natural ventilation for cooling, even for five-story buildings, can generate 100 percent of annual site energy whereas the IECC 2015 Baseline building cannot.

The team discussed this study and its application with leaders of the State of Hawaii Office of Planning, State of Hawaii Energy Office, and Hawaii Energy. The group indicated the study was useful in their activities such as consideration of financial incentives for energy modeling, energy code updates, Zero Code, and meeting institutional net-zero carbon emissions goals. There was interest in conducting similar studies for other buildings types (e.g., commercial) and providing a publicly available resource to design teams. The State suggested this study be combined with a Hawaii-based life cycle cost analysis for each energy efficiency measure building owners and design teams use to set new project targets or requirements.

Simulation methods could be expanded by advancing the parametric tool to account for time-of-use electricity pricing, which would enable study of PV and battery cost optimization or thermal storage (e.g., ice storage). Limitations include the long simulation time required to generate large data sets. Widespread adoption of these methods may be hindered by the high-level expertise required to effectively use the software.

This study demonstrated a replicable process to fill information gaps and assist jurisdictions or design teams in meeting high priority energy efficiency and renewable energy generation goals. An aspirational next step is training architecture and engineering students, the workforce of tomorrow, to conduct similar studies and reports. This would prepare students for the profession while creating resources to meet larger climate action goals.



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**Data Statement**
Data available on request from the authors.

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