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The Villages at 995 East Santa Clara St, San Jose

EPC 21-030 Next EPIC Challenge

Energy & Emissions Report

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This report summarizes results from simulation studies for 995 E Santa Clara to meet CEC grid response requirements; support resilience and reliability; and minimize operational energy, cost and greenhouse gas emissions.

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Summary

Our study uses EnergyPlus simulations to examine whole-building demand and energy end-use profiles for different design options and then uses these outputs to evaluate cost and carbon impacts of each scenario in Xendee, a modeling platform designed to “right size” and balance investments in distributed energy resources (DER).

Our results show that efficiency measures are key to meet the ambitious performance metrics for this project; however, most of the technology potential occurs for heating, ventilation and air conditioning (HVAC) or domestic hot water (DHW) loads which are a relatively small portion of a mid-rise multifamily building’s overall energy use. The most meaningful strategies to reduce or shift loads for this building include DHW load shifting, energy recovery ventilation, dynamic ventilation, and ceiling fans. Envelope strategies improve overall annual building performance but become an issue when lower heat loss increases cooling during the critical afternoon peak.

Compared to efficient, packaged air source heat pumps, a hydronic heating and cooling system (also serving DHW loads) with thermal energy storage has the best energy performance, highest load shifting capability, and best thermal resilience during outages. But because heating and cooling demands are small and hydronic systems are expensive, the net benefits of thermal energy storage are not substantial. On many days during the 4-9pm window, serving loads from the air source heat pump (ASHP) and battery yields similar costs as thermal storage.

For high density residential buildings, the roof area to support PV is a significant constraint in meeting the design requirements with reasonable battery sizes. An elevated PV canopy increases generation considerably. But allowing grid charging has similar results as a canopy in its ability to cover daily residential loads from 4-9pm with limited increase in emissions. Sizing on-site generation and storage systems to cover the “worst case” outage conditions significantly drives up system size and cost. Even small deviations from 100% coverage (95%, or 99%) can dramatically reduce size and cost without a very meaningful change in resilience.

Contents

1. Baseline model

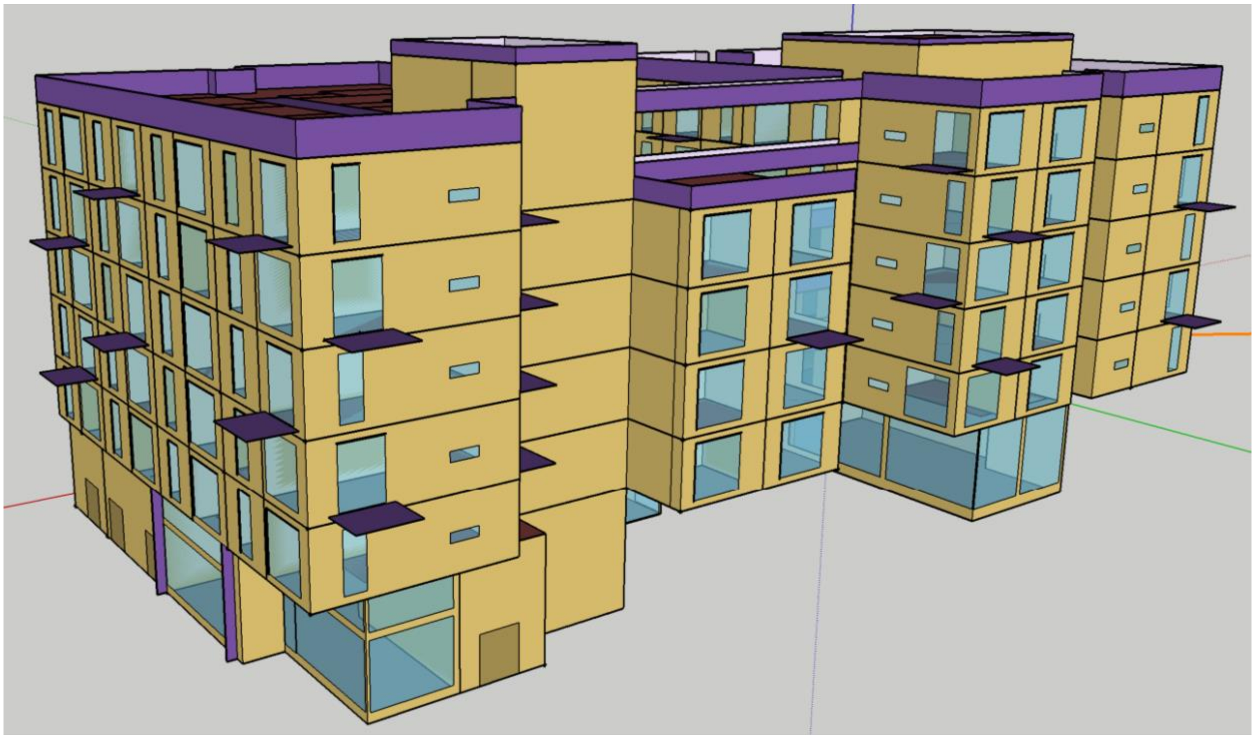

Figure 1: Visualization of the baseline model geometry.

1.1. About EnergyPlus

EnergyPlus is a whole-building energy simulation engine that implements the full ASHRAE Heat Balance method while providing detailed models that have been validated at the zone, system, and plant levels. EnergyPlus takes inputs such as weather, construction material thermophysical properties, occupancy, lighting, equipment, heating, ventilation, and air-conditioning (HVAC) design and operation strategies to estimate energy consumption and indoor environmental conditions. It also has the capability to output detailed information such as the total energy flowing in and out through windows and walls on an hourly basis.

1.2. Geometry and thermal zones

We developed the 995 E. Santa Clara St. Senior Apartments geometry for the EnergyPlus simulation using the latest floor plans and Revit model available from the design team. The first floor consists of offices, a laundry room, support, and common spaces. Floors two through six are residential apartment units which consist of 69 single-bedroom (~616 ft^2) and five two-bedroom (~840 ft^2) units. For the energy models, we assume one-person occupancy for the one-bedroom apartments and an average of 2.5 for the two-bedroom units. Each apartment unit consists of spaces for the bedroom(s), living room, kitchen, and bathroom. However, to simplify the energy model, we opted to model each unit as a single thermal zone. The main implication of this choice is that thermal heat gains entering and generating inside each apartment will get evenly distributed across its entire volume. Another implication is that the separating walls between the spaces are nonexistent in the model which provides thermal mass to the unit that helps dampen the temperature variations due to heat gains in the unit. To resolve this issue, we defined thermal mass objects in each unit to model the thermal effects of not only the inside walls but also the furniture that might be present in the unit. We use the same geometry, thermal zone layout, and thermal mass assumptions for all variations of the model.

1.3. Electricity and domestic hot water consumption

We gathered measured data from similar existing multifamily buildings with similar resident characteristics to develop the baseline energy and hot water consumption of the model, including daily electricity consumption datasets at the building or apartment level from multiple sites, and hourly data at the whole building level from another project. However, we note that there is limited hourly measured electricity consumption data available in the public domain to inform designs. We also supplemented the measured data with input data found in the Pacific Northwest National Lab (PNNL) multifamily reference whole building energy model[1]. The PNNL model contains the collective input of many building industry experts and organizations to create a representative energy model for a mid-rise multifamily building. The PNNL model was especially useful when we did not have any measured data to inform model inputs to the current project such as infiltration rates.

We used data, both measured and from the PNNL model, to inform the typical peak electrical load and diversity factor by hour of day. Specifically, we averaged apartment unit electrical load diversity factor profiles from the measured data and the PNNL model. We averaged the two diversity factor profiles because the measured data profile is from only one building and it is flatter with a higher baseload than the PNNL profile which is representative of many more multifamily buildings. We then normalized the diversity factor such that the average daily electricity consumption was within the range of the measured data from apartments serving a similar demographic. i.e., about 5.9 kWh/day per apartment (excluding HVAC and DHW). Finally, we added variation to the electrical load for each apartment as well as for each hour as seen in **Figure 2a**. The variation is based on the measured data. The electrical load includes the electricity consumption due to interior lighting and equipment which comprises the refrigerator, range, television, and all other miscellaneous plug loads. **Figure 2a inset** shows the distribution of average daily electricity consumption per apartment per year. Two two-bedroom units (manager's units) also contain a washer and dryer that we defined separately and discussed in a later section.

The measured data informed the design inputs for the domestic hot water system. Our analysis of measured data from several buildings shows that hot water consumption is more variable than electricity consumption. Furthermore, the hot water consumption data is for the whole

[1] https://www.energycodes.gov/prototype-building-models

building. Therefore, we opted to select one design peak flow estimate and diversity factor profile from the building we believe is the most representative of the 995 E. Santa Clara St. Senior Apartments and its target residents. **Figure 2b** shows the selected diversity factor profile for domestic hot water consumption for the whole building. The hot water heater module uses the design peak flow and diversity factor profile to estimate the energy consumption to produce the hot water for the building. We defined a hot water heat pump system with a coefficient of performance (COP) of 3.37 with rated evaporator inlet dry-bulb and wet-bulb air temperatures of 85 °F and 72 °F, respectively. The leaving water temperature is set at 140 °F. We also included a supplemental electrical resistance heating element for the storage tank to determine the times when the heat pump is incapable of providing hot water at the setpoint.

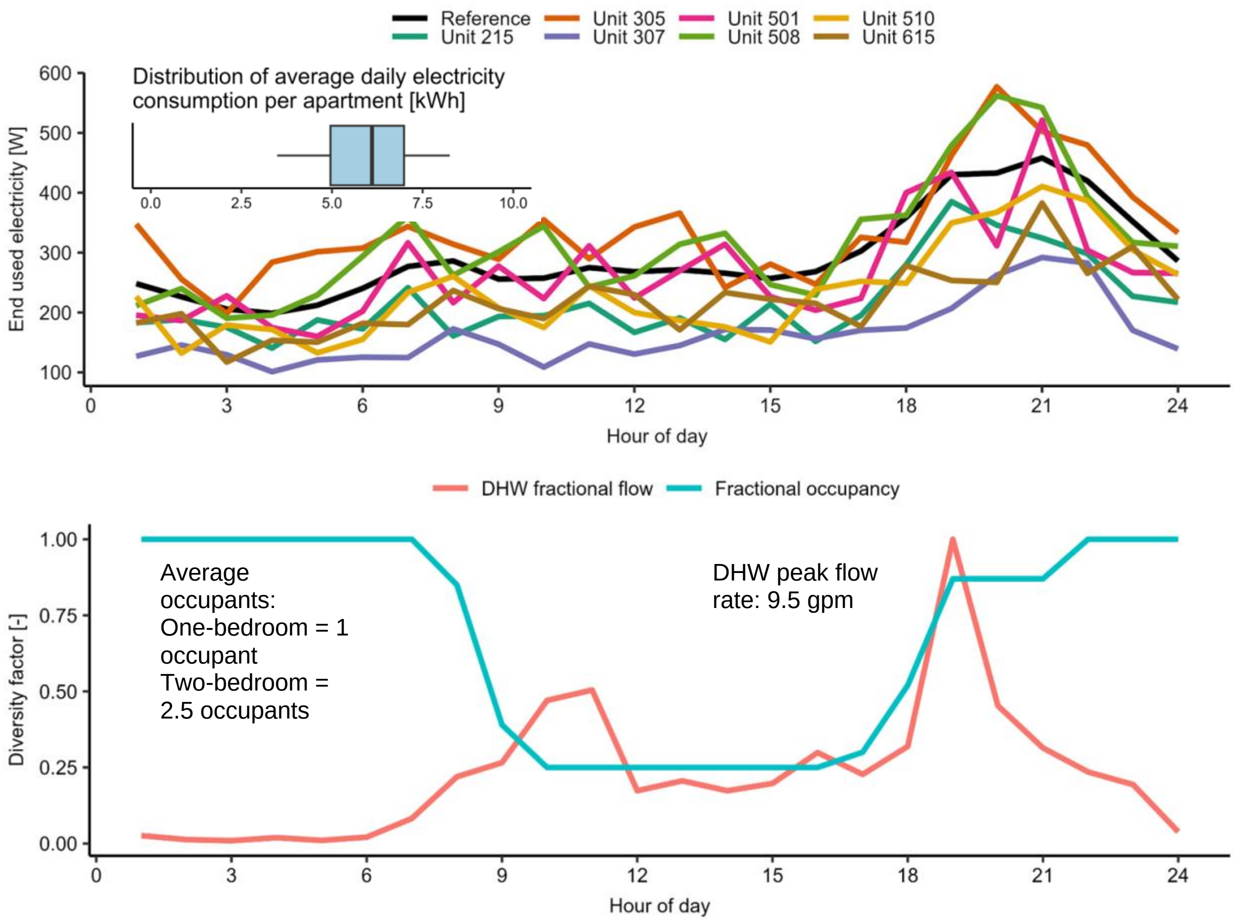

Figure 2: a) The reference electricity load (black) that was used to derive units' electrical load that varied by apartment and hour-by-hour basis (colored lines). The inset shows the distribution of average daily electricity consumption by apartment, excluding HVAC and DHW. b) The average occupancy and whole-building DHW consumption diversity profiles.

1.4. Ventilation and infiltration

The baseline ventilation system is a balanced ventilation system using a central supply system with a stand-alone exhaust fan at each apartment unit. There is no energy recovery ventilator (ERV) unit in the baseline model. We determined the initial ventilation rate using Equation 1 from Title 24-2022 energy code[2].

$$\text{Equation 1: } Q_{tot} = 0.03*A_{floor} + 7.5*(N_{br}+1)$$

Where Q_{tot} is the total ventilation rate in cubic feet per minute (CFM), A_{floor} is the area of the apartment unit in square feet, and N_{br} is the total number of bedrooms in the apartment unit. Using Equation 1 results in a ventilation rate of 34 CFM for one-bedroom and 48 CFM for two-bedroom apartments. However, we round up to 50 CFM for both unit sizes since the minimum flow rate for typical residential exhaust fans is 50 CFM. The design ventilation rate is supplied to the apartment at all times, i.e., 24/7 operation. The heating and cooling setpoints for the ventilation supply air are 65 °F and 74 °F, respectively. Ventilation supply air temperature is equal to the outdoor air temperature when the outdoor air temperature is in between these two setpoints.

We obtained the input value for infiltration using the PNNL reference model; 0.125 air changes per hour (ACH) per apartment unit. The infiltration is a constant flow with no variations due to heating, ventilation, and air-conditioning (HVAC) operation, wind, or indoor-outdoor temperature differences.

1.5. Heating and cooling

The baseline model includes a single standard packaged terminal heat pump (PTHP) serving each apartment unit. We used a conventional Amana ‘PTAC’ (air-conditioning with heat pump) as the basis of design for the baseline HVAC system[3]. The rated heating and cooling capacity defined in the energy model is 8,200 Btu/hr for heating and 8,300 Btu/hr for cooling. We selected these thermal capacities because they are the minimum equipment sizes across the various heating and cooling equipment we evaluated for the project design. The COP for the baseline PTHP is 3.1 for heating and 3.23 for cooling. There is no supplemental electrical resistance heating and the minimum temperature for heat pump operation is 24 °F. The design discharge air flow rate is 260 CFM. Because a conventional PTHP requires a large wall penetration, we increased the infiltration rate for the apartment unit based on the maximum allowed infiltration rate referenced in the standard for packaged terminal air-conditioners (PTAC)

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[2] https://energycodeace.com/site/custom/public/reference-ace-2022/index.html#!Documents/46indoorairqualityandmechanicalventilation.htm

[3] https://www.amana-ptac.com/pdfviewer.aspx?pdfurl=docs/librariesprovider4/default-document-library/mc-dptac028f3a0022fa6258827eff0a00754798.pdf?sfvrsn=277458c0_2?view=true

and heat pumps[4]. The standard requires PTAC and PTHP to have infiltration rates less than or equal to 2 CFM per foot of the wall sleeve perimeter length which led to an infiltration increase of about 0.180 ACH for the apartment. We set the thermostat setpoints to 70 °F and 75 °F for heating and cooling, respectively, for all hours of the day, for each apartment.

1.6. Building envelope

The gross exterior wall area for the entire building is 69,700 ft^2 while 11,200 ft^2 for the window area. This represents an overall window-to-wall ratio (WWR) of 16%. **Table 1** shows the distribution of WWR by orientation. The building's north axis is about 59° offset from the North cardinal direction.

Table 1: Window-to-wall ratio (WWR)

Orientation	(315° to 45°)	(45° to 135°)	(135° to 225°)	(225° to 315°)
WWR	16%	23%	22%	2%

The baseline envelope thermal properties correspond to Title 24-2022 prescriptive criteria. The walls have an R-value of 17.6 °F-ft^2-h/Btu while the window parameters are set to a U-factor of 0.30 Btu/h-ft^2-°F and solar heat gain coefficient of 0.23. The exterior roof R-value is 37.4 °F-ft^2-h/Btu and the raised mass floor on the second floor is 3.5 °F-ft^2-h/Btu. Interior floors have an R-value of 18.7 °F-ft^2-h/Btu.

The baseline model does not include external shading devices but it does account for shading from balconies, parapets, exterior corridors, and building massing.

1.7. Miscellaneous equipment and non-residential spaces

The elevator design power defined in the baseline model is based on the PNNL model which is set to a design power of 16 kW. We also used the elevator schedule from the PNNL model but adjusted it such that the annual consumption is within the EnergyStar Multifamily New Construction Program Simulation Guidelines[5]. We assumed a geared traction elevator.

We assumed a booster pump for the mains water system to the building. We modeled a pump that has a total flow rate of 210 gallons per minute (gpm) and increases the water pressure by 50 pounds per square inch (psi). The peak power demand for this pump is 15 kW and we implemented a diversity factor that has a similar shape as the DHW diversity factor discussed above but with values such that the daily energy consumption is about 10 kWh. The estimated

[4]https://www.ahrinet.org/search-standards/ahri-310380-2017-packaged-terminal-air-conditioners-and-heat-pumps-csa-c744-17

[5]https://www.energystar.gov/sites/default/files/asset/document/ENERGY_STAR_MFNC_Simulation_Guidelines_V1.pdf

booster pump energy consumption is based on typical load profiles found in pump sizing software for low income residential apartments.

We defined five washers and six dryers for the common laundry. We obtained cycle times and energy use per cycle from typical commercial washers and dryers to determine the design power for the equipment. We obtained the diversity factors for the equipment from a study on California Laundromats[6]. We collected measured data from a similar existing multifamily building's common laundry and we used this information to adjust the diversity factors. The measured data shows that the equipment does about 3.4 cycles per day. **Figure 3** shows the adjusted diversity factors and **Table 2** shows the summary input parameters for the washers and dryers. We used a similar approach to define the two manager's in-unit washer and dryer. However, we adjusted the in-unit diversity factor based on EnergyStar estimated annual energy consumption for the residential equipment. The estimated annual energy consumption for the residential equipment is about 105 kWh for the washer and about 605 kWh for the dryer.

Table 2: Summary input parameters used to determine the design power and diversity factor for the washers (5 total) and dryers (6 total) in the common laundromat.

	Laundromat Washer	Laundromat Dryer
Referenced cycle time	31 min	45 min
Referenced energy use per cycle	0.58 kWh	3.75 kWh
Calculated design power	1120 W	5000 W
Weekday cycles per day	3	2.1
Weekend cycles per day	4.5	3.1
7-day week average	3.4	2.3

[6] Sutter, Mary, Ted Pope, and Erika Walther. 2006. "Estimating Commercial Clothes Washer Use in California Coin Laundry Stores." In . https://www.aceee.org/files/proceedings/2006/data/papers/SS06_Panel9_Paper29.pdf.

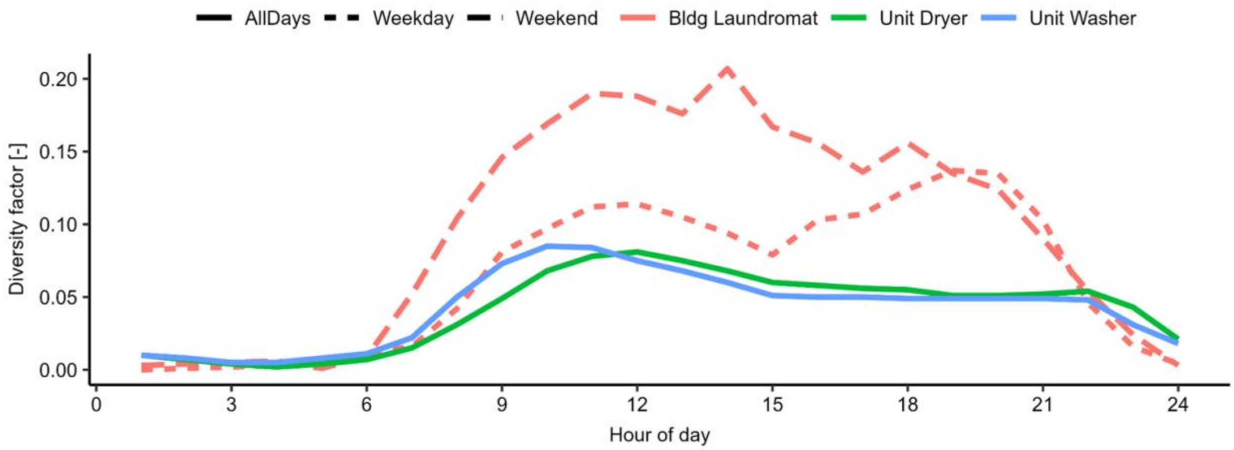

Figure 3: The diversity factors for the common laundromat and in-unit washer and dryer for the manager's unit.

1.8. Baseline performance results

The resulting energy use intensity (EUI) for the baseline building is 6.6 kWh/ft^2 (23 kBtu/ft^2). Almost half of the electricity consumption (48%) is in the residential apartment units as seen in **Figure 4** with a significant portion (74%) of this category assigned to the lighting, refrigerator, range, television, and all other miscellaneous plug loads. The next significant end-use is the domestic hot water heat pump system at 20%. Space heating and cooling are about 12% of the total annual electricity consumption and bathroom exhaust fans account about 3% of the total.

Aggregated NonResidential electricity use is about 27% of the total annual electricity consumption without including the domestic hot water and laundry. Lighting (45%) is a large component in the NonResidential category with exterior lighting for exterior corridors and common open space areas accounting for a significant proportion. The dedicated outdoor air system (DOAS) accounts for 40% of the NonResidential category or about 9% of the total annual electricity consumption. The DOAS includes heating, cooling, pump, and fan electricity consumption to provide ventilation air into the residential and nonresidential units.

Figure 5 shows the annual net heat gains and losses for the building. Infiltration and conduction through exterior walls are the major pathways for heat losses in the building. The heat generated by the equipment and occupants' bodies inside the residential apartment units is the major source of heat gains for the building. Overall, on an annual basis, the building is about evenly split between envelope heat losses and internal heat gains. However, the dynamics change during peak heating and cooling days. Infiltration, conduction, and solar are significant heat losses during the peak heating day and solar is a major heat gain for the peak cooling day. These heat pathways and their magnitudes are part of the decision-making for developing energy efficiency packages that will mitigate thermal energy inflows and outflows and balance them with the least amount of energy to maintain occupant thermal satisfaction.

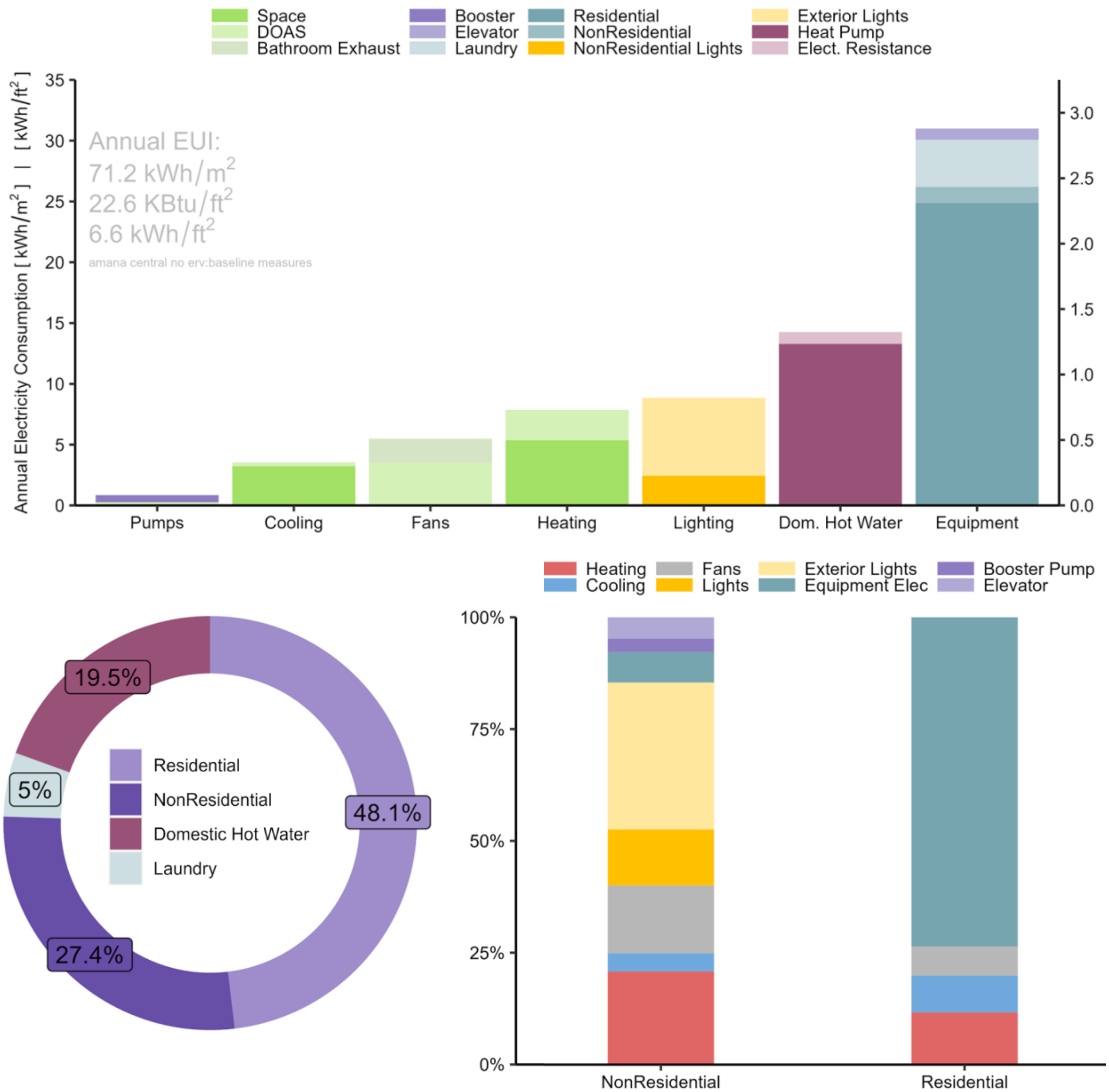

Figure 4: Top) annual electricity end-use consumption for the whole building. Bottom left) high-level breakdown of annual electricity consumption with a more granular breakdown (bottom right) of non-residential and residential electricity consumption. Lighting, refrigerator, range, television, and other miscellaneous plug loads are captured in the *Residential Equipment Electricity* subcategory.

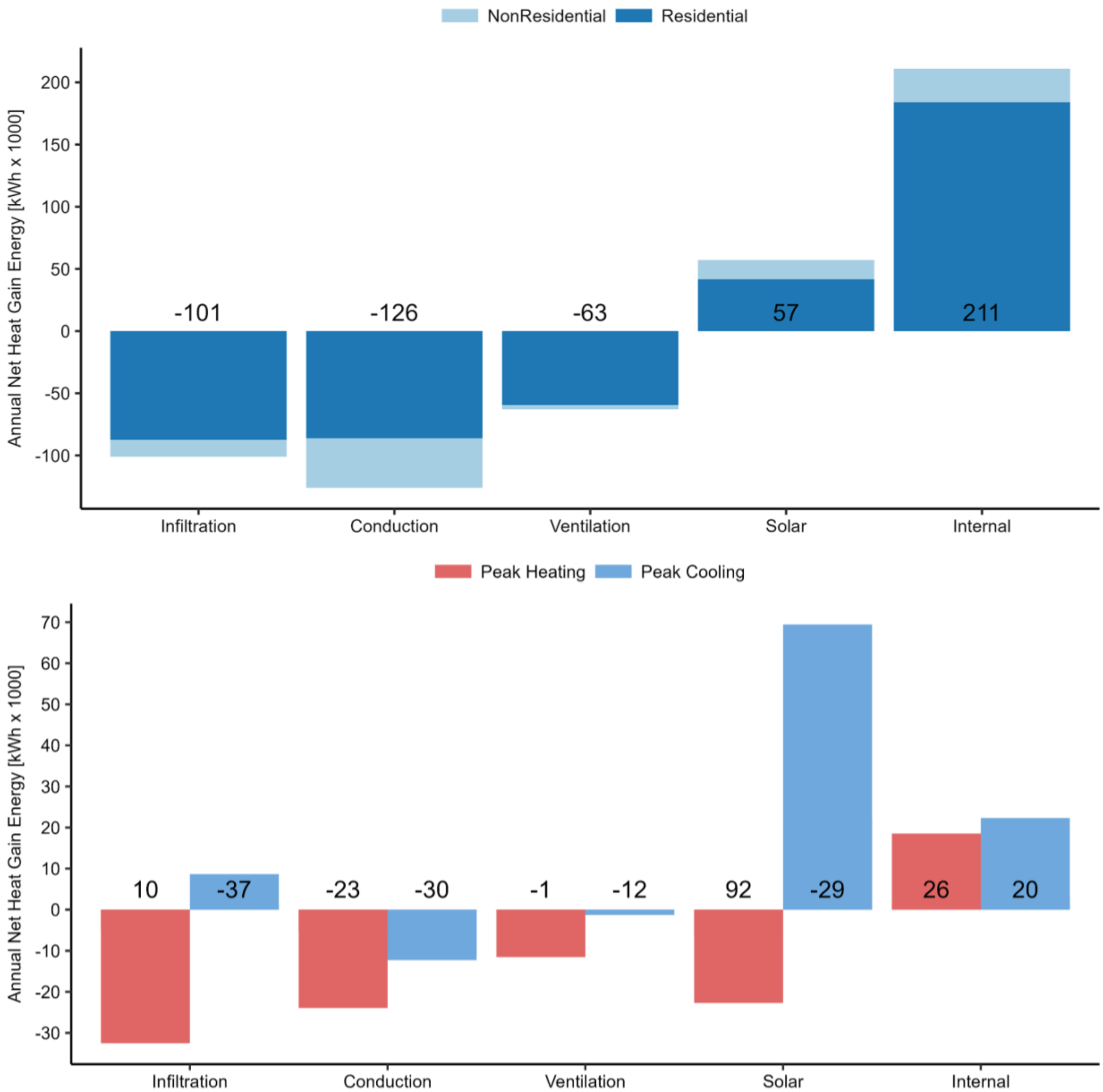

Figure 5: Top) annual and bottom) peak heating and cooling net heat gain energy entering or leaving the building. A negative value for a category, such as *Infiltration*, indicates a net loss of heat energy for the building in that category. *Internal* represents heat gains by occupants' bodies, lighting, and equipment.

Figure 6 shows a distribution of the design capacity of the HVAC system required to maintain indoor space temperatures within baseline setpoints (70 °F and 75 °F). For most zones, the required design heating and cooling capacity is well above the minimum capacity for the standard equipment we evaluated. Some zones exceed this threshold, but these are nonresidential zones, i.e., the common room and office suites on the first floor. Thus, based on the modeling results, the heating and cooling equipment is likely to be oversized for the apartment units. As a result, there are no hours in the simulation where the indoor temperatures exceed baseline setpoints as shown in **Figure 8**. The oversize HVAC equipment also allows the apartments to return to setpoint quickly after extreme indoor temperatures as later shown in Section 6.

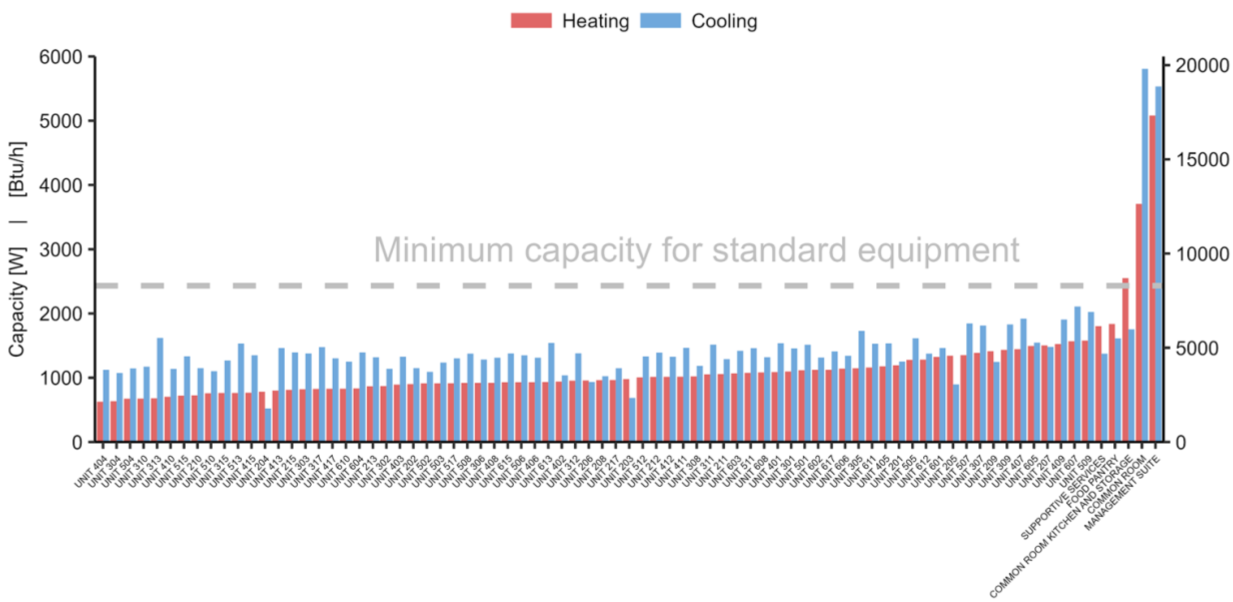

Figure 6: Distribution of the required heating and cooling capacity to maintain space temperature within baseline setpoints (70 °F and 75 °F).

Figure 7 shows the daily heating, cooling, and domestic hot water (DHW) thermal energy transfer to maintain relevant temperature setpoints for residential units and DHW supply water as a function of daily mean outdoor air temperature. A regression analysis shows a balance point, the outdoor temperature at which the operating mode of the building switches from heating to cooling and vice versa, at about 60 °F. It is also important to note that we did not model operable windows in the simulation model. It is likely that 60 °F is the point at which heating is no longer used and the point at which natural ventilation through window openings is employed by the tenants to offset some cooling needs. The overlay of the three plots shows the potential for heat recovery in an integrated HVAC plus DHW system. The cold exhaust air from the heat pump water heater could potentially be ducted to cool indoor spaces or the waste heat from space cooling could be recovered and stored in DHW tanks. Figure 7 shows that the DHW heat transfer has the potential to satisfy space cooling loads up to a daily mean outdoor temperature of about 74 °F. Conversely, recovered waste heat from space cooling can satisfy the heating needs of the DHW above a daily mean outdoor temperature of 74 °F. In a practical scenario, cold exhaust air from the heat pump water heater can be ducted into the battery room for aiding thermal management.

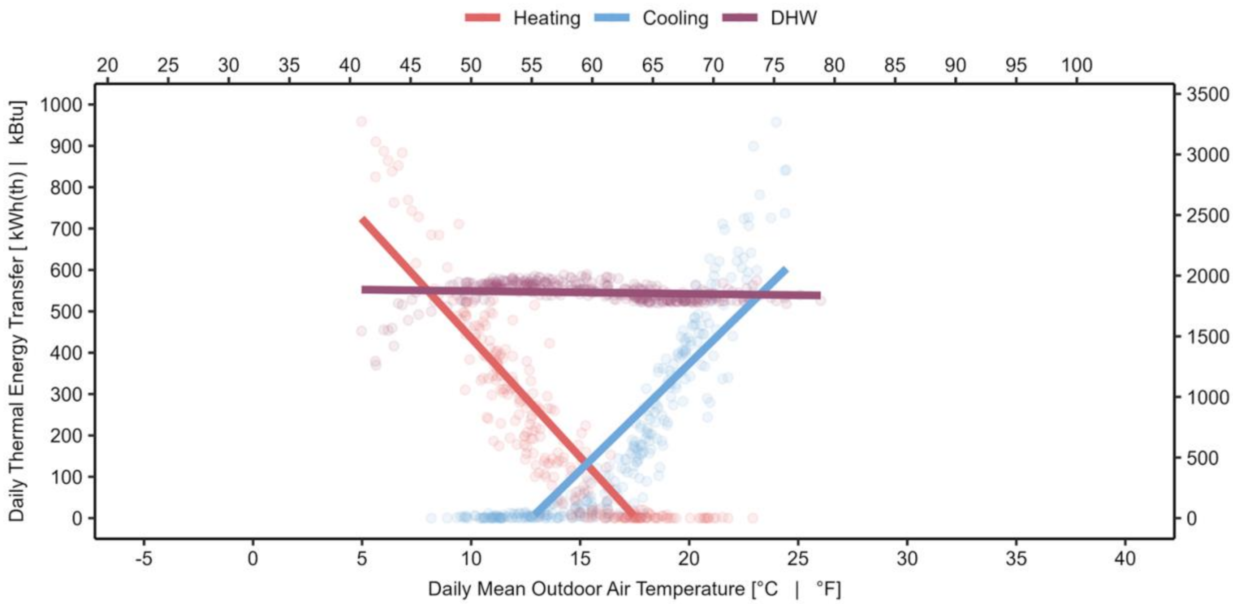

Figure 7: Daily heating (red), cooling (blue), and domestic hot water (purple) thermal energy transfer for residential units as a function of daily mean outdoor air temperature.

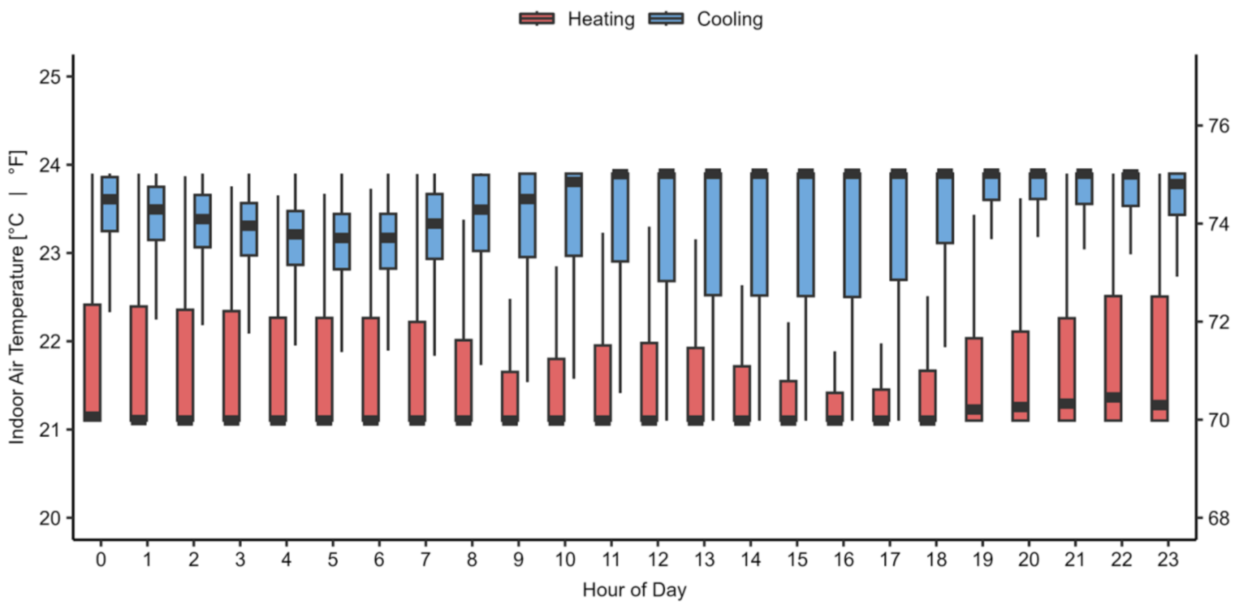

Figure 8: Indoor air temperatures for residential units during the heating (red) and cooling (blue) seasons.

Finally, **Figure 9** shows the end-use power demand in a 24-hour day at near peak heating and cooling conditions. The area plot shows that heating is a significant power demand in the night time during the heating season. Then, equipment electricity, DHW, and heating are large components during the critical period of 4-9pm. In contrast, cooling is a significant power demand during the critical period in the cooling season. In both seasons, DHW power demand peaks in two time frames, morning and evening, resulting from the measured data inputs we gathered from similar buildings with similar resident characteristics.

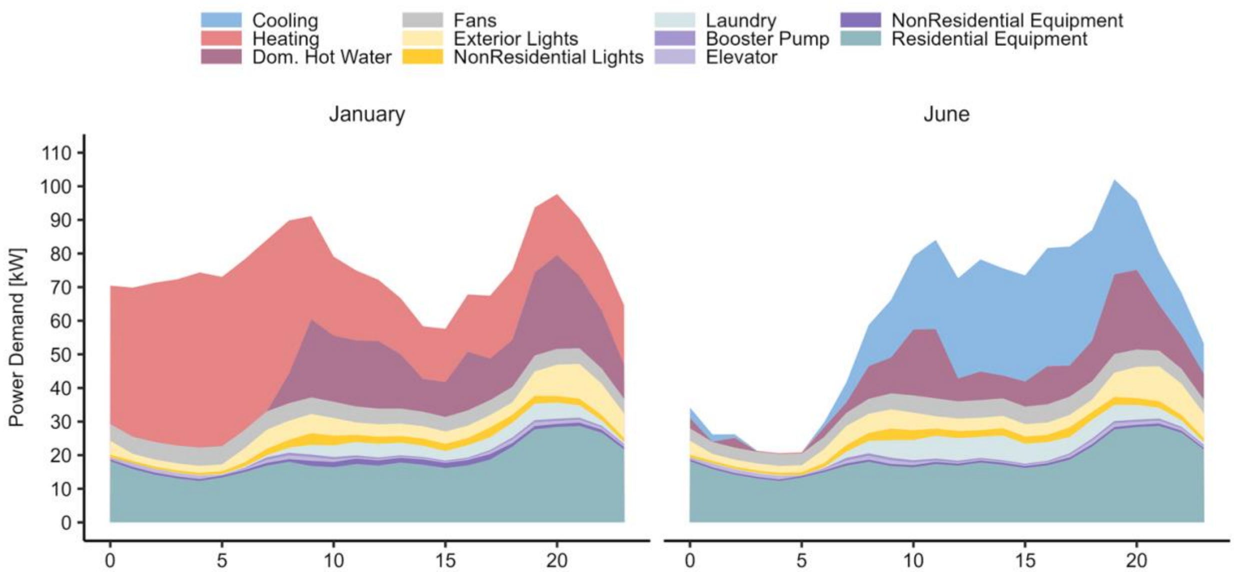

Figure 9: End-use power demand in a 24-hour day at near peak heating (left) and cooling (right) conditions for the baseline model.

2. Alternate designs

2.1. Energy efficiency measures

We identified a range of different energy efficiency measures, assessed them individually using the baseline model, and then selected measures to include based on the impact those measures had on energy performance, battery sizing, resilience, and their estimated first cost. **Table 3** describes the measures we evaluated. We mainly report detailed results for three scenarios: no efficiency measures (baseline), the combination of the most viable measures we include in the final design (combined measures), and all possible measures (all measures). In **Table 3** we highlight in bold and italics the subset of measures included in the combined measures package and put an asterisk on the measures we first evaluated because they had the highest potential at first glance. We evaluated the various packages and determined the ones that would be in the final proposed design (combined measures). The only measures that did not make it through to the proposed design are the one-inch continuous exterior insulation and exterior shading because of the high cost with little impact on the important metrics listed above.

Table 3: Description of energy efficiency measures evaluated in the baseline model. Bold and italicized measure names are measures implemented in the final design, described elsewhere in the document as 'Combined Measures'. The measures with an asterisk denote energy efficiency measures we first evaluated because they had the highest potential at first glance.

Energy Efficiency Measures
Envelope (adding 1" continuous exterior insulation)
Air tightness *(reduced leakage to 1 ACH @ 50 Pa)*
Window to wall ratio *(6ft vs 8ft high windows)*
Windows *(triple pane, 0.16 U Factor, 0.17 SHGC windows vs double pane, prescriptive requirement)*
Exterior shading (18" protrusion)
****Higher performing DHW*** *(higher rated heat pump water heater with 4.11 COP with load shifting)*
****Fixtures*** *(primarily shower, 15% lower DHW consumption)*
****Appliances*** *(primarily fridge, 5% lower in-unit loads which already use EnergyStar appliances)*
****Ceiling fans*** *(allows improved comfort at 78 °F cooling temperature setpoint vs 75 °F)*
****Dynamic ventilation*** *(vary ventilation rate above/below average to shift load)*
****High efficacy lighting with smart controls*** *(high lumens per watts and high dimming beyond code)*
****Laundry pricing incentives*** *(lower common laundry costs outside of 4-9pm)*

Figure 10 shows the impact of the energy efficiency measure packages on the annual energy use intensity (EUI) on the baseline model (PTHP with no ERV). The combined package reduces EUI by 23% while the all measures package reduces it by 24%. Adding in the one-inch continuous exterior insulation and the exterior shading improves annual electricity consumption by only 1% but adding substantial costs. Therefore, these measures are not cost effective for our proposed design. Applying combined or all measures packages will meet the ASHRAE Advanced Energy Design Guide zero net energy multifamily target EUI[7] of 5.7 kWh/ft^2 (19.3 kBtu/ft^2). **Figure 11** shows the end-use power demand in a 24-hour day at near peak heating and cooling conditions with the total baseline power demand in the black dashed line for reference. Applying the combined measures package has an average power demand reduction of 34% during the near peak heating day and 29% for the near peak cooling day during the 4-9pm period. The average power demand reductions during hours outside 4-9pm are 36% and 20% for near peak heating and cooling, respectively.

[7] https://www.ashrae.org/technical-resources/aedgs/zero-energy-aedg-free-download

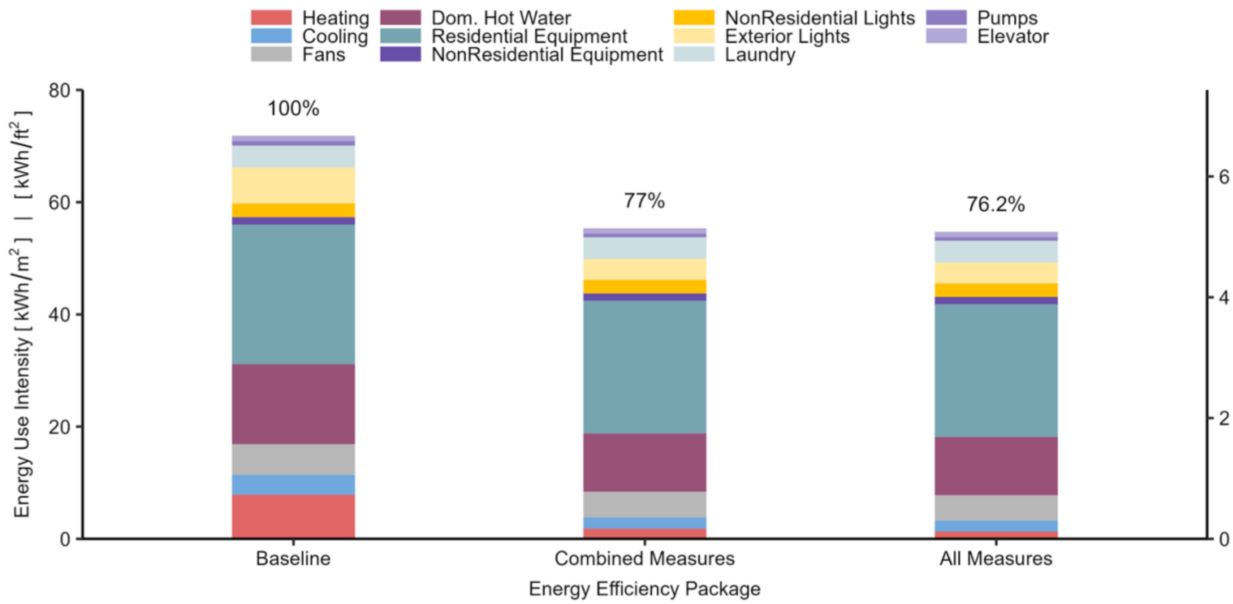

Figure 10: Annual energy use intensity by major end-use category by implementing the energy efficiency measure packages on the baseline HVAC system.

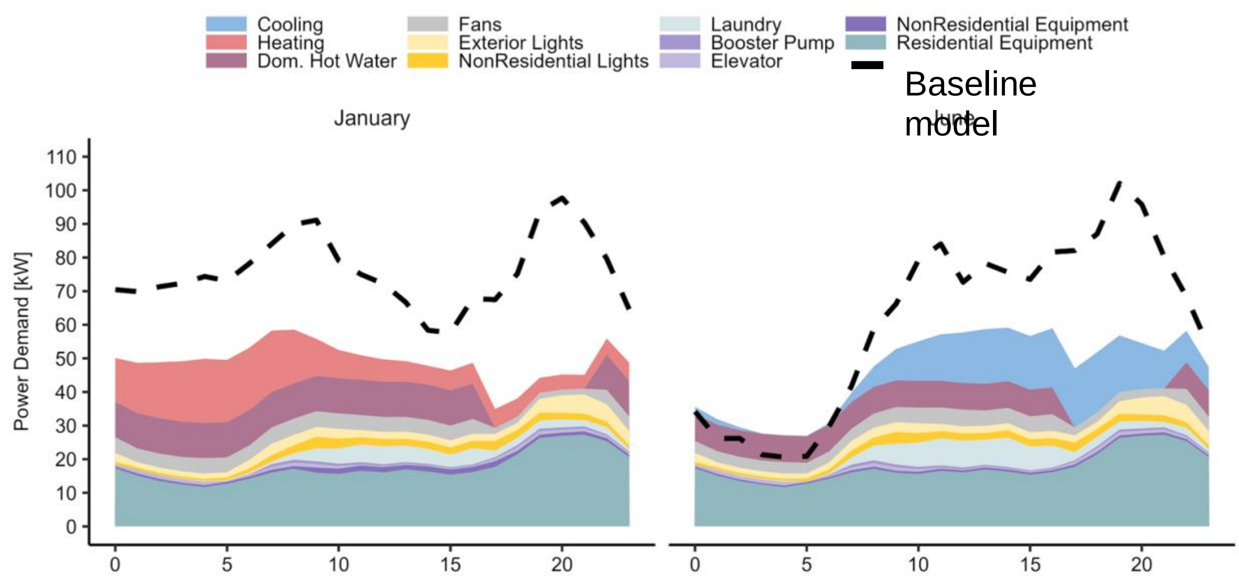

Figure 11: End-use power demand in a 24-hour day at near peak heating (left) and cooling (right) conditions for the combined measures energy model.

Figure 12 shows the effect of various energy efficiency measures packages on HVAC energy consumption for each hour of the day, averaged over a heating (January) month and cooling (June) month, for an example of one of the HVAC systems we assessed and compared to the baseline model. There is one interesting dynamic that occurs between the baseline and the first pass measures package on the heating month. The peak HVAC and plant electricity is higher for the first pass measures package compared to the baseline because of the dynamic ventilation measure. This trend reverses as we add additional measures such as improved air tightness, smaller-sized windows, and triple pane windows. We increase the ventilation rate by 20% above the baseline to be able to reduce it by 50% from the baseline ventilation rate during the critical period of 4-9pm. This resulted in a larger supply fan and exhaust for the ventilation system in the combined measures package. We give more details on dynamic ventilation in Section 3.

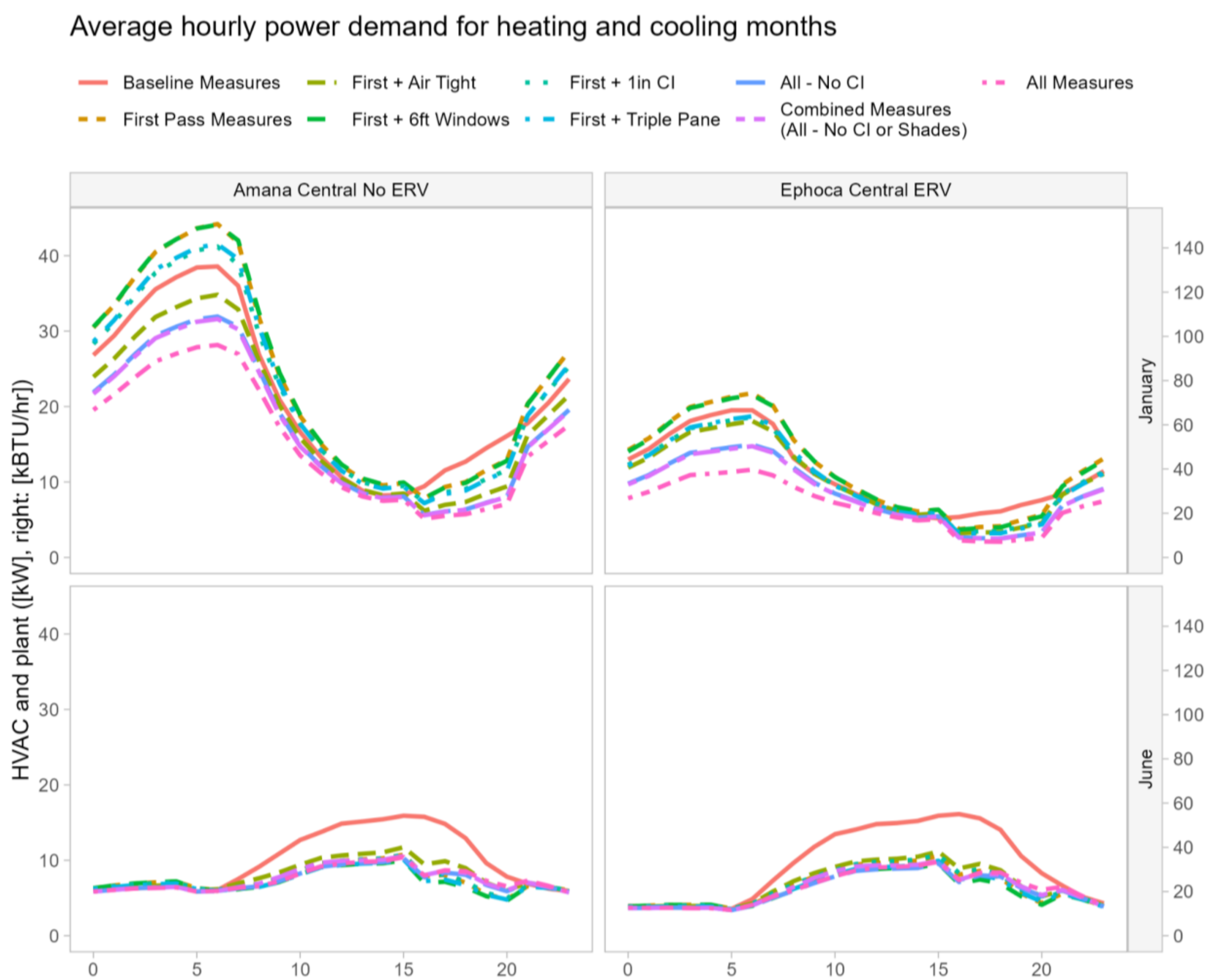

Figure 12: Hourly HVAC and plant electricity profiles in January and June for different energy efficiency measure packages, for Amana with no ERV and Ephoca with ERV. Both systems' ventilation are centralized.

2.2. HVAC configurations

We evaluated different terminal unit options. One solution was a 4-pipe hydronic fan coil and the others were a variety of different packaged terminal heat pumps: a conventional Amana 'PTAC', and the Ephoca All-In-One in ducted, unducted configurations and with and without an integrated ERV. For all cases that require a central ventilation system, we also evaluated the impact of having energy recovery (with bypass) on the central system. For the hydronic scenario, we did not explicitly model the thermal storage tanks as that storage component will be controlled and sized by Xendee. To estimate the effect in the energy simulation results shown in this section, we post-processed the E+ results under the assumption that the tanks are at least large enough to serve all heating and cooling demand from 4-9pm each day. This strategy then uniformly serves the daily heating/cooling load between 9-4pm each day (i.e. minimizes plant size, ignores the potential to operate more efficiently at different periods within the 9-4pm window). We also adjust the electricity demand to account for heating and cooling demands that overlap within the same 24-hour period (i.e. assuming they are served with a higher COP due to waterside heat recovery). **Figure 13** and **Figure 14** show the effect of including heat recovery as part of the HVAC system. **Figure 13** shows HVAC and plant power demand on an annual basis and **Figure 14** zooms in on winter and summer months. Overall, there is about a 28% reduction in annual HVAC electricity consumption when the HVAC system incorporates an ERV when compare to a system that does not. As expected, the largest reductions occur during the winter season when the ERV helps reduce the heating load due to the larger temperature differences between the indoors and outdoors. **Figure 14** shows the small difference there is between the two scenarios during the summer season. **Figure 14** also shows that dynamic ventilation has a larger effect when no ERV is used in a hydronic HVAC system.

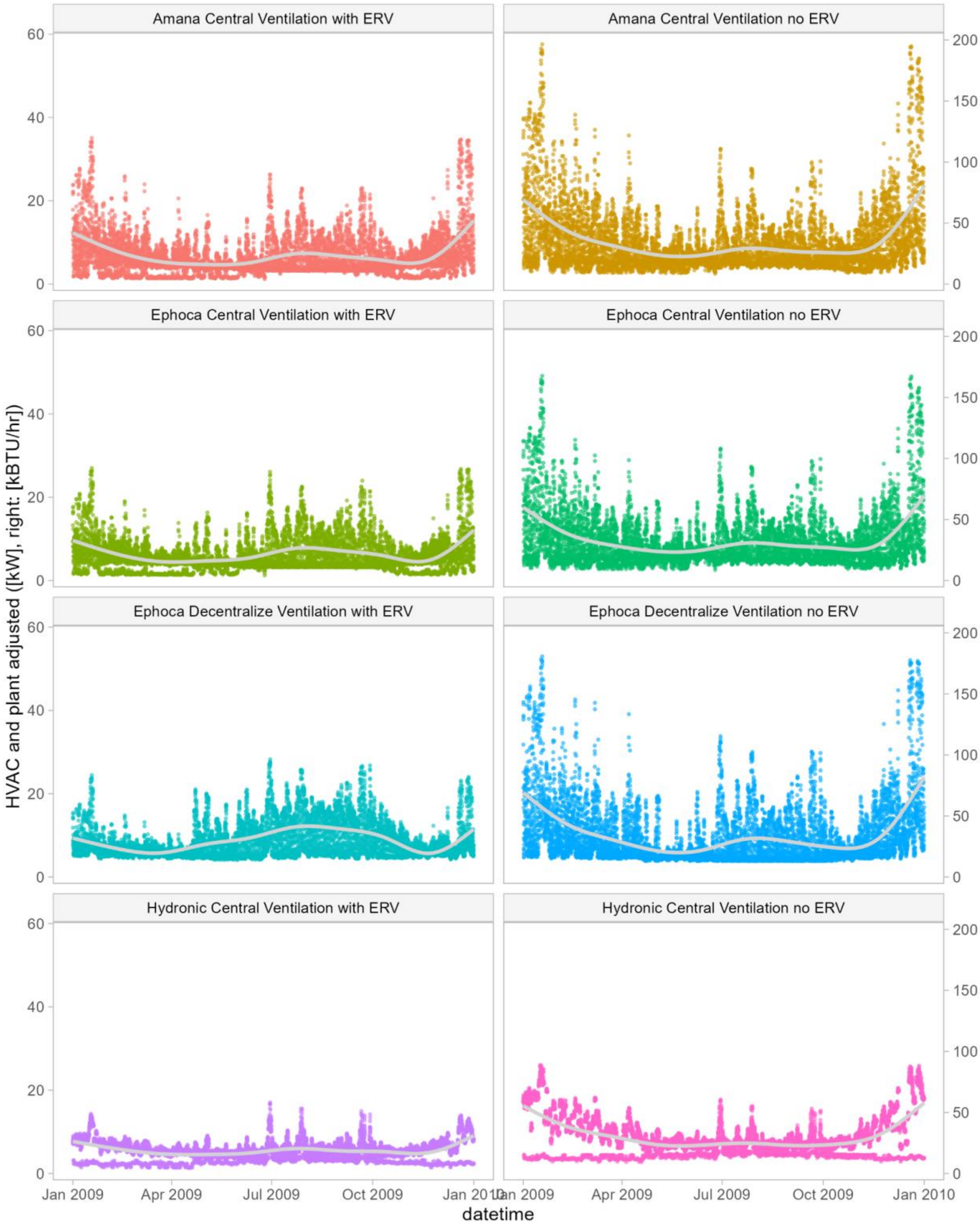

Figure 13: Annual HVAC and plant electricity demand for various HVAC configurations for the combined energy efficiency measures package.

Figure 14: Hourly HVAC power demand for each HVAC configuration for January and June months, with combined efficiency measures package. The Amana, Ephoca, and hydronic systems are all modeled with the same central ventilation system. Ephoca with integrated ERV case omitted for simplicity.

Figure 15 shows the HVAC and plant power demand comparison of the best energy performing scenario (hydronic with ERV and all measures package) with the worst (Amana without ERV and baseline measures package). There is a difference of about 54 kW of power demand between these two scenarios. For context, the peak electrical power for the entire building is about 108 kW for the worst performing scenario, so in some hours of the year there is nearly a 50% difference in total building load between these two scenarios. The biggest differences are observed during the cold winter nights and midday during the summer months, though this depends in part on the control strategy used for the hydronic system’s thermal storage.

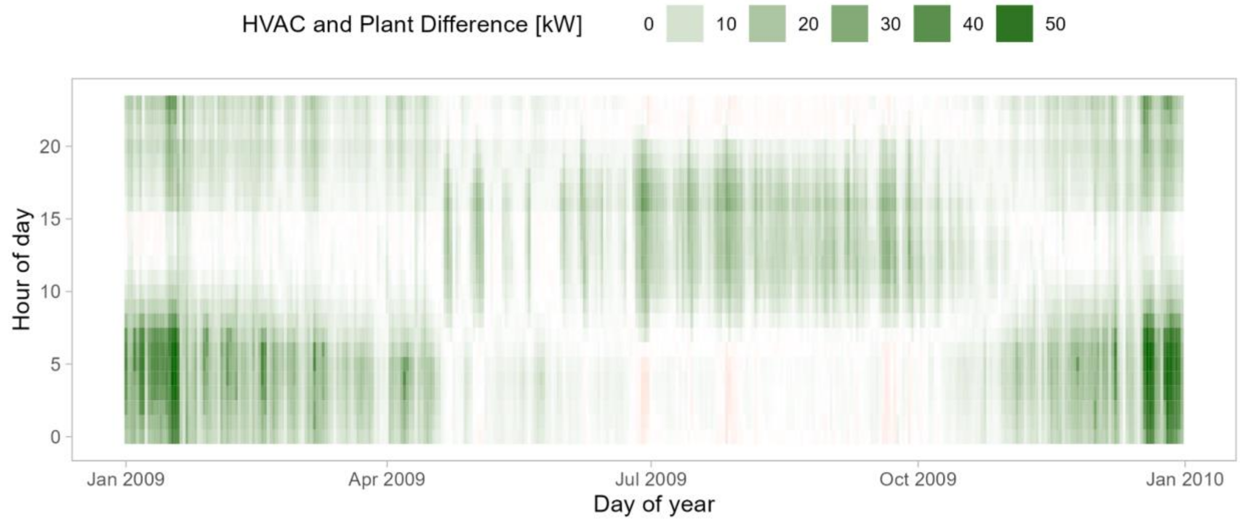

Figure 15: Annual heat map showing the change in HVAC and plant electrical power between the best (hydronic with ERV and all efficiency measures) and worst (Amana without ERV and baseline efficiency measures) performing scenarios modeled. Both have central ventila

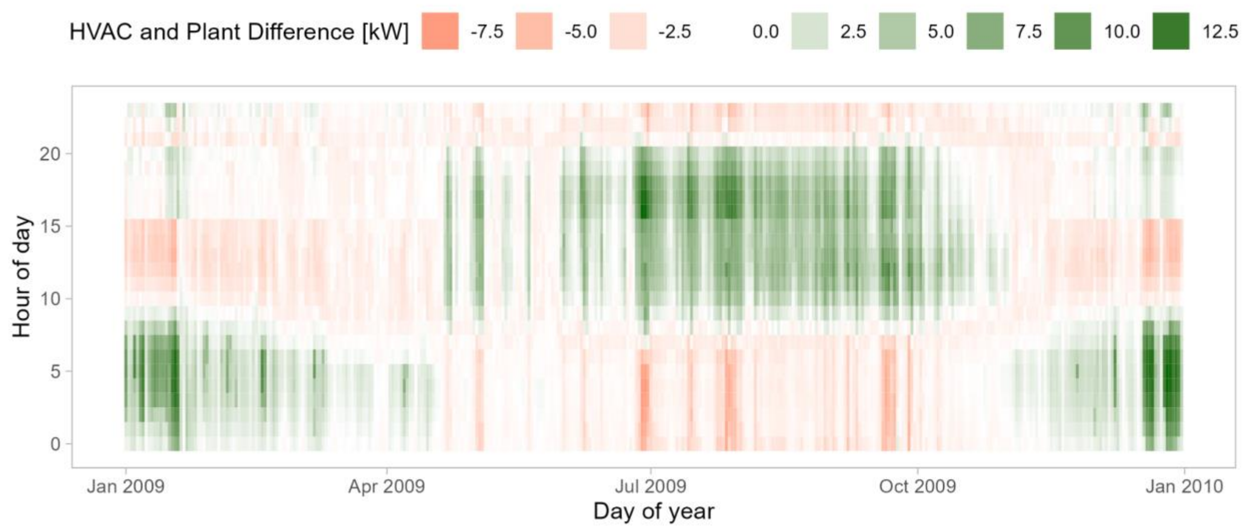

Figure 16: Annual heat map showing the change in HVAC and plant electrical power between a decentralized and centralized heating and cooling system, i.e Ephoca with ERV and hydronic and combined energy efficiency measures package for both HVAC systems.

Figure 16 shows a similar plot to the above but it is comparing the HVAC and plant power demand between a decentralized packaged terminal unit system (Ephoca with centralized ERV) to a centralized hydronic system (hydronic with ERV) using the combined measures package for both scenarios. The green areas show when the hydronic system performs better and the red areas where the Ephoca system performs better. For context, the peak electrical power for the entire building is 70 kW for the decentralized system scenario and 61 kW for the centralized. A 13% (9 kW) lower maximum power demand in any hour of the year. However, the total HVAC and plant energy consumption is 3% higher for the hydronic case. These results depend on the control strategy used for the hydronic system's thermal plant. In this result set, the plant discharges 4-9pm and charges uniformly between 9pm-4pm each day. The Xendee simulation output will result in a better performing scenario as this tool optimizes the discharges and charges according to important metrics such energy consumption, emission, PV and battery solar performance, etc. The hydronic system performs better during the cold winter night and midday during the summer months. On the other hand, a decentralized system is better in the midday during winter months and at night during the summer months.

Figure 17 shows five selected scenarios, spanning from least to most energy efficient. The upper left pane shows the average hourly profile for a typical year. The upper right panes show the average profile for the months of January and June, respectively. The lower panes show actual hourly data for the coldest and warmest days of the year. All use the same y-axis, highlighting that hourly average profiles, even when subset to show the coldest and warmest months of the year, will still obscure substantial variation in actual load profiles which should be considered when designing and sizing energy systems in buildings.

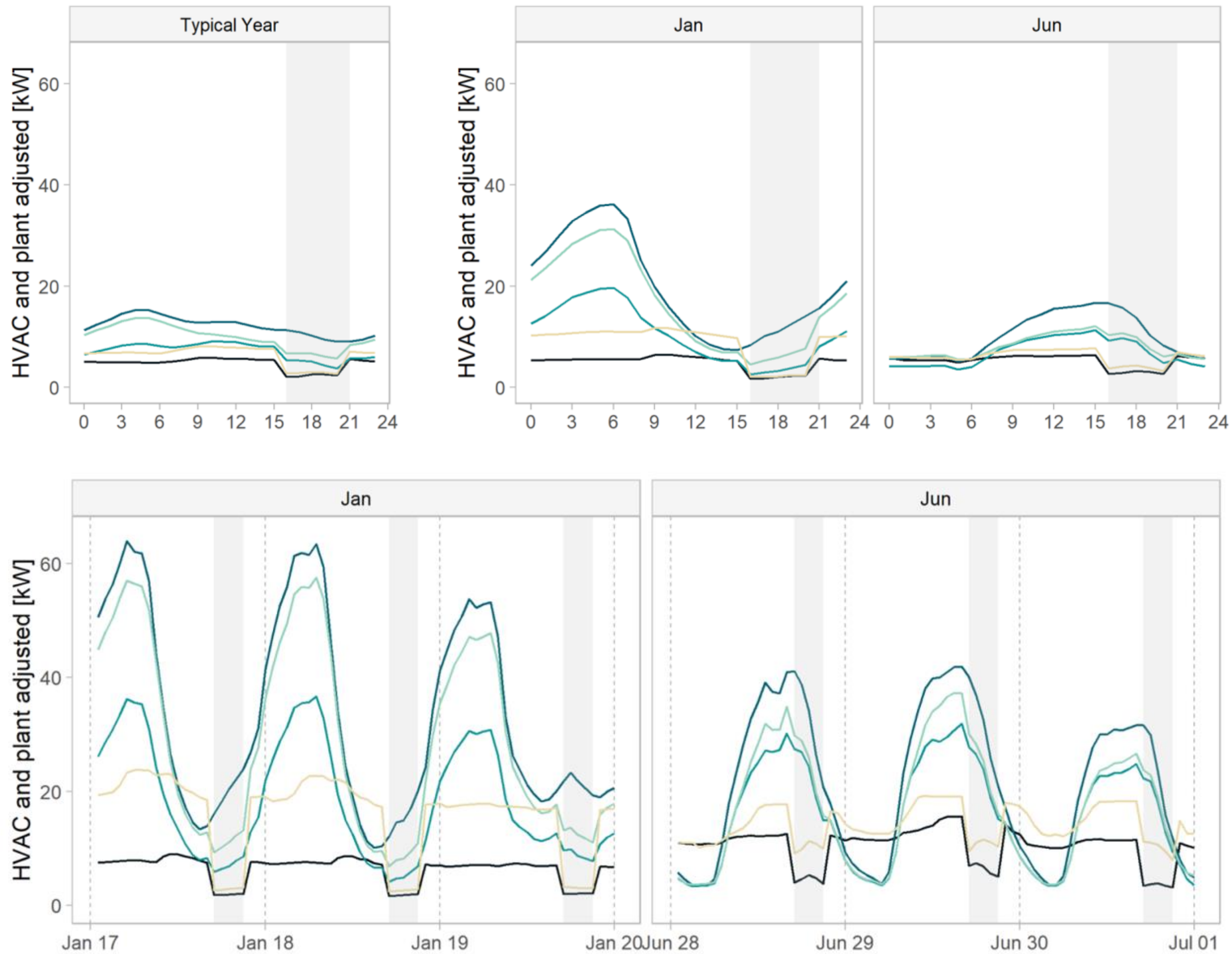

Figure 17: (Top) (right) Average hourly profiles on five select scenarios for a typical year and (left) heating and cooling seasons. (Bottom) Actual hourly data for the coldest and warmet days of the year.

3. Specific load control measures

3.1. Load shifting using setpoints

We investigated the potential of using the building mass to shift HVAC electrical load by varying thermostat setpoints. We studied several scenarios with the packaged terminal heat pump system. In each scenario, each zone stayed within the same upper and lower temperature ranges both with and without load shifting. **Figure 18** below shows the thermostat setpoints used for one scenario, which pre-cool the zone in advance of the 4-9pm period and shifts substantial electrical load outside this period. However, there is an overall energy consumption penalty from controlling the building to a narrower range of indoor conditions. When combined with the typical weather conditions at which precooling occurs compared to those between 4 pm and 9 pm each day, the overall energy penalty is substantial. For example, shifting 38 kWh of load out of the 4 pm 9 pm window on a typical June day increases the total energy consumption that entire day by 34 kWh (i.e. energy consumption 9 am - 4 pm is ~80kWh higher). We found a similar effect when using a simpler ‘step-up’ setpoint strategy, which maintained a 74 °F setpoint throughout the day which steps up to 78 °F between 4-9 pm. Last, the cost to implement this control with centralized control and local occupant override is not trivial compared to a typical thermostat solution. Given the added complexity of occupant interaction, the initial cost (compared to investing those costs in more battery storage), and the substantial energy consumption penalty, we did not pursue this option further.

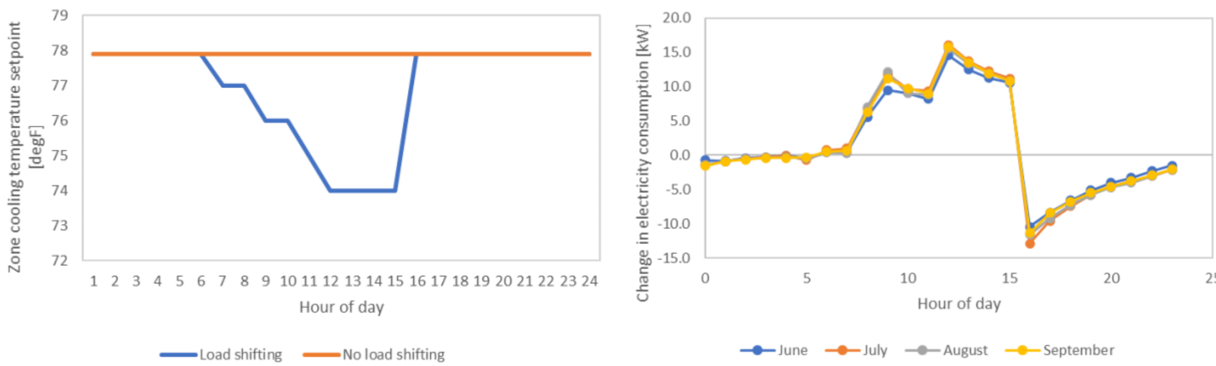

Figure 18: Left) Thermostat cooling setpoint and right) resulting difference in HVAC electricity consumption, averaged each hour of day by month from June to September.

3.2. Dynamic ventilation

We investigated shifting minimum ventilation rates to the building on a daily basis using a slightly oversized ventilation system. We over-ventilate (120% of minimum ventilation requirement) most hours of the day, and under-ventilate (50% of minimum ventilation requirement) during the 4-9pm period each day. This meets ASHRAE Standard 62.2 requirements as the annual average ventilation provided is above the minimum requirement, and concentrations of contaminants within each zone do not exceed - at any point in time - 5x the level that they would in an otherwise comparable constant ventilation rate system. **Figure 19** shows the hourly fan power consumption for January and June months by HVAC type with dynamic ventilation. Though technical challenges remain to implementation, this strategy has substantial potential to shift load at a low first cost. For example, total fan electricity consumption decreases by 10-15 kWh between 4-9 pm each day, depending on the scenario considered. Additionally, there can be heating and cooling energy savings depending on the control strategy used, which could be optimized to over-ventilate during favorable conditions (outdoor temperature, grid marginal carbon emissions, etc.) throughout the year and under-ventilate in less favorable conditions.

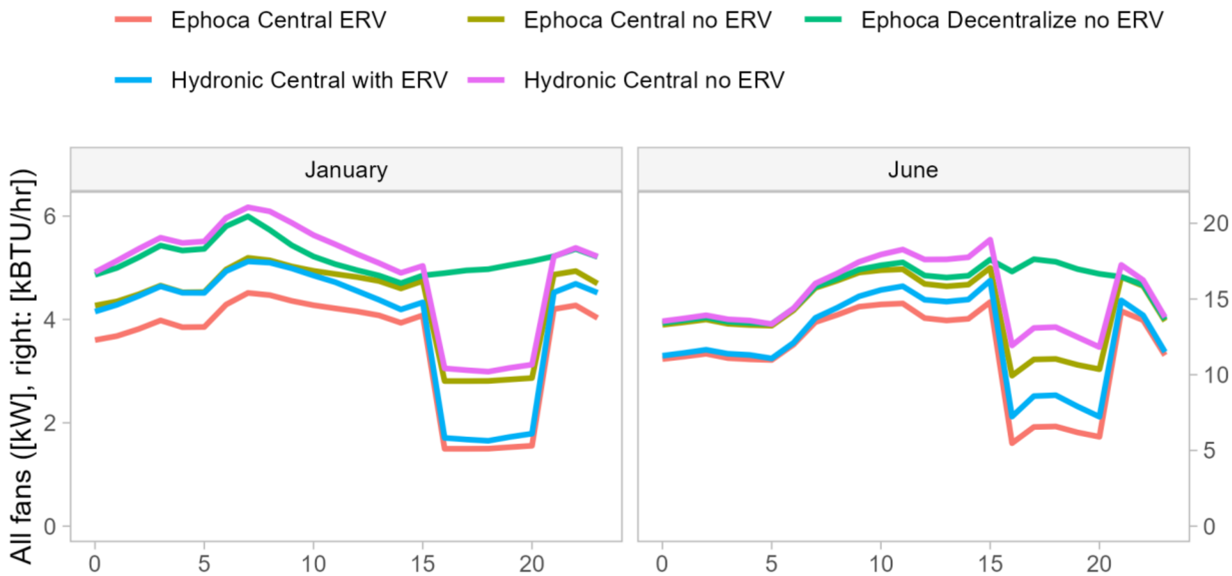

Figure 19: Hourly fan power consumption each month, by HVAC system type, averaged for January and September months. All HVAC systems are modeled with dynamic ventilation, except the Ephoca standalone ERV which handles ventilation locally at each zone.

4. Insights from EnergyPlus simulation

Efficiency measures are key to meet the ambitious energy performance and load shifting metrics for this project. However, the baseline building (all-electric LEED project, which is standard practice for the developer, First Community Housing) is already highly energy-efficient, and the majority of potential measures that have not already been applied are for HVAC and DHW loads which are a relatively small portion of overall annual energy consumption. Relatively few measures apply to the majority of the annual electrical consumption (i.e. residential, in-apartment plug loads) because many measures are already included in the baseline, such as EnergyStar appliances, high performance lighting and low flow fixtures. The most notable efficiency and load shifting measures are as follows:

- **Dynamic ventilation –** Increasing ventilation rates outside of peak hours and throttling them down between 4-9 pm meets ASHRAE 62.2 ventilation requirements and has substantial energy savings and load shifting potential.
- **Load shifting** using thermostat setpoints has load shifting potential, but it comes at a substantial energy penalty each day.
- **Ceiling fans** add an amenity that occupants value, at low first cost, while generating substantial energy savings and providing resilience during combined heat stress/power outage events.
- **Central hydronic heating and cooling** has the best energy performance, highest load shifting capability, and best thermal resilience during outages among residential HVAC systems examined, though it comes at a substantial price premium compared to the

packaged terminal heat pump options - one that is far above the cost of additional battery capacity that would be required to achieve similar load shifting capability..

- **Energy recovery ventilation** has limited benefit in the cooling season, but is beneficial in the heating season particularly given the lower solar production during those months and the energy and load shifting targets for this building. Having a bypass on the energy recovery for summer months is essential for energy recovery to make sense; the Ephoca All-in-One with ERV does not have bypass capability and does not perform as well as central ventilation in this climate because it cannot take advantage of free cooling during summer months.

5. Carbon and Cost Optimization

Using the energy outputs from the EnergyPlus models, we evaluated optimal sizing and dispatch of solar PV, electrochemical batteries, thermal energy storage, and load flexibility using Xendee. Xendee is a microgrid and distributed energy resources (DER) modeling platform that is designed to support decision making throughout the design and project implementation phases. Xendee takes inputs about utility rate tariffs, hourly load profiles by end use, as well as cost and performance parameters about various distributed energy resources, and then optimizes component sizing and dispatch for cost, carbon, or both. It is also capable of modeling outage scenarios when the grid is down and the building is islanding (see **Figure 20** below). Xendee was used to find the least cost design combinations of the building energy systems capable of meeting the minimum design requirements outlined by the award solicitation.

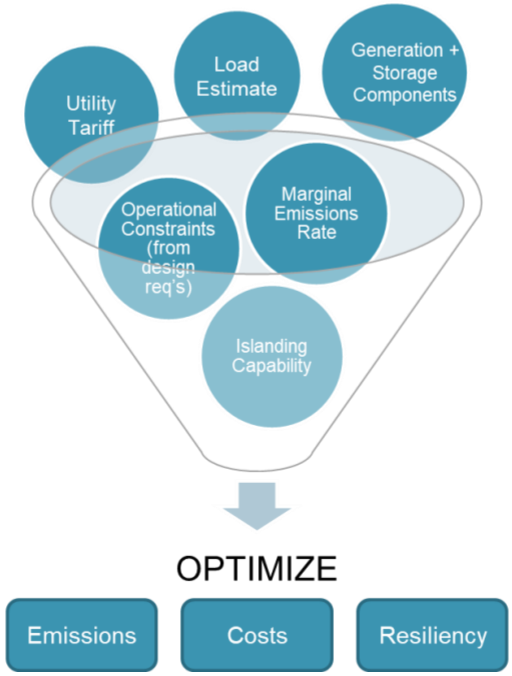

Figure 20: Representation of the modeling process for carbon and cost optimization of the building energy systems

5.1. Inputs and Assumptions

5.1.1. Building load

In order to evaluate the design requirement that no grid electricity should be used for residential loads from 4-9pm each day, we pulled just the residential loads from EnergyPlus outputs for each scenario (energy efficiency measure bundle and HVAC system alternate described above). Loads were input into Xendee by end use – electrical loads were input into Xendee as electrical demand and thermal end uses (DHW and space conditioning) were input as thermal demand. This allows Xendee to optimally size thermal energy storage (where applicable) alongside solar PV and battery storage. Xendee model assumptions are outlined in a supplemental workbook titled, "Appendix: Xendee Life Cycle Cost and Performance Assumptions.xlsx."

In order to evaluate the design requirements that Tier 1 loads should be powered indefinitely with on-site resources, and that Tier 1 and Tier 2 loads maintain power through likely outage scenarios, we employ two approaches to analyze the building load. First, we used the CEC recommended guidelines that Tier 1 loads be 10% of building peak loads and Tier 2 loads be 25% of building peak loads, as defined by the annual peak load for each efficiency and HVAC system scenario. In the second approach, we make ground-up estimates of Tier 1 and Tier 2 loads based on resident and property management feedback, the building design, and systems considered. These assumptions are outlined in Section 6: Resilience Assessment.

5.1.2. Solar PV

We evaluated a number of solar PV orientations and racking systems, including fixed tilt, east-west racking, an elevated rooftop PV canopy, and facade mounted on the southwest facade. Row spacing, tilt angle, shading from the parapet, and panel orientation were all important factors in optimizing the PV design. Ultimately, the team elected to eliminate the SW facade-mounted option because the adjacent lot, while open now, is buildable, and would potentially completely shade these panels in the future. Based on the annual energy production and annual energy/system size ratio, the team elected to move forward with two PV scenarios in the modeling process: 1) rooftop east-west racking at a 37.3 degree tilt, and 2) elevated PV canopy with flat panels oriented with the long axis in the SW-NE direction.

Table 4: PV and Canopy Costs, federal ITC incentive accounted

PV Cost Input	
Per Unit Installed Cost ($/Wdc)	2.8
Monthly Fixed Maintenance ($/kWdc)	2.42
PV system Lifetime (years)	30
Elev PV canopy structure cost ($)	415,520

Table 5: Summary of PV performance in the design alternatives considered

PV Design	Scenarios	Total PV power (kWp)	kWh/kwp	Annual Energy (MWh)
East-West Racking	**Tilt 37.3**	**130.4**	**1238**	**161.5**
	Tilt 25	98.5	1338	131.7
	Tilt 30	118.3	1270	150.2
	Tilt 45	130.4	1110	144.7
Fixed Tilt Tacking SW Elevated Canopy Flat	Row 4’ spacing	94.6	1392	131.7
	Row 3’ spacing	107.8	1320	142.3
Elevated Canopy Flat	**SW orientation**	**171**	**1629**	**279.5**
Elevated Canopy East-West Racking	37.3 tilt	211	1194	252
SW Facade	90 tilt, opaque wall	85.9	1076	92.5

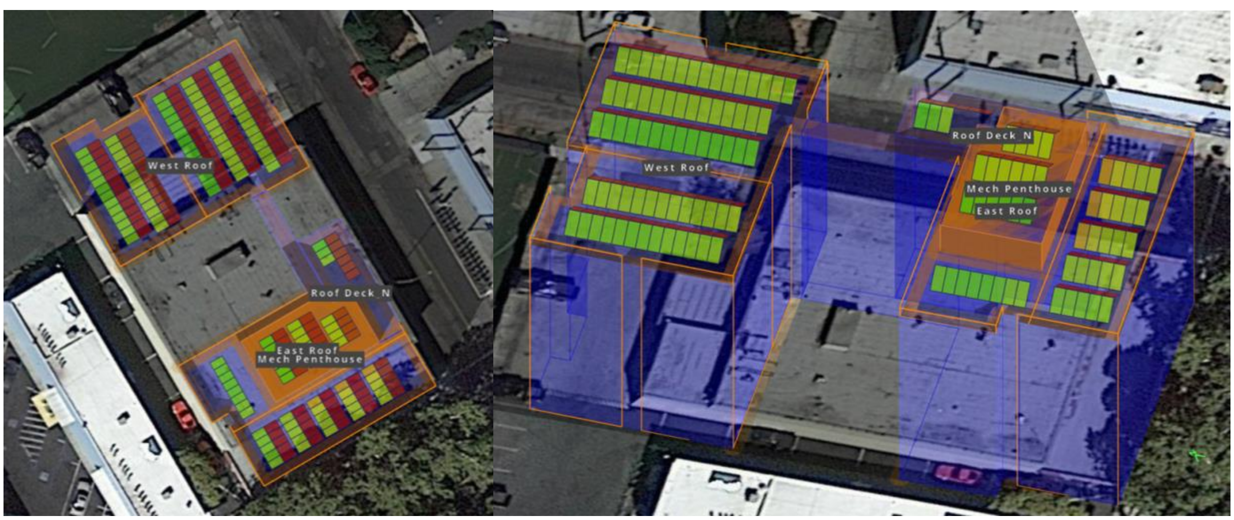

Figure 21: Rooftop PV Layout (130 kWp); tilt 37.3, SW-NE racking

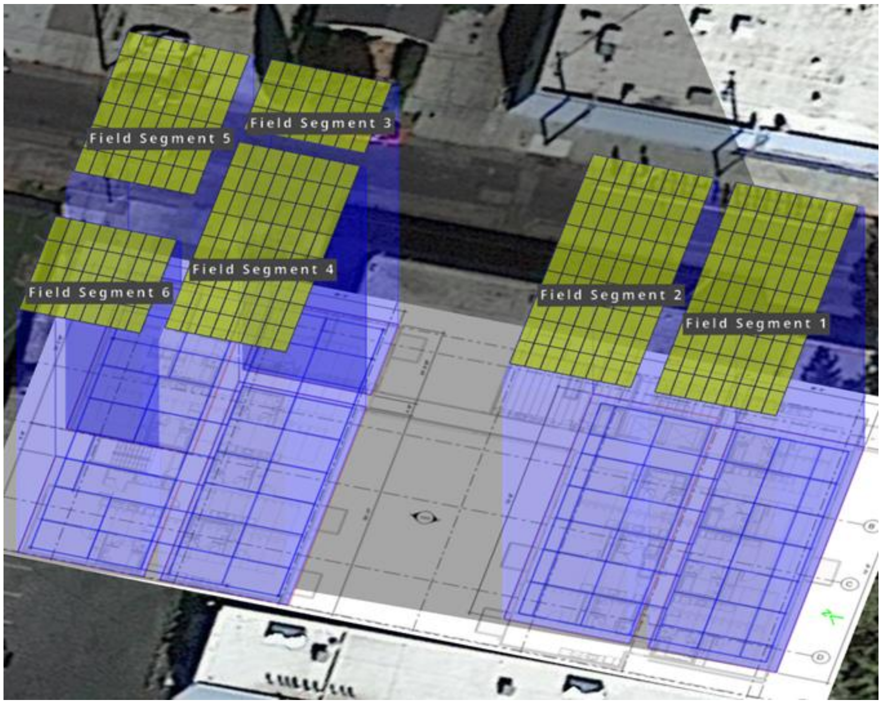

Figure 22: Elevated PV layout (171 kWp); flat orientation,facing SW

5.1.3. Battery Energy Storage

An electric battery storage system is incorporated into the Xendee model to store and supply electricity when required (eg. to meet daily residential loads from 4-9pm) or advantageous (to reduce operating costs or carbon). This battery system is integrated with the solar PV system and, in some scenarios, the utility grid to store excess PV or low-cost/carbon energy and discharge electricity as required for load shifting, power outages, and daily usage during peak hours. We evaluate an optimal electric battery system for the following three scenarios in Xendee:

- Daily 4-9 pm residential loads (co-optimized dispatch for cost and carbon): Evaluation of scenarios where the battery is allowed to charge from the grid and where it can only charge from on-site resources.
- Tier 1 electricity indefinitely: constant load at 10% of annual peak load
- 24 hours and 72 hours Outage: selected Tier 1 and 2 load based on resident surveys

The battery system performance and cost assumptions are outlined below for reference. The battery cost accounts for the battery incentive from the BUILD program.

Table 6: Battery parameters

Battery Parameters	
depth of discharge	95%
roundtrip efficiency	81%
charging rate (% capacity/hr)	50%
discharging rate	50%
Total installed cost ($/kWh)	837
Lifetime (years)	12

Source: Cost and Performance_Input.xlsx - Google Sheets

5.1.4. Thermal Generation and Storage

For the packaged terminal heat pump HVAC configuration, a hot water storage system is modeled as part of the DHW system. Sizing, charging and discharging of the DHW tank is evaluated alongside the battery system in Xendee to fulfill daily 4-9 pm residential load. For the hydronic HVAC configuration, hot water storage is modeled for both DHW and space heating, and chilled water storage is modeled for space cooling. Note that the hydronic case does not account for the benefits of waterside heat recovery due to technical limitations. We estimate this savings to be ~7 MWh/year (Combined and All Measures) or ~14 MWh/year electricity consumption.

Thermal energy is produced by an air-source heat pump that is modeled according to the performance parameters of the basis of design products. The thermal storage system's parameters and cost assumptions are shown below in **Table 7**.

Table 7: Thermal storage parameters

Thermal Storage Performance	
charge efficiency	100%
discharge efficiency	100%
charging rate upper limit	50%
discharge rate upper limit	50%
Standby losses	0%
Installed Cost ($/kWhth)	100
Lifetime (years)	30

Source: Cost and Performance_Input.xlsx - Google Sheets

5.1.5. Electricity Emissions Rate

Hourly marginal electricity emissions data is input into the Xendee model and used to calculate operational carbon of the various scenarios, as well as to inform dispatch strategies to reduce operational carbon. Two emissions profiles are considered:

1) A 3-yr historical average “TMY” profile is pulled from WattTime data to evaluate current emissions projections for the facility.
2) A future, 2035 profile is pulled from the NREL Cambium database to calculate the emissions projections in a future scenario in which the electricity system in CA is nearly decarbonized.

Figure 23: Marginal emissions rate in 2019-2022 TMY (left) and 2035 under a 95% carbon free electricity by 2035 scenario (right)

5.1.6. Utility Tariff

We modeled three utility tariff rates in Xendee including residential time of use rates E-TOUC, non residential time of use rates B-1, electric vehicle rates B-EV-1 listed in the table below. The generation rates are from San José Clean Energy and distribution rates are from PG&E.

CARE rates were applied to assess the cost-benefit of design cases, factoring in a 10% discount for generation rates and a 30% discount for distribution rates.

Export rates are the same as time of use rates assuming the building will be under NEM 2.0 and the PV generation is less than total electricity consumption.

Table 8: Electricity Tariff Rate Schedules

Residential E-TOUC	Rates ($/kWh)	
TOU Period	**October 1 through May 31**	**June 1 through Sept 30**
4pm to 9pm every day	0.35	0.45
all other hours	0.34	0.39
Non-residential B-1	**Rates ($/kWh)**	
4pm to 9pm every day	0.35	0.43
2pm to 4pm	0.33	0.37
all other hours	0.31	0.35
Electric Vehicle B-EV-1	**Rates ($/kWh)**	
TOU Period	Year round	
4pm to 9pm every day	0.37	
9pm to 9am and 2pm to 4pm	0.19	
9am to 2pm	0.16	

Source: (San José Clean Energy, PG&E)

5.2. Optimization Results

Below we present results from the cost and emissions optimizations described above. Costs are on an annual basis (thousands of $/yr) inclusive of capital costs for system components and operational costs from utility purchases (net of export credits).

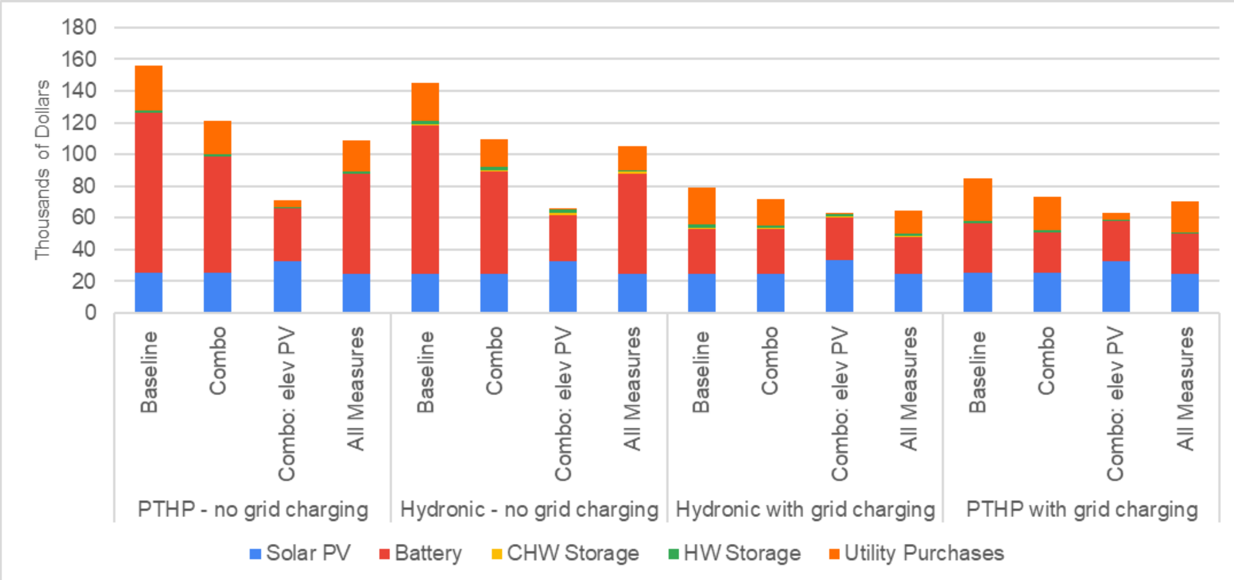

Figure 24: Annualized DER costs and utility purchases by efficiency package and HVAC system type. All results meet 100% of annual 4-9 residential loads without grid imports.

The scenario with the lowest overall annual costs is the hydronic combo efficiency package with elevated PV and grid charging ($62,712/yr), followed very closely by the PTHP combo efficiency package with elevated PV and grid charging ($62,964/yr). For scenarios with the same size PV system (130 kW rooftop PV), adding efficiency decreases total DERs cost in all cases, but the cost reduction from the “baseline” efficiency package to “combo” is much greater than the cost reduction from the “combo” to “all” efficiency measures. It is important to note that the cost of the efficiency packages and HVAC system variants are not explicitly considered in these results, however, the relative DER cost reductions provide a benchmark for what the efficiency and HVAC measure incremental cost would need to be in order to be cost effective.

In all cases with 130 kW rooftop PV, allowing grid charging of the battery drops overall costs significantly (due to reduced battery size). But with the elevated PV canopy, this reduction more or less disappears. This is likely due to the fact that when the building is more PV constrained and no grid charging is allowed, it is difficult to sufficiently charge the battery enough each day to meet the 4-9pm residential loads, thus the battery size must increase. Allowing grid charging makes a big difference in battery size/cost, because it removes this charging constraint. But in the elevated PV scenarios, when PV generation is more sufficient, this dynamic disappears, as the battery is able to charge sufficiently whether or not grid charging is allowed.

Figure 25 below shows the annual operational carbon for the same set of scenarios.

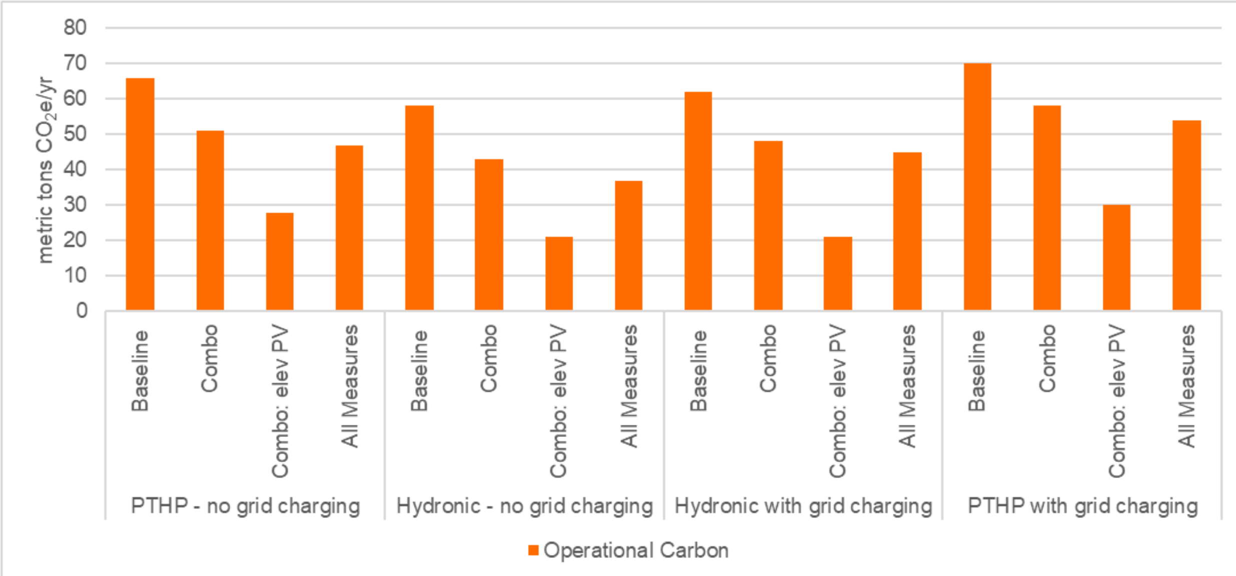

Figure 25: Operational carbon emissions by scenario and HVAC system type, 3-yr historical average emissions intensity profile.

The two hydronic HVAC with the "combo" efficiency package and elevated PV (with and without grid charging) are tied for the lowest operational carbon (21 mTCO2/yr), followed by the PTHP combo with elevated PV and no grid charging (28 mTCO2/yr). For the scenarios with the 130 kW rooftop PV, in all cases, increasing efficiency lowers operational carbon and allowing grid charging of the battery increases carbon. But with the elevated PV scenarios, carbon is equal in the hydronic cases between grid charging vs no grid charging, and much closer for the PTHP cases than with the 130 kW PV system. This is likely due to the fact that, as described above, with lower PV generation, the battery is forced to do more grid charging if allowed, and therefore ends up charging at times of relatively higher emissions intensity. If grid charging is disabled, the battery size is forced to get much bigger which decreases operational carbon, but significantly increases cost.

In the hydronic-combo efficiency-elevated PV case with grid charging, electricity exports to the grid are roughly twice as much as in the no-grid charging case, meaning that the emissions offset from these exports are equal to the emissions value of self-consumption in the no-grid charging case over the course of the year. **Figure 26** below shows average daily battery charging profiles by month for these two hydronic cases. The profiles look very similar between the grid charging and no grid charging cases, and both occur during the daily solar PV generation window, highlighting the ability to sufficiently charge from the larger amount of on-site PV generation in both cases, and that when grid charging does occur, it is during a daily period of low emissions intensity.

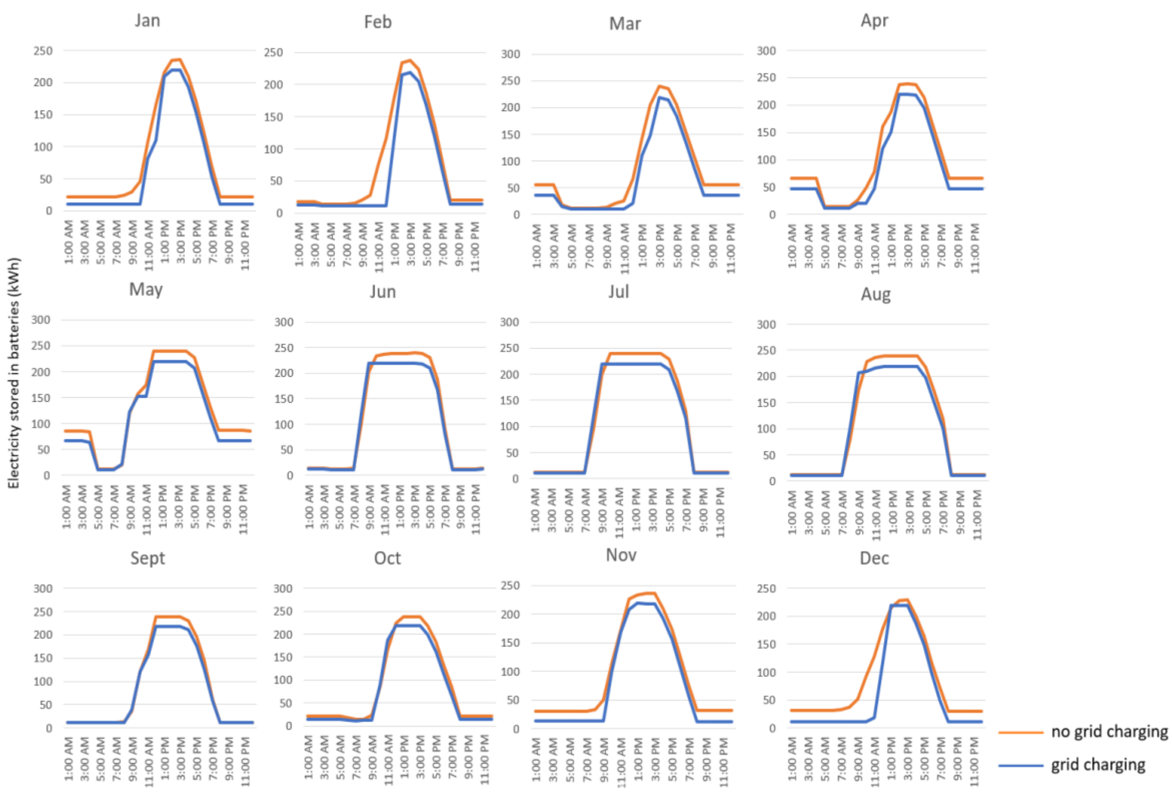

Figure 26: Average daily battery charging profiles by month for the hydronic-combo efficiency-elevated PV scenarios.

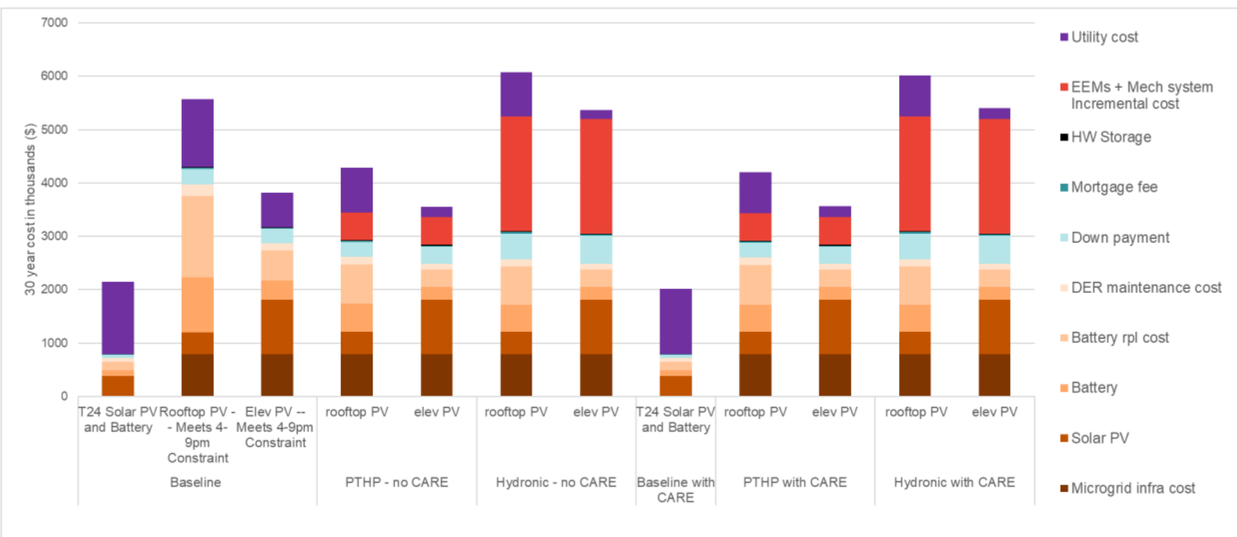

Figure 27: 30-year life-cycle net present cost of T24 baseline, baseline that meets the 4-9pm constraint and all the alternatives with and without CARE rates.

Figure 28 shows the 30-year lifecycle net present cost for the T24 baseline design, a baseline that meets the 4-9pm constraint, and the proposed design. Due to our proposed VNEM configuration, the battery system can only be charged by on-site PV (i.e. no grid charging), thus the elevated PV array was selected for the proposed design which reduces the required battery size and lifecycle costs. For a detailed discussion of how we arrive at the proposed design and trade offs of adopted energy measures, see the emerging technologies report. Please Detailed information of the life-cycle analysis is in Emissions & Cost Benefit Report.

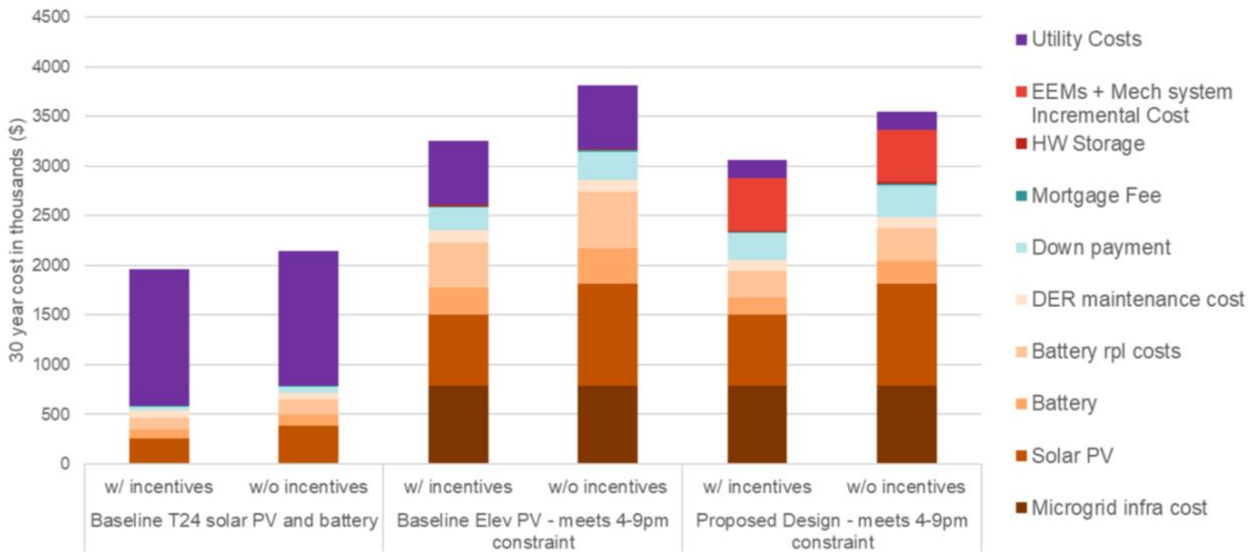

Figure 28: 30-year life-cycle net present cost of T24 baseline, baseline that meets the 4-9pm constraint and the proposed design with and without incentives.

We combined the embodied carbon and operational carbon emissions for the T24 Baseline, the Baseline with elevated PV, and the proposed design, shown in **Figure 29**. The proposed design has the lowest total carbon emissions among all cases considered. The total carbon emissions of the proposed design is approximately 30% lower than baseline with elev PV indicated in **Figure 29**. This significant reduction in carbon emissions can be attributed to the embodied carbon reductions (mostly from concrete and reduced battery size) and reduced operational emissions resulting from the enhanced energy efficiency measures.

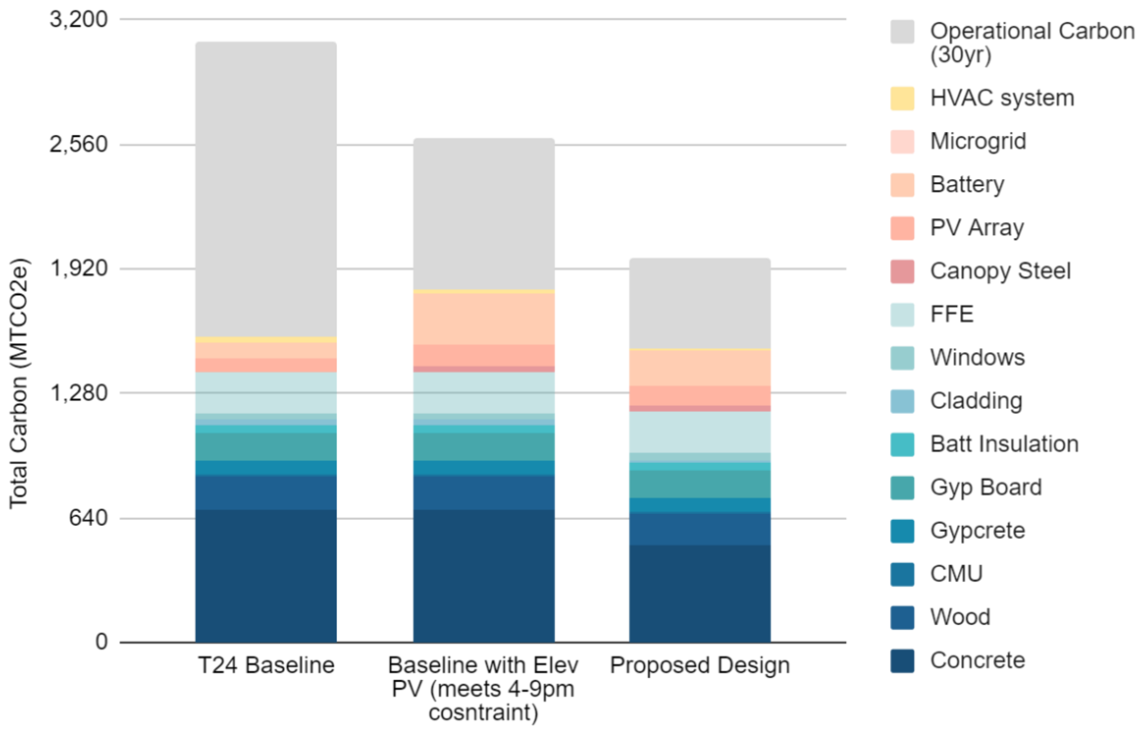

Figure 29: Total carbon comparison (embodied and operational) of baseline and design alternatives considered

5.2.1. Comparison of Top Scenarios

Considering the results discussed above, the two DER configurations with the best performance across dimensions of cost and emissions are the hydronic-combo efficiency-elevated PV-with grid charging and the PTHP-combo efficiency-elevated PV-with grid charging. **Table 9** below shows a comparison between these two scenarios:

Table 9: Comparison of the best performing DER configurations

Component | Scenario	Hydronic | Combo Efficiency | Elevated PV | Grid Charging	PTHP | Combo Efficiency | Elevated PV | Grid Charging
PV System Size (kW)	171	171
Battery Energy Storage (kWh)	219	202
HW Storage (kWh)	294	187
CHW Storage (kWh)	131	NA
Annual Energy Consumption (kWh/yr)	383,764	384,940
Peak Load (kW, Date)	53.4, Jan 16th, 10pm	63.7, June 28th, 7pm
Operational Carbon (mTCO2/yr)	21	30
Exports (kWh/yr)	228,623	117,922

Figure 24 and **25** below show daily electricity profiles for these two scenarios on a winter and summer peak battery sizing day. Note, these days (Jan 19th and Sept 28) are not the same as the peak load days shown above. This is because the battery sizing is driven by a combination of relatively high loads and low solar PV production (cloudy day). In both cases, during the September peak, the 4-6pm hours receive a little bit of solar PV production, whereas in the winter the entire 4-9pm window must be met with the battery.

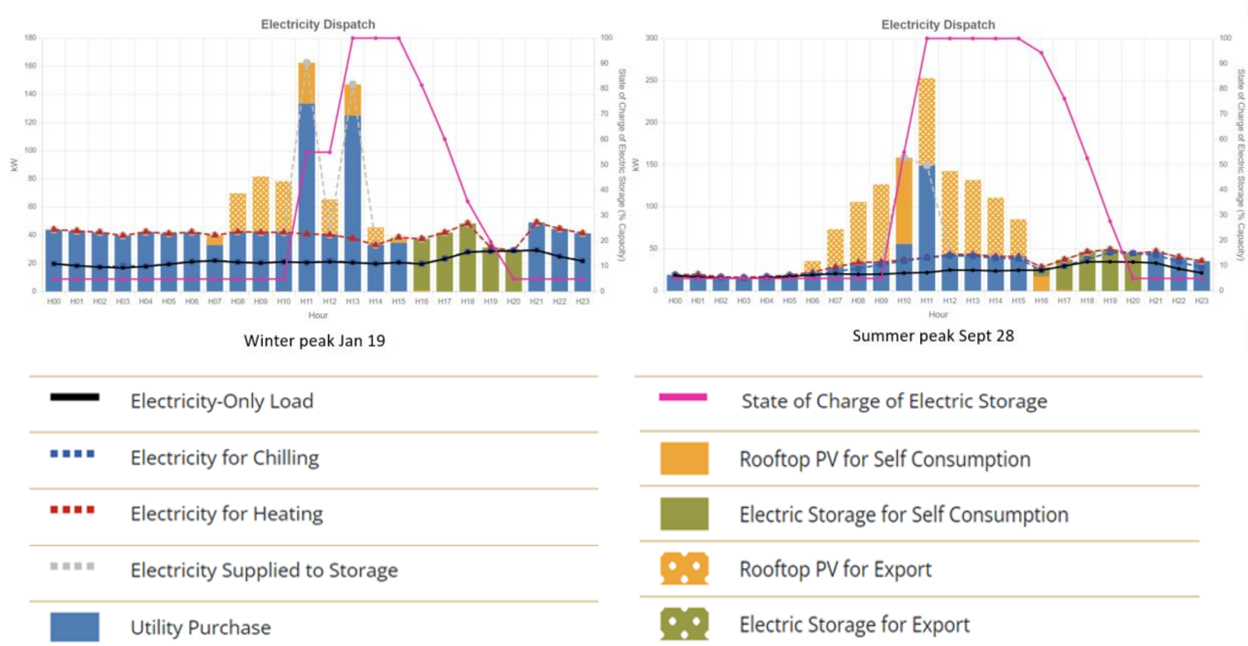

Figure 24: Peak days electricity dispatch for Hydronic with ERV, the combined efficiency measures and elevated PV, grid charging

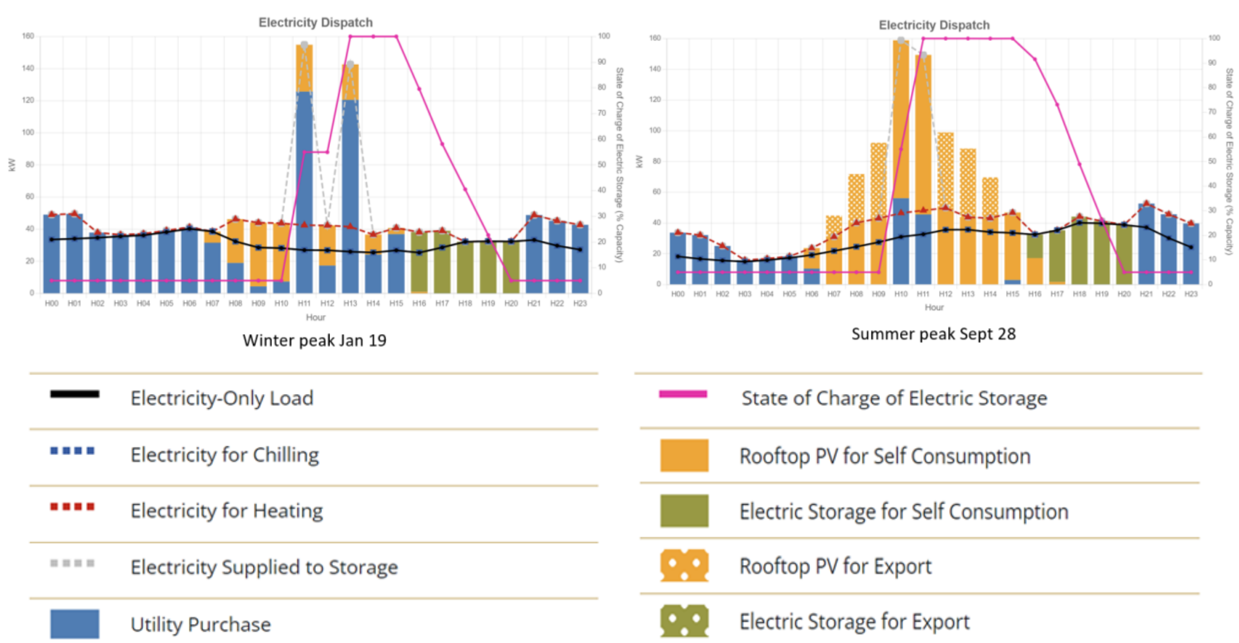

Figure 25: Peak days electricity dispatch for Ephoca with ERV, the combined efficiency measures and elevated PV, grid charging

6. Resilience Assessment

6.1. Passive resilience in extreme weather

We evaluated the building for passive resilience in extreme weather conditions. **Figure 26** shows the first two scenarios in extreme summer conditions. The first scenario involves completely shutting down the power to the building. The second scenario is tier 1 operation where 10% of the loads are used in the apartment units and the central ventilation with an ERV is still operating. The two plots show the apartment units' indoor temperatures do not start to exceed thresholds beyond thermal comfort (with the aid of fans, which are a TIER 1 load) until about day four. These scenarios do not include the impact of operable windows. **Figure 27** shows that if we assume operable windows at night during these scenarios then occupants gain an extra day where indoor temperatures are reasonably controlled within thermal comfort criteria. After the shutoff is over, we can see that the HVAC system quickly brings down the indoor temperatures to the cooling setpoint. This quick response is partially due to the oversized equipment as discussed in Section 1.8 and **Figure 6**.

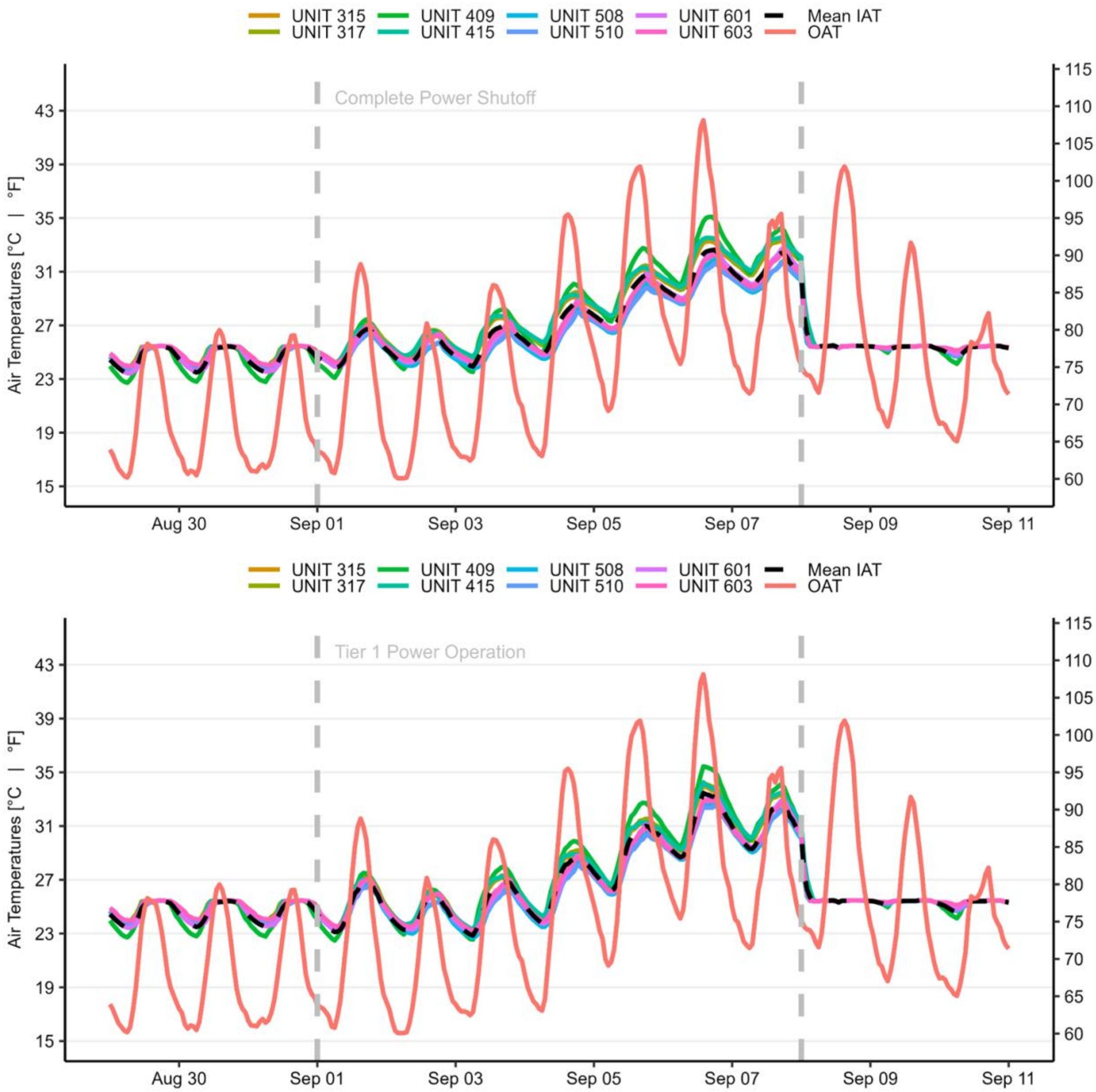

Figure 26: A sample of residential units' indoor air temperatures after (top) a complete power shutoff and (bottom) tier 1 power operation that includes energy recovery ventilator operation during a summer extreme condition. Mean indoor air temperature (IAT) for all residential units and outdoor air temperature (OAT) are also shown for reference. We assume windows to be closed all the time.

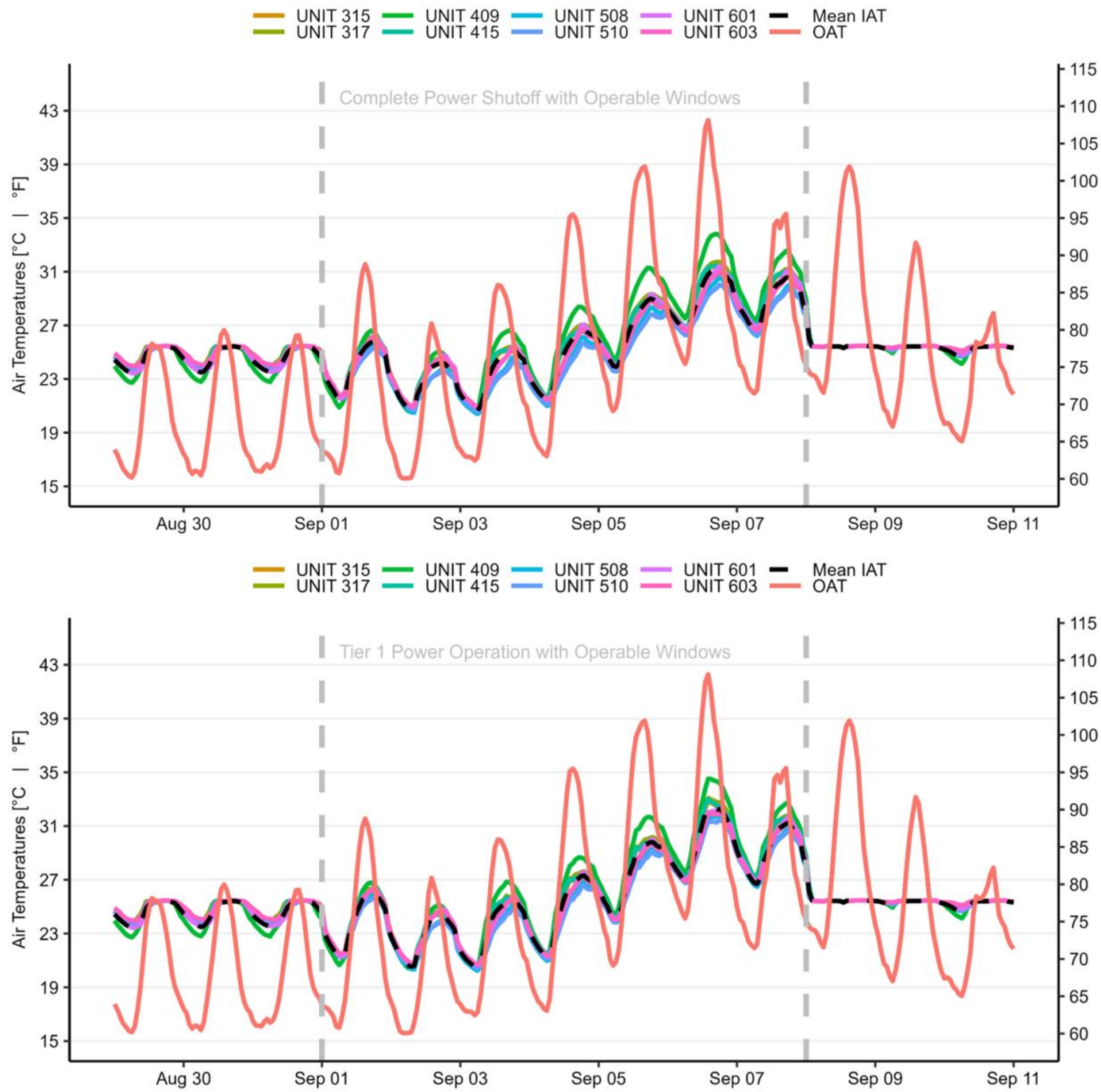

Figure 27: A sample of residential units' indoor air temperatures after (top) a complete power shutoff and (bottom) tier 1 power operation that includes energy recovery ventilator operation during a summer extreme condition. Mean indoor air temperature (IAT) for all residential units and outdoor air temperature (OAT) are also shown for reference. We assume windows to be open during the night providing 2 ACH of outdoor air.

Figure 28 shows a similar analysis to the above but for extreme winter conditions. We assumed that occupants would not open windows during winter days and did not simulate that scenario. The winter condition analysis shows that some apartment units will have colder indoor temperatures than others. This is because of their orientation and if they are facing the core of the building or not. Apartment units facing southeast result in higher indoor temperatures during the power shutoff. The apartment units that face the core or on the northwest orientation experience lower indoor temperatures. The central ventilation ERV has the effect of bringing the indoor temperatures toward the mean indoor air of all apartment units.

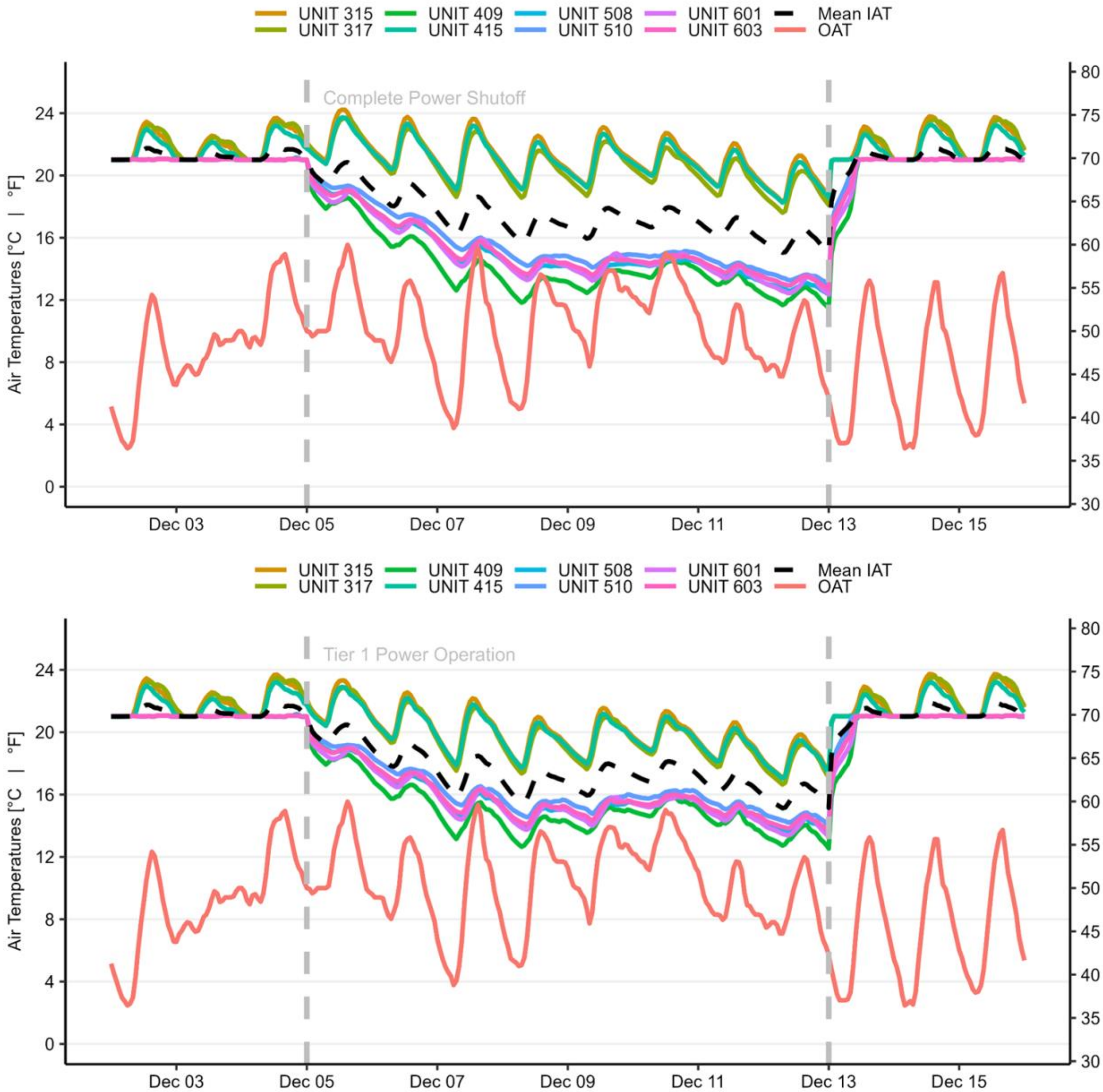

Figure 28: A sample of residential units' indoor air temperatures after (top) a complete power shutoff and (bottom) tier 1 power operation that includes energy recovery ventilator operation during a winter extreme condition. Mean indoor air temperature (IAT) for all residential units and outdoor air temperature (OAT) are also shown for reference. We assume windows to be closed all the time.

6.2. Tier 1 Loads Indefinite Coverage

The cost of battery and PV investment significantly increases to meet more than 97% of the tier 1 load throughout the year shown in **Figure 29**. With the same 130 kWp rooftop PV system, a 200 kWh battery system costing $0.6 million dollars can meet 96.4% of the tier 1 annual load. However, meeting 100% of the tier 1 annual load requires a 3500 kWh battery costing $4.2 million dollars, over 17x increase to cover the last 3.6% of the annual loads. The size of the required battery can vary significantly depending on the level of PV generation and energy demand. During periods with low PV generation, especially multiple cloudy days in a row (relatively rare in San Jose, CA), a much larger battery is needed to cover the tier 1 load, which significantly drives up size and cost. In the example below, a 211 kWh battery paired with a 130 kW rooftop PV system can meet 100% of the annual residential loads from 4-9pm and 96% of the annual Tier 1 loads without grid imports. A similar sized battery (202 kWh) paired with the 171 kW elevated PV canopy can cover 100% of the residential 4-9pm loads and 99.1% of the annual Tier 1 loads without grid imports. And, with the additional PV generation of the elevated canopy, 100% tier 1 coverage would require a 723 kWh battery – still over a 3x increase for the remaining 1% of annual loads, but much less than 17x increase!

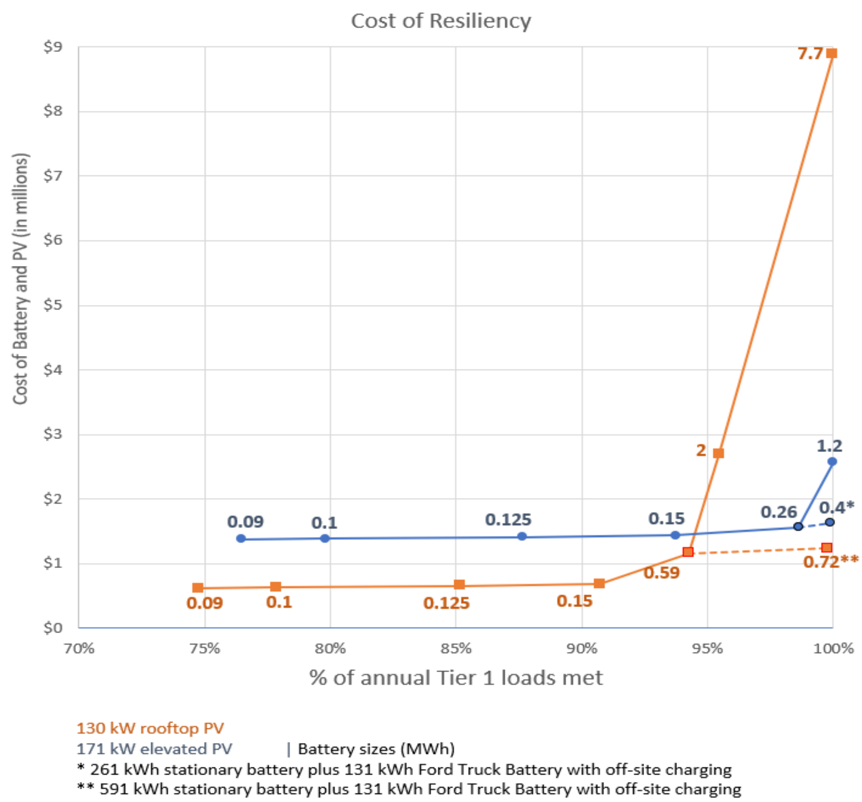

Figure 29: Required battery sizes (in MWh) and corresponding costs of batteries and photovoltaic (PV) systems to sustain Tier 1 load consistently throughout a year without grid power. Orange line is with 130kW rooftop PV and blue line is with 171kW elevated canopy PV. Dotted line shows the cost of truck, battery and PV with T1 % coverage when 131kWh ford truck battery charges offsite and discharges on site.

6.3. Tier 1 and Tier Loads During Likely Outages

The team came up with most likely outage scenarios in Santa Clara, CA in **Table 10**. Based on surveys with existing residents at nearby First Community Housing properties, the team summarized essential and priority services for each scenario. The expected duration of a potential outage varies from 1 hour to 72 hours, with a decreasing frequency as the duration increases. During an outage, exiting and safety are top priorities along with food spoiling. 30% of residents mentioned elevator service, stair or corridor lighting as a top priority. 30% of residents mentioned refrigerators or freezers as a top concern as well. Refrigerators, kitchen plugs and hot water are ranked the most preferred functions to maintain during an outage. Essential services including HVAC and lights are ranked less important.

Table 10: Outage scenarios

Outage Scenarios	Heat wave-related rolling black-out (coincident with a smoke event)	Winter storm/downed power line	Major earthquake
duration	1-3 hours	12-24 hours	3 days
likelihood	1-5 times a year	once every 1-3 years	once in next 30 years
Essential service continuity	Building entry access and security		
	Emergency lighting		
	Domestic water booster pump		
	(1) Elevator		
	Ventilation system, building wide (with sufficient filtration)		
	Basic function in (1) office suite: lighting, printers, servers		
	Building-wide data/communications		
		Residential refrigerators	
Priority service continuity	(1) common refrigerator		
	Common area plugs and minimum lighting		
	ADA access to building, common room and outdoor spaces		
	Ceiling fans (apartments and offices)	Space conditioning	
		Residential lighting	
		Residential hot water recirc pump	
		Residential cooktop	

The resilience analysis is conducted for 24 and 72 hours outage scenarios throughout a typical year. The team identified Tier 1 and tier 2 load assumptions for these scenarios in **Table 11**.

Table 11: Tier 1 and Tier 2 load assumptions

Space	Description	TIER	Total load (kW)	Total daily load (kWh)
Residential electric loads	One ceiling fan/light (living room)	1	2.2	21.3
	Refrigerator (single receptacle)	1		71.0
	One kitchen USB receptacle (phone charging/communication)	1	.74	2.7
Plumbing	Domestic cold water booster pumps	1	11.0	10.0
	Central DHW heat pumps	2	16.1	115.9
Building electric loads	Elevator (15hp)	1	16.6	17
	Elevator support (cab lights, control room, etc.)	1	2.6	8.5
	Building entry/access system, electronic locks	1	0.2	4.8
	Microgrid system hardware	1	0.15	3.6
	Informational lights	2	0.1	14.4
	Centralized wifi routers (Tier 2 for whole building) (300w per switch in each IDF+600w in MPOE, see above)	2	1.8	43.2
	Building security cameras CCTV system and fire alarm	2	1.0	48.0
	Fire Alarm	1	0.06	2.9
	Egress lighting	1	1.4	69.1
Common Spaces	Community Room plugs	1	0.3	5.8
	Community Room lighting, ceiling fans	1	0.2	4.8
	Common kitchen refrigerator and induction range	1	0.5	3.7

	Common WC light, exhaust fan	2	0.1	0.5
	private offices and server room servers, lighting, receptacles, ceiling fans	2	1.0	8.4
HVAC	Residential Ventilation (Central ERV)	1	1.0	24
	Community Room Ventilation	1	0.3	4.3
	Community Room Heating/Cooling	2	6.4	30.8
	Office Ventilation	2	0.3	2.5
	Office Heating/Cooling	2	6.4	15.4
Tier 1 Total			37.8	265.3
Tier 2 Total			34.6	270
Total daily T1/2 kWh	535.3			
Hourly T1/2 kWh	22.3			

The battery is sized to provide power through every 24-hr and every 72-hr outage scenarios with PV on rooftop (130 kW) or elevated canopy (171 kW) based on following assumptions:

- Battery SoC is 100% at the start of an outage
- Battery parameters as described in section 3.1.3
- constant load for each hour

The assumption that the battery is at full capacity when outages occur would rely on predictive battery controls in reality that would alter normal battery dispatch when there is increased likelihood of an outage (summer grid stress, big winter storm, etc…). As illustrated in **Figure 24** depicting the monthly average electricity stored in batteries, the battery's state of charge (SOC) is low for a significant portion of each day during most months. In the event of a completely unexpected outage, a low battery SOC may provide insufficient coverage depending on PV output. To prepare for these events, a battery reserve level would need to be implemented that would keep the capacity available at all times, and be used for little else.

To obtain the 24-hour and 72-hour photovoltaic (PV) generation profile, the hourly electricity generation of the two PV systems is summed over a period of 24 and 72 hours on each day of the year, respectively shown in **Figures 30** and **31**.

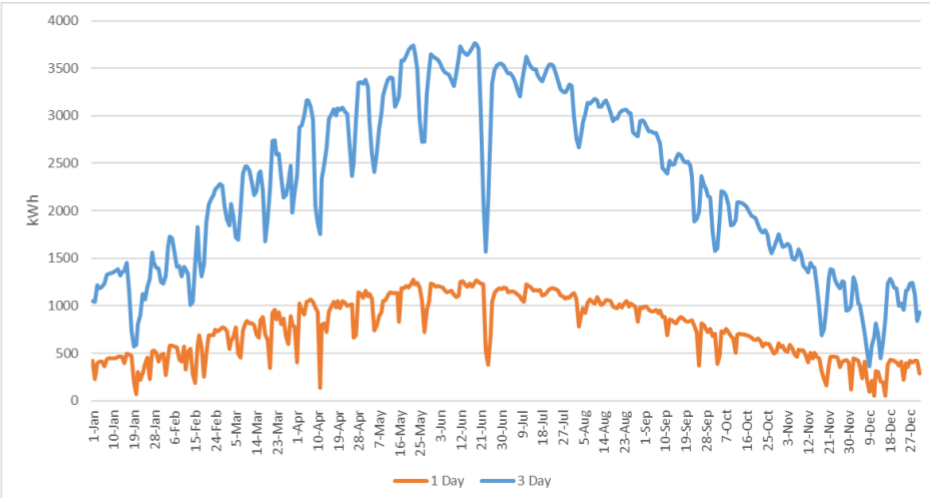

Figure 30: Elevated canopy PV generation for 24/72 hours outage

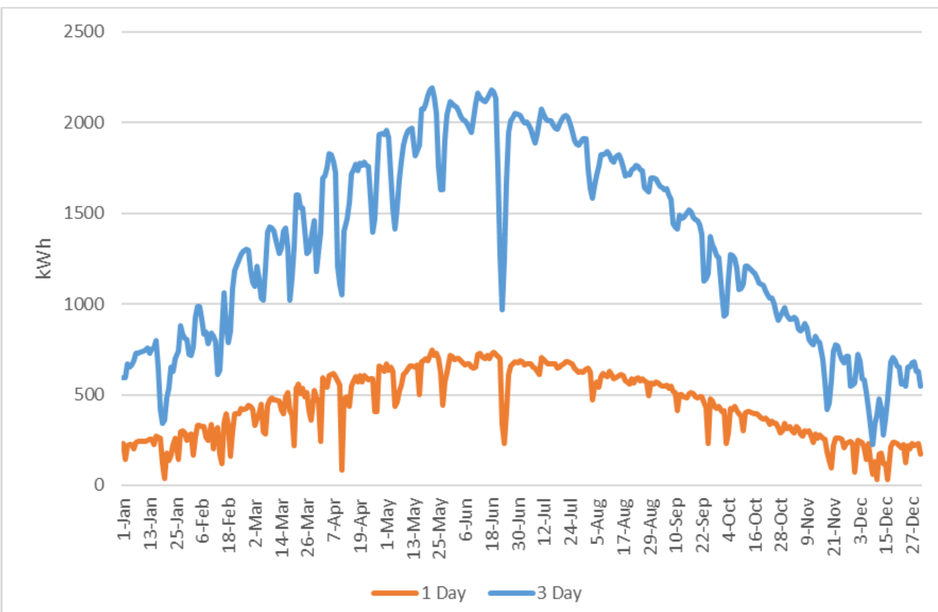

Figure 31: Rooftop PV generation for 24/72 hours outage

Figure 32 and **33** illustrate the 5% worst PV generation scenarios with varying battery sizes. These figures demonstrate the battery size required to provide power during 24/72-hour outages for 100%-95% of the year.

With rooftop 130 kWp PV,

- For 95% of the year, a 434 kWh battery is sufficient to power a 24-hour outage.
- For 95% of the year, a 1203 kWh battery is sufficient to power a 72-hour outage.
- A 434 kWh battery can provide 52% coverage of the 3-day outages in a year.

With elevated canopy 171 kWp PV,

- In 95% of the year, a 349 kWh battery is sufficient to power a 24-hour outage.
- In 95% of the year, a 877 kWh battery is sufficient to power a 72-hour outage.
- A 349 kWh battery can provide 76% coverage of the 3-day outages in a year.

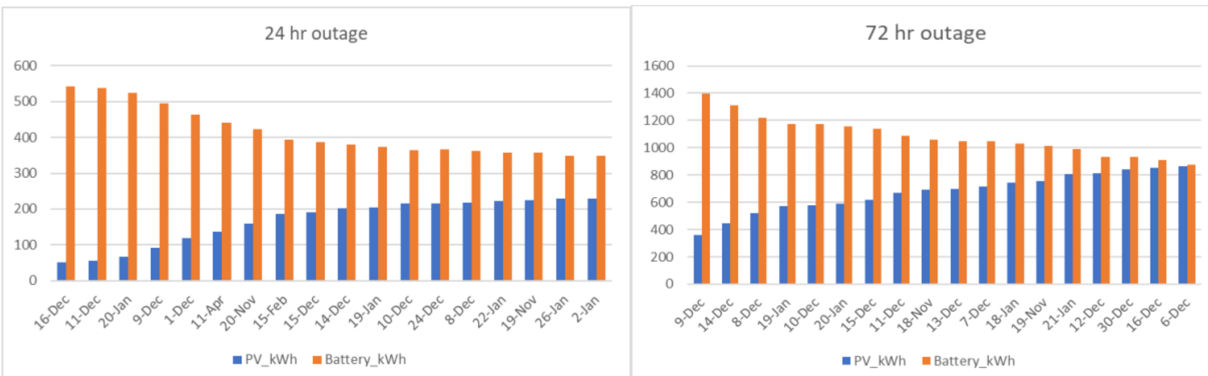

Figure 32: 24/72 hours outage battery sizing with PV on elevated canopy for 5% worst PV generation

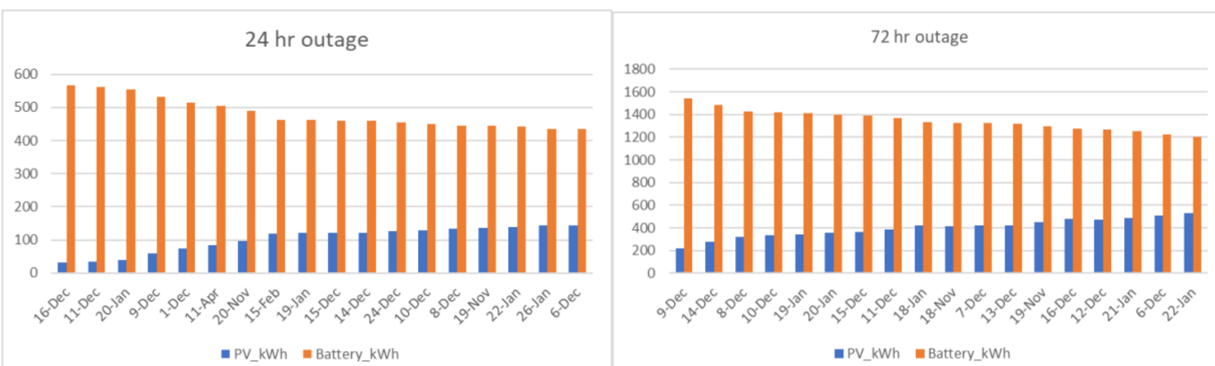

Figure 33: 24/72 hours outage battery sizing with rooftop PV for 5% worst PV generation

7. Insights from DER Optimizations

For a 6-story, 74 unit building like this with high unit density, PV generation is a significant constraint in meeting the design requirements with reasonable battery sizes. An elevated PV canopy increases generation considerably and makes it more feasible to meet design requirements, but likely has a high cost associated with it. Facade PV is another potentially promising way to increase generation, but available area is limited, and the most ideal facade for PV is a property line wall.

In PV-constrained scenarios, allowing grid charging significantly reduces battery size and cost with limited increase in CO_2 emissions. With more PV generation (elevated PV canopy scenarios), allowing grid charging slightly reduces cost and emissions are very close to equal with no grid charging scenarios.

Because heating and cooling demands are relatively small compared to other end uses, the benefit of thermal energy storage is small – On many days during the 4-9pm window, serving heating and cooling loads directly from the ASHP and battery results in similar or lower costs than serving them with thermal storage.

Sizing on-site renewable generation and storage systems to cover the “worst case” outage conditions significantly drives up system size and cost. Even small deviations from 100% coverage (eg. 95+%), can dramatically reduce system sizes and drop capex costs.

For the same size PV system, the biggest drivers of battery size are in the following order: 100% annual coverage for 72-hr Tier 1 & 2 outages, 100% annual coverage of Tier 1 loads, 100% annual coverage for 24-hr Tier 1 & 2 outages, 100% annual coverage of 4-9pm residential loads. For less dense sites with more potential for solar PV (e.g. a 3 story building, or predominantly larger 2- and 3- bed apartments), the order of these drivers would change, to the point that the 4-9pm requirement would be the dominant factor in battery sizing.

8. Appendix A: Summary results from an additional site

While working on the main building of interest, 995 East Santa Clara, the team automated as much of the modeling and parametric analysis as possible so that the process would be reasonably easy to port to future projects. To demonstrate this portability and further assess the generalizability of the findings to other projects in California, we modeled another building currently in design by DBA: the Harvey West building in Santa Cruz shown schematically in **Figure A-1.**

Located off Route 1 close to downtown Santa Cruz, Harvey West is 55,000 SF and includes 121 studios for formerly homeless residents in 4 wood-framed levels over a concrete podium housing resident services, case managers, property managers and a wellness clinic in approximately 10,000 SF.

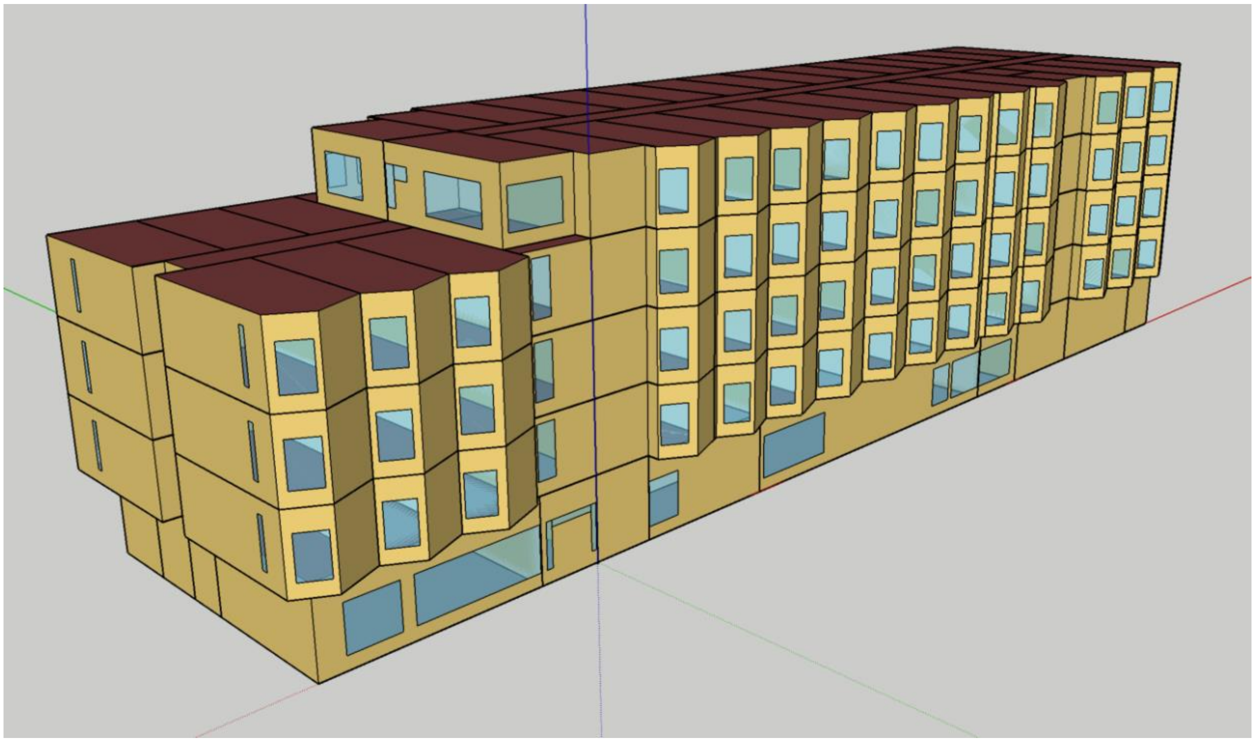

Figure A-1: Visualization of the Harvey West model geometry.

Overall, the project team found that it was also technically feasible to meet the CEC design goals for this building. The baseline energy model summary results for Harvey West are shown in **Figure A-2** and **Figure A-3**. The general strategy of leading with relatively cost-effecitive energy efficiency measures first, before designing more advanced systems or adding substantial battery storage, was the most cost-effective way to meet the load shifting related goals. Most of the individual measures adopted for the 995 ESC site were also optimal for Harvey West, though in several cases there was a substantial difference in the relative effect of individual measures. The same combined measures applied to 995 ESC resulted in an overall energy consumption reduction of 21% in Harvey West as shown in **Figure A-4**.

The building itself has smaller individual apartments (studios), less exposed exterior wall per apartment, and was designed to passive house standards. The location is cooler than San Jose causing the building's HVAC loads to be more heating-dominated as depicted in **Figure A-3**. Both the Ephoca and the hydronic system options had a more substantial performance boost over the Amana due to improved air tightness, less conduction with the outdoors, and improved efficiency in colder weather. Similarly, energy recovery was still an effective strategy, but there was less penalty for not having a bypass so the standalone in-unit ERV option was less negatively impacted. Again, due to the cooler climate, there is limited cooling load and little to no benefit from heat recovery for the hydronic system, so this option barely outperformed the otherwise comparable Ephoca case for this building, making it even further from being a viable option.

There are also more substantive differences between the two buildings. For example, the climate is cool enough in this location that individual in-unit cooling is not essential, and can be provided solely by the ventilation air system in rare, heat wave conditions. This minimum cooling energy consumption is observed both in the baseline (**Figure A-3**) and proposed (**Figure A-5**) design results during near-peak conditions. In addition, with the combined effective measures, the proposed design's heating consumption is almost non-existent. In theory, it may be feasible to design a primarily two-pipe hydronic system (i.e., heating only fan-coils in the apartments, served from the Domestic Hot Water piping via heat exchanger), though we did not explore this option in detail.

We also saw a similar effect that achieving 100% resilience to provide continuous TIER 1 capabilities indefinitely during a power outage was very challenging and costly, primarily due to the battery size required to pass through rare multi-day cloudy periods with very little solar power generation. Relaxing this constraint to 95% or even 99% has a large impact on costs

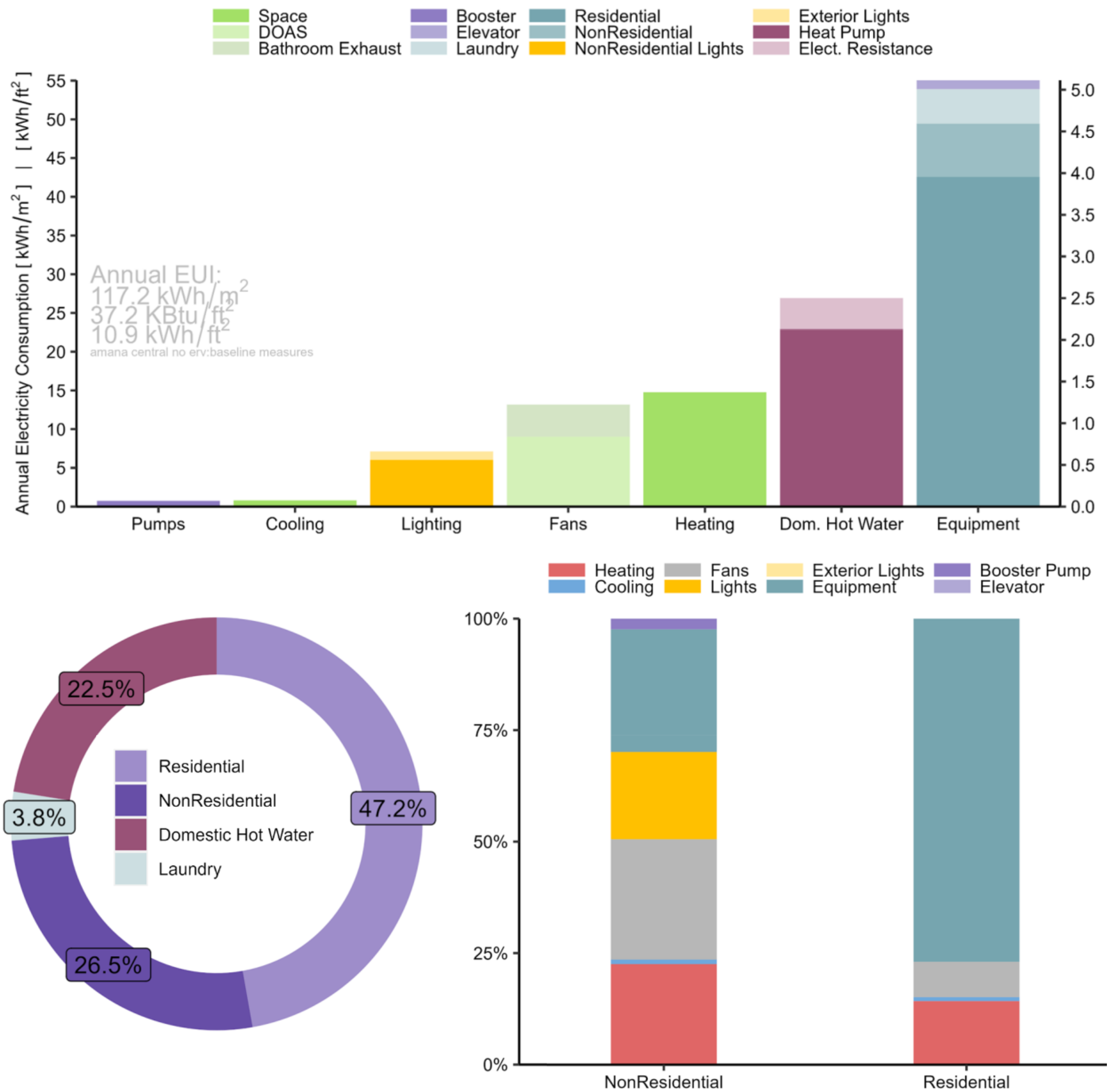

Figure A-2: Summary results for baseline building for Harvey West Apartments. Top) annual electricity end-use consumption for the whole building. Bottom left) high-level breakdown of annual electricity consumption with a more granular breakdown (bottom right) of non-residential and residential electricity consumption. Lighting, refrigerator, range, television, and other miscellaneous plug loads are captured in the *Residential Equipment Electricity* subcategory.

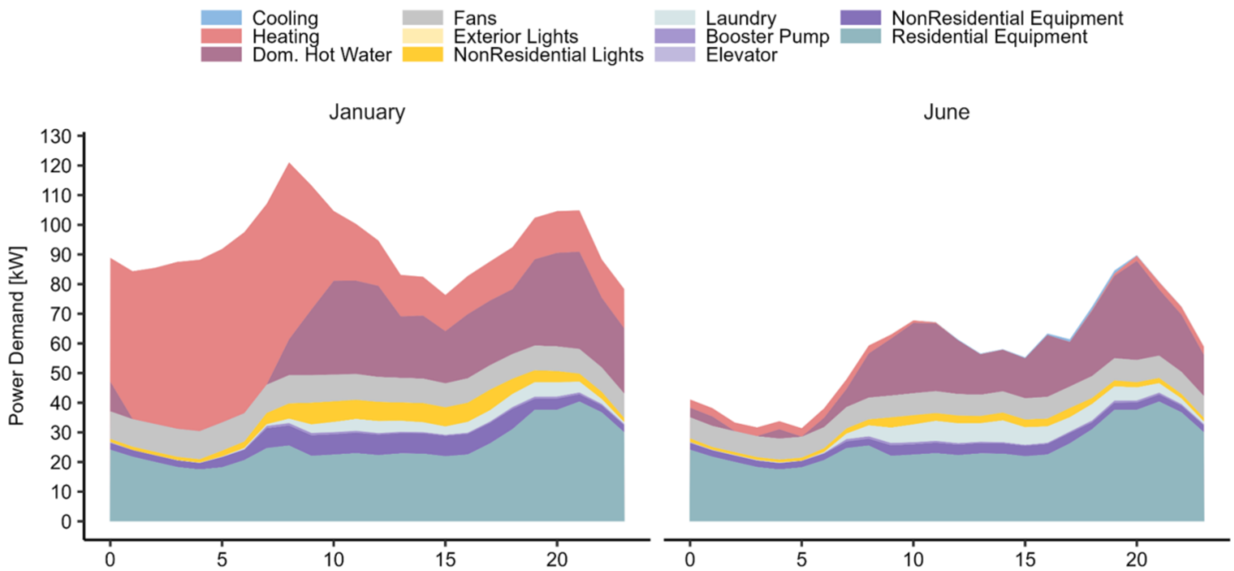

Figure A-3: Baseline design end-use power demand in a 24-hour day at near peak heating (left) and cooling (right) conditions for the combined measures energy model of Harvey West Apartments.

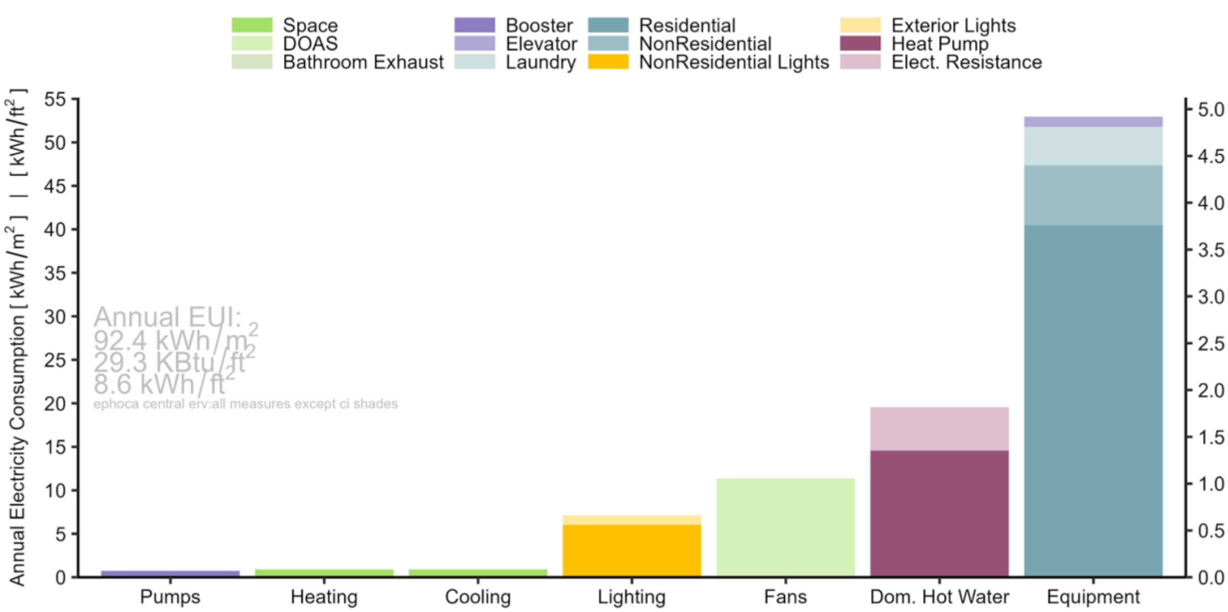

Figure A-4: Annual electricity end-use consumption for the whole building of the proposed design of Harvey West Apartments with combined measures.

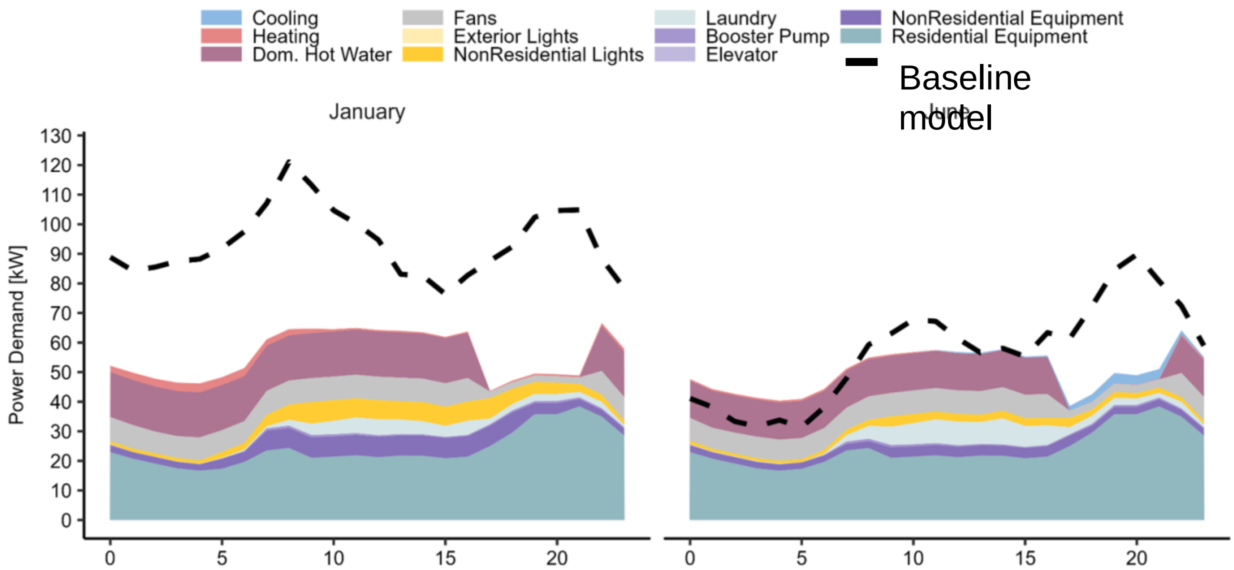

Figure A-5: Proposed design end-use power demand in a 24-hour day at near peak heating (left) and cooling (right) conditions for the combined measures energy model of Harvey West Apartments with combined measures.