

Task 1: State Department of Hawaiian Homelands: Technical Support, Subtask 2: Energy Simulation and Design Recommendations

FINAL PROJECT REPORT

Methods for Establishing and Validating Architectural Models to Analyze Building Performance
of Existing Conditions and Simulated Design Options for Three Department of Hawaiian
Homeland Residential Buildings in Kapolei, Oahu, Hawai'i

Submitted to
Hawai'i Natural Energy Institute (HNEI)
School of Ocean and Earth Science and Technology
University of Hawai'i at Manoa

Submitted by
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We thank the staff of Department of Hawai'ian Home Lands for information on the inventory of the homes in Kanehili neighborhood in Kapolei, the staff of Gentry for providing construction documents and other information on the houses they built in the neighborhood, and the staff of Honsador and Habitat for Humanity Leeward for feedback. We would also like to sincerely thank the volunteer homeowners for kindly opening their homes to us for this study.

We would like to thank the Environmental Research and Design Lab student research team, including Benjamin Thrun, Shane Matsunaga, Dustin Chang, Riley Josephson, Kathryn Paradis, Carlos Paradis, Aarthi Padmanabhan, and Branden Annino for their contributions and inspirations.

SECTION 1 – EXECUTIVE SUMMARY

The overall goal of the collaboration between the School of Architecture’s Environmental Research and Design Lab (ERDL) and the Hawai’i Natural Energy Institute (HNEI) is to reduce Hawai’i’s dependence on imported oil and reduce greenhouse gas emissions. This study focused on providing house design and operation guidance to improve thermal comfort and reduce energy use and energy cost. The technical support was provided to the Department of Hawaiian Home Lands (DHHL) and two of their designers/builders who build hundreds of houses for Native Hawaiian families. The lessons learned can be applied to future houses constructed in this climate zone. Three existing house types were studied: centrally air-conditioned; partially air-conditioned; and naturally ventilated (no air-conditioning). For each house type, whole building energy models representing the following cases were compared: 1. Existing house; 2. House minimally compliant with IECC 2015; 3. Sensitivity studies for individual design variables; 4. House with combined energy efficiency measures; 5. House with on-site renewable energy generation for net-zero energy.

Objectives:

1. Characterize the energy performance of typical single-family homes built on lands administered by DHHL.
2. Evaluate Building Energy Optimization Tool (BEopt) software for its ability to estimate relative performance of design options in terms of site and source energy use, greenhouse gas emissions, and thermal comfort.
3. Evaluate the ease of use of performance simulations for detached residential design as a flexible compliance pathway for the new Hawai’i State Energy Code based on IECC 2015 and create models that are minimally compliant to this code for the three DHHL house types.
4. Calibrate the computational models against the actual monitored energy use and temperatures gathered from the existing houses.
5. Identify and quantify potential future design strategies to exceed the new energy code and improve thermal comfort in the DHHL house types. Estimate the size of a photovoltaic array that would achieve net-zero site energy.
6. Communicate these design strategies to DHHL, the designers, and the builders for consideration in future thousands of homes planned for development.
7. Train advanced-level architecture and engineering students, who are the design professionals of tomorrow in building monitoring, data analysis, and computer building performance simulation.

It is important to acknowledge that building energy simulations estimate energy use based on several inputs that may vary in actual building operation. They are valuable design tools used to quantitatively compare design options in terms of relative, rather than absolute, savings in energy and greenhouse gas emissions.

Summary Results

Based on the parametric analyses, the team selected the energy efficiency measures at the point of diminishing returns and anticipated acceptability by builders and residents. These were inputs to an energy model named “Combined Measures” for each house type. The selected measures and their individual and combined annual energy reductions as compared to the IECC 2015 base case are listed below.

For the centrally air-conditioned house:

- Variable speed SEER 24.5 HVAC (28.6%); five premium efficiency fans with occupancy sensors and increased cooling set-point from 75°F to 79°F (17.6%); all energy efficient appliances (8.1%); light-colored exterior finish with absorptivity of 0.3 (3.5%); white metal roof with absorptivity of 0.30 (2.8%); double sided foil radiant barrier (1.4%); and 100% LED lighting (0.3%).
- This combination of measures reduced the annual site energy consumption by 47.3% compared to a minimally compliant IECC 2015 model. This results in an energy utilization index (EUI) of 13.9 kBtu/sf/yr (4.1 kWh/sf/yr).
- Net-zero site energy could be achieved by using 41% of available roof area for a 4.5-kW photovoltaic (PV) array. A maximum potential production of 208% could be achieved by using all available roof area for a 10.9-kW array (e.g. for electric vehicles).

For the partially air-conditioned house:

- Two premium efficiency ceiling fans and increased cooling set-point from 75°F to 79°F (19.4%); all energy efficient appliances (10.0%); a mini-split heat pump, 36 kBtu/h, SEER 20 HVAC (7.8%); fraction of window area openable 0.5 with 100% of windows open (3.7%); light exterior finish with absorptivity 0.3 (2.3%); wall insulation R-20 open cell spray foam (1.5%); window SHGC 0.15 (1.3%); 100% LED lighting (1.2%); white metal roof with absorptivity 0.3 (0.9%); double sided foil radiant barrier (0.4%). Increasing the window area to 20% of finished floor area increased energy consumption by 0.3%, but the team selected it to provide better natural ventilation for the unconditioned zones.
- This combination of measures reduced the annual site energy consumption 41.1% compared to a minimally compliant IECC 2015 model. This results in an EUI of 12.2 kBtu/sf/yr (3.6 kWh/sf/yr).
- Net-zero site energy could be achieved by using 11% of available roof area for a 3.7-kW photovoltaic (PV) array. A maximum potential production of 875% could be achieved by using all available roof area for a 34.6-kW array.

For the naturally ventilated house:

- All energy efficient appliances (15.4%); three premium efficiency fans with occupancy sensors (6.2%); solar water heater with electric backup (1.2%); 100% LED lighting (0.5%); light color exterior with absorptivity 0.3 (0.3%); low-e windows with SHGC 0.3 (0.2%); attic insulation at

ceiling and vented (0.2%); and double sided foil radiant barrier (0.1%). While solar hot water system was selected for this two-bedroom home, it could be argued that a favorable return-on-investment would not been seen for such low occupancy.

- This combination of measures reduced the annual site energy consumption 23.5% compared to a minimally compliant IECC 2015 model. This results in an EUI of 16.2 kBtu/sf/yr (4.7 kWh/sf/yr).
- Net-zero site energy could be achieved by using 18% of available roof area for a 2.8-kW photovoltaic (PV) array. A maximum potential production of 590% could be achieved by using all available roof areas for a 15.2-kW array.
- Thermal comfort was assessed using ASHRAE 55-2017 with an elevated air speed of 200 fpm provided by fans. The IECC 2015 baseline model was predicted to have 290 hrs/yr (3.3% of the time) of unacceptably hot indoor conditions vs. the combined strategies model with just two hrs/year. The thermal comfort studies show that the interior temperature varies significantly depending on when occupants open and close the windows.

Evaluation of BEopt software:

- It is an efficient, versatile and readily usable software application. Simulation could be used more widely in Hawai'i as a design tool to demonstrate energy code compliance and give designers more flexibility in design choices. While our team chose to spend significant time learning about the default and custom design options, the residential-specific pre-set design options are helpful and could be used quickly.
- The output from BEopt was very useful and easily generated, with graphs available in many metrics and time periods. The team required experience and expertise to analyze and interpret the simulation results.
- BEopt cannot divide the house in multiple zones, so thermal comfort could not be analyzed for the partially air-conditioned house type.
- The cost optimization portion of the BEopt software was not effective for our analysis since it continually crashed the program. Also, Hawai'i-specific costs for labor and material were not readily available for the BEopt options used in the simulations. The determination of such unit cost was beyond the scope of this project.
- Model validation: The simulation's single interior temperature was reasonably like the measured interior temperature in the relatively small naturally ventilated house. In the building energy simulation for each house type, the number of occupants and plug loads required adjustment to reflect observed conditions in order to align with the measured data.

Greenhouse gas emissions in metric tons of carbon dioxide equivalents (MT CO₂e) saved:

Modifying the existing house designs to minimally meet IECC 2015 energy code increased greenhouse gas emissions. This was due the existing houses having more efficient appliances and air-conditioning equipment than is required by IECC 2015 and an increased ventilation rate requirement of the IECC 2015 code. Also House 2 changed from using some propane to using all electricity which has a higher source to site ratio. Improving house designs from minimally compliant to IECC 2015 energy code for the fully conditioned, partially conditioned, and naturally ventilated house designs saved 14.6 MT CO₂e, 9.5 MT CO₂e, and 2.8 MT CO₂e, respectively (Figure 1.1). That is a 23% to 47% reduction. Metrics are explained in detail in section 2.4.

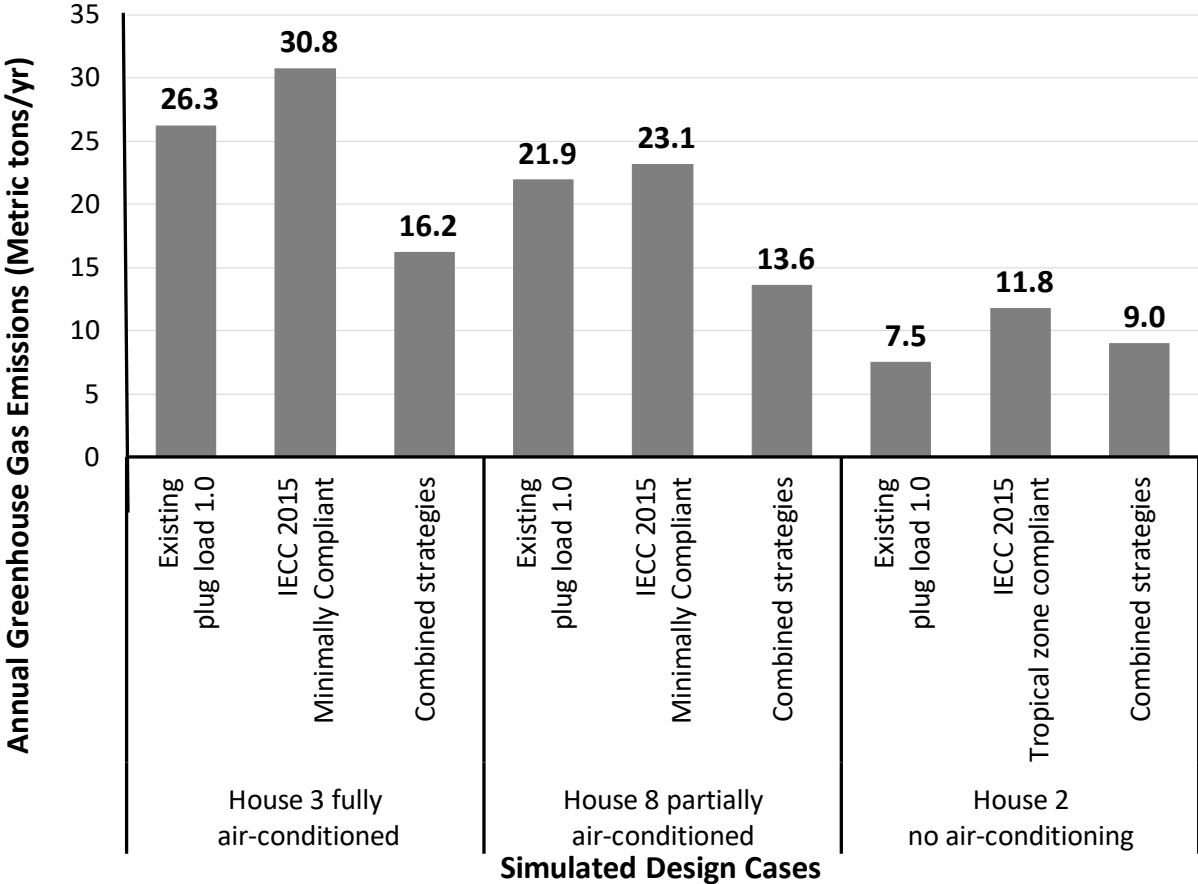


Figure 1.1 Greenhouse gas emissions (CO₂e metric tons/yr) for the existing design, IECC2015 minimally compliant design, and the combined strategies design for house 3 (centrally conditioned), house 8 (partially conditioned), and house 2 (naturally ventilated).

Energy costs saved:

Modifying the existing house designs to minimally meet IECC 2015 energy code increased energy costs for the conditioned houses. This was due the existing houses having more efficient appliances and air-conditioning equipment than is required by IECC 2015 and an increased ventilation rate requirement of the IECC 2015 code. Costs were based on \$0.28/kWh for electricity and \$7.02/gallon of delivered propane¹. This was due to less efficient appliances and air-conditioning equipment, and an increased ventilation rate requirement. Improving house designs from minimally compliant to IECC 2015 energy code for the fully conditioned, partially conditioned, and naturally ventilated house designs saved \$1,689, \$1,107, and \$321 annually, respectively (Figure 1.2). That is 47%, 41%, and 23% reductions in costs, respectively.

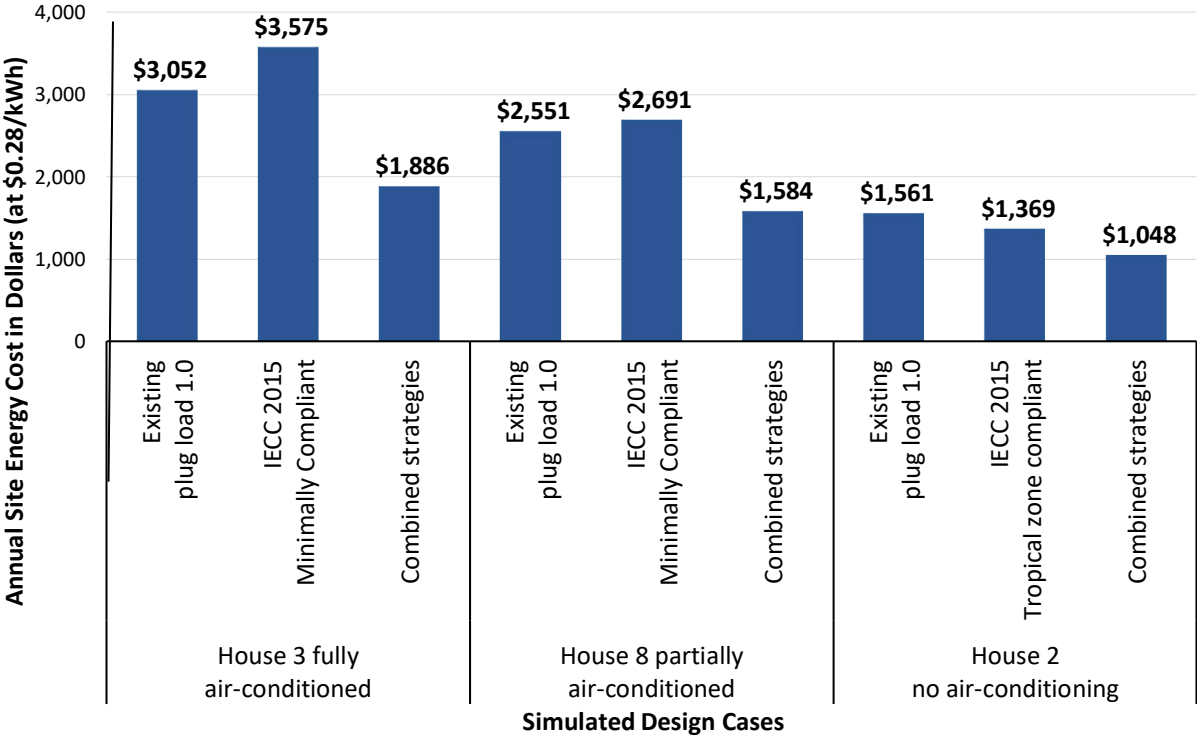


Figure 1.2 Annual energy costs in dollars based on \$0.28/kWh for electricity and \$7.02/gallon for propane.

This report is organized into a 1) Executive Summary, 2) Background Information and Objectives, 3) Detailed Performance Analysis of Three Example Residential House Types 4) General Conclusions and Recommendations, and 5) Appendices.

¹ Quote from the Gas Company by phone on 6/24/19: \$540.77 + 4.5% tax on 80 gallons delivered by truck.

SECTION 2 – BACKGROUND INFORMATION AND OBJECTIVES

2.1 Introduction

The overall objective of the collaboration between the School of Architecture’s Environmental Research and Design Lab (ERDL) and the Hawai’i Natural Energy Institute (HNEI) is to reduce Hawai’i’s dependence on imported oil, reduce greenhouse gas emissions, and to ensure tangible benefits to the Hawai’i consumer through outreach, professional technical development and demonstration projects. This study focused on providing technical support to the Department of Hawaiian Home Lands (DHHL) and two sets of their design/builders (Gentry; Habitat for Humanity using a Honsador packaged design) to improve comfort and energy efficiency of homes built in their neighborhoods. The lessons learned can be applied to future houses constructed in this climate zone.

The main function of DHHL is to facilitate housing for native Hawaiian beneficiaries. In the past 20 years, DHHL has built over 2,590 homes. It currently owns over 200,000 acres of land on which it plans to construct another 875 homes over the next 5 years². DHHL is the only housing developer in Hawai’i dedicated to providing new homes to Hawaiian families. Historically, the homes have been adequate and affordable, but DHHL has not provided aggressive standards for building performance beyond code and there has been no post-occupancy work done to evaluate the energy performance or the level of occupant comfort in the various house types that have been constructed and occupied. The staff at ERDL is working with DHHL to reduce energy use and improve comfort through data-based building performance standards.

This study demonstrates how to improve the design of three typical house types in Hawai’i: fully air-conditioned, partially air-conditioned, and naturally ventilated (no air-conditioning). It was conducted from June 2017 to April 2019 and consisted of three components: monitoring existing houses; creating energy simulation models; and making design recommendations. The monitored houses, located in the DHHL neighborhood of Kaneheli in Kapolei, Oahu, were built between 2009 and 2017, when the Hawai’i energy code was based on the 2006 International Energy Conservation (IECC 2006) energy code. A team of researchers at ERDL used construction documents, field notes and other information to create energy simulation models of the three house types. The houses were sub-metered for a year and the data were used to validate the energy models. These three existing-house models were modified to be minimally compliant to the new Hawai’i energy code based on IECC 2015. Some features were upgraded and others were downgraded to minimally meet the code.

The IECC 2015 models were used as a baselines to compare how different energy conservation measures (ECMs) would individually affect the predicted annual energy consumption. A combination of ECMs were then selected by the research team to create a “combined strategy” model for each house type. The simulation models for the naturally ventilated house were also assessed for thermal comfort.

² Personal communication, Darrel Ing, DHHL, Kapolei, email 10/5/16

2.2 Objectives and Benefits of this Project

The project had the following objectives:

1. Characterize the energy performance of typical single-family homes built on lands administered by DHHL.
2. Evaluate Building Energy Optimization Tool (BEopt) software for its ability to estimate relative performance of design options in terms of site and source energy use, greenhouse gas emissions, and thermal comfort.
3. Evaluate the ease of use of performance simulations for detached residential design as a flexible compliance pathway for the new Hawai'i State Energy Code based on IECC 2015 and create models that are minimally compliant to this code for the three DHHL house types.
4. Calibrate the computational models against the actual monitored energy use and temperatures gathered from the existing houses.
5. Identify and quantify potential future design strategies to exceed the new energy code and improve thermal comfort in the DHHL house types. Estimate the size of a photovoltaic array that would achieve net-zero site energy.
6. Communicate these design strategies to DHHL, the designers, and the builders for consideration in future thousands of homes planned for development.
7. Train advanced-level architecture and engineering students, who are the design professionals of tomorrow in building monitoring, data analysis, and computer building performance simulation.

The project has the following additional benefits:

- The investigation into the energy consumption of typical DHHL building types has benefits for the general understanding of residential building strategies in Hawai'i and this climate zone.
- This strategy would support DHHL's mission of providing affordable housing: not just the purchase of the house, but the operational costs as well.

2.3 Project Team

The project work has been carried out by the staff of ERDL and one outside consultant.

The project work has been under the direction of:

- Stephen Meder, D.Arch, ERDL, Director though Aug.31, 2018
- Wendy Meguro, M.Sc, AIA, ERDL, Director as of September 1, 2018

The ERDL staff responsible for monitoring and analyzing the existing homes, and authoring the separate monitoring report and editing this report:

- Eileen Peppard, M.Sc., Sustainability Specialist, ERDL and Sea Grant program

The outside consultant who supported the research work, trained the students and staff in the use of the simulation tools, advised about building physics principles, was the sole author of Appendix A on general building performance measures and Appendix B on building performances benchmarked in the study, and drafted the initial project report:

- Manfred Zapka, Ph.D., P.E., Principal, Sustainable Design & Consulting, LLC

The following ERDL-paid student researchers carried out literature reviews, monitoring, building energy simulations, appliance research, graphs, draft report writing, preliminary results for developers, and an outreach flyer for homeowners under guidance of the ERDL staff:

- Dustin Chang
- Riley Josephson
- Shane Matsunaga
- Benjamin Thrun
- Carlos Paradis
- Kathryn Paradis
- Aarthi Padmanabhan
- Branden Annino

In-person outreach to DHHL, developers, and homeowners was conducted by Eileen Peppard and Wendy Meguro.

2.4 House Performance Metrics Used in the Project

The following section discusses the metrics used to achieve the project objectives of quantifying potential energy and comfort improvements to the existing residential building types. More detailed descriptions of general building performance measures can be found in Appendix A, and more information on building performance processes benchmarked in study can be found in Appendix B.

2.4.1 Building Energy Consumption and Savings

For this project, electric energy and propane gas consumption of houses was quantified. Some of the building design alternatives include solar thermal and photovoltaic energy sources which were considered within the boundary of the building system and decrease the amount of external energy supplied to the building. Some design alternatives evaluated the use of propane as an external energy supply to lower the electric energy consumption. For this study, annual site energy, expressed in kilowatt hours (kWh) or millions of British thermal units (MMBtu) per year, was quantified. Annual source energy, usually expressed in MMBtu, can be calculated from site energy and it factors in the effectiveness of the energy conversion process and transmission and distribution losses. The source-site ratios used for this study are listed in Table 2.4.3.1. Energy savings in USD for design alternatives were calculated and compared to a benchmark.

Table 2.4.1.1 Source-site ratios for energy types.

Energy Type	Ratio
Electricity, grid supply	3.17 ¹
Propane	1.15 ²

¹Hawai'i electrical grid (Hawai'i Energy 2018)

²US National average (Wilson et al. 2014)

2.4.2 Indoor Thermal Comfort

Indoor thermal comfort is a subset Indoor Environmental Quality (IEQ) which includes indoor air quality, acoustic, light, odor, daylighting, and others. The scope of this study considers only the effects building design and forced ventilation rates on thermal comfort and energy demand.

The thermal comfort objectives were motivated by the over-heating complaints from residents of existing homes. The scope was to measure actual interior conditions and identify and simulate potential improvements. The quantitative assessment of indoor thermal comfort for the naturally ventilated house type in this study followed the ASHRAE 55-2017 adaptive comfort standard. Indoor thermal comfort levels were assessed using indoor air temperatures that were measured or were results of building simulations.

2.4.3 Greenhouse Gases

The amount of greenhouse gas (GHG) that is associated with energy consumption is an increasingly important metric of building performance and a critical concern for Hawai'i to reach its clean energy goals. A greenhouse gas in the atmosphere is defined as a gas that absorbs and then emits radiant energy, causing thermal conditions that contribute to the greenhouse effect. This effect makes life as we know on earth possible as it elevates the global average temperature from subzero temperatures which would prevail without the greenhouse effect. On the other hand, an accelerated greenhouse effect is reported to have serious negative repercussions in the future when higher temperatures will likely cause a range of significant negative impacts on the natural environment. Among a range of greenhouse gases, carbon dioxide, through a combination of its high concentration in the atmosphere, atmospheric lifetime and radiative effect, contributes the most to the greenhouse effect. Carbon dioxide has therefore become the trace gas used to assess the risk for increasing the greenhouse effect.

The leading anthropogenic causes for the increased carbon dioxide levels are the burning of fossil fuels and the diminishing sink for this gas due to widespread deforestation. Both causes are the result of changes in the built environment which can be mitigated by using more sustainable urban and building design approaches. A reduction of carbon emissions in buildings can be achieved in several ways. First, by reducing the amount of electric energy consumed by the building will reduce emissions at the power plant, where electricity is generated. Second, by replacing grid- supplied electric energy by electricity generated at the building, such as with photovoltaic panels. Third, by replacing electricity with either renewable or fossil fuels for thermal energy services such as domestic hot water production. And fourth, by converting energy at the site in combined heat and electric energy generating processes. In these cases, waste heat can be harnessed for processes that would normally require a significant primary energy source.

For this study, carbon emissions in metric tons per year were calculated from source energy. Carbon emissions for Oahu's electricity was calculated using this formula:

$$\frac{(Annual\ electricity\ in\ kWh) * (1.675\ lbs\ CO_2-e/kWh^3)}{(2204.62\ lbs\ per\ metric\ ton) * (3.17\ source\ to\ site\ ratio^4)}$$

Carbon emissions for propane use was calculated using the following formula:

$$\frac{(Annual\ gallons\ of\ propane) * (91,333\ Btu\ per\ gallon^5) / (1\ million) * (139\ lbs\ CO_2\ per\ million\ Btu^6)}{(2204.62\ lbs\ per\ metric\ ton) * (1.15\ source\ to\ site\ ratio^7)}$$

³ eGrid calculator (USEPA 2016)

⁴ Hawaii Energy 2018

⁵ USEIA 2019a

⁶ USEIA 2019b

⁷ Wilson et al. 2014

2.4.4 Net Zero Energy Performance

While the goal of the net-zero energy building concept is to generate the same or more energy by renewable means than energy consumed, even a partial replacement of energy generated by fossil fuel is desirable. These “nearly net zero energy houses” represent an important stepping stone on the path to achieve significant curbing of greenhouse gas emissions from buildings.

Some of the primary building technology measures (not project-specific) that make net zero energy performance possible include the following:

- High performance building envelope, which reduce energy use for heating and cooling.
- High performance all insulation and glazing.
- High efficiency building conditioning equipment, including heating, cooling and space ventilation
- High efficiency heat pumps and thermal systems to replace some of the electricity loads for thermal processes.
- High efficiency lighting, including controls, and use of daylighting
- Replacing electricity with other energy forms that reduce the source energy
- High efficiency appliances and miscellaneous energy use
- Solar panels or small-scale wind generators which generate energy at the site
- Off-site renewable energy conversion processes which offset energy used in the building.
- Storage for renewable energy generated at the site to avoid drawing energy from the grid during periods of intermittent renewable energy generation or to become totally independent from grid supplied energy
- Other technologies if applicable

The study uses the degree of “net-zero energy”, which means the percentage of full net-zero energy performance, as a building performance metric.

2.4.5 Energy Use Intensity

The energy use intensity (EUI) is one of the key metrics of the Energy Star Portfolio Manager. While the EUI metric is primarily an energy performance metric for commercial and institutional buildings, the EUI is also useful to define the energy performance of residential homes. Based on the EUI the building can be issued a rating or the building can be benchmarked against a selected standard performance building. The most common application of the EUI performance metric is the energy use per square foot on an annual basis. The EUI can either be expressed in terms of site and source energy. Typically, the lower the EUI, expressed as kBtu per square foot (sqft.) per year, the better is the building energy performance. Our study uses the Energy Use Intensity (EUI) to represent the overall energy performance of the buildings.

2.5 Mandatory Energy Code and Main Governing Standards Used in Project

This section presents a short introduction in the energy code and other relevant building standards that were used and referred to in the study. The new Hawai'i State Energy Code has been introduced on state level and county wide adoptions of the new energy code is expected in the second half of 2019.

2.5.1 2015 IECC and Hawai'i Amendments

The new Hawai'i energy code is based on the 2015 IECC (International Energy Conservation Code), with a Hawai'i Specific amendment. The amendment defines Hawai'i climate and regional specific additions or modifications of the 2015 IECC base code. Figure 2.5.1.1 illustrates the Hawai'i specific structure of the Hawai'i energy code.

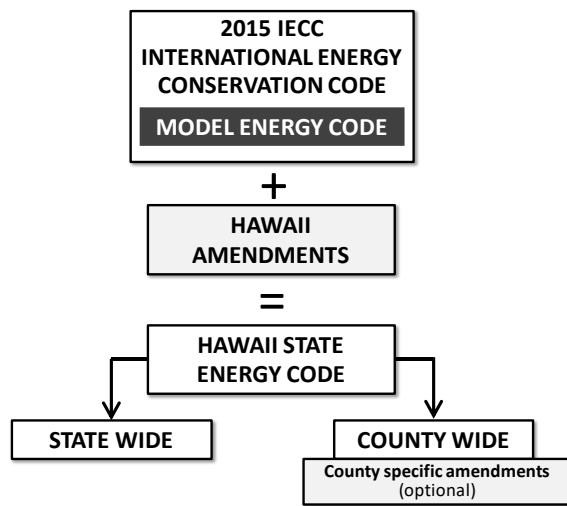


Figure 2.5.1.1: Structure of the Hawai'i energy code.

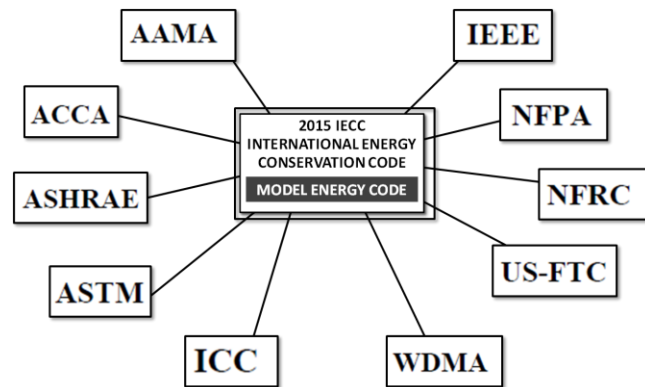


Figure 2.5.1.2: Industry standards referenced and/or required in the 2015 IECC

The IECC refers to a range of building standards which delineate the specific energy performance metrics that is required under the code. The present study has considered, directly or through the building energy simulation software, some 10 building performance standards. These 10 building performance standards are illustrated in Figure 2.5.1.2 and the names of the Organizations responsible for the publishing and maintaining the standard are provided in Table 2.5.1.1.

SECTION 2 – BACKGROUND INFORMATION AND OBJECTIVES

Symbol	Name	Main functions
AAMA	American Architectural Manufacturers Association	Specifications for Windows, Doors and Unit Skylights
ACCA	Air Conditioning Contractors of America	Residential Cooling sizing and Equipment Selection
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.	Fundamentals and Airtightness of HVAC Equipment
ASTM	ASTM International	Standard test methods for large range of building materials and performance
ICC	International Code Council, Inc.	Family of codes regulating building methods and designs ; including codes for building, fire, mechanical, plumbing, sewage, residential code
IEEE	The Institute of Electrical and Electronic Engineers, Inc.	Testing, Design, Installation, and Maintenance of Electrical equipment
NFPA	National Fire Protection Association.	National Electrical Code
NFRC	National Fenestration Rating Council, Inc.	Specification for Fenestration including U-factors, Solar Heat Gain Coefficients, Visible Transmittance, Air Leakage
US-FTC	United States-Federal Trade Commission	R-value Rule (in CFR)
WDMA	Window and Door Manufacturers Association	Fenestration Standard/Specification for Windows, Doors and Unit Skylights

Table 2.5.1.1: Names of organizations publishing standard reference in 2015 IECC

The Hawai'i State Energy Code provides the required as well as recommended building energy measures. The code covers both commercial and residential buildings. Figure 2.5.1.3 illustrates a comparison of the electable compliance pathways for commercial and residential buildings. Since the present study is only concerned with residential buildings only the residential part of the Hawai'i energy code will be discussed.

As illustrated in Figure 2.5.1.3 there are three categories of compliance under the residential part of the Hawai'i energy code, with the performance-based compliance option offering two compliance pathways. The compliance pathways are briefly discussed in Table 2.5.1.2:

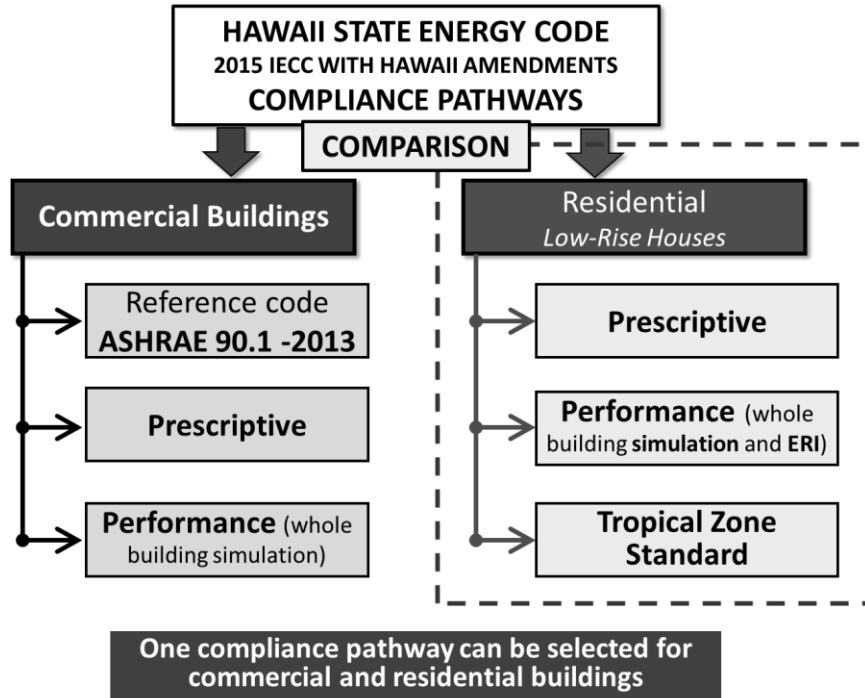


Figure 2.5.1.3: Compliance pathways comparison of 2015 IECC for commercial and residential buildings

Table 2.5.1.2: Four compliance pathways under the Residential part of the Hawai'i State Energy Code

No.	Category of compliance pathway	Description of compliance pathway
1	Prescriptive	Follow the requirements of Sections R401 to R404 of the code; Provides practical and ready identification what energy efficiency measure (EEM) to use in proposed design. The prescriptive compliance pathway is satisfied if the proposed design incorporates are required EEMs.
2	Performance based	Use of an accepted simulation tool to determine if energy performance of proposed design is equal or better than a Standard Reference Design. The Standard References Design is delineated in Section R405 of the code.
3	Performance based	Use an Energy Rating Index (ERI) to determine and quantify the energy performance of a building. The code indicates that the HERS index (Home Energy Rating System (HERS)) can be used to show compliance with the ERI pathway. HERS index assigns a score with 100 being the energy performance of the “American Standard Building” and with 0 indicating a Zero Energy Building). The ERI compliance pathway is satisfied with a score of equal or under 52.

Table 2.5.1.2: Four compliance pathways under the Residential part of the Hawai'i State Energy Code

No.	Category of compliance pathway	Description of compliance pathway
4	Tropical Zone standard	Code compliance is achieved when all energy efficiency measures which are prescribed in the code are satisfied. The Tropical Zone compliance path differs from the prescriptive path as the Tropical Zone standard is tailored to promote houses built for the Hawai'i specific climate and with no or limited use of mechanical cooling.

The following approach was used in the present study to apply the different code compliance pathways:

No.	Name of compliance pathway	Approach of using the code compliance pathway
1	Prescriptive	The prescriptive compliance was used as a reference to determine the energy performance of selected building components and designs.
2	Performance based - simulation	The present study mainly used the performance-based compliance pathway using whole building simulation and benchmarking against a 2015 IECC standard reference design, which is consistent with the design intent of the proposed design
3	Performance based - ERI	The ERI pathway is not used.
4	Tropical Zone Standard	The requirements of the Tropical Zone Standard were used to determine the energy use of a building that conforms to the Tropical Zone Standard. The Tropical Zone Standard was not used directly for code compliance.

2.5.2 ASHRAE 62.2 - Required Ventilation

The ASHRAE standard 62.2 was used for the present study to determine compliance with the mandated ventilation rates in the residential buildings. The Hawai'i energy code refers to the Standard 62.2 and the simulation software used for the present study uses the standard.

The ASHARE Standard 62.2 applies to spaces intended for human occupancy within single- family houses and multifamily buildings. The standard delineates the minimum requirements for indoor ventilation, which could include mechanical as well as natural ventilation. The three main objectives of the standard are whole-building ventilation, local demand-controlled exhaust and indoor source control.

Under the Tropical Zone Standard of the Hawai'i energy code an exception is granted for the mechanical ventilation requirement if a threshold size of operable openings per floor area can be achieved and surpassed.

2.5.3 ASHRAE 55 - Thermal Comfort

An acceptable level of thermal comfort in an indoor space adds value to the owner and occupant. There is no code requirement to achieve a certain level of thermal comfort and therefore comfort is a voluntary, albeit important function of the overall building performance.

In the present study, achieving acceptable thermal comfort levels was a goal specifically for designing naturally ventilated buildings. In the absence of mechanical cooling, the effect of a high-performance envelope does not have an effect, or at least only a negligible effect, on the overall energy performance of the building.

A high-performance building envelope, with significant wall and ceiling insulation and high efficiency glazing, of a natural ventilated building mitigates high conductive, convective and radiative heat gains to the interior. In this sense investments in a better performing building envelope primarily creates value through better thermal comfort. A smaller benefit of the higher performing envelope would be in saving plug load energy, such as reduced use of fans, to mitigate higher indoor temperatures. As is discussed later in the report, fans can significantly alleviate high indoor temperatures that would create marginal or unacceptable indoor thermal comfort levels.

The ASHRAE 55 standard (ASHRAE, 2017) provides quantitative metrics to determine the level of measured or predicted indoor thermal comfort. The ASHRAE 55 standard differentiates between spaces that are mechanically cooled and spaces that are naturally ventilated by using the Predicted Mean Vote (PMV) and the Adaptive Comfort prediction models, respectively. Both standards share the notion that the assessment is subjective, meaning that the experience of thermal comfort inside spaces with identical indoor environmental conditions might differ between occupants. The subjective aspect of the thermal comfort calculating model is solved by describing compliance with the standard of at least 80% of the occupants are satisfied. Expressed differently, it means that less than 20% of occupants can be dissatisfied.

The PMV model uses a calculation method that determines thermal comfort by using six input variables, which belong to two categories:

- Environmental thermal conditions which represent the indoor climate with indoor variables including air temperature, mean radiant temperature, humidity and air speed.
- Individual thermal conditions which represent the occupant level of physical activity and response to the indoor thermal conditions, including metabolic rate and clothing insulation.

The PMV model calculates a PMV value that is correlated to the Percentage People Dissatisfied (PPD). When the PPD is larger than 20%, which means when more the 20% of the occupants are expected to be dissatisfied with the thermal comfort conditions, the ASHRAE 55 standard indicates a “non-conformant” with the standard. The PMV model is based on heat balance equations of the human body and experimental data.

It should be noted that ASHRAE 55 requires that the use of the PMV and the adaptive comfort models for fully-conditioned and non-conditioned spaces, respectively. When spaces have mechanical cooling and the cooling is not operational it is generally accepted, while not explicitly endorsed by ASHRAE 55, to use the PMV model when the cooling system is in operation and the Adaptive Comfort model when space conditioning occurs without mechanical systems.

2.6 Simulation Software BEopt

The building performance analysis was carried out with the energy simulation software BEopt (Building Energy Optimization). The team used energy modeling protocols in the Building America Simulation Protocol, except to replace IECC 2009 values with IECC 2015 values.

BEopt is a software tool developed by the National Renewable Energy Laboratory (NREL). The BEopt software is available free of charge. BEopt provides capabilities to evaluate residential building designs and identifies cost-optimal efficiency packages at various levels of whole-house energy savings along the path to zero net energy. BEopt can be used to analyze both new construction and existing home retrofits, through evaluation of single building designs, parametric sweeps, and cost-based optimizations. BEopt uses existing, established simulation engines (currently DOE2.2 or EnergyPlus). Default simulation assumptions are based on the Building America House Simulation Protocols (Wilson et al, 2014). The default assumptions can be overwritten in the “options menu”. BEopt provides detailed simulation-based analysis based on specific house characteristics, such as size, architecture, occupancy, location, and utility rates. Discrete envelope and equipment options, reflecting realistic construction materials and practices, are evaluated.

The project team focused on the BEopt simulation software and utilize whole house single-zone simulation in lieu of the more detailed multi-zone and demanding simulation procedure provided by other energy simulation software products. It was decided that BEopt offered a readier pathway to accomplish relevant energy simulation by the ERDL team that lacked simulation experience at the start of the project.

SECTION 3 – DETAIL PERFORMANCE ANALYSIS OF THREE EXAMPLE RESIDENTIAL HOUSE TYPES

This section describes the comprehensive building performance analysis that was performed for three DHHL house types. They are referred to as House 3, House 8 and House 2, and they are representative of a fully air-conditioned house, a partially conditioned house and a naturally ventilated house, respectively. They are three of the nine existing houses monitored in the neighborhood. The effect of minimal compliance to the new Hawai'i State Energy Code (based on IECC 2015) on energy consumption is assessed as one house design case and compared with a “combined strategies” house design case that utilizes the best energy efficiency options selected from a parametric analysis.

3.1 Scope of Analysis

The objectives were to simulate the energy performance of three types of houses and compare the simulation results to measured data of the existing houses. Specific design cases tested for each house type were: the existing house design; an IECC 2015 minimally compliant house design; and a combined strategies house design that further reduces energy consumption. The combined strategies design will be recommended for future DHHL housing construction and developments. In addition, thermal comfort levels were determined for the naturally ventilated house type and the net-zero energy performance was assessed for all three house types. Table 3.1.1 shows three categories of analysis that were used for the three house types.

Table 3.1.1. Categories of analysis used for each house type.

Main categories of analysis	House 3: fully conditioned house type	House 8: partially conditioned house type	House 2: naturally ventilated house type
<u>Energy analysis:</u> Determining the energy consumption using energy simulation with BEopt and comparison with measured energy data	Applies	Applies	Applies
<u>Thermal comfort analysis:</u> Determining the indoor thermal comfort (only adaptive comfort approach) using indoor environmental data obtained from simulation with BEopt and comparison with measured data	Does not Apply	Does not Apply	Applies
<u>Net-zero energy performance:</u> Determining achievable levels of net-zero energy	Applies	Applies	Applies

SECTION 3 – DETAIL PERFORMANCE ANALYSIS OF THREE EXAMPLE RESIDENTIAL HOUSE TYPES

Figure 3.1.1 illustrates the data management for the performance analysis of energy and thermal comfort.

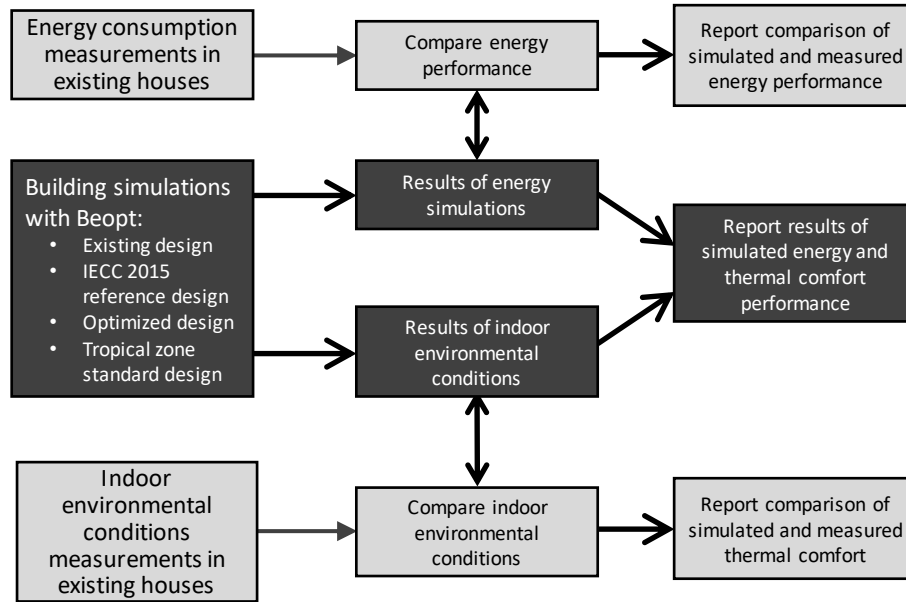


Figure 3.1.1: Illustration of data management for the performance analysis of energy and thermal comfort

Table 3.1.2 shows an overview of the house design cases which were used for the building simulations of the three types of houses.

Table 3.1.2 Overview of the house designs used in the building energy simulations for the three types of houses.

House design cases	House 3: fully conditioned	House 8: partially conditioned	House 2: naturally ventilated
Existing house design: House design case that represent the existing condition.	Applies	Applies	Applies
2015 IECC reference house design case: The proposed design case that is consistent with the 2015 IECC code and amended Hawai'i State Energy Code.	Applies	Applies	Applies: Note the Tropical Zone Standard design case is the 2015 IECC Reference
Combined strategies house design case: A proposed house design case with a combination of proposed energy efficiency measures.	Applies	Applies	Applies
Tropical Zone standard house design case: A design case that follows the specific code compliant house design created for Hawai'i's hot and moist climate.	Does not apply	Does not apply	Applies: Note the Tropical Zone Standard design case is the 2015 IECC Reference for House 2

SECTION 3 – DETAIL PERFORMANCE ANALYSIS OF THREE EXAMPLE RESIDENTIAL HOUSE TYPES

Table 3.1.3 Metrics uses for reporting the results of the study.

Description of metrics	Units
Site energy – Electricity	kWh/yr or kWh/day
Site energy – Propane	gal/yr
Site energy combined	MMBTU/yr
Site energy use intensity	kBtu/sqft/yr
Source energy combined	MMBTU/yr
Carbon emissions	Metric tons/yr
Energy costs (utility bills)	\$/yr
Indoor air temperature (air temperature is assumed as the operative temperature)	°F
Outdoor air temperature (to calculate the prevailing mean outdoor temperature for adaptive comfort analysis)	°F

3.2 Measurement of Energy Use, Temperature, and Humidity

The homes for this study are in the Department of Hawaiian Home Lands neighborhood of Kanehili in Kapolei on the island of Oahu, Hawai'i (approximately 21 20'11" N, 158 03'18" W, elevation 75'). A total of nine homes were monitored for a year: one 2-bedroom Honsador packaged home built by Habitat for Humanity (House 2), one 4-bedroom home built by the Center for Native Hawaiian Advancement (House 8), four 4-bedroom homes built by Gentry (including House 3), one 3-bedroom and one 5-bedroom homes built by Gentry (Table 3.2.1).

Table 3.2.1 Characteristics of the nine houses in the study and dates of monitoring.

House ID#	Air-conditioning	Total floor area (sqft)	Living area (sqft)	Bed-rooms	Stories	Year built	Occupancy	PV	Dates monitored
1	Central	2,116	1,603	4	2	2015	6	No	6/23/17–2/09/18
2	None	1,368	792	2	1	2010	1	No	11/1/17–9/14/18
3	Central	2,167	1,654	4	2	2010	8	No ¹	6/29/17–6/28/18
4	Central	2,167	1,654	4	2	2009	2	Yes	6/28/17–6/27/18
5	Central	2,116	1,603	4	2	2009	2	Yes	9/15/17–9/14/18
6	Central	2,426	1,603	4	2	2009	3	Yes	6/28/17–6/27/18
7	Central	2,040	1,527	3	1	2009	3	Yes	9/15/17–9/14/18
8	Partial/split	2,480	1,788 ²	4	1	2011	5	Yes	6/28/17–6/27/18
9	Central	2,189	1,676	5	2	2010	6	No	6/28/17–6/27/18

¹House 3 added PV during the year but it was not monitored

²House 8's original living area was 1,581 sqft and that value was used in the simulation model. A small lanai was closed in during the study, so the larger area of 1,788 sqft was using to calculate the existing house's EUI.

SECTION 3 – DETAIL PERFORMANCE ANALYSIS OF THREE EXAMPLE RESIDENTIAL HOUSE TYPES

Energy data were collected in 1-minute intervals by sub-metering breaker panels for major loads: whole house, air-conditioner compressor, air handling unit, water heater, dryer, refrigerator, stove, and photovoltaic production if present. “Other” loads were calculated by subtracting loads from whole house energy use and these include plug loads and lighting which are generally not placed on separate breakers in homes. The “other” category is affected by lifestyle choices and the number of residents in the home. Disaggregated energy use is shown in Table 3.2.2. Only 3.5 months of power data were collected from House 2, but propane use for 11 months was measured (stove, instant water heater, and dryer were propane) and annual use was estimated for both (1,964 kWh/yr and 32.7 gal/yr). Site energy use intensities are listed in Table 3.2.3.

Table 3.2.2 Annual energy use (kWh/yr) disaggregated by end use and PV production for eight of the nine metered houses.

End-use	House ID#							
	1 ¹	3	4	5	6	7	8	9
AC compressor	5,393	5,540	1,374	5,270	5,069	3,636	3,895 ⁴	5,753
AC air handling unit	573	1,211	1,081	918	1,069	706		1,063
Water Heater	816	625	108	387	146	62	149	548
Large appliances								
Dryer	1,393	1,128	186	607	856	729	1,111	1,274
Refrigerator	323	1,203	839	714	718	1,045	939	1,151
Stove	985	571	224	93		212	393	487
Plug loads and lights	4,153	3,747	2,375	3,479	4,523	4,065	8,682	2,845
Whole house	13,636	14,025	6,187	11,468	12,381	10,455	15,169	13,121
PV Production	0	0 ²	5,422	5,262	4,066	6,851 ³	12,454	0
Net Use	13,636	14,025	765	6,206	8,315	3,604	2,715	13,121

¹House 1 annual data was estimated based on 7.5 months of metered data.

²House 3 added PV during the year but it was not metered.

³House 7 was missing 21 days of PV data, which was estimated.

⁴House 8 had a split-ac with only one point of measurement.

Table 3.2.3. Metered annual site energy use intensity based on total floor area and living area.

House ID#	Site energy use intensity (kBtu/sqft/yr)	
	Based on total floor area	Based on living area
1	22.1	29.2
2	7.1	12.2
3	22.1	28.9
4	9.7	12.8
5	18.5	24.4
6	17.4	26.4
7	17.5	23.4

SECTION 3 – DETAIL PERFORMANCE ANALYSIS OF THREE EXAMPLE RESIDENTIAL HOUSE TYPES

8	20.9	28.9
9	20.4	26.7

House 2 had only one resident with very energy-efficient habits and therefore had lower than typical “other” loads for a 2-bedroom home. House 3 had eight residents and therefore had higher than normal loads for a 4-bedroom home, based on national averages which would have fewer people in the home. House 8 had five residents, but had very energy-intensive habits compared to other 4-bedroom homes. House 4 had only two residents with very energy-efficient habits, did not use air-conditioning all of the time and used about half the energy of similar houses with two residents (Houses 5 and 6).

Air temperature and relative humidity were measured in the living room area, three bedrooms, and outdoors out of direct sunlight. Data were collected in 15-minute intervals. Several outdoor sensors were lost over the year and the data from one was removed from the analysis because it was considered an outlier. Since all were in the same neighborhood, data from the outdoor sensors were aggregated to an average temperature.

Table 3.2.2 shows the average (with standard deviation) for indoor temperatures and humidity inside all houses. Figure 3.2.1 shows sample data diagram for the outdoor temperature and the representative indoor temperatures for Houses 2, 3 and 8 and the outdoor temperature (all calculated as 2-day rolling averages to simplify the graph). The naturally ventilated House 2 is slightly warmer than the outdoor temperature, e.g. in March it was 2°F to 3°F warmer. The partially-conditioned House 8 is significantly warmer than the outdoor temperature, e.g. in March it was 6°F to 11°F warmer, even though it has some mechanical cooling. This was possibly due to the large number of occupants and plug loads. The mechanically-conditioned House 3 is about 70-75°F year-round.

Table 3.2.2 Mean and standard deviation of the annual indoor temperature and humidity of the nine monitored houses.

House ID#	Temperature (°F)		Relative Humidity (%)	
	Average	(standard deviation)	Average	(standard deviation)
1	72.4	(2.1)	57.5	(2.8)
2	81.1	(4.0)	66.0	(4.7)
3	73.5	(2.0)	63.8	(6.3)
4	80.4	(3.0)	61.0	(5.7)
5	73.4	(3.5)	61.2	(6.0)
6	73.6	(2.2)	58.1	(3.4)
7	77.1	(1.2)	62.4	(6.0)
8	82.1	(3.1)	57.3	(5.4)
9	73.7	(1.9)	62.4	(5.6)

SECTION 3 – DETAIL PERFORMANCE ANALYSIS OF THREE EXAMPLE RESIDENTIAL HOUSE TYPES

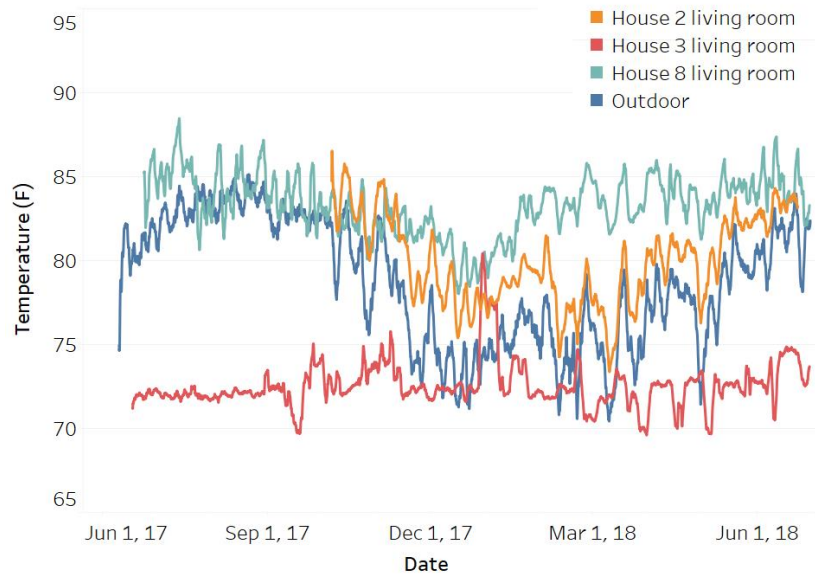


Figure 3.2.1. Sample plot of measured temperature readings (rolling 2-day averages) in houses 2, 3 and 8 and measured outdoor temperature.

3.3 House 3 - Fully Air-Conditioned House

Section 3.3 presents the performance of House 3, which is selected to represent a typical fully air-conditioned residential building that is used or planned for future use by DHHL.

3.3.1 Description of the House 3 Geometry

The existing conditions of House 3, a centrally air-conditioned 4-bedroom home is described in Table 3.3.1.1. And the geometry of House 3 is depicted in in Figures 3.3.1.1 and 3.2.1.2. Inputs for the simulation model that is used for validation against the measured data are taken from the drawing set and translated into BEopt and are listed in Table 3.3.1.2.

Table 3.3.1.1. House 3 size, bedrooms, and occupancy.

House component description	Values
Finished floor area	1,654 sqft
Garage area	472 sqft
# of bedrooms	4
# of bathrooms	3
# of occupants	8



Figure 3.3.1.1. Floor Plan of House 3 with the blue representing the conditioned spaces.

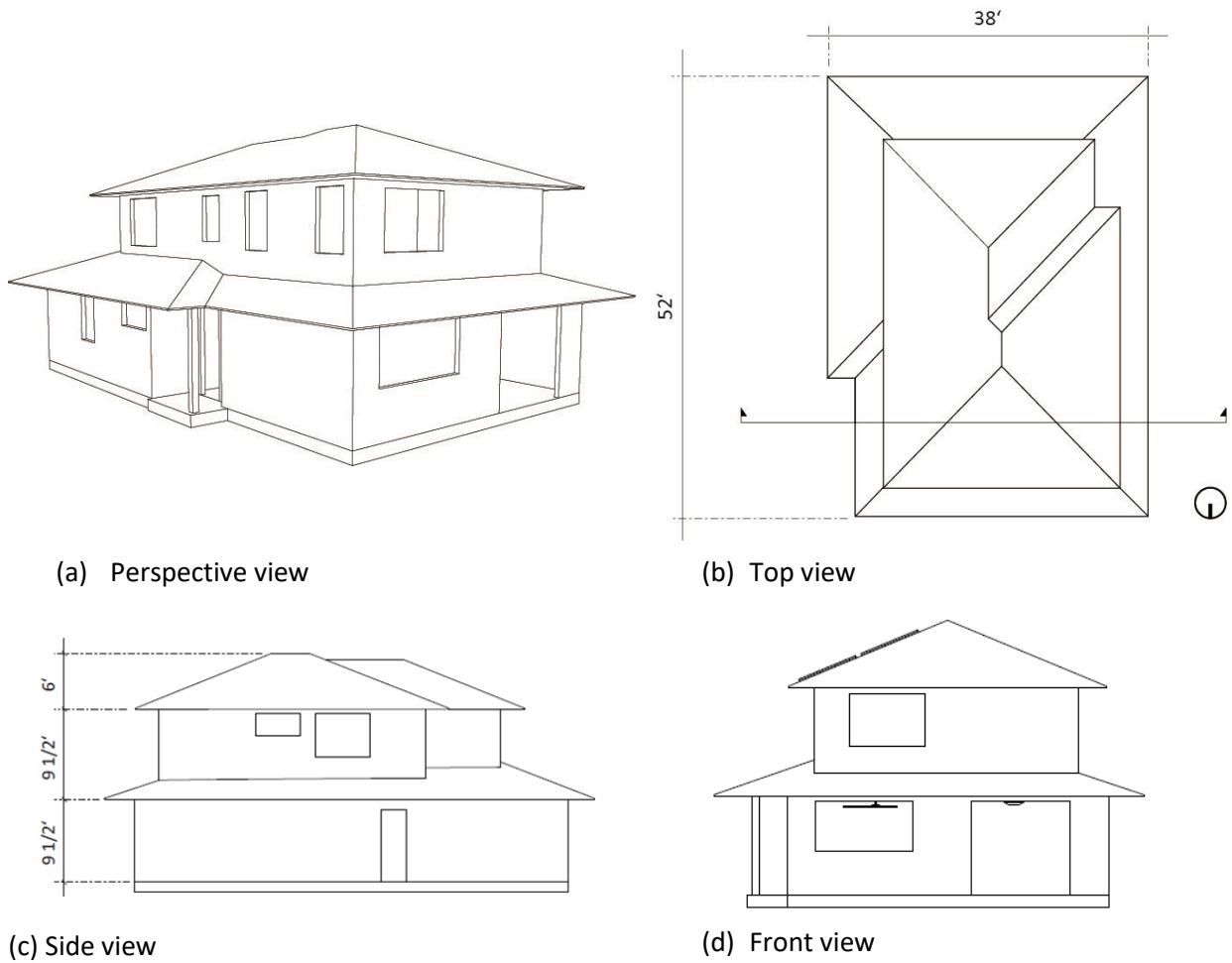


Figure 3.3.1.2. House 3 views and sections.

SECTION 3 – DETAIL PERFORMANCE ANALYSIS OF THREE EXAMPLE RESIDENTIAL HOUSE TYPES

Table 3.3.1.2 Existing House 3 plug load 1.5 BEopt modeling inputs.

Existing house component	Modeling Inputs
Wall assembly	½" gypsum board side R-13 h-sqft-°F/Btu fiberglass batt 2x4, 16" o.c wood studs Vapor barrier OSB sheathing Vinyl siding, light color, R-value 0.6 h-sqft-°F/Btu, absorptivity 0.3
Roof assembly	½" gypsum board ceiling R-19 h-sqft-°F/Btu Roof fiberglass batt, unvented Pre-engineered wood trusses Asphalt shingles, medium color, absorptivity 0.85
Floor	Wood Surface Interzonal floor R-19 h-sqft-°F/Btu fiberglass batt Uninsulated slab
Doors	Wood doors, 20 sqft, U-Value 0.48 Btu/h-sqft-°F
Glazing	Window area 309 sqft (18.7% finished floor area) Clear, double pane, air filled, metal thermally broken windows U-value = 0.34 Btu/h-sqft-°F, SHGC = 0.3
Natural ventilation	Fraction of window area openable 0.33 20% windows are open Natural ventilation can occur year-round, 7 days/week
Mechanical ventilation	0.9583 of ASHRAE 62.2 2010 Standard exhaust, Flow rate 51.8 cfm, 32.4 W
Exterior shading	2-ft eaves
Lighting	75% high efficacy (866 kWh/yr)
Cooling	SEER 16, EER 12.8 Ducts in finished space, supply/ return R-Values 1.7/1.7 h-sqft-°F/Btu, 0.0 leakage Cooling set-point 75°F
Infiltration	7 air changes per hour with a 0.5 shelter coefficient
Plug load factor	1.5 (3,434 kWh/yr)
Solar water heater	Solar hot water flat panel, collection area 64 sqft, tank volume 120 gal Electric backup, energy factor 0.65, cycle derate 0.0, Tank volume 66 gal Distribution via R-2 h-sqft-°F/Btu, trunk branch, Copper pipes
Appliances	Refrigerator with side freezer, water and ice in door, 553 kWh/yr Stove, electric, use factor 1.2, 701 kWh/yr Dishwasher use factor 1.2, 155 kWh/yr Clothes washer use factor 1.2, 60 kWh/yr Dryer, electric, use factor 1.2, energy factor 3.1 lb/kWh Hot water fixtures factor 1.5

SECTION 3 – DETAIL PERFORMANCE ANALYSIS OF THREE EXAMPLE RESIDENTIAL HOUSE TYPES

Ceiling fans	None
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3.3.2 Comparison of Simulated to Measured Energy Performance Data for House 3

In order to give the research team confidence in the simulation model, the simulated house’s energy use is compared to the actual house’s energy use. Since this house is fully air-conditioned with interior temperatures maintained by a thermostat set-point, the indoor temperatures were not compared. The energy demand for the existing House 3 was measured for a period of a year (June 29, 2017 – June 28, 2018). The methodology of energy measurements in exiting houses is described in Section 2.

Some loads are increased to accommodate for the occupancy being eight people instead of the U.S. national average of 3.23 people for a 4-bedroom home (Wilson et al., 2014). Load factors that are increased relative to the national average: plug load factor of 1.5 (50% greater than national average), hot water fixtures of 1.5, and appliance use factor of 1.2 (Table 3.3.1.2). This model is referred to as “House 3 existing plug load 1.5” and is used only for model validation purposes.⁸ For subsequent analyses, all of these factors were changed back to 1.0 to represent more typical energy use and referred to as “House 3 existing plug load 1.0” model.

Figure 3.3.2.1 shows the comparison of monthly site energy consumption data between the measured House 3 with an annual energy use of 14,025 kWh/yr, and the weather normalized (using cooling degree days based on 10°C) simulated “House 3 existing plug load 1.5” model with an annual energy use of 13,005 kWh/yr.

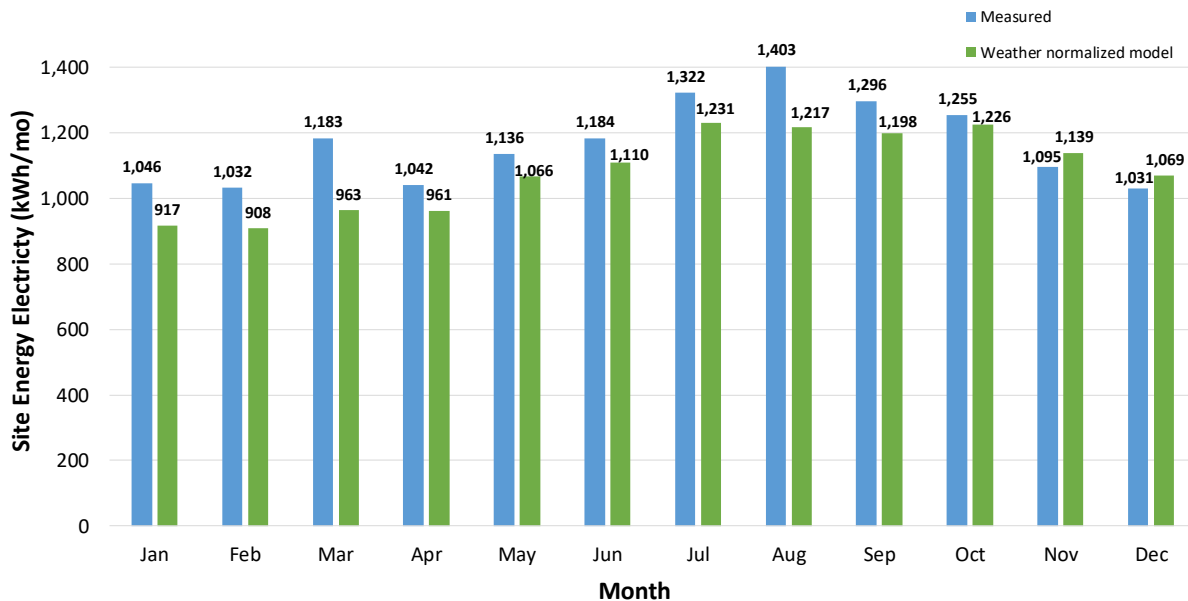


Figure 3.3.2.1 Comparison of monthly site energy (kWh/mo) use of the measured House 3 and the weather normalized simulated “House 3 existing plug load 1.5” model.

⁸ The validated model was later refined to more accurately reflect disaggregated monitored data and used for publication purposes but is not included in this report.

The comparison of measured and simulated results indicates a good correlation for the total energy consumption and thus gives the research team confidence in the validity of the energy models. It should be noted that it is not unusual for results obtained from simulations and measurements of building energy performance differ. This divergence of simulated (*e.g.*, estimated) and measured results is due to the fact the simulation process relies on simplified and often standardized assumptions of energy use, whereas the actual energy use in the residential houses is significantly affected by individual energy use behavior.

3.3.3 Energy Performance of House 3 as Minimally Compliant to IECC 2015 Energy Code

The “House 3 existing plug load 1.0” model (which has plug loads, hot water use, and appliance loads based on the national averages) was compared to the same model changed to just be minimally compliant to the IECC 2015 energy code. The inputs to the models that differ are shown in Table 3.3.3.1.

Table 3.3.3.1 BEopt model inputs that were changed to minimally comply with IECC 2015 code.

Category Name	House 3 Existing Plug Load 1.0	House 3 IECC 2015 Minimum
Exterior Finish	Vinyl, light color, R-value 0.6 h-sqft-°F/Btu, absorptivity 0.3	Fiber cement, medium/dark R-value 0.2 h-sqft-°F/Btu, absorptivity 0.75
Unfinished Attic	Ceiling R-19 h-sqft-°F/Btu fiberglass batt, unvented, specific leakage area = 0	Ceiling R-30 h-sqft-°F/Btu fiberglass batt, vented, specific leakage area = 0.0051
Roof Material	Asphalt shingles, medium color absorptivity 0.85	Asphalt shingles, medium color absorptivity 0.75
Glazing	309 sqft (18.7% finished floor area) U-value = 0.34 Btu/h-sqft-°F and SHGC = 0.3	278 sqft (15.0% finished floor area) U-value = 0.5 Btu/h-sqft-°F and SHGC = 0.25
Interior Shading	Summer = 0.7, winter = 0.7	Summer = 0.87, winter = 0.87
Doors	Wood doors, 20 sqft U-value 0.48 Btu/h-sqft-°F	Wood doors, 40 sqft U-value 0.5 Btu/h-sqft-°F
Air Leakage	7 air changes per hour at 50 Pa 0.5 shelter coefficient	5 air changes per hour at 50 Pa
Mechanical Ventilation	0.9583 fraction of ASHRAE 62.2 2010 Standard, exhaust 51.8 cfm, 8.1 W	1.0 fraction of ASHRAE 62.2 2013 Standard, exhaust 87.1 cfm, 13.1 W
Central AC	SEER 16.5, 12.8 EER	SEER 14, 12.0 EER
Ceiling Fan	None	Standard efficiency fans (1.7 fans)
Distribution	R-2 h-sqft-°F/Btu, trunk branch, copper	R-3 h-sqft-°F/Btu, trunk branch, copper
Solar Water Heater	Solar water heater collection area 64 sqft tank storage 120 gal backup heater electric tankless with energy factor 0.65 and cycling derate 0.0	Solar water heater collection area 64 sqft tank storage 96 gal backup heater electric tankless with energy factor 0.99 and cycling derate 0.0
Appliances	Refrigerator with side freezer, water and ice in door, 553 kWh/yr Stove, electric, 1.0 usage factor, 584 kWh/yr Dishwasher, 1.0 usage factor, 130 kWh/yr Clothes washer standard, 1.0 usage factor, 50 kWh/yr Clothes dryer, electric, 1.0 usage factor, 3.1 lb/kWh Hot water fixtures factor 1.0	Refrigerator with side freezer, water and ice in door, 718 kWh/yr Stove, electric, 1.0 usage factor, 584 kWh/yr Dishwasher none Clothes washer standard, 1.0 usage factor, 50 kWh/yr Clothes dryer electric, 1.0 usage factor, 3.1 lb/kWh Hot water fixtures factor 1.0

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Figure 3.3.3.1 shows the energy consumption per major building load category modelled with BEopt for the existing house 3 and the model that is minimally compliant to IECC 2015. The 2015 IECC reference design is 16% more energy intensive than the House 3 existing 1.0 plug load design case. A major contributor to the increase in energy use is the increased ventilation rate. The existing house also has a more efficient air conditioner than is required by IECC 2015 (SEER 16 vs 14).

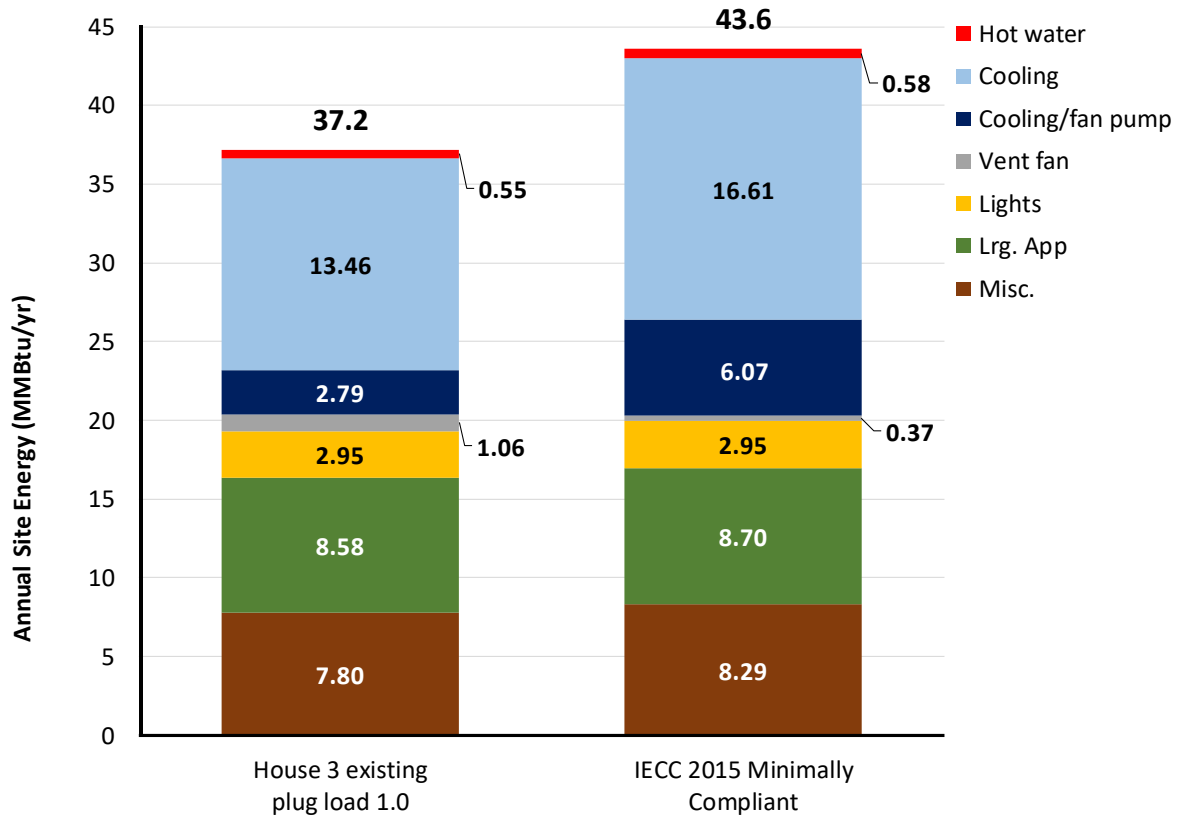


Figure 3.3.3.1. Annual site energy consumption (MMBtu/yr) per major building load category modelled with BEopt for existing House 3 plug load 1.0 case and IECC 2015 baseline case.

3.3.4 Parametric Energy Performance Analysis

A parametric energy performance analysis is conducted by using a baseline model, in this case, the minimally compliant IECC 2015 model, and comparing it to a similar model with only one building envelope component or piece of equipment changed at a time. Parametric simulations allow a wide range of option comparisons side by side. The comparisons indicate direct effect of each option on the energy performance of the house. The team tested modifications to the building envelope, windows, HVAC system, lighting, and appliances. We tested energy efficiency measures that we think are reasonable for the client to consider and implement.

The whole range of the energy efficiency options that were investigated, but not all made a significant impact. Table 3.3.4.1 lists the top twelve options tested with the percent decrease in site energy consumption from the baseline IECC 2015 minimally compliant model.

Table 3.3.4.1. Ranked results of parametric analysis for House 3 using the IECC 2015 model as the baseline; the asterisk (*) indicates the option was included in the combined strategies case.

Rank	Baseline IECC 2015 minimum Option	Upgraded Option	Annual Energy Savings [%]
1	HVAC: SEER 14	HVAC: SEER 24.5	28.6*
2	Ceiling fans: standard efficiency, number of fans at the national average (1.840 fans)	Ceiling fans: premium efficiency (5 fans) With occupancy sensors and 4°F temperature offset	17.6*
3	HVAC: SEER 14	HVAC: SEER 21	16.9
4	HVAC: SEER 14	HVAC: SEER 18	11.9
5	Appliances: standard efficiency	Appliances: energy efficient	8.1*
6	HVAC: SEER 14	HVAC: SEER 16	7.6
7	Exterior finish: fiber cement Medium/dark color, absorptivity 0.75	Exterior finish: fiber cement Light color, absorptivity 0.3	3.5*
8	Roof material: asphalt shingles medium color, absorptivity 0.75	Roof material: metal white color absorptivity 0.3	2.8*
9	Windows: 15% of finished floor area (FFA)	Windows: 9% of finished floor area (FFA)	2.8
10	No radiant barrier	Radiant barrier, double-sided	1.4*
11	Lighting: 75% high efficacy	Lighting: 100% LED	0.3*
12	Wall insulation: fiberglass batt, R-13 h-sqft- °F/Btu	Wall insulation: fiberglass batt, R-15 h-sqft- °F/Btu	0.2

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In Figures 3.3.4.1 through 3.3.4.4, the IECC 2015 minimally compliant baseline case is displayed on the far left, and the columns to the right represent simulation cases where one specific option parameter was changed relative to the 2015 IECC minimally compliant baseline case. The final column on the right of Figure 3.3.4.4, termed “combined strategies”, indicates the results of the simulation case with the options identified as the most energy efficient options that the team deemed reasonable for the client to consider (indicated by * in Table 3.3.4.1).

Figure 3.3.4.1 shows that increasing the wall insulation from R-13 h-sqft-°F/Btu to R-15 h-sqft-°F/Btu, R-20 h-sqft-°F/Btu, and R-25 h-sqft-°F/Btu results in very modest improvements in energy performance (0.2% to 1%) and are not included in the combined strategies. Changing the exterior finish from a medium/dark color to a light color saves 3.5% of annual site energy consumption and changing the roof material from a medium color asphalt shingle to white metal saves 2.8%. Adding a double-sided radiant barrier saves 1.4% of annual site energy. These strategies are all included in the combined strategies case.

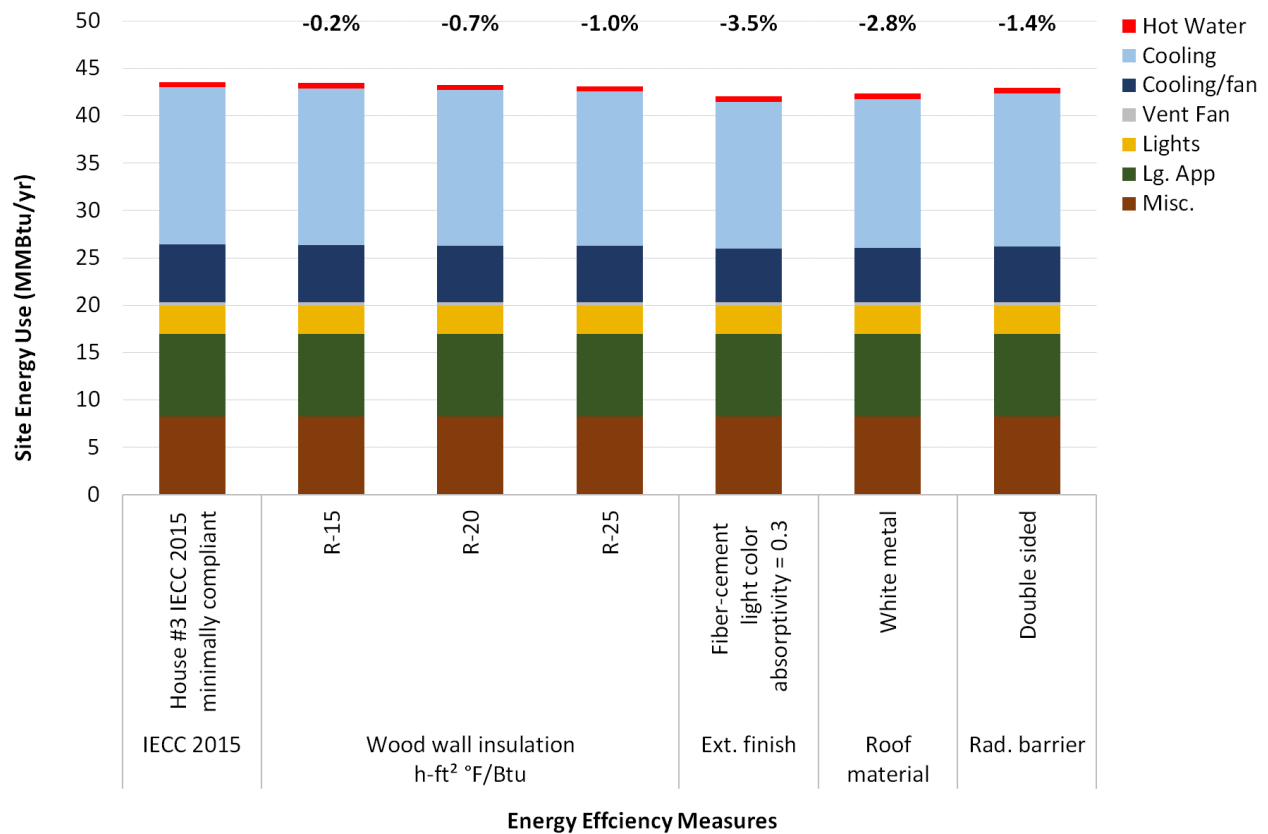


Figure 3.3.4.1 Parametric analysis results for annual site energy use (MMBTu/yr) for House 3: envelope options.

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Figure 3.3.4.2 shows that decreasing the window area from 15% of conditioned floor area to 13%, 11% or 9% of the floor area saves 0.9%, 1.7% and 2.8%, respectively, but is not included in the combined strategies case since it is not likely to be an appealing design. Decreasing the U-value of the windows from 0.5 Btu/h-sqft-°F to 0.4 Btu/h-sqft-°F and 0.3 Btu/h-sqft-°F showed an increase of 0.1% and 0.3% site energy compared to the IECC 2015 baseline case, respectively. This was due to higher cooling energy at night and in the cooler months for the lower U-value windows. The baseline U-value of 0.5 Btu/h-sqft-°F was used in the combined strategies case. Adding window overhangs of 2ft and 3ft saved 0.5% and 1.3% of annual energy (not shown in figure) but was not used in the combined strategies case because the builder said the land lots were too small to allow for the necessary setback. Changing the lighting from 75% LED to 100% LED saves only 0.3% of energy consumed but is easy to implement, so it is included in the combined strategies case.

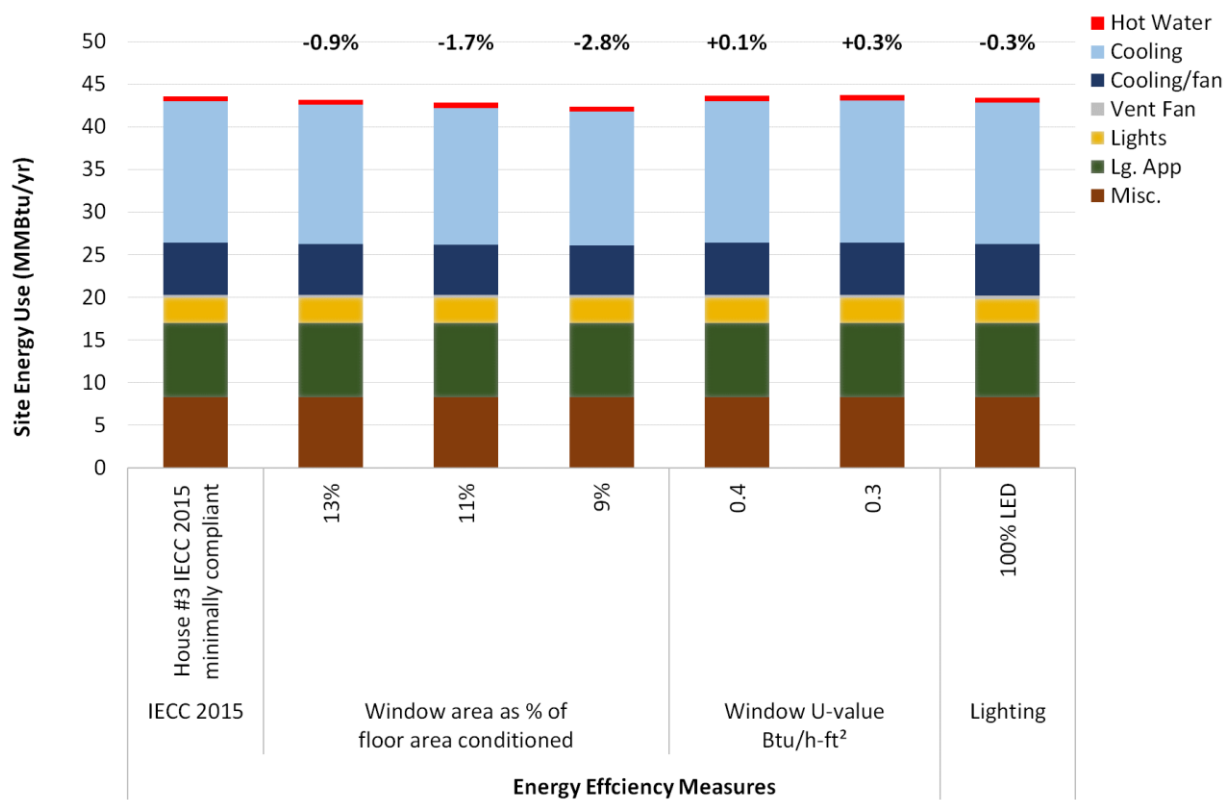


Figure 3.3.4.2 Parametric analysis results for annual site energy use (MMBtu/yr) for House 3: windows and lighting options.

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Figure 3.3.4.3 shows that improving the efficiency of the HVAC has a large impact on energy performance. Changing from SEER 14 to 16, 18, 21, and 24.5 saves 7.6%, 11.9%, 16.9%, and 28.6% of annual site energy consumption, respectively. The SEER 24.5 is included in the combined strategies case. Adding an energy recovery ventilator (ERV; total recovery efficiency of 0.48) or heat recovery ventilator (HRV; total recovery efficiency of 0.20⁹) actually increases estimated energy consumption by 1.8% and 3.2%, respectively, mainly due to increased ventilation fan energy. Cooling and cooling/fan energy decreased slightly with the ERV and increased slightly with the HRV. Both were set to use ASHRAE 62.2 2013 ventilation rate (same as the IECC 2015 benchmark).

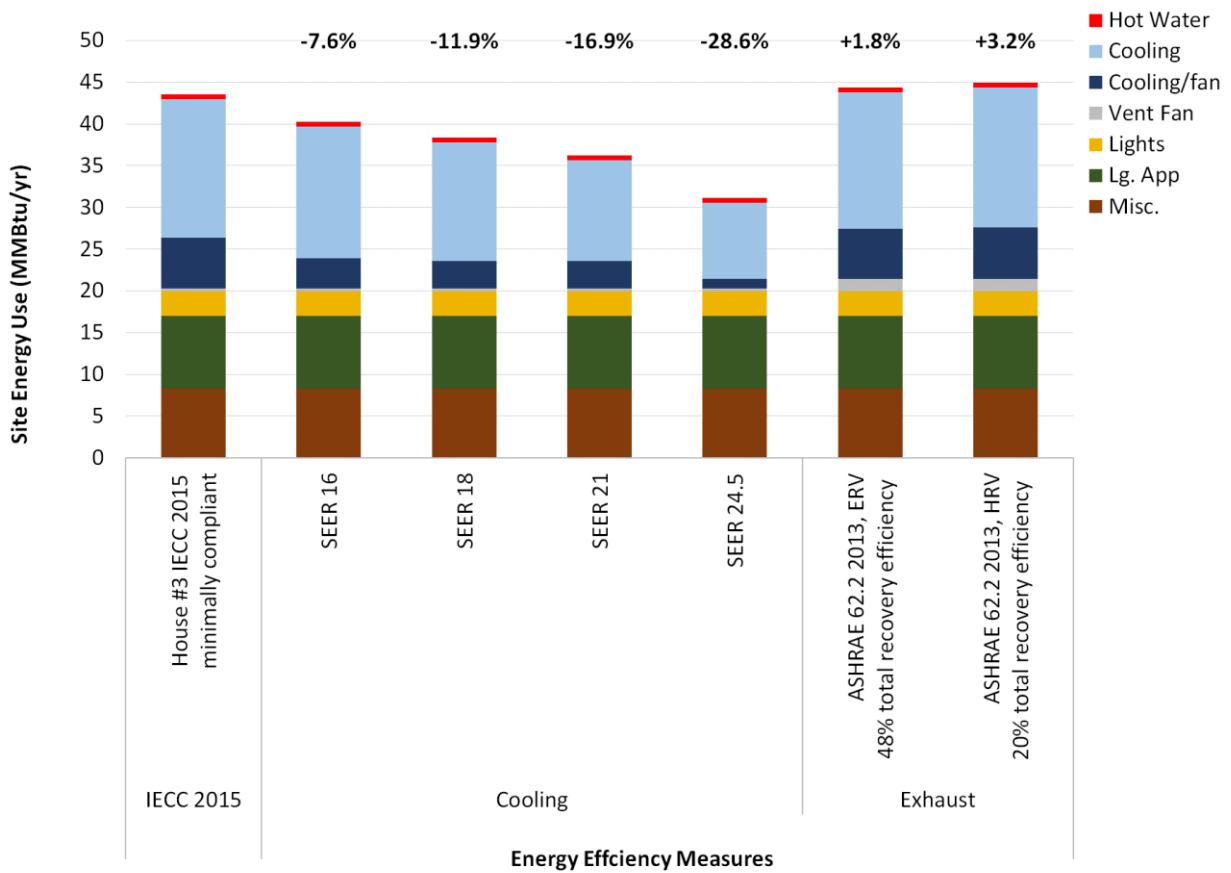


Figure 3.3.4.3 Parametric analysis results for annual site energy use (MMBtu/yr) for House 3: HVAC and ventilation options.

Figure 3.3.4.4 shows that just adding five premium efficiency fans alone increases energy consumption by 3.2%, but combining the fans with occupancy sensing and increasing the thermostat set-point by 4°F (from 75°F to 79°F) saves 17.6% of annual site energy and is included in the combined strategies case. A separate parametric energy analysis (not shown) was conducted to compare the energy use of standard appliances in the IECC 2015 case to Energy Star or more energy-efficient appliances (more information can be found in Appendix B). After this analysis was completed, the top energy saving options were

⁹Personal communication, Kosol Kiatreungwattana, senior engineer, NREL, Golden, CO, email 5/30/19

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placed into one case called “energy efficient appliances” (Figure 3.3.4.4) which shows an 8.1% annual site energy savings compared to the IECC 2015 case and is included in the combined strategies case. The appliance upgrades from the IECC 2015 baseline case include the following:

- Clothes dryer from electric standard (energy factor 3.1 lb/kWh) to electric premium (energy factor 3.93 lb/kWh);
- Clothes washer from standard (50 kWh/yr) to Energy Star compliant (41 kWh/yr);
- Stove from a standard electric (584 kWh/yr) to an induction stove (552 kWh/yr); and
- Refrigerator with a side freezer, water and ice in door (718 kWh/yr) to a refrigerator with a top freezer and no ice maker (348 kWh/yr).

The “combined strategies” case uses all seven options the team considered to be the best and most reasonable options. These are indicated in Table 3.3.4.1 with an asterisk (*). This combination of energy efficiency measures results in an estimated annual site energy use of 23.0 MMBtu (6,735 kWh), a 47.3% (Figure 3.3.4.4) compared to the IECC 2015 minimally compliant baseline case with an estimated annual site energy use of 43.6 MMBtu (12,770 kWh). This improved design would cut greenhouse gas emissions by 14.5 metric tons of CO₂e annually. The homeowner would save (at \$0.28/kWh) an estimated \$1,690 annually on their utility bills.

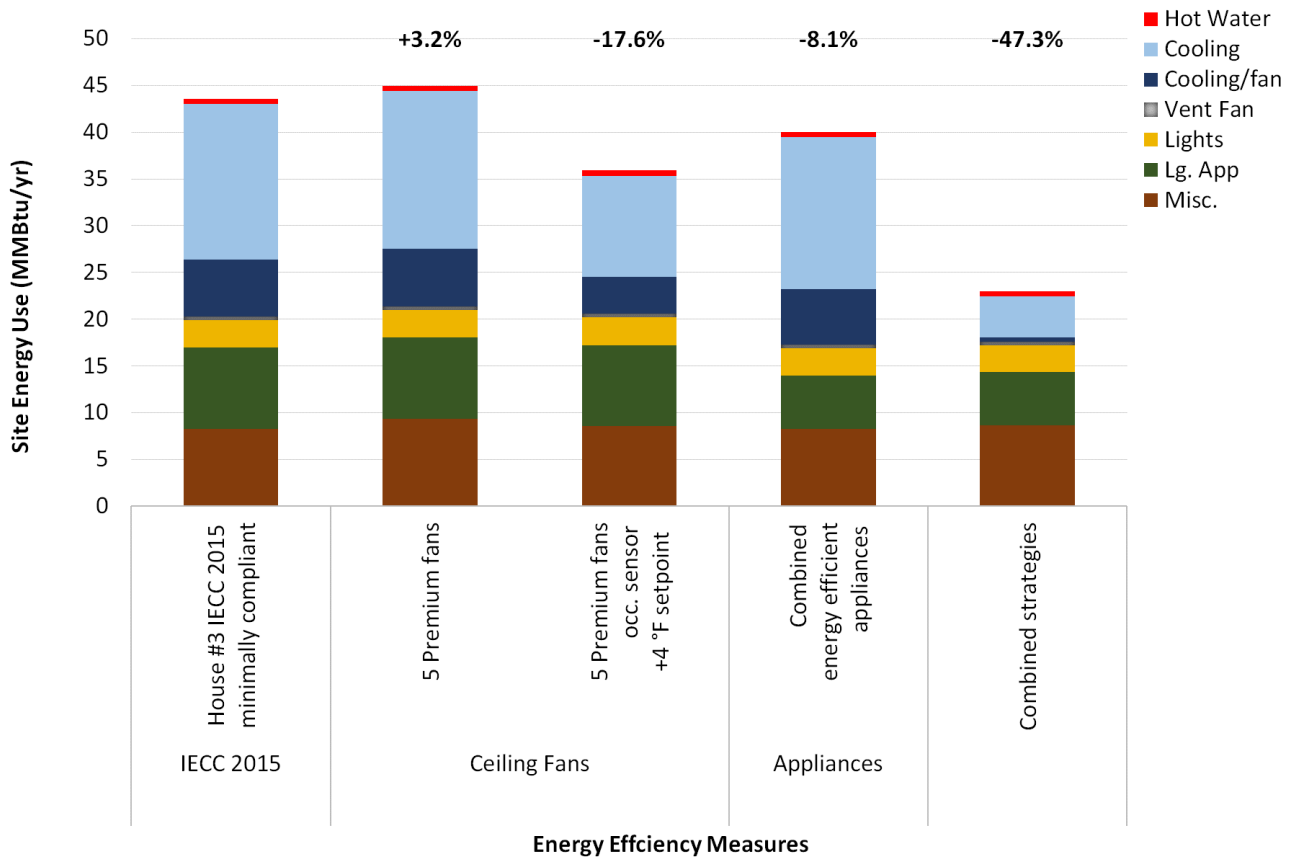


Figure 3.3.4.4 Parametric analysis results for annual site energy use (MMBtu/yr) for House 3 for fans, appliances, and the combined strategies case.

3.3.5 PV Production and Net-zero Energy Potential for House 3 Combined Strategies Case

The PV production and net-zero performance analysis of the combined strategies case for House 3 is performed using PV-Watts®, a free online application. The following values for input variables are used:

- Latitude and longitude: 21.33, -158.1 (“Kapolei” input)
- Module type: standard
- Array type: roof mounted
- System losses: 14.1 % (default)
- Tilt angle: same as roof angle
- DC to AC size ratio: 1.1 (default)
- Inverter efficiency (%): 96% (default)
- Ground coverage ratio: 0.4 (default)
- Panel efficiency 16%

The PV-Watts application provides median, minimum, and maximum annual electric production (kWh/yr) estimates for a given size in array capacity (kW). The conservative minimum value is used in this assessment.

The usable roof area of the House 3 geometry is determined and divided into segments according to their orientation to determine the potential of PV generation on these roof areas. Figure 3.3.5.1 illustrates the roof area segments which are available for the placement of PV-panels. The dashed lines indicate the required setback distances from ridge lines and sides of roof areas, in accordance to the International Fire Code (IECC 2015b).

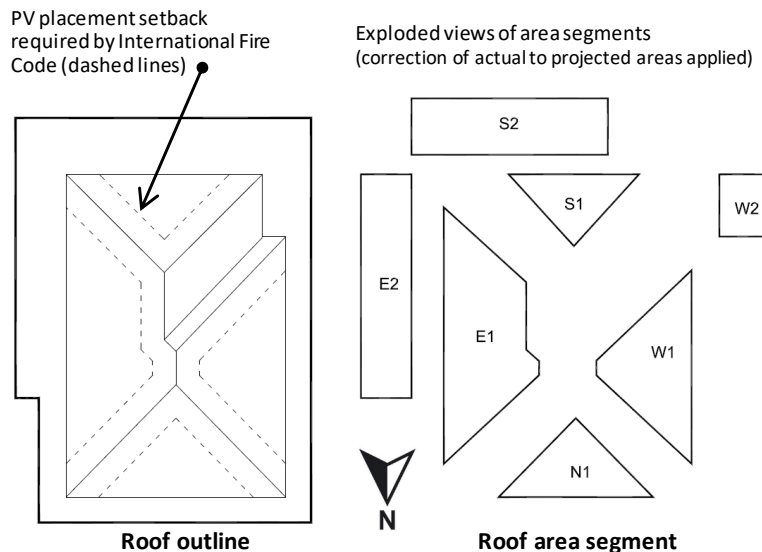


Figure 3.3.5.1 Roof area segments of House 3.

A panel nesting factor is applied to the available areas: the ratio of achievable panel area coverage inside the area. The resulting PV array areas are listed in Table 3.3.5.1. Table 3.3.5.2 shows the calculation of the achievable PV electric generation and net-zero performance.

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Table 3.3.5.1. Size of roof areas segments of House 3 and area available for PV array.

Roof Area Segment ID	Direction of Panel Face	Panel Nesting Factor	Area Available on Roof (sqft)	Area Available for PV Array (sqft)
S1	South	0.6	80	50
E1	East	0.7	250	180
W1	West	0.7	160	110
N1	North	0.6	100	60
S2	South	0.85	180	150
E2	East	0.85	180	150
W2	West	0.85	50	40

Table 3.3.5.2 Calculation of the achievable PV electric generation and net-zero performance for House 3.

PV Electricity Potential of House 3 Combined Strategies Case				PV Production to Achieve Basic Net-Zero			PV Production to Achieve Maximum Net-Zero		
Roof Area Segment ID	Max. Installed ¹ (kW)	Potential Production per 1 kW installed (kWh/yr)	Production Potential (kWh/yr)	Percent Area Used	Capacity of Panels Installed (kW)	Production (kWh/yr)	Percent Area Used	Capacity of Panels Installed (kW)	Production (kWh/yr)
S1	0.7	1,590	1,100	100%	0.7	1,100	100%	0.7	1,100
E1	2.7	1,480	4,000	100%	2.7	4,000	100%	2.7	4,000
W1	1.6	1,420	2,300	0%	0	0	100%	1.6	2,300
N1	0.9	1,230	1,100	0%	0	0	100%	0.9	1,100
S2	2.2	1,590	3,500	50%	1.1	1,750	100%	2.2	3,500
E2	2.2	1,480	3,300	0%	0	0	100%	2.2	3,300
W2	0.6	1,230	700	0%	0	0	100%	0.6	700
¹ Default PV panel efficiency = 16%				Totals:	4.5	6,850	Totals:	10.9	16,000
				Required PV for net-zero: 6,735 kWh/yr			Achievable net-zero performance: 208%		

The assessment of the PV-production potential and possible net-zero performance of House 3 indicates that the roof geometry provides enough area to install the required PV-system capacity achieve a net-zero energy performance. A basic net-zero performance can be achieved by installing a minimum of 4.5 kW PV-panel capacity. The maximum net-zero capacity of about 200% can be achieved by installing PV panels on all suitable roof areas and achieve a total PV-system capacity of 10.9 kW.

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3.3.6 House 3 Takeaways

Cooling systems are a large energy component of House 3. Since thermal comfort is a high priority to many home owners, it is important to maximize savings in this area. By testing many simulations and hypotheses, it was determined that the combination of a highly efficient air conditioning system with an integrated ceiling fan that offsets the thermostat’s cooling set-point (4°F higher) has by far the largest effect on energy savings. This makes a much larger difference in annual cost than building envelope features such as a highly reflective roof or wall insulation. While these components do matter, a homeowner would save more money by investing in an air conditioner with a higher SEER value than they would by putting additional insulation in the walls.

These simulations suggest that House 3’s large appliances and miscellaneous categories (miscellaneous includes plug loads and ceiling fans in our simulations) make up roughly 40-50% of the home’s energy cost. While some of this energy is saved by investing in efficient appliances, much of the energy costs in these categories comes down to individual lifestyles.

These two main takeaways, in conjunction with energy saving measures discovered in parametric studies and are simulated in the combined strategies run are shown in Figure 3.3.6.1.

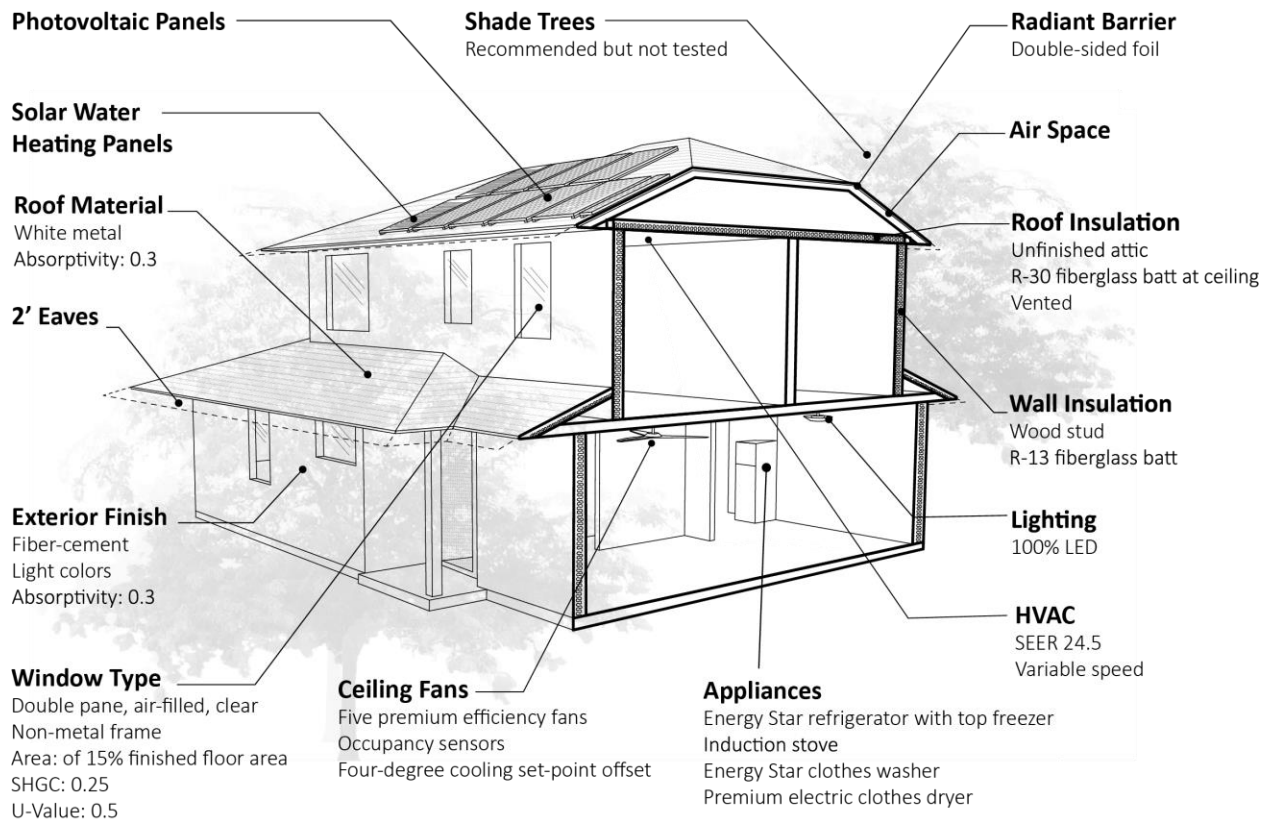


Figure 3.3.6.1. Improved House 3 design incorporating the combined strategies selected from the parametric analysis.

3.4 House 8 - Representing of Partially-Conditioned House Design Type

Section 3.4 presents the performance of House 8, which is selected to represent a typical, partially-conditioned residential building that is used by DHHL or planned for future use. The living room, kitchen, and master bedroom are conditioned by a SEER 16.5 mini-split heat pump. The third bedroom had a portable window unit AC system that was rarely used. Bedrooms #2 and #4 were naturally ventilated. Both HVAC systems were retrofitted after the house was occupied. It is common for Hawai'i homeowners to partially condition their homes with window unit AC systems, however mini-split heat pumps are now emerging as an affordable option to cool their homes by zones.

3.4.1 Description of the House 8 Geometry

The existing conditions of House 8 are described in Table 3.4.1.1, Figure 3.4.1.1 and Figure 3.4.1.2. The modeling inputs for “House 8 existing plug load 2.6” case is described in Table 3.4.1.2.

Table 3.4.1.1. House 8 size, bedrooms, and occupancy.

House component description	Values
Finished floor area	1,581 sqft
Conditioned floor area	853.7 sqft (54% of finished floor area)
Garage area	592 sqft
# of bedrooms	4
# of bathrooms	3
# of occupants	5

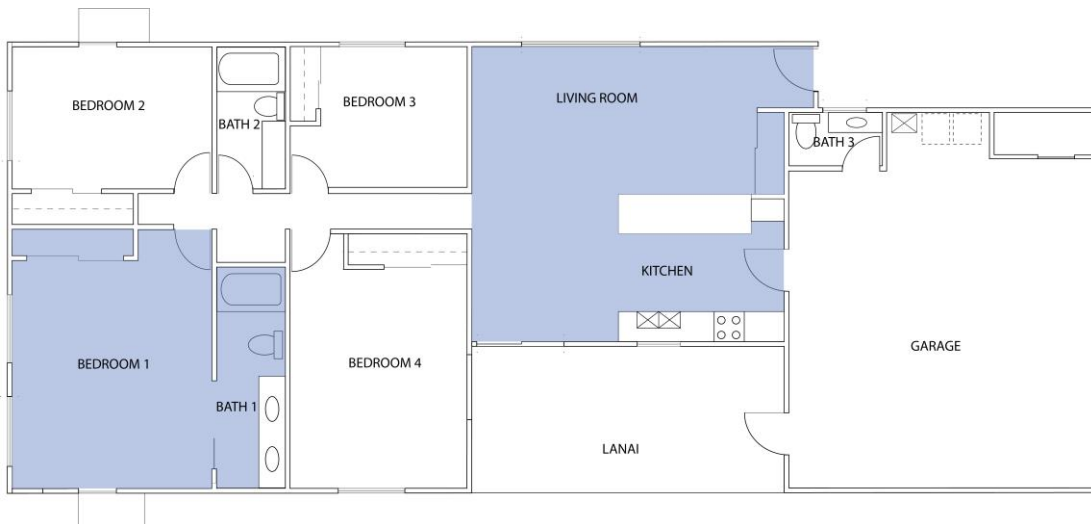


Figure 3.4.1.1. Floor plan of House 8, highlighted blue area are conditioned spaces.

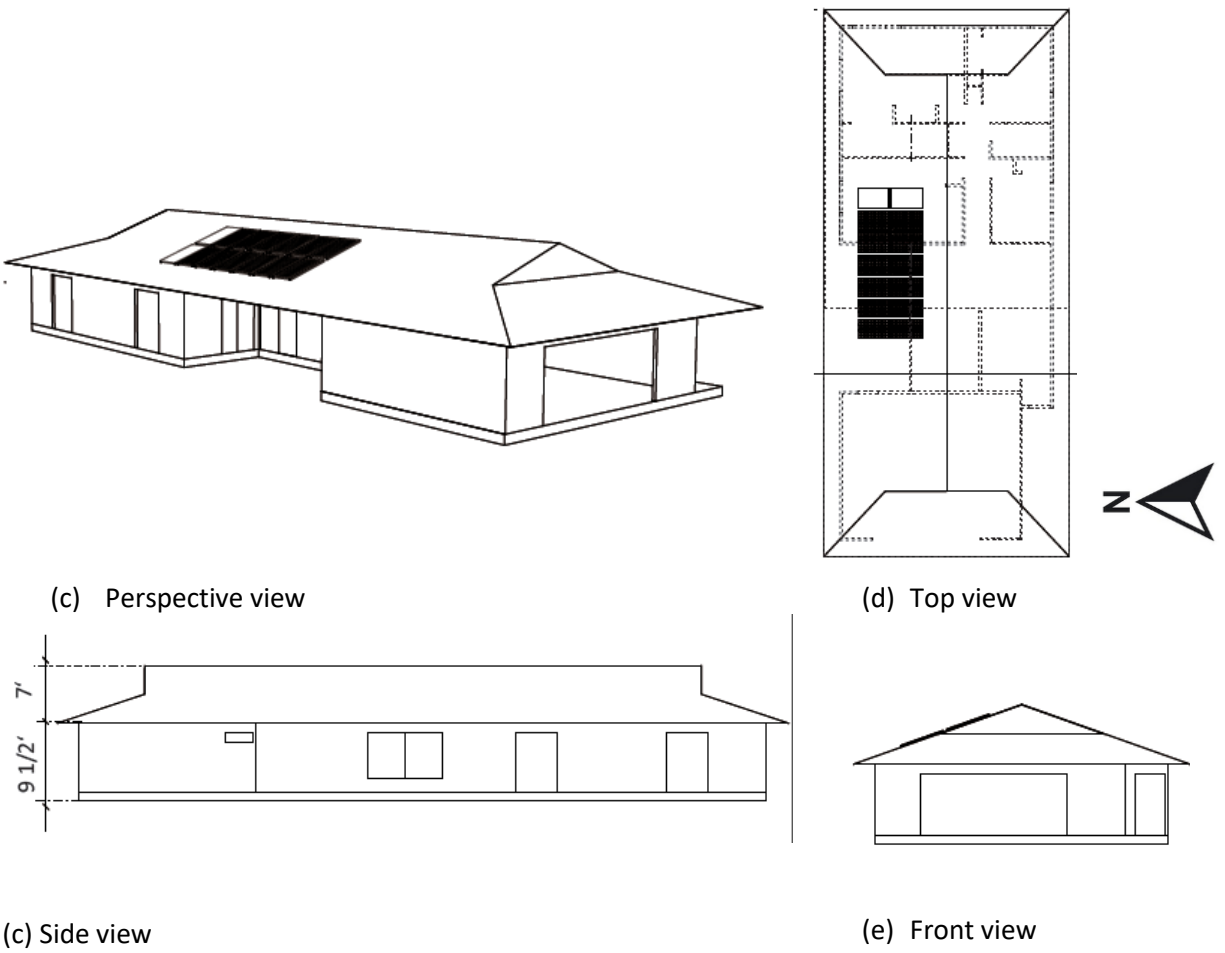


Figure 3.4.1.2. House 8 geometry, views and sections.

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Table 3.4.1.2 House 8 existing plug load 2.6 BEopt modeling inputs.

Existing house component	Modeling Inputs
Wall assembly	½" gypsum board side R-13 h-sqft-°F/Btu fiberglass batt 2x4, 16" o.c steel studs Vapor barrier, Fiber cement, med./dark color, R-value 0.2 h-sqft-°F/Btu, absorptivity 0.75
Roof assembly	½" gypsum board ceiling R-30 h-sqft-°F/Btu fiberglass batt at ceiling, vented Pre-engineered wood trusses Double-sided foil radiant barrier Asphalt shingles, medium color, absorptivity 0.85
Floor	80% carpet Uninsulated 5" slab
Doors	Wood doors, 40 sqft, U-Value 4.8 Btu/h-sqft-°F
Glazing	Window area 246 sqft (16% finished floor area) Clear, double pane, air filled, thermally broken windows U-value = 0.63 Btu/h-sqft-°F , SHGC = 0.62
Natural ventilation	Fraction of window area openable 0.5 20% of windows are open, 0.0115 max outdoor air humidity Natural ventilation can occur year-round, 7 days/week
Mechanical ventilation	None
Exterior shading	2-ft eaves
Lighting	75% high efficacy (994 kWh/y)
Cooling	Mini-split heat pump: 36 kBtu/h/unit SEER 16.5, Heating season performance factor 9, 54% of finished floor area conditioned Mini-split heat pump ducting: supply/return R-value 5.6/6.3 h-sqft-°F/Btu, leakage 0.4, Cooling set-point 75 °F
Infiltration	7 air changes per hour at 50 Pa with a 0.5 shelter coefficient
Plug load factor	2.6 (5,885 kWh/y)
Solar water heater	Solar hot water flat panel, collection area 64 sqft, tank volume 120 gal electric backup tankless, energy factor 0.65, cycle derate 0.0, distribution via R-2 h-sqft-°F/Btu, trunk branch, copper pipes
Appliances	Refrigerator with side freezer, water and ice in door, 553 kWh/y Stove, electric, use factor 1.0, 584 kWh/y Dishwasher electric, 1.0 usage factor, 130 kWh/y Clothes washer use factor 1.0, 50 kWh/yr Dryer, electric, use factor 1.0, energy factor 3.1 lb/kWh Hot water fixtures factor 1.0
Ceiling fans	Standard efficiency, 4 fans 45 W each

3.4.2 Comparison of Simulated to Measured Energy Performance Data for House 8

To give the research team confidence in the simulation model, the simulated house’s energy use is compared to the actual house’s measured energy use. The temperature, humidity, and energy demand for the existing House 8 was measured over a year (June 28, 2017 to June 27, 2018). The methodology for measuring energy in existing houses is described in Section 3.2. House 8 is 54% conditioned, but the team could not with confidence determine when each zone was being cooled and therefore only the energy use was compared between the model and the measured data, not temperatures.

The energy simulation in BEopt provides default assumptions of options for building components including energy efficiency options that are based on national average energy consumption metrics. Most of the default assumptions are based on square footage and assumed number of occupants. The default setting can be overwritten with performance factors that are multiples of the default values. This allows adjustments to the options to better reflect actual conditions.

To represent the large number of plug loads (televisions, security equipment, workshop tools, etc.) in the existing House 8, the miscellaneous loads in the “House 8 Existing Plug 2.6” model were adjusted to a factor of 2.6 times the default miscellaneous loads value (260% of the national average for a 4-bedroom home). The air conditioning system of House 8 is comprised of a mini-split system that conditions 40% of the living area (632 sqft) and serves two zones: the living room/kitchen and the master bedroom. The portable unit could cool 14% of the living area (221 sqft), but was rarely used. BEopt can only represent one cooling system in a simulation, so the research team increased the mini-split system cooling capacity to include the portable window unit and used this in all simulations. The existing mini-split was partly solar powered but this could not be simulated. This feature did not appear to make the system more efficient.

Figure 3.4.2.1 shows the comparison of monthly site energy consumption data between the measured House 8 with an annual energy use of 15,169 kWh/yr, and the weather normalized (using cooling degree days based on 10°C) simulated “House 8 existing plug load 2.6” model with an annual energy use of 13,307 kWh/yr.

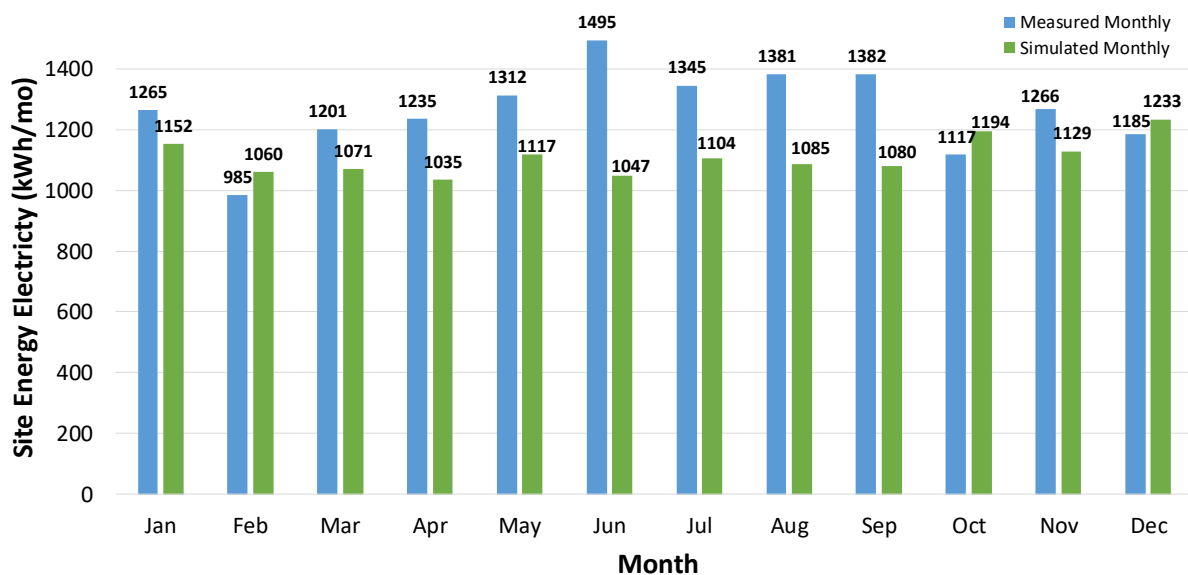


Figure 3.4.2.1 Comparison of monthly site energy (kWh/mo) use of the measured House 8 and the weather normalized simulated “House 8 existing plug load 2.6” model.

The comparison of measured and simulated results indicated good data correlation for the total energy consumption. The measured energy used for air-conditioning was 30% higher than the model's, suggesting that the air-conditioning equipment did not perform as well as its SEER rating. Just as for House 3, it should be noted that it is not unusual that results obtained from simulations and measurements of building energy performance can differ. This divergence of results is due to the simulation process relying on simplified and often standardized assumptions of energy use whereas the actual energy use in the residence is significantly affected by individual energy use behavior.

3.4.3 Energy Performance of House 8 as Minimally Compliant to IECC 2015 Energy Code

The team took the model “existing house 8 plug load 2.6” and created a model that was not reliant on the current occupant’s energy usage habits, but in line with the national average, and called it “existing house 8 plug load 1.0.” This model was compared to the same model changed to just be minimally compliant to IECC 2015. The inputs to the models are shown in Table 3.4.3.1.

Table 3.4.3.1 BEopt model inputs that were changed to minimally comply with IECC 2015 code.

Category Name	House 8 Existing Plug Load 1.0	House 8 IECC Minimum
Roof assembly	Radiant barrier, double sided foil asphalt shingles, medium color absorptivity 0.85	No radiant barrier asphalt shingles, medium color absorptivity 0.75
Glazing	246 sqft, 16% of finished floor area (FFA) U-value 0.63 Btu/h-sqft-°F, SHGC = 0.62	191 sqft, 15% of finished floor area (FFA) U-value 0.5 Btu/h-sqft-°F, SHGC = 0.25
Interior shading	Summer = 0.7, winter = 0.7	Summer = 0.87, winter = 0.87
Doors	Wood doors, 40 sqft U-value 0.48 Btu/h-sqft-°F	Wood doors, 40 sqft, U-value 0.39 Btu/h-sqft-°F
Infiltration	7 air changes per hour at 50 Pa with 0.5 shelter coefficient	5 air changes per hour at 50 Pa
Natural ventilation	Windows: fraction of area openable 0.50 20% of windows are open 0.0115 max outdoor air humidity Natural ventilation can occur year-round, 7 days/week	Windows: fraction of area openable 0.33 20% of windows are open 0.0115 max outdoor air humidity Natural ventilation can occur year-round, 7 days/week
Mechanical ventilation	None	1.0 fraction of ASHRAE 62.2 2013 Standard, exhaust 87.1 cfm/unit, 13.1 W
Mini-split heat pump	SEER 16.5, 36 kBtuh heating season performance factor 9 54% of finished floor area conditioned cooling set-point 75°F	SEER 14, 9 kBtuh heating season performance factor 8.2 54% of finished floor area conditioned cooling set-point 75°F
Ceiling fan	Standard efficiency, 4 fans, 45 W each	Standard efficiency fans, 5 fans, 45 W each
Solar water heating	Solar water heater collection area 64 sqft tank storage 120 gal backup heater electric tankless with energy factor 0.65 and cycling derate 0.0 distribution R-2 h-sqft-°F/Btu, trunk branch, copper	Solar water heater collection area 64 sqft tank storage 96 gal backup heater electric tankless with energy factor 0.99 and cycling derate 0.0 distribution R-3 h-sqft-°F/Btu, trunk branch, copper
Appliances	Refrigerator with side freezer, water and ice in door, 553 kWh/y Stove, electric, 1.0 usage factor, 584 kWh/y Dishwasher, 1.0 usage factor, 130 kWh/y Clothes washer standard, 1.0 usage factor, 50 kWh/y Clothes dryer, electric, 1.0 usage factor, 3.1 lb/kWh	Refrigerator with side freezer, water and ice in door 718 kWh/y Stove, electric, 1.0 usage factor, 584 kWh/y Dishwasher none Clothes washer standard, 1.0 usage factor. 50 kWh/y Clothes dryer, electric, 1.0 usage factor, 3.1 lb/kWh

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Figure 3.4.3.1 shows the energy consumption per major building load category modelled with BEopt. The results suggest that the existing house design case for House 8 with a standard plug load assumption is as energy efficient as the 2015 IECC baseline design (the IECC2015 case uses 5% more energy).

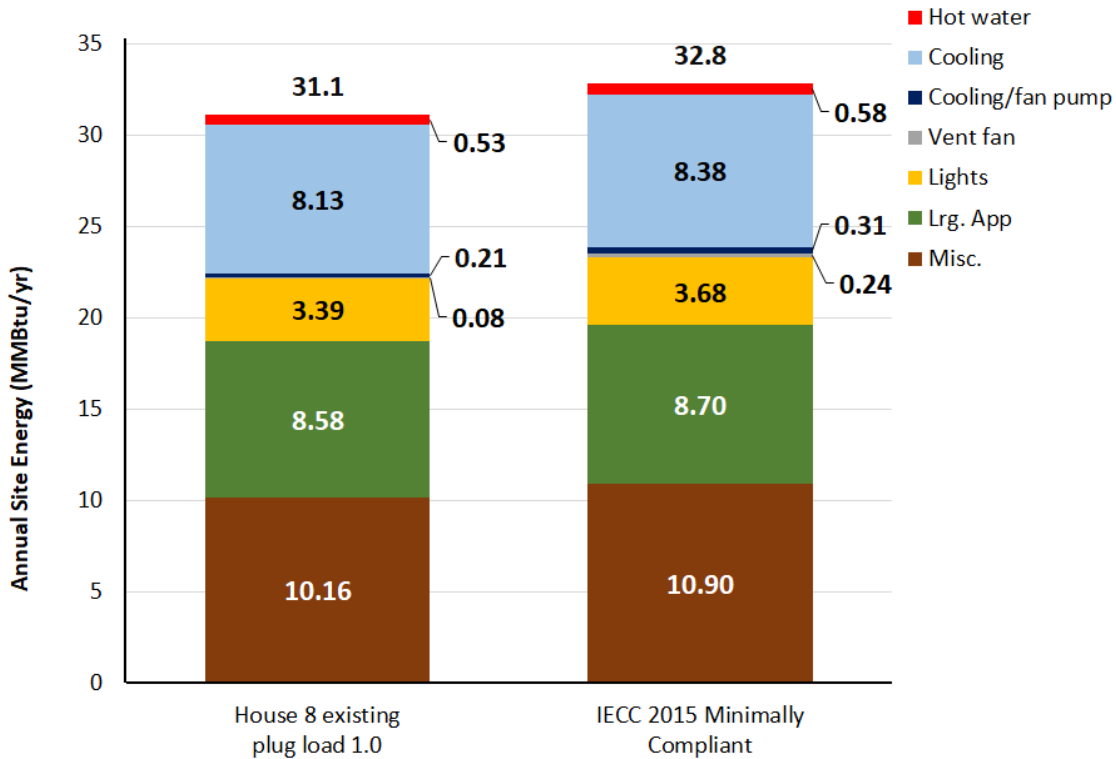


Figure 3.4.3.1. Annual site energy consumption (MMBtu/yr) per major building load category modelled with BEopt for existing House 8 plug load 1.0 case and IECC 2015 baseline case.

3.4.4 Parametric Energy Performance Analysis

A parametric energy performance analysis is performed by using a baseline model, in this case, the minimally compliant IECC 2015 model, and comparing it to a similar model with only one building envelope component or piece of equipment changed at a time. Parametric simulations allow a wide range of option comparisons side by side. The comparisons indicate the direct effect of each option on the energy performance of the house. The team tested modifications to the building envelope, HVAC system, lighting, and appliances. The team tested energy efficiency measures that we think are reasonable for the client to consider and implement.

The whole range of the energy efficiency options that were investigated, but not all made a significant impact. Table 3.4.4.1 lists the top twenty options tested ranked by the percent decrease in site energy consumption from the baseline IECC 2015 minimally compliant model. The options with the asterisk in the far right column were used in the “combined strategies” case.

Table 3.4.4.1. Ranked results of parametric analysis for House 8 using the IECC 2015 model as the baseline; the asterisk (*) indicates the option was included in the combined strategies case.

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Rank	Baseline IECC 2015 minimum Option	Upgraded Option	Annual Energy Savings [%]
1	Ceiling fans: standard efficiency (5 fans)	Ceiling fans: premium efficiency (2 fans) Occupancy sensors 4°F temperature offset	19.4*
2	Ceiling fans: standard efficiency (5 fans)	Ceiling fans: premium efficiency (5 fans) Occupancy sensors 4°F temperature offset	18.0
3	Appliances: standard efficiency	Appliances: energy efficient	10.0*
4	HVAC mini-split heat pump, 9 kBtuh, SEER 14 Heating season performance factor 8.2 54% conditioned	HVAC: mini-split heat pump, 36 kBtuh, SEER 20 Heating season performance factor 9 54% conditioned	7.8*
5	HVAC: mini-split heat pump, 9 kBtuh, SEER 14 Heating season performance factor 8.2 54% conditioned	HVAC: mini-split heat pump, 12 kBtuh, SEER 18 Heating season performance factor 9 54% conditioned	4.1
6	HVAC: mini-split heat pump, 9 kBtuh, SEER 14 Heating season performance factor 8.2 54% conditioned	HVAC: mini-split heat pump, 36 kBtuh, SEER 16.5 Heating season performance factor 9 54% conditioned	4.0
7	Windows: fraction of area openable 0.33 20% of widows are open 0.0115 max outdoor air humidity	Windows: fraction of area openable 0.50 100% of windows are open 1.0 max outdoor air humidity	3.7*
8	Exterior finish: fiber cement Medium/dark color, absorptivity 0.75	Exterior finish: wood Light color, absorptivity 0.3	2.3*
9	Windows: fraction of area openable 0.33 20% of windows open 0.0115 max outdoor air humidity	Windows: fraction of area openable 0.50 100% of windows open 0.0115 max outdoor air humidity	1.7
10	Wall insulation: fiberglass batt, R-13 h-sqft- °F/Btu	Wall insulation: open cell spray foam, R-20 h- sqft-°F/Btu	1.5*
11	Windows: SHGC 0.25	Windows: SHGC 0.15	1.3*
12	Lighting: 75% high efficacy	Lighting: 100% LED	1.2*
13	Wall insulation: fiberglass batt, R-13 h-sqft- °F/Btu	Wall insulation: fiberglass batt, R-25 h-sqft- °F/Btu	1.2
14	Roof material: asphalt shingles, medium color, absorptivity 0.75	Roof material: metal, white color, absorptivity 0.3	0.9*
15	Wall insulation: fiberglass batt, R-13 h-sqft- °F/Btu	Wall insulation: fiberglass batt, R-15 h-sqft- °F/Btu	0.9
16	Windows: SHGC 0.25	Windows: SHGC 0.20	0.6
17	No radiant barrier	Radiant barrier, double-sided foil	0.4*
18	Windows: 15% of finished floor area (FFA)	Windows: 18% of finished floor area (FFA)	+0.2
19	Windows: 15% of finished floor area (FFA)	Windows: 20% of finished floor area (FFA)	+0.3*
20	Windows: 15% of finished floor area (FFA)	Windows: 25% of finished floor area (FFA)	+0.7

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In Figures 3.4.4.1 to 3.4.4.4, the 2015 IECC minimally compliant baseline case is displayed on the far left, and the columns to the right represent simulation cases where one specific option parameter was changed relative to the 2015 IECC baseline case. The final column on the right of Figure 3.4.4.4, termed “combined strategies”, indicates the results of the simulation case with the options identified as the most energy efficient options that the team deemed reasonable for the client to consider (indicated by * in Table 3.4.4.1).

Figure 3.4.4.1 shows that changing the wall insulation from R-13 h-sqft-°F/Btu fiberglass batt to R-15 h-sqft-°F/Btu fiberglass batt, R-20 h-sqft-°F/Btu open cell spray foam, and R-25 h-sqft-°F/Btu fiberglass batt results in a decrease in site energy use by 0.9%, 1.5%, and 1.2%, respectively. The R-20 h-sqft-°F/Btu open cell spray foam option is included in the “combined strategies” case. Changing the exterior finish from fiber cement in a medium/dark color (absorptivity 0.75) to wood in a light color (absorptivity 0.3) decreases site energy use by 2.3%. Changing the roof material from asphalt shingles in a medium color (absorptivity 0.75) to metal in a light color (absorptivity 0.3) decreased site energy use by 0.9%. Adding a radiant barrier (double sided) decreased site energy use by 0.4%. All three of these options are included in the “combined strategies” case.

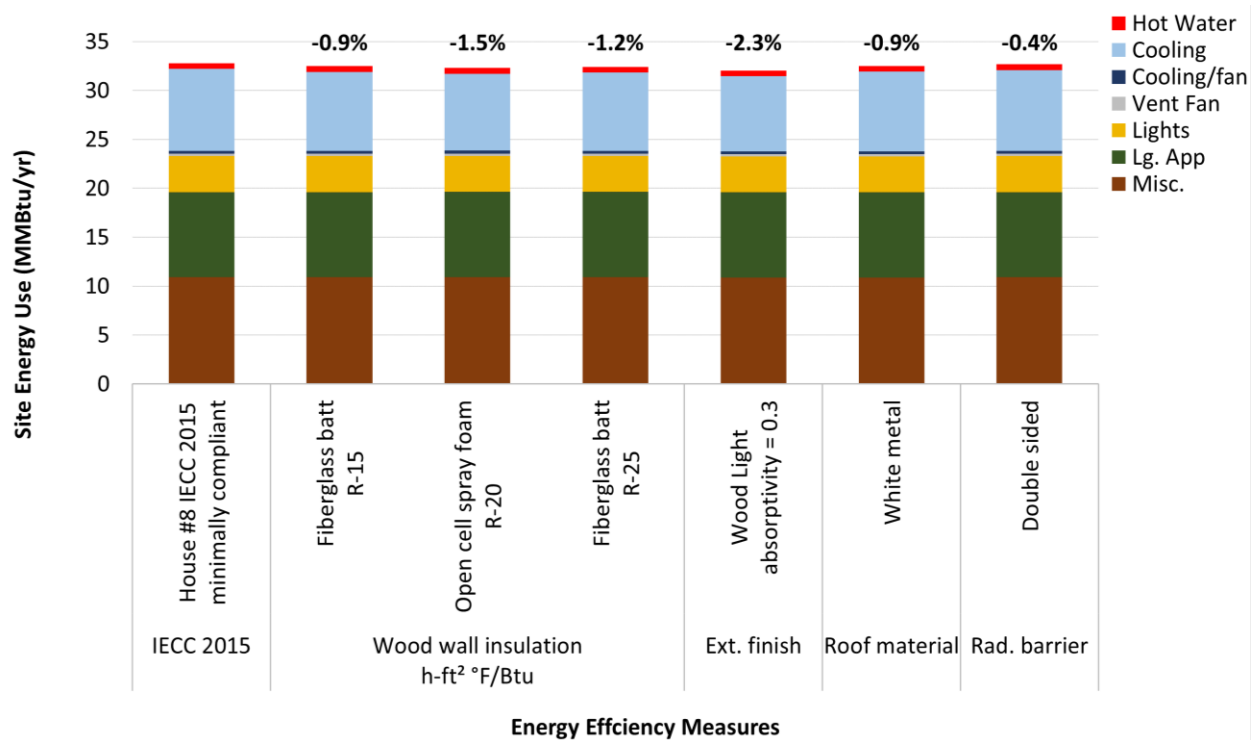


Figure 3.4.4.1 Parametric analysis results for annual site energy use (MMBTu/yr) for House 8: envelope options.

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Figure 3.4.4.2 shows that changing the window area from 15% of finished floor area (FFA) in the IECC 2015 baseline case to 18%, 20%, and 25% increases the annual site energy consumption by 0.2%, 0.3%, and 0.7% due to increased cooling energy for the conditioned part of the house. The larger window openings would allow for better natural ventilation of the unconditioned portion of the home and the hourly file from BEopt showed that during some times of the year indoor temperatures are reduced by of 0.30°F, 0.39°F, and 0.56°F for 18%, 20%, and 25% of FFA, respectively. BEopt can only give one temperature for the interior of the model, so it can't provide a good prediction of the unconditioned spaces, but it does show a trend toward decreased temperature. The team decided to choose the 20% FFA option as a middle ground to include in the “combined strategies” case. The BEopt software does not account for daylight harvesting, so increasing the window areas does not reduce lighting energy use. Changing the windows from a solar heat gain coefficient (SHGC) of 0.25 to 0.2 or 0.15 saves 0.6% and 1.3% of site energy use, respectively. The SHGC of 0.15 is used in the “combined strategies” case. Changing the lighting from 75% high efficacy to 100% LED saves 1.2% of annual site energy and this option is used in the “combined strategies” case.

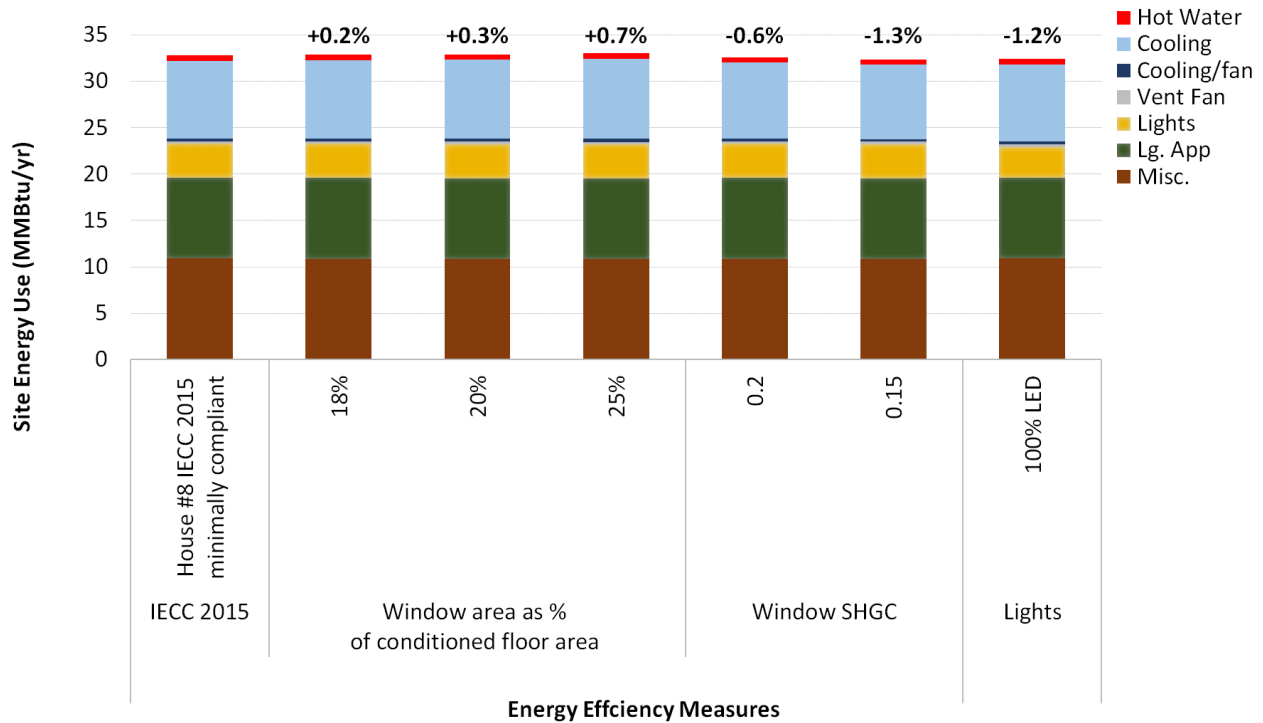


Figure 3.4.4.2 Parametric analysis results for annual site energy use (MMBtu/yr) for House 8: windows and lighting options.

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Figure 3.4.4.3 shows how changing the HVAC system, a 9 kBtu/h, SEER 14 mini-split heat pump in the IECC 2015 baseline case to a 36 kBtu SEER 16, or 12 kBtu SEER 18, or 36 kBtu SEER 20 heat pump saves 4.0%, 4.1%, and 7.8% of annual site energy, respectively. The 36 kBtu SEER 20 option is included in the “combined strategies” case. Changing the windows from 33% openable area with 20% of windows open to 50% openable area with 100% of windows open saves 1.7% of annual site energy compared to the IECC 2015 baseline. Both of those window options use a maximum outdoor humidity ratio of 0.0115 as specified by the 2014 Building America Protocols (Wilson et al. 2014). By changing the maximum outdoor humidity ratio to 1.0, meaning the occupants will not close the windows in high humidity conditions, the energy savings for the window change increases to 3.7%. This final window option is used in the “combined strategies” case.

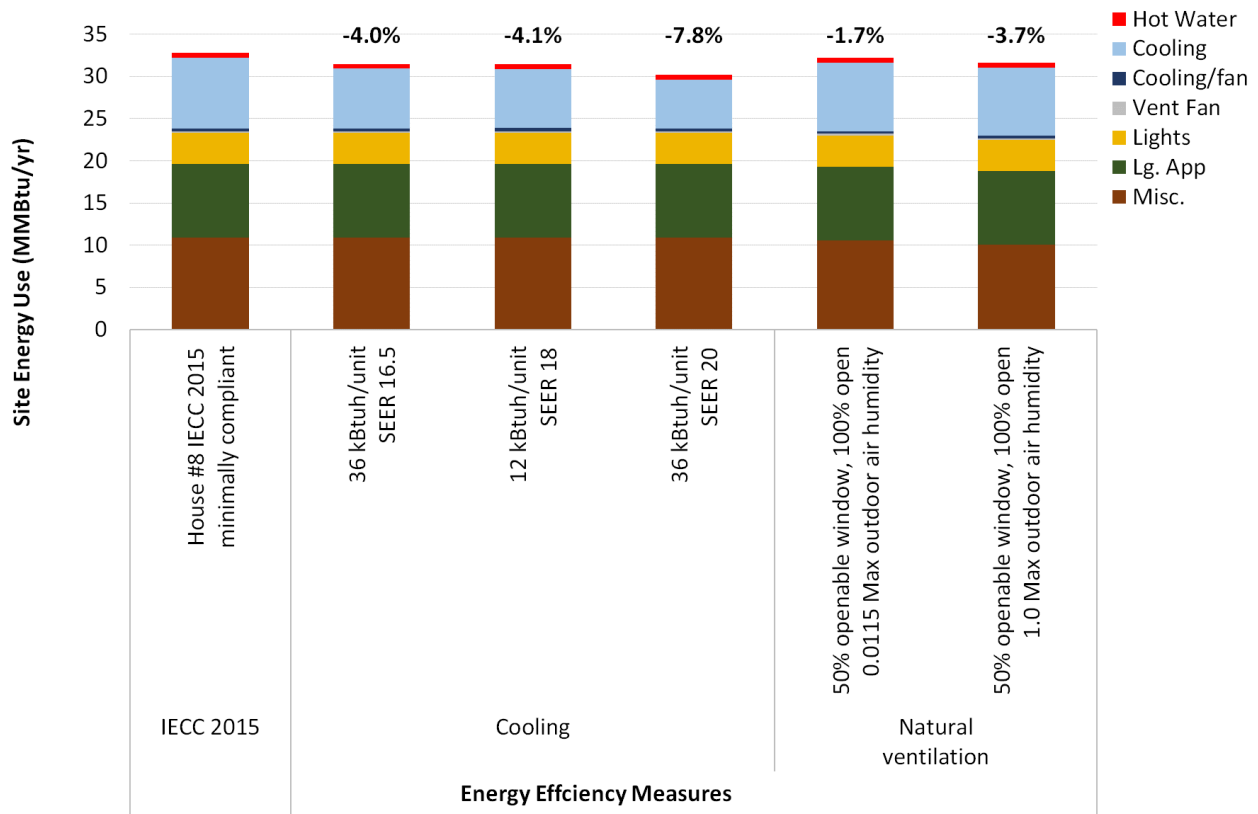


Figure 3.4.4.3 Parametric analysis results for annual site energy use (MMBtu/yr) for House 8: cooling and ventilation options.

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Figure 3.4.4.4 shows how changing the ceiling fans from five standard efficiency fans to two premium efficiency fans with occupancy sensors and a 4°F increase in the thermostat set-point (from 75°F to 79°F) saves 19.4% of annual site energy and this option is included in the “combined strategies” case. Changing the fans to five premium efficiency fans with occupancy sensors and 4°F increase in set-point saves 18% of annual site energy. Changing the appliances from standard efficiency to energy efficient saves 10% of annual site energy and is used in the “combined strategies” case. The appliance upgrades from the IECC 2015 baseline case include the following:

- Clothes dryer from electric standard (energy factor 3.1 lb/kWh) to electric premium (energy factor 3.93 lb/kWh)
- Clothes washer from standard (50 kWh/yr) to Energy Star compliant (41 kWh/yr)
- Stove from a standard electric (584 kWh/yr) to an induction stove (552 kWh/yr)
- Refrigerator with a side freezer with water and ice in door (718 kWh/yr) to a refrigerator with a top freezer and no ice maker (348 kWh/yr)

The “combined strategies” case uses all eleven options the team considered to be the best and most reasonable options. These are indicated in Table 3.4.4.1 by an asterisk (*). This combination of energy efficiency measures results in an estimated annual site energy use of 19.3 MMBtu (5,657 kWh), a 41.1% savings in annual site energy compared to the IECC 2015 baseline case with an estimated annual site energy use of 32.8 MMBtu (9,610 kWh). This improved design would cut greenhouse gas emissions by 9.5 metric tons of CO₂e annually. The homeowner would save (at \$0.28/kWh) an estimated \$1,107 annually on their utility bills.

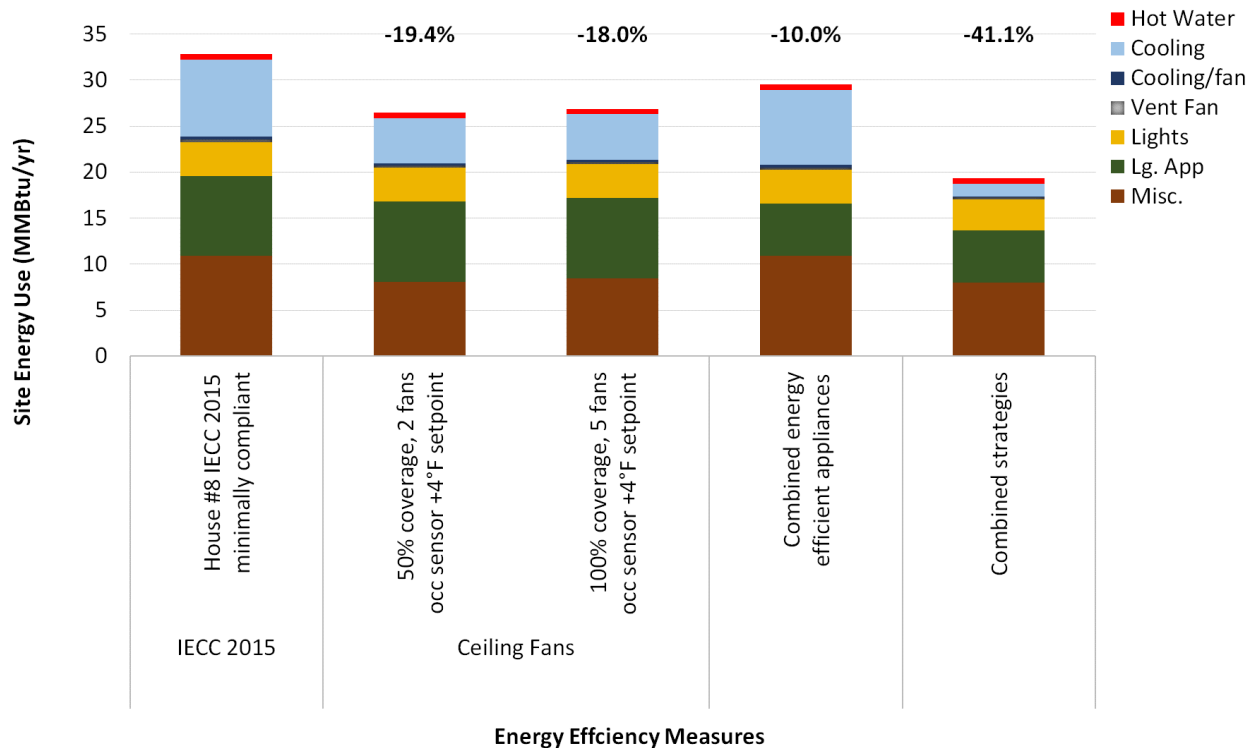


Figure 3.4.4.4 Parametric analysis results for annual site energy use (MMBTu/yr) for House 8 for fans, appliances, and the combined strategies case.

3.4.5 PV production and Net-zero Performance of House 8 Combined Strategies Design

The PV production and net-zero performance of the combined strategies case for House 8 is performed using the PV-Watts®, a free online application. The following values for input variables are used:

- Latitude and longitude: 21.33, -158.1 (“Kapolei” input)
- Module type: premium
- Array type: roof mounted
- System losses: 14.1 % (default)
- Tilt angle: same as roof angle
- DC to AC size ratio: 1.1 (default)
- Inverter efficiency (%): 96% (default)
- Ground coverage ratio: 0.4 (default)
- Panel efficiency 16%

The PV-Watts application provides median, minimum, and maximum annual electric production (kWh/yr) estimates for a given size in array capacity (kW). The conservative minimum value is used in this assessment.

The usable roof area of the House 8 geometry is determined and divided into segments according to their orientation to determine the potential of PV generation on these roof areas. Figure 3.4.5.1 illustrates the roof area segments which are available for the placement of PV-panels. The dashed lines indicate the required setback distances from ridge lines and sides of roof areas, in accordance to the International Fire Code (IECC 2015b).

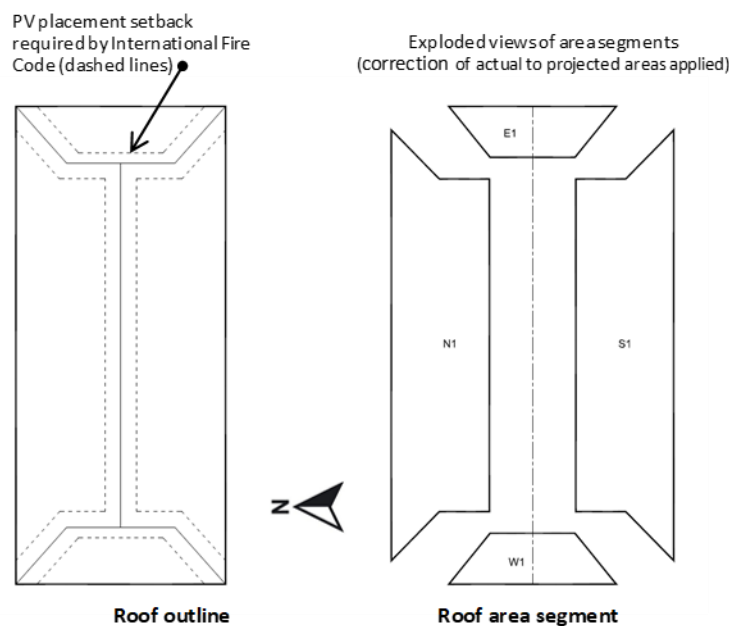


Figure 3.4.5.1 Roof area segments of House 8.

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A panel nesting factor is applied to the available areas: the ratio of achievable panel area coverage inside the area. The resulting PV array areas are listed in Table 3.4.5.1. Table 3.4.5.2 shows the calculation of the achievable PV electric generation and net-zero performance.

Table 3.4.5.1 Definition of roof areas segments of House 8.

Roof Area Segment ID	Direction of Panel Face	Panel Nesting Factor	Area Available on Roof (sqft)	Area Available for PV Array (sqft)
S1	South	0.8	1,250	1,000
E1	East	0.7	230	160
W1	West	0.7	230	160
N1	North	0.8	1,250	1,250

Table 3.4.5.2 Calculation of the achievable PV electric generation and net-zero performance of House 8.

PV Electricity Potential of House 8 Combined Strategies Case				PV Production to Achieve Basic Net-Zero			PV Production to Achieve Maximum Net-Zero		
Roof Area Segment ID	Max. Installed ¹ (kW)	Potential Production per 1 kW installed (kWh/yr)	Production Potential (kWh/yr)	Percent Area Used	Capacity of Panels Installed (kW)	Production (kWh/yr)	Percent Area Used	Capacity of Panels Installed (kW)	Production (kWh/yr)
S1	14.9	1,590	23,700	25%	3.7	5,900	100%	14.9	23,700
E1	2.4	1,480	3,600		0.0	0	100%	2.4	3,600
W1	2.4	1,420	3,400		0.0	0	100%	2.4	3,400
N1	14.9	1,230	18,300		0.0	0	100%	14.9	18,300
				Totals:	3.7	5,900	Totals:	34.6	49,000
¹ Default PV panel efficiency = 16%				Required PV for net-zero: 5,657 kWh/yr			Achievable net-zero performance: 875%		

The assessment of the PV-production potential and possible net-zero performance of House 8 indicates that the roof geometry of House 8 provides enough area to install the required PV-system capacity achieve a net-zero energy performance. The results of the calculation suggest that basic net-zero performance can be achieved with installing a minimum of 3.7-kW PV-panel capacity. The maximum net-zero capacity of about 875% can be achieved by installing PV panels on all suitable roof areas and achieve a total PV-system capacity of about 35 kW.

3.4.6 House 8 Takeaways

Cooling systems are a large energy component of House 8. Since thermal comfort is a high priority to many home owners, it is important to maximize savings in this area. By testing many simulations and hypotheses, it was determined that the combination of a highly efficient air conditioning system with an integrated ceiling fan that offsets the thermostat’s cooling set-point (4°F higher) has by far the largest effect on energy savings. This makes a much larger difference in annual cost than building envelope features such as a highly reflective roof or wall insulation. While these components do matter, a homeowner would save more money by investing in an air conditioner with a higher SEER value than they would by putting additional insulation in the walls.

These simulations suggest that House 8’s large appliances and miscellaneous categories (miscellaneous includes plug loads and ceiling fans in our simulations) make up roughly 60% of the home’s energy cost. While some of this energy is saved by investing in efficient appliances, much of the energy costs in these categories comes down to individual lifestyles.

These two main takeaways, in conjunction with energy saving measures discovered in parametric studies and are simulated in the combined strategies run are shown in Figure 3.4.6.1.

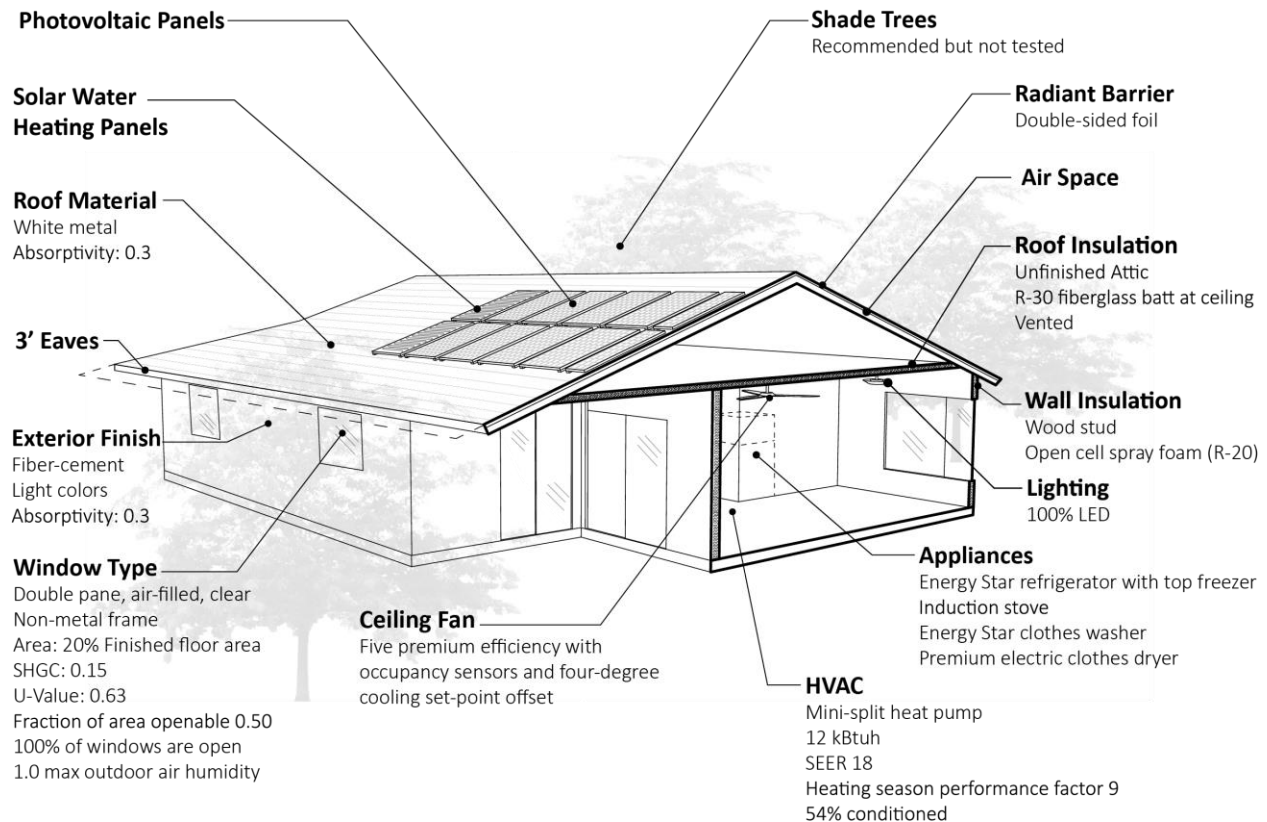


Figure 3.4.6.1 Improved House 8 design incorporating the combined strategies selected from the parametric analysis.

3.5 House 2 - Representing House Type with Natural Ventilation

Section 5.5 presents the performance of House 2, which is selected to represent a typical residential building using only natural ventilation that is used by DHHL or planned for future use.

3.5.1 Description of the House 2 Geometry

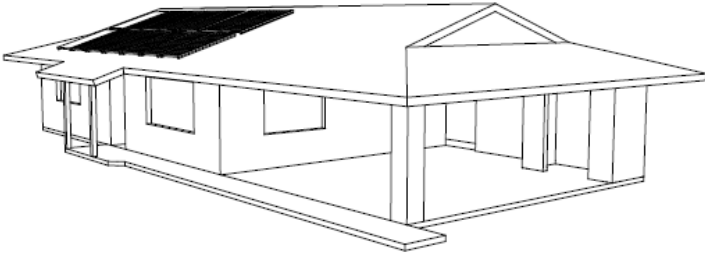
The existing conditions of House 2, a naturally ventilated 2-bedroom home is described in Table 3.5.1.1. The geometry of House 2 is depicted in Figure 3.5.1.1 and Figure 3.5.1.2. This home has gas appliances: stove, clothes dryer, and instant water heater. Inputs for the simulation model that is used for validation against the measured data are taken from the drawing set and are listed in Table 3.5.1.2.

Table 3.5.1.1 House 2 size, bedrooms, and occupancy.

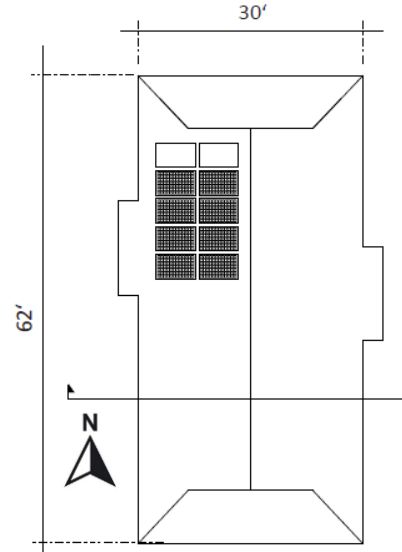
House component description	Values
Finished floor area	792 sqft
Carport area	576 sqft
# of bedrooms	2
# of bathrooms	1
# of occupants	1



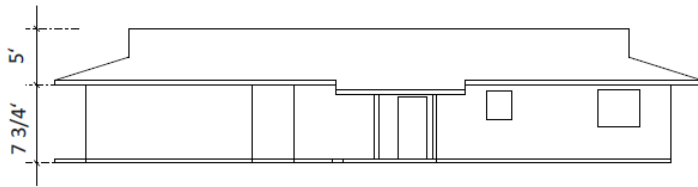
Figure 3.5.1.1 Floor Plan of House 2.



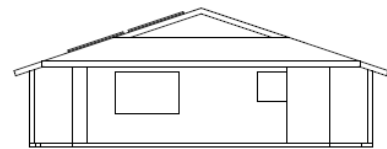
(a) Perspective view



(b) Top view



(c) Side view



(d) Front view

Figure 3.5.1.2 House 2, views and sections.

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Table 3.5.1.1 Existing House 2 plug load 0.5 BEopt modeling inputs.

Existing house component	Modeling Inputs
Wall assembly	½" gypsum board side R-13 h-sqft-°F/Btu fiberglass batt 2x4, 16" o.c wood studs Vapor barrier Medium/dark fiber-cement siding
Roof assembly	½" gypsum board ceiling R-30 h-sqft-°F/Btu fiberglass batt at rafters Pre-engineered wood trusses Radiant barrier, double sided foil Asphalt shingles, dark, absorptivity 0.92
Floor	Finished flooring 4" concrete slab Vapor barrier
Doors	Wood doors Screen doors counted in window area for ventilation
Glazing	Window area: 169 sqft (19.6% of finished floor area) Clear, double pane, air filled, thermally broken windows U-Value: 0.4 Btu/h-sqft-°F SHGC: 0.4
Natural ventilation	Fraction of window area openable: 0.5 100% of windows are open Natural ventilation can occur: 7 days/week, year round
Mechanical ventilation	None
Exterior shading	3-ft eaves
Lighting	75% high efficacy
Cooling	None
Infiltration	5 air changes per hour at 50 Pa with a 0.7 shelter coefficient
Plug loads	0.5 usage factor
Water heater	Propane tankless instant water heater
Appliances	Refrigerator with top freezer, no water or ice dispenser Stove, propane, usage factor 0.5 Dishwasher, none Clothes washer, usage factor 0.5 Clothes dryer, propane, usage factor 0.5 Water fixtures factor 0.5
Ceiling fans	None

3.5.2 Comparison of Simulated to Measured Energy Performance Data for House 2

In order to give the research team confidence in the simulation model, the simulated house’s energy use is compared to the actual house’s energy use. The temperature and humidity conditions in the existing house were monitored for 10.5 months (November 1, 2017 to September 14, 2018) and propane consumption was measured for that period. Electricity consumption in hourly averages was monitored for a shorter period (November 1, 2017 to February 10, 2018) due to equipment failure. Since there was no air-conditioning, the loads were assumed to not be significantly affected by the seasons and an annual estimate was made from the available data.

The existing house had only one occupant and the measured data showed atypically low plug load use, so the simulation model used an input of 0.5 usage factor for plug loads (50% lower than the national average for a 2-bedroom home). This model is called “House 2 existing plug load 0.5” and its energy consumption is compared with measured data in Figure 3.5.2.1.

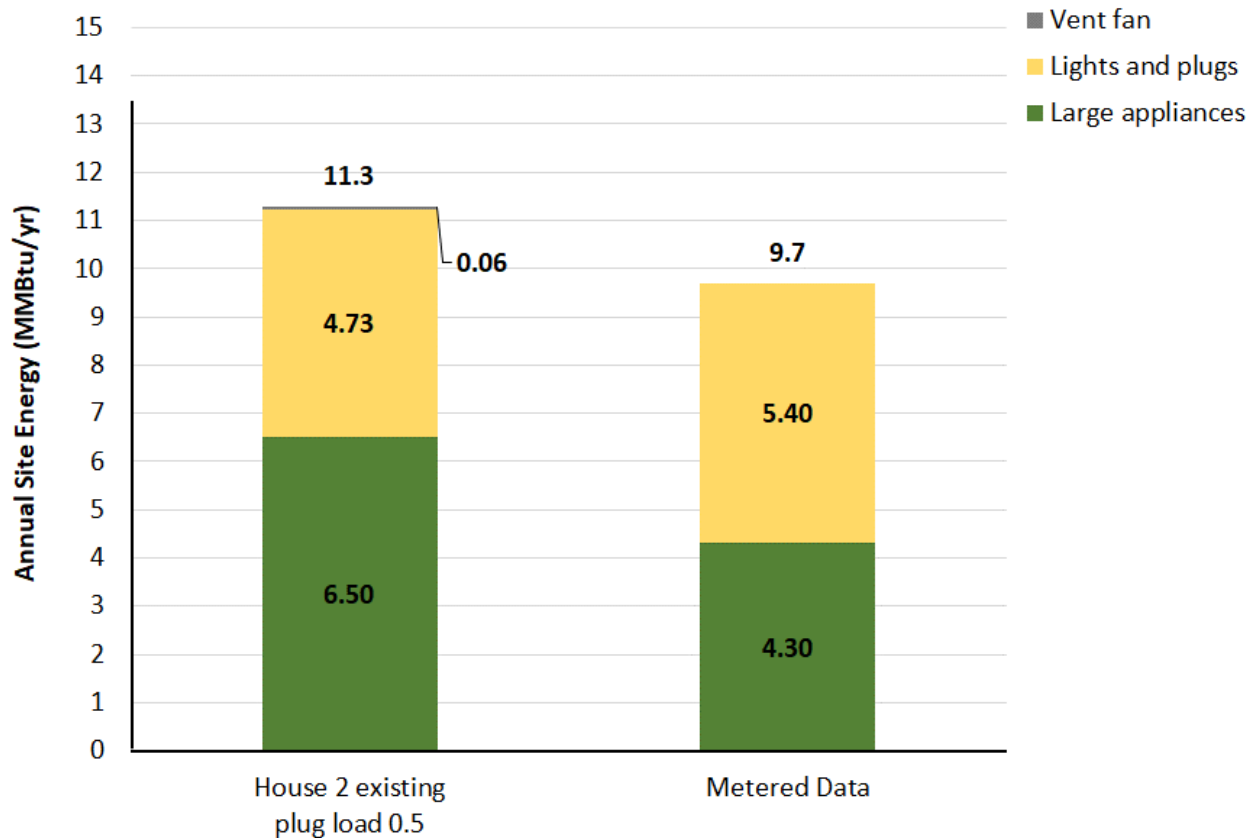


Figure 3.5.2.1 Comparison of measured and simulated site energy (MMBtu/yr) consumption

The comparison of measured and simulated results indicates a good correlation for the total energy consumption and thus gives the research team confidence in the validity of the energy models. It should be noted that it is not unusual for results obtained from simulations and measurements of building energy performance differ. This divergence of simulated (e.g., estimated) and measured results is due to the fact the simulation process relies on simplified and often standardized assumptions of energy use,

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whereas the actual energy use in the residential houses is significantly affected by individual energy use behavior. After the comparison with measured data was complete, the model of the existing house was changed to reflect the national average energy use by changing the plug load and appliance usage factor to 1.0 and this model is called “house 2 existing plug load 1.0” and used in the following analysis.

3.5.3 Energy Performance of House 2 as Minimally Compliant to IECC 2015 Energy Code

The “house 2 existing plug load 1.0” model (reflecting national average energy use for plug loads and appliances) is compared to the same model changed to be minimally compliant to the IECC 2015 energy code for the Tropical Zone with Hawai‘i amendments which is being adopted by counties in Hawai‘i in 2019. This model is called “IECC 2015 Tropical Zone,” and the inputs that are changed from the existing house are listed in Table 3.5.3.1. The IECC2015 Tropical Zone model uses all electric appliances and a solar water heating system.

Table 3.5.3.1. BEopt model inputs that were changed to minimally comply with IECC 2015 code.

Category Name	House 2 Existing Plug Load 1.0	House 2 IECC 2015 Tropical Zone Minimum
Attic insulation	Roof R-30 h-sqft-°F/Btu fiberglass batt at rafters, vented	Roof R-19 h-sqft-°F/Btu fiberglass batt at rafters, unvented
Roof material	Asphalt shingles, dark Absorptivity 0.92	Asphalt shingles, white or cool colors Absorptivity 0.45
Radiant barrier	Double-sided, foil	None
Window area	17.4% of finished floor area	19.1% of finished floor area
Window type	Clear, double, thermal-break, air U-value = 0.4 Btu/h-sqft-°F, SHGC = 0.4	Clear, double, non-metal, air U-value = 0.49 Btu/h-sqft-°F, SHGC = 0.56
Interior shading	Summer = 0.7, Winter = 0.7	None
Ceiling fans	None	Standard, 3 fans
Water heater	Propane tankless	Solar hot water with electric standard backup
Water heating distribution	R-2 h-sqft-°F/Btu insulation, trunk-and-branch, copper	Uninsulated, trunk-and-branch, copper
Appliances	Refrigerator, top freezer, 348 kWh/yr Stove, propane Clothes washer, ENERGYSTAR, 29 kWh/yr Clothes dryer, propane, energy factor 2.75 lb/kWh	Refrigerator, side freezer, 718 kWh/yr Stove, electric, 417 kWh/yr Clothes washer, standard, 36 kWh/yr Clothes dryer, electric, energy factor 3.1lb/kWh

Figure 3.5.3.1 shows the energy consumption per major building load category modelled with BEopt for the “house 2 existing plug load 1.0” and a model that is minimally compliant to the IECC 2015 Tropical Zone. The IECC minimally compliant case is 15% more energy efficient than the existing design. This is mainly driven by the addition of the solar water heating system.

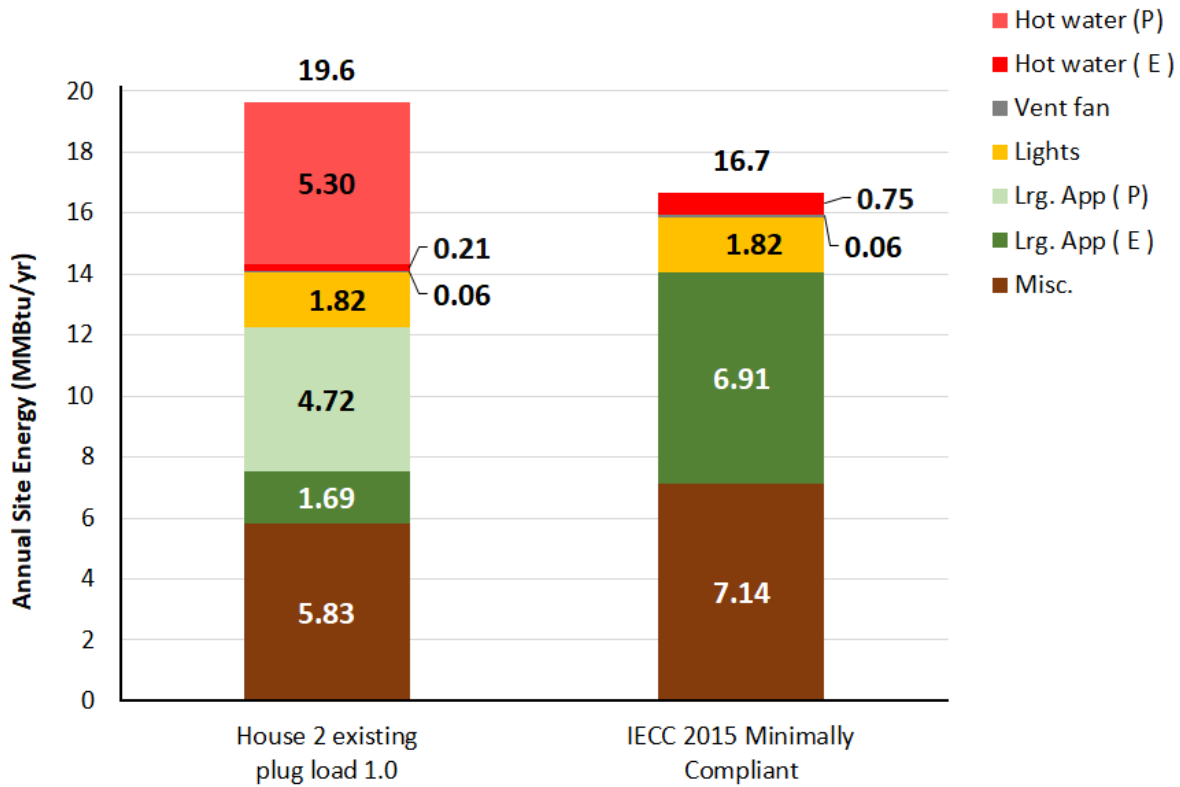


Figure 3.5.3.1. Annual site energy consumption (MMBtu/yr) per major building load category modelled with BEopt for existing House 2 plug load 1.0 case and IECC 2015 Tropical Zone baseline case. Propane is indicated with (P) and electricity with (E).

3.5.4 Parametric Energy Performance Analysis for House 2

A parametric energy performance analysis is conducted by using a baseline model, in this case, the minimally compliant IECC 2015 Tropical Zone model, and comparing it to a similar model with only one building envelope component or piece of equipment changed at a time. Parametric simulations allow a wide range of option comparisons side by side. The comparisons indicate the direct effect of each option on the energy performance of the house. The team tested modifications to the building envelope, windows, lighting, appliances, and water heating. We tested energy efficiency measures that we think are reasonable for the client to consider and implement.

House 2 is a unique case in that it is naturally ventilated, which means that no HVAC system is present. The HVAC system is typically a major contributor to the total house energy consumption. Improvements of the building envelope reduce the heat entering the indoor spaces, thus lowering the amount of heat energy that must be rejected from indoor spaces with an AC system. Since there is no mechanical cooling, changes in the envelope don't have a large effect on energy consumption but will affect thermal

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comfort which will be discussed in more detail in Section 3.5.6. Ceiling fans can provide some thermal comfort at a fraction of the energy cost of an HVAC system. Three ceiling fans (150 W) compared to an HVAC for a house this size (1.6 kW), both run 45% of the time, would use 9% of the energy of the HVAC.

In the absence of the energy demands of a HVAC system in House 2, the selection of energy efficiency measures to lower energy costs in the naturally ventilated house is limited to energy efficient appliances, lighting, water heater and miscellaneous loads. The whole range of the energy efficiency options that were investigated, but not all made a significant impact. Table 3.5.4.1 lists the twelve important options tested ranked by the percent site energy savings from the baseline IECC 2015 minimally compliant model. An asterisk indicates the option was included in the “combined strategies” case, combining the options that seems most favorable for energy performance and thermal comfort.

Table 3.5.4.1 Ranked results of parametric analysis for House 2 using the IECC 2015 Tropical Zone model as the baseline; the asterisk (*) indicates the option was included in the combined strategies case.

Rank	Baseline IECC 2015 Tropical Zone Minimum Option	Upgraded Option	Annual Energy Savings [%]
1	Appliances: standard efficiency	Appliances: energy efficient	15.4%*
2	Ceiling fans: standard efficiency (3 fans)	Ceiling fans: premium efficiency with occupancy sensors (3 fans)	6.2%*
3	Water heater: solar water with standard electric backup	Water heater: solar with premium electric backup	1.2%*
4	Lighting: 75% high efficacy, 533 kWh/yr	Lighting: 100% LED, 512 kWh/yr	0.5%*
5	Exterior finish: fiber cement medium/dark color, absorptivity = 0.75	Exterior finish: vinyl light color, absorptivity = 0.30	0.3%*
6	Windows: clear, double pane, air filled non-metal frame U-value: 0.49 Btu/h-sqft-°F, SHGC: 0.56	Windows: low-E, double pane, air filled non-metal frame U-value: 0.37 Btu/h-sqft-°F, SHGC: 0.30	0.2%*
7	Eaves 3-ft	Eaves 2-ft	0.2%
9	Roof insulation: fiberglass batt R-19 h-sqft-°F/Btu at rafters, unvented	Roof insulation: fiberglass batt ceiling R-19 h-sqft-°F/Btu at ceiling, vented	0.2%*
10	Radiant barrier: none	Radiant barrier, double sided foil	0.1%*
11	Wall insulation: R-13 h-sqft-°F/Btu fiberglass batt	Wall insulation R-19 h-sqft-°F/Btu fiberglass batt	0.1%
12	Water heater: solar water with standard electric backup	Water heater: Electric tankless	-24.3%

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In Figures 3.5.4.1 through 3.5.4.3, a baseline case that is minimally compliant to the IECC 2015 Tropical Zone code is displayed on the far left, and the columns to the right represent simulation cases where one specific option parameter was changed relative to the IECC 2105 baseline case. The final column on the right of Figure 3.3.4.3, termed “combined strategies”, indicates the results of the simulation case with the options identified as the most energy efficient or more thermally comfortable options that the team deemed reasonable for the client to consider (indicated by an asterisk in Table 3.5.4.1).

Figure 3.5.4.1 shows that changing the wall insulation from R-13 h-sqft-°F/Btu to R-19 h-sqft-°F/Btu would save 0.1% of annual site energy compared to the IECC 2015 baseline, but due to the increase in first costs was not included in the combined strategies case. The exterior finish was changed from a fiber cement in medium/dark color to a light colored vinyl showed a 0.3% energy savings. The insulation in the attic was moved from the rafters to the ceiling and the attic was vented, saving 0.2% of energy. This change is also beneficial in case the homeowner retrofits the home with air-conditioning in the future. Adding a radiant barrier saves 0.1% of energy. These three envelope changes were implemented in the combined strategies case.

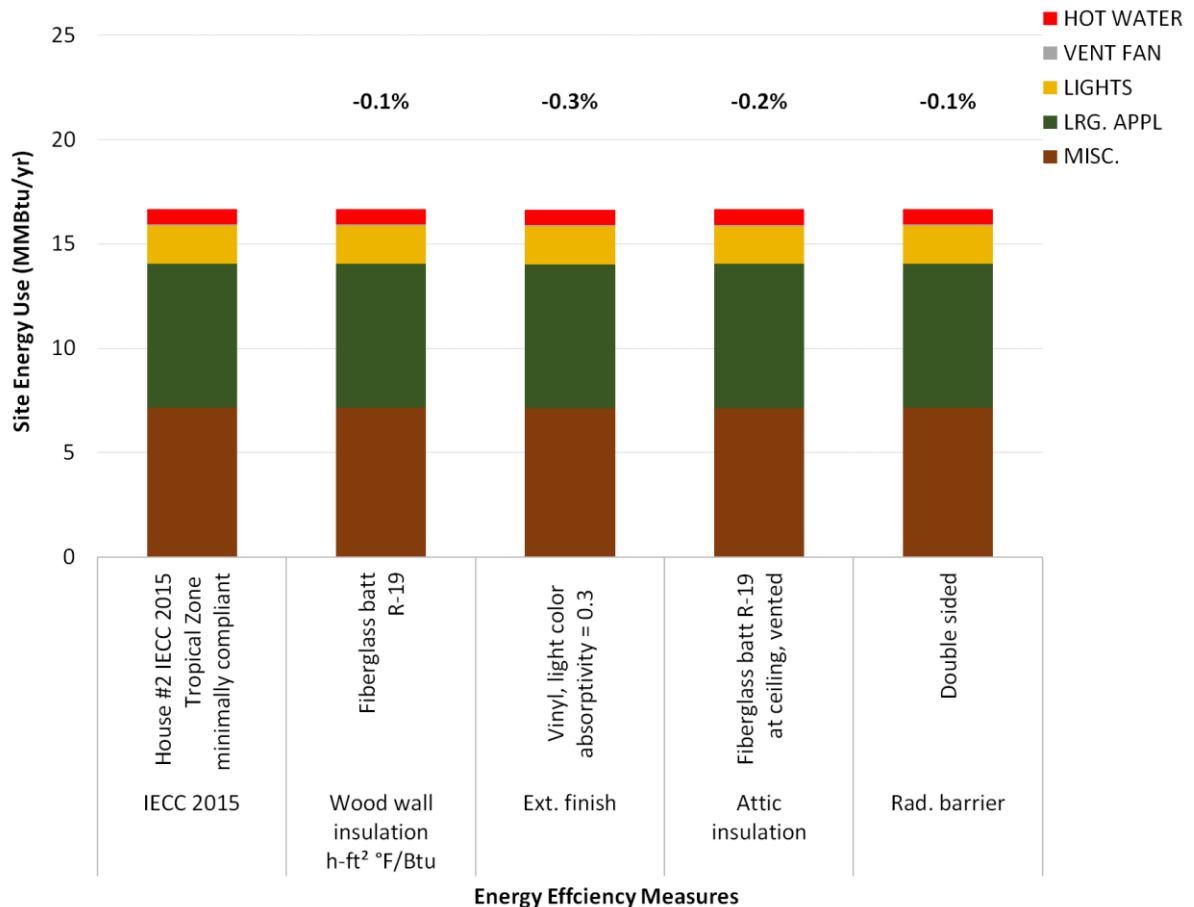


Figure 3.5.4.1 Parametric analysis results annual site energy use (MMBtu/yr) for House 2: envelope options.

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Figure 3.5.4.2 shows that changing from 3-ft eaves to 2-ft eaves, saves 0.2% of annual site energy, but this was not included in the combined strategies case due to thermal comfort reasons which will be addressed in section 3.5.6. Changing the windows from a U-value of 0.49 Btu/h-sqft-°F to 0.3 Btu/h-sqft-°F saves 0.2% of annual site energy compared to the IECC 2015 baseline. Changing the lighting to 100% LED saves 0.5%. Both of these options were included in the combined strategies case.

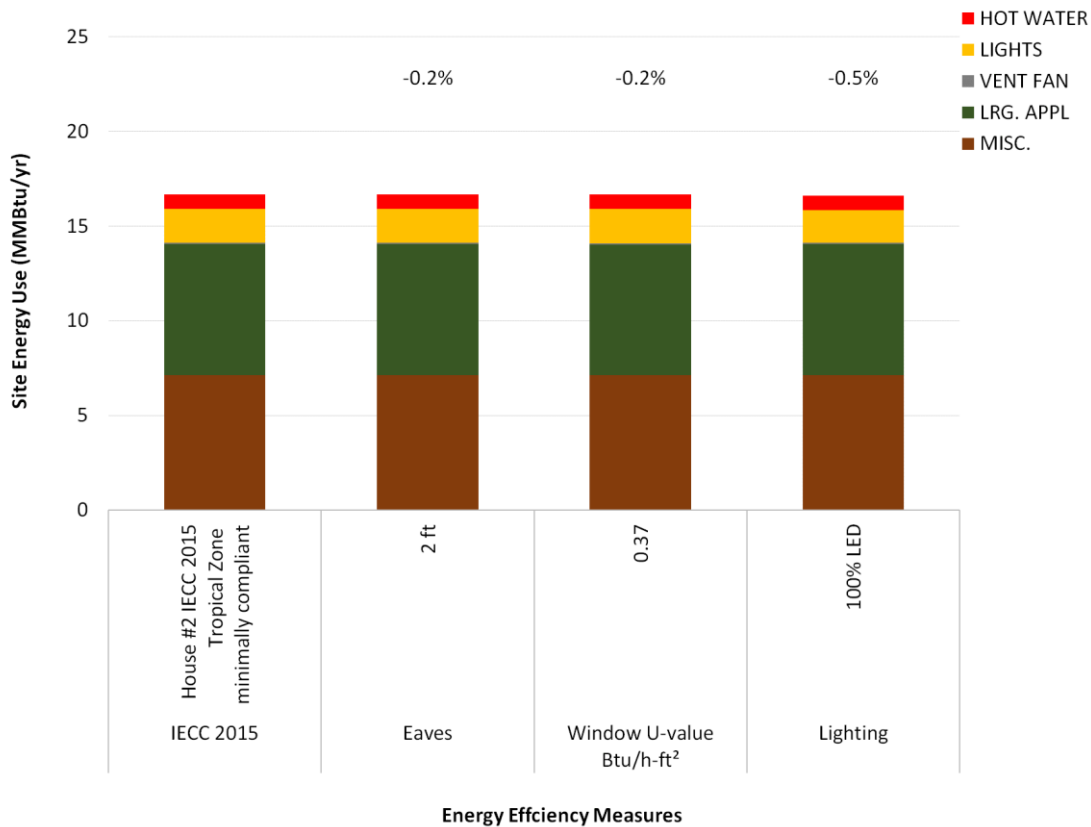


Figure 3.5.4.2 Parametric analysis results annual site energy use (MMBtu/y) for House 2: eaves, window, and lighting options.

Figure 3.5.4.3 shows that changing from a solar water heater with electric backup to an electric tankless heater increased annual site energy use by 24.3% and was not included in the combined strategies case. It can be argued that including a solar water heating system in such a small household is not economical (see Appendix B, Section B.6.2 for a financial analysis of solar water heating systems). Changing the backup water heater for the solar water heating to premium efficiency saves 1.2% of annual site energy compared to the IECC 2015 baseline. Changing the standard ceiling fans to premium efficiency fans with occupancy sensor resulted in 6.2% annual site energy savings. Changing the appliances to more energy efficient models saves 15.4% of annual site energy. The appliance upgrades from the IECC 2015 baseline case include the following:

- Clothes dryer from electric standard (energy factor 3.1 lb/kWh) to electric premium (energy factor 3.93 lb/kWh);

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- Clothes washer from standard (36 kWh/yr) to Energy Star compliant (29 kWh/yr);
- Stove from a standard electric (417 kWh/yr) to an induction stove (394 kWh/yr); and
- Refrigerator with a side freezer, water and ice in door (718 kWh/yr) to a refrigerator with a top freezer and no ice maker (348 kWh/yr).

These three options that save energy in Figure 3.5.4.3 are included in the combined strategies case which includes all the strategies listed in Table 3.5.4.1 indicated with an asterisk.

The “combined strategies” case uses all eight options the team considered to be the best and most reasonable options. These are indicated in Table 3.5.4.1 by an asterisk (*). This combination of energy efficiency measures results in an estimated annual site energy use of 12.8 MMBtu (3,743 kWh), a 23.5% savings (Figure 3.5.4.3) compared to the IECC 2015 Tropical Zone code baseline design with an estimated annual site energy use of 16.7 MMBtu (4,889 kWh). This improved design would cut greenhouse gas emissions by 2.8 metric tons of CO₂e annually. The homeowner would save (at \$0.28/kWh) an estimated \$321 annually on utility bills. These strategies also improved thermal comfort which will be discussed in Section 3.5.6.

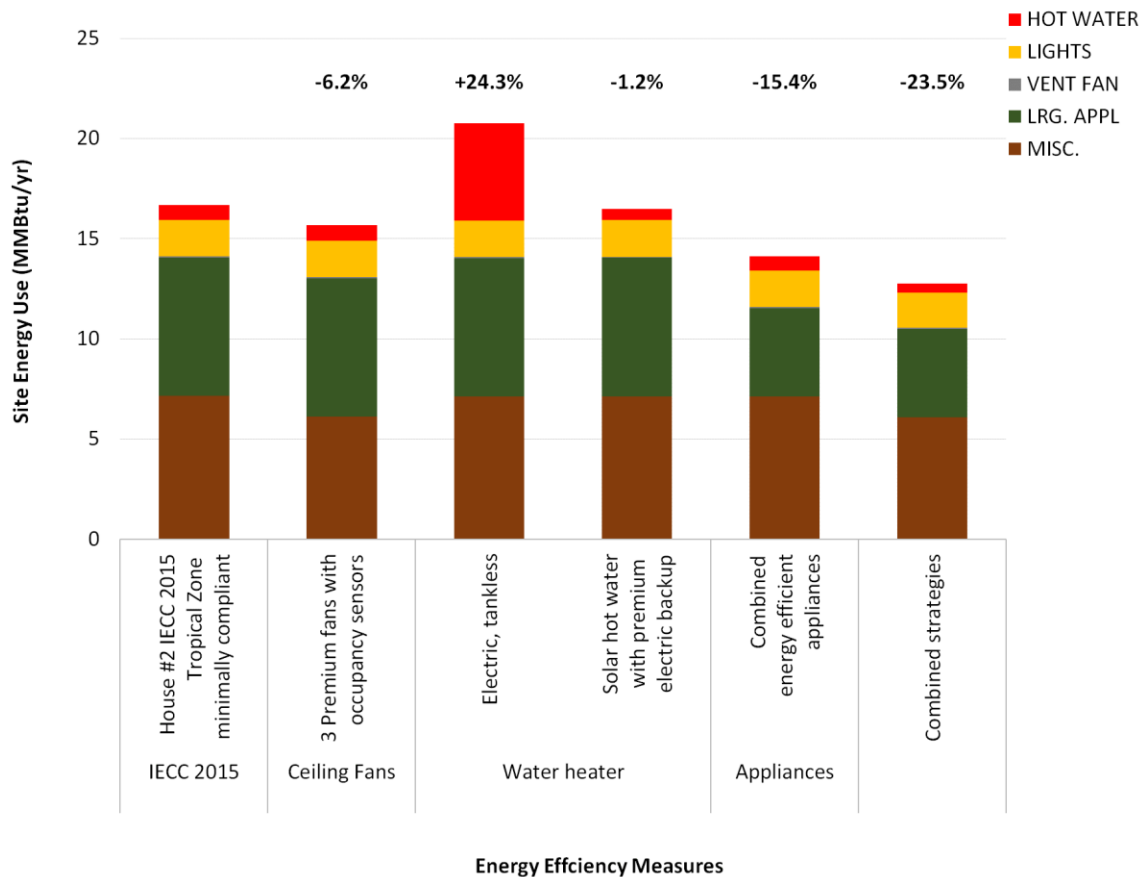


Figure 3.5.4.3 Parametric analysis results annual site energy use (MMBTU/yr) for House 2: ceiling fan, water heater and appliances options, and combined strategies case.

3.5.5 PV production and Net-zero Performance of House 2 Combined Strategies Design

The PV production and net-zero performance of the combined strategies design case of House 2 is performed using the PV-Watts software application. The following values of input variables are used:

- Latitude, longitude: 21.33, -158.1 (“Kapolei” input)
- Module type: standard
- Array type: roof mounted
- System losses: 14.1 % (default)
- Tilt angle: same as roof angle
- DC to AC size ratio: 1.1 (default)
- Inverter efficiency (%): 96% (default)
- Ground coverage ratio: 0.4 (default)
- Panel efficiency 16%

The PV-Watts application provides median, minimum, and maximum annual electric production (kWh/yr) estimates for a given size in array capacity (kW). The conservative minimum value is used in this assessment.

The usable roof area of the House 2 geometry is determined and divided into segments according to their orientation to determine the potential of PV generation on these roof areas. Figure 3.5.5.1 illustrates the roof area segments which are available for the placement of PV panels. The dashed lines indicate the required setback distances from ridge lines and sides of roof areas, in accordance to the International Fire Code (IECC 2015b).

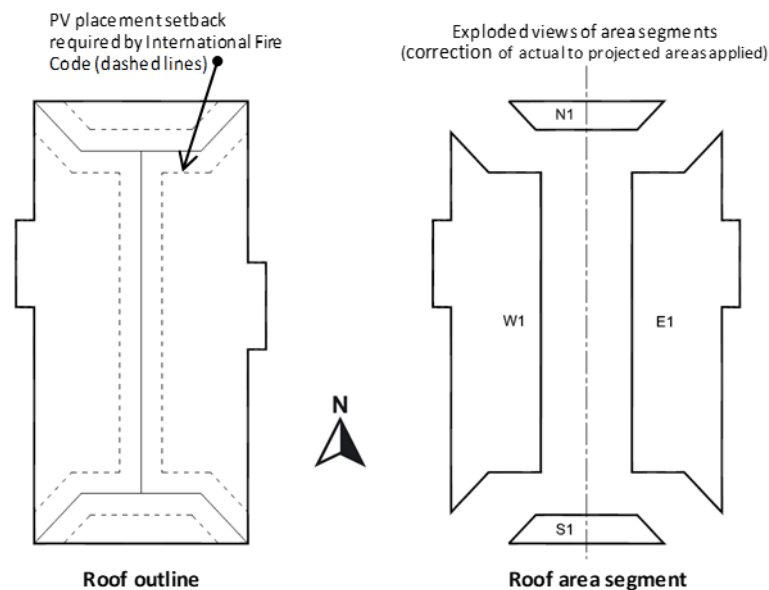


Figure 3.5.5.1. Roof area segments of House 2.

A panel nesting factor is applied to the available areas: the ratio of achievable panel area coverage inside the area. The resulting PV array areas are listed in Table 3.5.5.1. Table 3.5.5.2 shows the calculation of the achievable PV electric generation and net-zero performance.

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Table 3.5.5.1. Size of roof area segments of House 2 and area available for PV array.

Roof Area Segment ID	Direction of Panel Face	Panel Nesting Factor	Area Available on Roof (sqft)	Area Available for PV Array (sqft)
S1	South	0.8	75	40
E1	East	0.7	590	470
W1	West	0.7	590	470
N1	North	0.8	75	40

Table 3.5.5.2 Calculation of the achievable PV electric generation and net-zero performance of House 2.

PV Electricity Potential of House 2 Combined Strategies Case				PV Production to Achieve Basic Net-Zero			PV Production to Achieve Maximum Net-Zero		
Roof Area Segment ID	Max. Installed ¹ (kW)	Potential Production per 1 kW installed (kWh/yr)	Production Potential (kWh/yr)	Percent Area Used	Capacity of Panels Installed (kW)	Production (kWh/yr)	Percent Area Used	Capacity of Panels Installed (kW)	Production (kWh/yr)
S1	0.6	1,590	1,000		0.0	0	100%	0.6	1,000
E1	7	1,480	10,400	40%	2.8	4,400	100%	7	10,400
W1	7	1,420	9,900		0.0	0	100%	7	9,900
N1	0.6	1,230	700		0.0	0	100%	0.6	700
¹ Default PV panel efficiency = 16%				Totals:	2.8	4,400	Totals:	15.2	22,000
				Required PV for net-zero: 3,743 kWh/yr			Achievable net-zero performance: 590%		

The assessment indicates that the roof geometry of House 2 provides enough area to install the required PV-system capacity achieve a net-zero energy performance. A basic net-zero performance can be achieved with installing a minimum of 2.8 kW PV-panel capacity. The maximum net-zero capacity of about 590% can be achieved by installing PV panels on all suitable roof areas and achieve a total PV-system capacity of about 15 kW.

3.5.6 Thermal Comfort Conditions in House 2

The indoor thermal comfort of House 2 is determined by the ASHRAE 55 adaptive comfort standard which defines acceptable operative temperatures inside naturally ventilated spaces as a linear correlation function of the prevailing mean outdoor temperature, defining the upper and lower limits.

The equations used to define the acceptability range in Fahrenheit are:

$$\text{Upper limit (°F)} = 0.31 * (\text{prevailing mean outdoor temperature}) + 60.5$$

$$\text{Lower limit (°F)} = 0.31 * (\text{prevailing mean outdoor temperature}) + 47.9$$

Figure 3.5.6.1 illustrates the adaptive comfort standard. The prevailing mean outdoor temperature (x-axis) is determined by a moving data filter that averages the outdoor temperatures (a rolling average) preceding the time of the operative temperature observation (y-axis). The basic premise of the adaptive comfort standard is that as outdoor temperatures increase so does the predisposition of occupants to regard a higher operative temperature to be within their thermal comfort acceptability. Calculating data for the adaptive comfort graph is accomplished by correlating the operative temperatures with the prevailing mean outdoor temperature. If the resulting data point lies between the upper and lower acceptability limits, as defined in Figure 3.5.6.1, the operative temperature observation is within “acceptable” thermal comfort range. If the resulting data points are above the upper limit or below the lower limit, the operative temperature observation is considered not comfortable and does not conform with the ASHRAE 55 adaptive comfort standard.

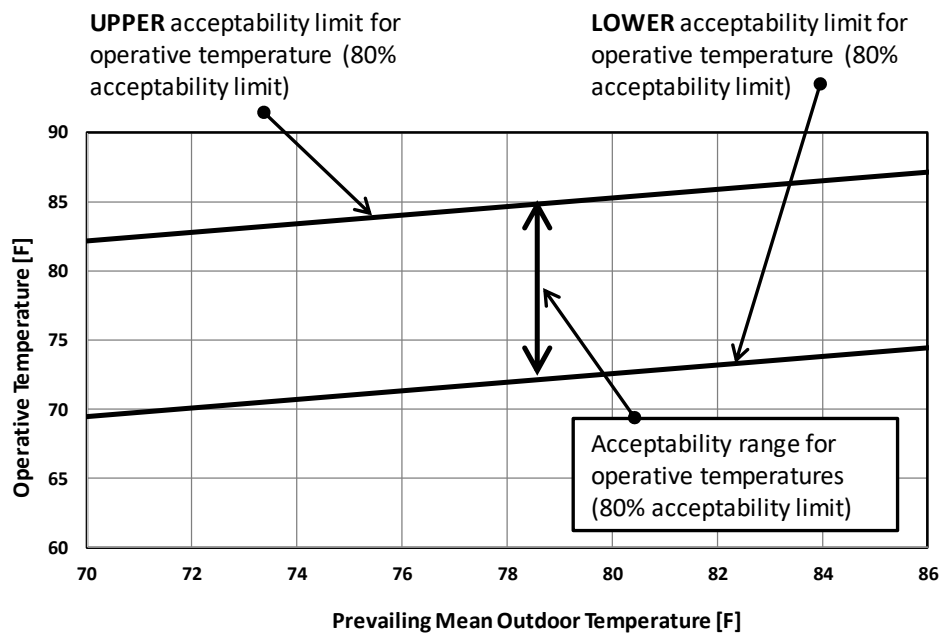


Figure 3.5.6.1 Illustration of the adaptive comfort standard of ASHRAE 55.

The upper acceptability limit can be increased by increasing air speed above 59 fpm. To predict the expanded range of comfort that could be provided by air movement from a fan, the upper limit is increased by 2.27°F for air speeds of 120 fpm and increased by 3.49°F for air speeds of 200 fpm (these are calculated by regression using data from ASHRAE 55-2017 Table 5.4.2.4).

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Outdoor and indoor air temperatures were measured for House 2 over a duration of 45 weeks (November 1, 2017 – September 14, 2018). The prevailing outdoor temperature was calculated on a rolling average of the previous 15 days’ temperatures. The operative temperature was based solely the dry bulb temperature since mean radiant temperature was not measured. Figure 3.5.6.2 shows the result of the adaptive comfort assessment of House 2 with each dot representing one hour of temperature data. The indoor temperature was considered comfortable, without any air flow provided by fans, 88.7% of the time. By using fans to provide air flow of 120 fpm or 200 fpm, the proportion of time the temperature would be considered comfortable was increased to 97.3% and 99.3% of the time, respectively. The proportion of time the home was unacceptably hot, even with fans running, was 0.7%. This unconditioned house was surprisingly comfortable.

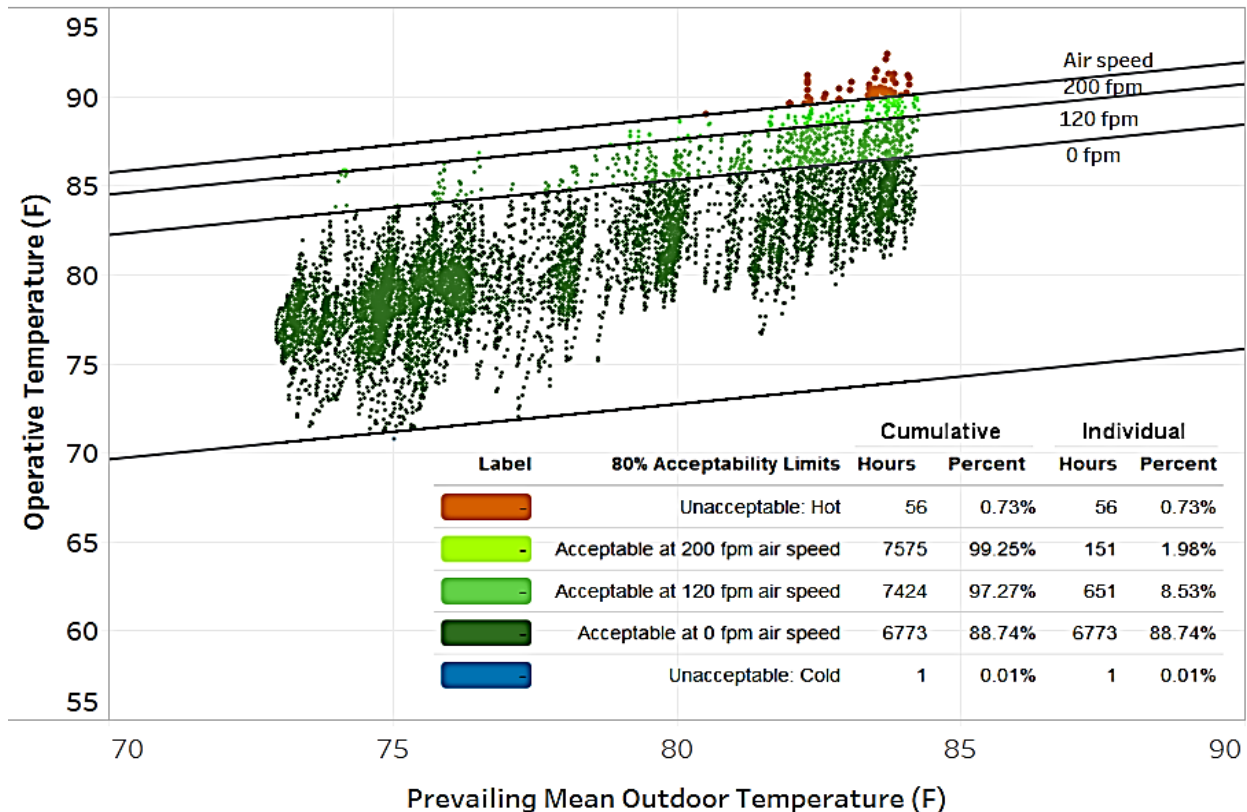


Figure 3.5.6.2 Thermal comfort assessment of House 2 measured temperature based on the ASHRAE 55 adaptive comfort standard including comfort zones for elevated air speeds of 120 fpm and 200 fpm.

The thermal comfort condition in the simulated house designs for House 2 are assessed by using the hourly outputs of the BEopt energy simulation runs. It should be noted that the primary purpose of the BEopt program is the assessment of the energy consumption of residential houses. Nevertheless, it is possible to extract hourly data of the simulated thermal conditions inside the house. Mean radiant temperature is not available, so dry bulb temperature represents operative temperature. The prevailing outdoor temperatures are calculated using a 15-day rolling average of the TMY weather file.

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Thermal comfort in a naturally ventilated space is primarily determined by a thermally effective envelope, which curbs heat from entering the indoor spaces, and the ability of ventilating outdoor air through the space to remove heat. Ten scenarios of building envelope and natural ventilation optimizations are simulated and the resulting adaptive comfort level determined.

Rather than plotting each simulation on a separate graph like we did in Figure 3.5.6.2, we will summarize the number of hours in each comfort zone. Figure 3.5.6.3 shows the percent of hours of the year from the simulations that are in the three different comfort zones (air speeds of 0 fpm, 120 fpm, and 200 fpm) and the number of hours that are unacceptably hot according to the ASHRAE 55 adaptive comfort standard. The y-axis starts at 80% to make the comparisons easier. Unacceptably cold hours are not reported since they are so few (one to four hours) and can be accommodated by closing windows or wearing more clothing. The case in the far left is the simulated case that is minimally compliant to the IECC 2015 Tropical Zone code and has 84.9% of annual hours in the comfort zone without need of elevated air speed provided by fans. With fans speeds of 120 fpm and 200 fpm, the total number of hours in the comfort zone would be raised to 93.1% and 96.7%. An estimated 3.3% of the time (290 hours per year) this simulated home is unacceptably hot even with fans running.

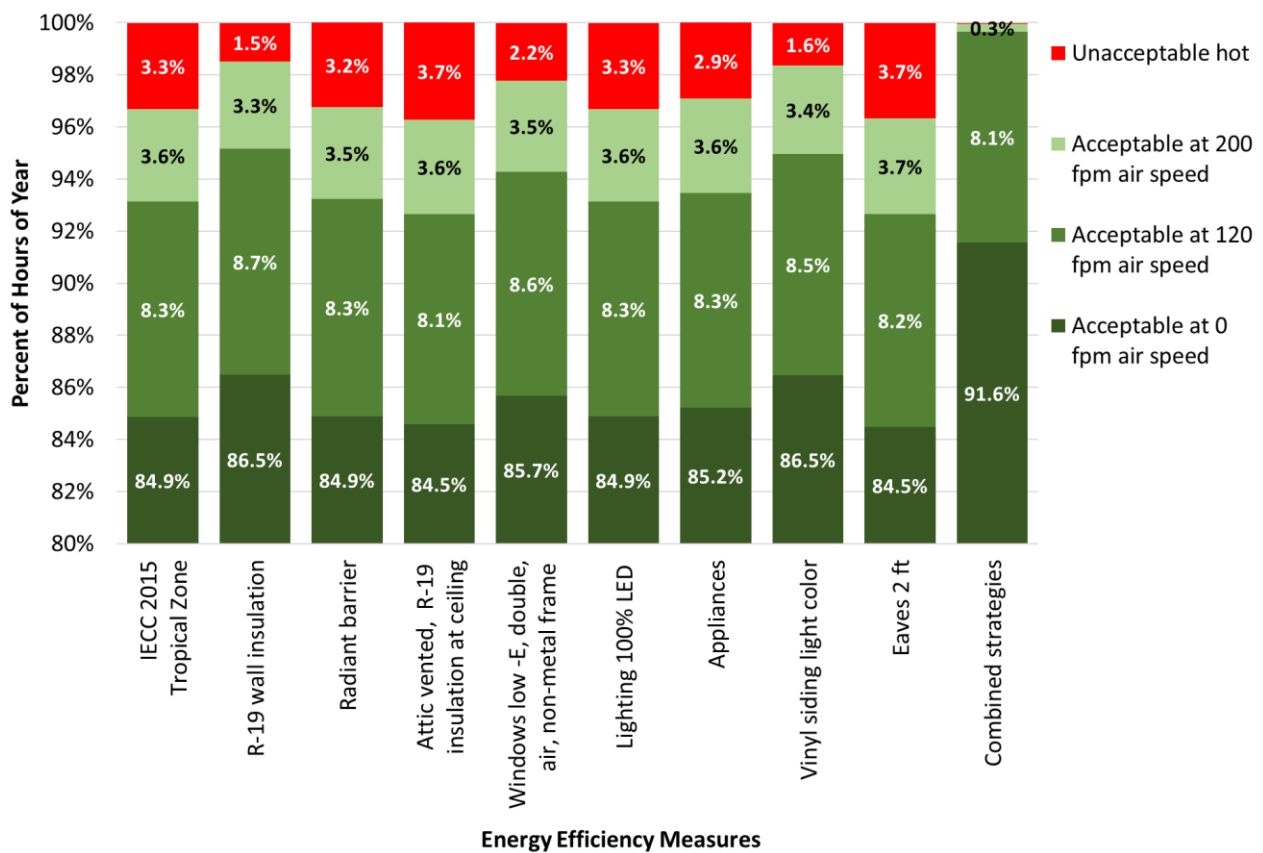


Figure 3.5.6.3 Summary of thermal comfort analysis using ASHRAE 55 adaptive comfort standard for the monitored House 2, the IECC 2015 Tropical Zone baseline simulations, and the parametric analysis simulations.

Increasing the wall insulation from R-13 h-sqft-°F/Btu to R-19 h-sqft-°F/Btu decreases the percent of time conditions are uncomfortably hot even with air speeds up to 200 fpm from 3.3% to 1.5%, although this measure was not included in the combined strategies since the team thought the added cost would be a deterrent. Adding a radiant barrier did not make a measurable difference in this simulation, reducing the percent of time unacceptably hot even with 200 fpm air speed from 3.3% to 3.2%. The simulation results do not give a prediction of the mean radiant temperature. This is an inexpensive option, so it is included in the combined strategies case. Moving the attic insulation to the ceiling and venting the attic did not improve thermal comfort but it would be the better choice if the homeowner added air-conditioning at a later date. Changing the windows to low-E, double pane, air-filled, with a non-metal frame decreases the percent of time it is uncomfortably hot with 200 fpm air speed to 2.2% of the time. Changing the lighting to 100% LED did not change thermal comfort. The energy efficient appliance option decreases the percent of time unacceptably hot to 2.9%. Changing the siding to a light color vinyl reduced the percent of time unacceptably hot to 1.6%. Changing the eaves from three feet to two feet increases the percent of time the house is unacceptably hot to 3.7% of the time and was not used in the combined strategies case.

The combined strategies case used all the energy efficient options indicated by and asterisk in Table 3.5.4.1. This case not only reduces energy consumption by 23.5%, it reduces the percent unacceptably hot hours, even with fans on, to a negligible 0.02% (two hours per year) and increases the percent of time the house is comfortable without the use of fans from 86.5% for the IECC 2015 Tropical Zone baseline case to 96.2% of the time.

3.5.7 House 2 Takeaways

The fact that this home relies solely on natural ventilation means that it started off fairly energy efficient by not having an HVAC system. Changing to all energy efficient appliances, efficient ceiling fans with occupancy sensors, and an efficient water heater as a backup to the solar water heating made the biggest savings in energy. The improvements to the lighting, exterior finish, radiant barrier made very modest improvements to energy consumption. The combined strategies case saves 23.5% of the energy use of the IECC 2015 Tropical Zone case. The features in the combined strategies case are illustrated in Figure 3.3.7.1.

Many of the improvements contribute to the increased thermal comfort of the house. The improved design increased the percent of hours within the comfort zone, without the need for ceiling fans, from 86.5% for the IECC 2015 Tropical Zone baseline case to 96.2% of the time. If the occupants use ceiling fans to provide 200 fpm air speed, the percent of unacceptably hot hours is reduced from 3.3% (290 hours per year) for the IECC 2015 Tropical Zone baseline case to nearly zero (two hours per year).

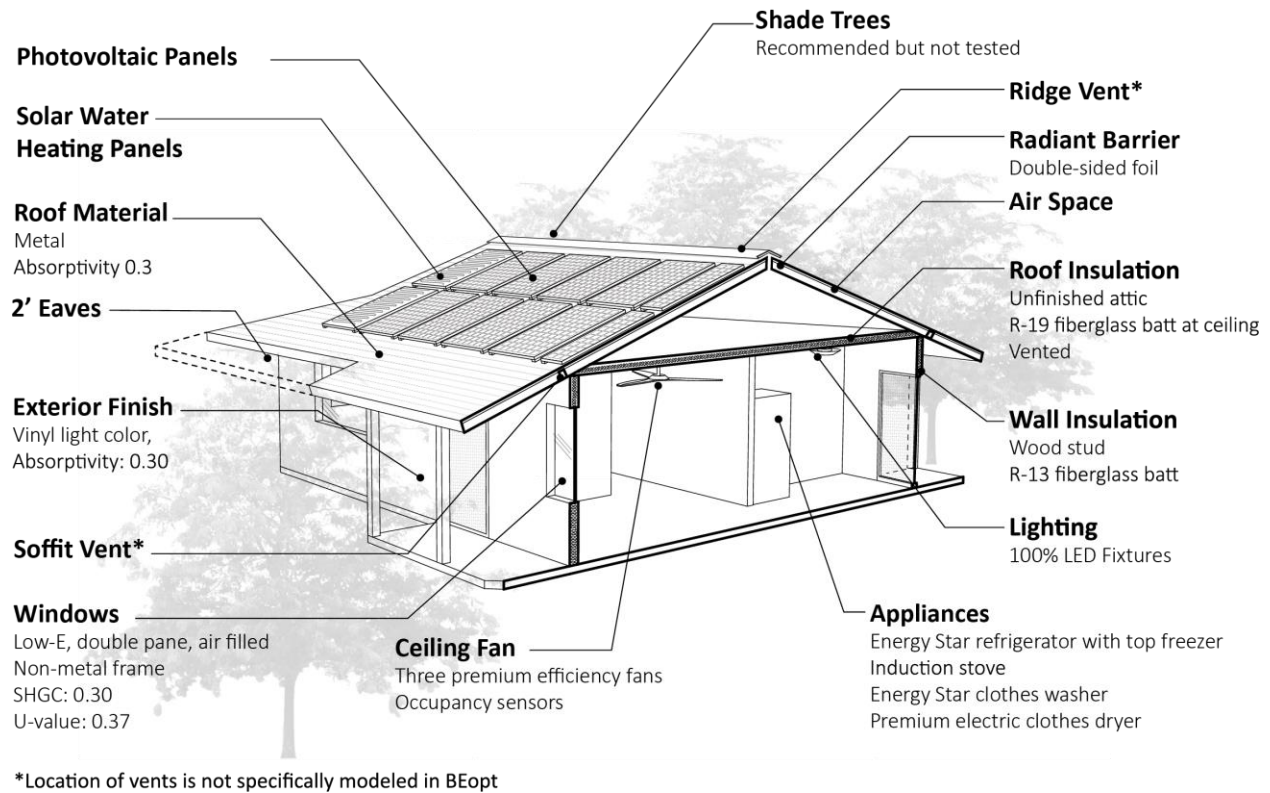


Figure 3.5.7.1 Improved House 2 design incorporating the combined strategies selected from the parametric analysis.

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3.6 House to House Comparison Summary

Table 3.6.1 summarizes the results of the energy savings and reduction in greenhouse gases for the three combined strategies cases vs the IECC 2015 minimally compliant cases for the three houses.

Table 3.6.1 Comparison of energy performance metrics of the three houses in this study.

Description	Units	House 3	House 8	House 2
Type of space conditioning		Fully conditioned with central air-conditioning	Partially conditioned with a mini-split heat pump	Naturally ventilated, no mechanical cooling
Simulation results reported:				
Energy simulation		Yes	Yes	Yes
Thermal comfort		No	No	Yes
Net-zero energy analysis		Yes	Yes	Yes
Floor area	sqft	1,654	1,581	792
Energy performance				
Annual site energy use of IECC minimally compliant case	MMBtu	43.6	32.8	16.7
	kWh	12,770	9,610	4,889
	Dollars ¹	\$3,576	\$2,691	\$1,369
Annual site energy use of combined strategies case	MMBtu	23	19.3	12.8
	kWh	6,735	5,657	3,743
	Dollars ¹	\$1,886	\$1,584	1,048
Annual savings between the IECC 2015 baseline case and combined strategies case	Percent	47.3%	41.1%	23.5%
	MMBtu	20.6	13.5	3.9
	kWh	6,035	3,963	1,146
	Dollars ¹	\$1,690	\$1,107	\$321
Metric tons ² CO ₂ e		14.5	9.5	2.8
Energy use intensity (EUI) of combined strategies case				
Site EUI	kBtu/sqft/yr	13.9	12.2	16.2
	kWh/sqft/yr	4.1	3.6	4.7
Source ³ EUI	kBtu/sqft/yr	44.1	38.7	51.2
	kWh/sqft/yr	12.9	11.3	15.0
Net-zero performance				
PV array to achieve net-zero annual energy	kW	4.5	3.7	2.8
Maximum size PV array to fit the roof space	kW	10.9	34.6	15.2
Maximum annual production	kWh	16,000	49,000	22,000
Thermal comfort – adaptive comfort⁴				
Conditions unacceptably hot with 200 fpm air flow for IECC 2015 case	hr/yr	N/A	N/A	290
Conditions unacceptably hot with 200 fpm air flow for combined strategies case	hr/yr	N/A	N/A	2

¹Based on \$0.28/kWh electricity cost

²See section 2.4.3 for formula used for calculation greenhouse gas emissions

³Source to site ratio 3.17 (Hawai'i Energy 2008)

SECTION 3 – DETAIL PERFORMANCE ANALYSIS OF THREE EXAMPLE RESIDENTIAL HOUSE TYPES

⁴Based on ASHRAE 55 Adaptive Comfort Standard for naturally ventilated spaces

SECTION 4 – GENERAL CONCLUSIONS AND RECOMMENDATIONS

In a hot and humid climate, thermal comfort is a major driver in determining the energy consumption of a home and the satisfaction of the occupants. For fully air-conditioned homes, cooling is the single largest end-use of energy: 40% to 54% of annual consumption for homes in this study. For naturally ventilated homes, improving thermal comfort will improve the occupants' experience and possibly reduce the chance that air-conditioning will be retrofitted into the house in the future. Below are the results of our energy simulation analyses with recommendations on which upgrades should be made to a home that is minimally compliant to IECC 2015 energy code.

Fully air-conditioned house

The parametric energy modeling showed that the upgrade that had the largest energy savings in the fully air-conditioned house was increasing the energy efficiency of the HVAC system from SEER 14 to SEER 24.5. The upgrade with the second largest energy savings was using premium efficiency ceiling fans in conjunction with increasing the thermostat set-point by 4°F. The upgrade with the third largest energy savings was selecting the most energy efficient appliances on the market: a premium electric clothes dryer; an Energy Star clothes washer, an induction stove, and an Energy Star refrigerator with top freezer and no through-the-door water or ice service. Other changes that resulted in less significant savings but seemed reasonable to implement were: selecting a light color exterior finish, selecting a white roof material, adding a radiant barrier, installing 100% LED lighting. Combining all of these upgrades resulted in an annual site energy reduction of 47.3% (reduced from 12,700 kWh/yr to 6,735 kWh/yr). This would save the homeowner approximately \$1,690 annually (at \$0.28/kWh). A 4.5-kW PV array could make this improved design net-zero energy.

Options that were determined to be unfavorable were: reducing the U-value of the windows which increased cooling energy use at night during cooler months; reducing window area which we considered to be unappealing; installing an energy recovery ventilation or heat recovery ventilator in the HVAC system which increased energy use.

Partially air-conditioned house

The parametric energy modeling showed that the upgrade that had the largest energy savings in the partially air-conditioned house was using premium efficiency ceiling fans combined with an increase in the thermostat set-point of 4°F. The upgrade with the second largest energy savings was selecting the most energy efficient appliances on the market: a premium electric clothes dryer; an Energy Star clothes washer, an induction stove, and an Energy Star refrigerator with top freezer and no through-the-door water or ice service. The upgrade with the third largest energy savings changing the HVAC mini-split heat pump efficiency from a SEER 14 to a SEER 20. Other changes that resulted in less significant savings but seemed reasonable to implement were: increasing the window opening from 20% of windows open 0.33 of a fraction to 100% of windows open 0.50 fraction; selecting a light color exterior finish; increasing the wall insulation to R-20; lowering the window solar heat gain coefficient to 0.15; installing 100% LED lighting; selecting a white roof material; and adding a radiant barrier. Although increasing the

window area from 15% of finished floor area to 20% slightly increased energy consumption due to an increase in cooling energy for the conditioned part of the house, it reduced the temperature in the unconditioned part of the house. Combining all of these upgrades resulted in an annual site energy reduction of 41.1% (reduced from 9,610 kWh/yr to 5,657 kWh/yr). This would save the homeowner approximately \$1,107 annually (at \$0.28/kWh). A 3.7-kW PV array could make this improved design net-zero energy.

Naturally ventilated house

The naturally ventilated house was already somewhat energy efficient since it lacked an HVAC system, but simulations showed that upgrades to the minimally compliant IECC 2015 model reduced energy consumption as well as improved thermal comfort. The upgrade that had the largest energy savings was selecting the most energy efficient appliances on the market: a premium electric clothes dryer; an Energy Star clothes washer, an induction stove, and an Energy Star refrigerator with top freezer and no through-the-door water or ice service. The second largest upgrade was changing from standard efficiency ceiling fans to premium efficiency ceiling fans. Other changes that resulted in less significant savings but seemed reasonable to implement were: improving the efficiency of the backup electric water heater for the solar water heating system; installing 100% LED lighting; selecting a light color exterior finish; selecting low-E windows with improved solar heat gain coefficient of 0.30; moving the attic insulation to ceiling level and venting the attic; and adding a radiant barrier. Combining all of these upgrades resulted in an annual site energy reduction of 23.5% (reduced from 4,889 kWh/yr to 3,743 kWh/yr). This would save the homeowner approximately \$321 annually (at \$0.28/kWh). A 2.8-kW PV array could make this improved design net-zero energy. This improved design would also improve occupant comfort. According to our analysis using the ASHRAE 55 Adaptive Comfort Standard, the percent of time the interior condition would be uncomfortable even with high fan speeds would be reduced from 3.3% to almost 0% of the time.

Because this was a 2-bedroom house, it could be argued that a tankless electric water heater would be a more economical choice. A net present value assessment (see Appendix B.6.2 for details) suggests that a solar water heating system has a long-term positive return only for occupancy levels of four to five people. We chose the solar water heating system purely on the basis of reducing greenhouse gas emissions for this recommendation.

Other Considerations and Limitations

Some energy-efficient upgrades suggested here do not affect the occupants' experience in the house, but some might not be preferred. For example, our energy efficient appliance package includes a refrigerator with a top freezer and no through-the-door ice and water service. This configuration of refrigerator is the most efficient but not necessarily the most popular. Also, the induction stove requires the use of special pots and may not come with as many sizes, colors, and features as a standard electric stove.

The energy simulations used a cooling set-point of 75°F which is suggested by the IECC 2015, but it is our experience that many homeowners with air-conditioning prefer a lower thermostat set-point. In order to meet a net-zero energy goal, designers may want to consider the likelihood of higher HVAC energy use than our models suggest.

Limitations:

- Longer window or roof overhangs could reduce cooling loads but may be a problem for required setback or be difficult to include in the desired design.
- A radiant barrier in the roof might be difficult to include for designs that have multiple roof trusses or spray-foam insulation at the roof.
- The scope of this study used a single IECC baseline model for the parametric analysis and did not extend to include a sensitivity analysis of all combinations of efficiency measures and how they might interact with each other.
- Shade trees would lower cooling loads but this was not modeled.

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APPENDIX A – GENERAL BUILDING PERFORMANCE MEASURES

Authored by Manfred Zapka

Appendix A introduces general building performance measures, which affect the process of energy consumption, onsite energy generation of buildings as well as comfort and indoor environmental quality. While the focus of this study is on residential buildings, most building performance measures can equally apply to commercial buildings. The building performance measures presented in Section 3 reflect the range of options used in the building simulation conducted for the present study.

The discussion in this section is of a more general nature. Appendix B contains a more detailed discussion of selected building performance measures where a quantitative analysis is presented to illustrate the effect of varying input parameters of selected measures on the overall energy and indoor environmental quality performance of the building.

The discussion in this section of each energy performance measure includes a description of the specific importance of the measure to the overall building performance. This includes a description of the contributing main building physics principles. Since the specific building performance parameters of the measures can have a wide application range, the present study focuses on specific characteristics, which are specified in this section.

It must be noted that the primary focus of present project work is on energy use and onsite generation of energy. Aspects of indoor environmental quality, mainly thermal comfort, is an aspect that is treated in conjunction with the discussion of energy performance.

The present study investigates building energy and comfort performance for **Hawaii's climatic conditions**. Therefore, space heating as well as heat loss due to low exterior temperature was not considered. Only those thermal building performance issues that contribute to heat gain from warm and moist outdoor conditions and cooling were considered in the course of this investigation.

A.1 Building Location, Orientation and Exposure

Buildings are physically integrated into and exposed to the natural environment. Consequently, the buildings receive a range of impacts from the environment. The types and scope of those impacts are dependent on the location, orientation and exposure of the building. While these impacts are invariably present, the building design can either mitigate negative impacts or use the impacts to bring about positive effect on the building performance.

A.1.1 Weather TMY

The location of the building determines a wide range of impacts, notably the thermal performance, the ventilation effectiveness by natural driving forces and the ability to generate onsite renewable energy, both thermal and electric energy.

For the building performance modelling the location of the building commands the use of the appropriate weather file, which is a recording of the weather conditions, preferably over the length of

one year. Micro-climate around the building can exist within a broader regional climate. Such micro climate can significantly affect the building performance. Therefore, the best weather information would be based on actual measurements.

But most of the time these actual measurements are not available, and therefore the building simulation must use standard weather information as input for the simulation runs. Since these weather files are of a representative nature of a certain region, micro-climatic information cannot be provided.

Therefore, building simulations require standardized input and simplification and bear a generalization aspect that must be considered when interpreting results, or especially when comparing predicted, or simulated, building performance result with actual measurements of the same type of data.

It is customary to use the pre-established weather files of the Typical Meteorological Year (TMY). These TMY files are providing selected weather data for many locations. TMY files represent typical weather conditions and they have been assembled from many weather recordings at the specific location. TMY files do not provide extreme weather conditions but rather represent average weather conditions which reflect long-term trends. Many TMY files are freely available.

The present study used the TMY files of “Barbers Point airport” whose weather observations were used to assemble this TMY file. Slight data errors were identified in the official TMY file and corrections were implemented in the TMY file that was used for the project.

A.1.2 Importance for Building Performance

As indicated before, the location, orientation and exposure of the building should be considered in the design to implement so-called “passive” building performance features. Passive measures suggest that measures can increase the building performance without the need to creating artificial driving forces to drive the effect.

A.1.3 External Parameters Considered for this Study

Table A.1.3.1 shows external parameters of location, orientation and exposure which were used in the simulating and analysis of building performance:

Type of building performance aspect	Description and/or value used in present study
TMY	USA-HI-Barbers Point; the weather station is located less than 15 miles from the location of the existing and planned buildings.
Exposure	Terrain – suburban; the terrain is used to define the vertical wind profile, where the suburban terrain is characterized by adjacent buildings and structure and the building density. The “suburban” terrain has a smaller influence on the wind

Type of building performance aspect	Description and/or value used in present study
	patterns than the “city” and a larger than the “rural” terrain types.
	Neighbors – the distance to structures surrounding the building prototype; the distance can be set for all four cardinal directions. Obstructions can affect building performance characteristic that consider external convective and radiative environmental impacts.
Orientation	The orientation of the front façade described by the azimuth as defined in the simulation software

A.2 Walls and Roofs

Walls have the function of structural support of the ceiling, floors and roof and to provide an envelope around the interior spaces. Exterior walls and roof give shape to the building form and provide shelter for security and a boundary to exterior environmental impact. Interior walls and ceiling also provide structural support functions and separate spaces inside the building.

A.2.1 Importance for Building Performance

Regarding the present study exterior walls provide the essential function of insulating the house and keeping moisture out. The exterior walls are typically built in layers with structural elements surrounded by inside and outside finishes.

Exterior walls come in different types and building materials, such as wood, stone, engineered walls systems like structural insulated panels. Exterior walls typically feature building components that improve the thermal performance of the wall, as well as moisture sealing to avoid vapor and liquid moisture intrusion into the building. Thermal insulation is added to walls to decrease the transfer of conductive heat through the walls. Water vapor and air sealing exterior walls decreases leak rates of warm outdoor air and curb the influx of water vapor through and into the wall, which can cause significant humidity related problems, both for the building structure and for the health and welling for the occupants. Exterior finishes reduce the heat absorptions rate by increasing the reflectance and increasing the heat rejecting to the exterior by controlling the emissivity.

Roofs are the topmost element of the building and its essential function is providing protection to occupants and interior building elements and possessions. Roofs are primarily designed to provide shelter against the elements, rain, snow, wind and sunshine. Roof are important for humidity protections and roof have many features that keep liquid water from entering the interior spaces.

The thermal performance of roofs is essential to mitigate convective and radiative heat transfer to the interior spaces. Building components and technologies which amplify the thermal performance of roof by decreasing heat transfer rates include: thermal insulation that decrease heat conduction, exterior roof finishes that lower the heat absorption of the roof membrane (e.g., “cool roof”), roof internal

thermally induced convection that disrupts the heat conduction through walls and interior radiant barriers which mitigate radiant heat transfer from the roof internal surfaces.

A.2.2 Performance Parameters Considered for this Study

Tables A.2.2.1 through A.2.2.3 show building performance parameters of exterior walls and roofs, respectively, which were used in the simulating and analysis of building performance:

Type of building performance aspect	Description and/or value used in present study	
Wall type: For the present study only, wood stud walls were considered (Figure A.2.2.1 illustrates a representative cross section of a wood stud wall)	Pertinent performance design parameters are:	
	Interior thermal insulation performance	Fiberglass, cellulosic and foam insulation material, installs as batts, rolls, board, and spray; important aspects are thermal insulation value (nominal and installed R-value), cavity fill, and spacing of the structural framing, which affect heat transfers through “heat bridges”
	Exterior thermal insulation performance	Different sheathing material and thicknesses that provide different insulation rates (R-values)
	Exterior finish	Type of coating applied to the exterior walls which regulate the amount of heat absorption into the roof membrane through a combination of heat reflection, thermal emissivity and thermal insulation.
	Thermal mass	Affects the thermal dynamic performance to absorb, store and release sensible and latent heat. Important performance metrics are sensible heat, density and latent capacity

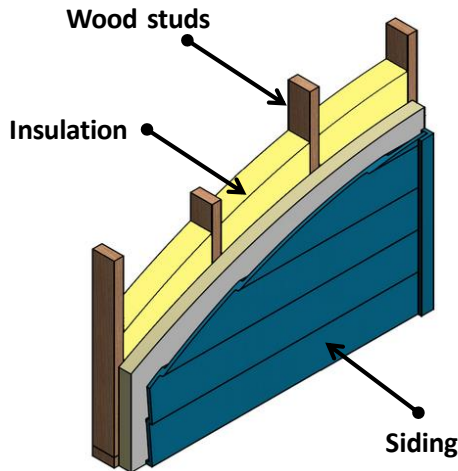


Figure A.2.2.1 Representative cross section of a wood stud wall)

The figure illustrates the elements of a wood stud wall as the wood studs, which are the structural frame, the siding and the insulation. Not shown is the interior finish of the wall which is frequently a layer of drywall.

Table A.2.2.1: Performance parameters for roofs		
Type of building performance aspect	Description and/or value used in present study	
Roof type: For the present study gable and hip roofs were considered	Pertinent performance design parameters are:	
	Type of attic, vented or unvented	If the attic beneath the roof is outside the thermal building envelope, and thus “unfinished”, it has a significant effect on thermal performance of the roof. A vented attic typically has a better thermal performance since heat that penetrates through the roof membrane is rejected by convective heat transfer.
	Thermal insulation	The effectiveness of the thermal insulation of the roof is given by the type of insulation and the nominal R-value; the quality of insulation installation and the fraction of roof area has missing effective insulation; the type and spacing of framing to lower the heat transfer through thermal bridges
	Exterior finish	The material and exterior composition of the roof regarding the absorption, reflectivity and emissivity: Darker roof material typically has a higher absorptivity, which increase the heat gain, than roof of lighter color. Emissivity is important since high emissivity promotes the heat rejection to the outside environment and

Table A.2.2.1: Performance parameters for roofs	
Type of building performance aspect	Description and/or value used in present study
	therefore reduces the heat migration to the interior space of the building. The best thermal performance is achieved with exterior finish that has low absorptivity and high emissivity.
	<p>Radiant barrier</p> <p>Radiant barriers are installed to significantly decrease heat flux to the interior of the building through radiative heat transfer. Radiant barriers are made of very low emissivity material, such as aluminum foil. Radiant barriers require an air film on side that avoids radiant heat transfer.</p>
	<p>Eaves</p> <p>Eaves provide some protection against water impinging on walls. Eaves also provide shading for parts of the wall, thereby limiting the amount of solar radiation received by the exterior walls and windows that are close to the eaves. The pertinent performance metric of eaves is the extent of the overhang of the roof over the exterior walls.</p>

A.3 Fenestrations

Building fenestrations refer to opening in the building envelope and include windows, doors and skylights.

A.3.1 Importance for Building Performance

Windows are important for the comfort of occupants as they allow natural light to enter the interior. Fenestration allows necessary outdoor air to enter the interior spaces, which contributes to intentional ventilation and increase the indoor air quality.

Windows as well as door and skylights, however, provide a break in the seal of the building envelope, which promotes air and water as well as heat to enter the interior spaces. This contributes to unintentional mass and energy (heat) transfer, thereby lowering the overall thermal and humidity performance of the envelope.

Regarding the thermal performance of windows, doors and skylights the following aspects must be considered:

- Conductive heat transfer through the glazing and frame.
- Convective heat transfer by means of moving over and through air parts of the window or door
- Radiative heat transfer through the glazing and other parts of the window, where glazing is the governing portion of the radiative heat transfer due to the relative size of the glazing to the framing.

A.3.2 Types of window – High Performance Windows

The thermal performance of windows is intrinsically lagging the opaque parts of the building envelope. While the lesser thermal insulation of windows already increases the heat gain relative to the opaque envelope, the transparent glazing allows solar radiation to enter the interior of the building and increase the surface temperature of the interior layers of the glazing. These forms of heat gain increase the indoor air temperature and cause radiation heat emitting from the glazing.

High performance windows have thermal properties that decreases the conductive, convective and radiative heat gain. Multiple panes with an air or inert gas filled gap separating the panes increase the thermal insulation. A low-emissivity coating on glass panes decreases radiant heat gain in the interior.

A.3.3 Performance Parameters Considered for this Study

Table A.3.3.1 shows pertinent building performance parameters of windows, which were used in the present simulation analysis of building performance: (note: only windows are discussed since they represent the major effect on the overall thermal performance of the building):

Table A.3.3.1: Performance parameters for windows		
Type of building performance aspect	Description and/or value used in present study	
Size of windows	Pertinent performance design parameters are:	
	Total size of the windows	The window fraction on the four cardinal directions of the building; the fraction is defined as the quotient of absolute window area divided by the area of the façade.
	Window perimeter	The window perimeter to area ratio affect the thermal performance through the U-value and the solar heat gain.
Type of window	Type and performance of window	The thermal insulation (U-value) and the solar heat gain (SHGC) of various types of windows with different number of panes used.
Interior shading	Type and operation of interior shades	Interior shades block direct solar radiation into spaces and thereby lower the associated heat gain. Performance parameters is the fraction of shades closures and the reduced heat gain.
Overhang (exterior shading)	Configuration of exterior overhang	Exterior overhang provides shades and partially or fully block direct solar radiation from passing through the glazing. The pertinent performance parameter is the dimensions of the overhang.

A.4 Ventilation and Air Movement

Air moving into, through and out of indoor spaces has the purpose of improving the indoor air quality and improving the indoor thermal comfort.

A.4.1 Importance for Building Performance - Fresh Air, Removal of Heat and Moisture

Air moving through indoor spaces entrains, dilutes and then expels potentially harmful pollutants from indoor spaces, thereby improving and safeguarding indoor air quality. The amount of air passing through the indoor spaces is directly related to the improvement of indoor air quality, since larger air quantities and more frequent air changes promote dilution through the kinetic mixing energy and the increase the convective transport mechanisms.

Air moving thorough the space also controls the moisture level in indoor air and on surfaces of indoor building components and other surfaces. Moving air supports the regulation of humidity levels and thereby diminishes harmful growth of fungi and pathogens.

Another function of air movement in indoor spaces is the regulation of sensible heat. Air flowing over surfaces entrain sensible heat. The heat contained in the mass of air is then rejected to the outside by either air exchange with the exterior environment or by removing of the heat from the air by air passing over actively cooled surfaces.

Air movement requires a differential pressure as a driving force that can either be provided by natural or be mechanical means.

A.4.2 Mechanical Ventilation

Mechanical ventilation is air movement induced by mechanical fans. Mechanical ventilation actively creates a pressure differential between the exterior and interior air mass, thereby providing a driving force to bring outdoor air into the space and expelling indoor air to the outside environment. The amount of energy needed for mechanical ventilation depends on the air mass moved, the pressure losses along the air flow pathways and the efficiency of fan systems.

While the primary function of mechanical ventilation is to safeguard enough quantities of fresh air entering the indoor spaces, mechanical ventilation can also be used for cooling. Under the cooling function the outdoor and indoor air masses are mixed and the mixed air is then expelled to the exterior. An effective cooling can only occur if the outdoor air is cooler than the indoor air, since the amount of the heat that can be removed by the air flow is proportionate to the temperature differential between indoor and outdoor air temperatures. This principle of space cooling is used by the so-called whole house fan.

A.4.3 Natural Ventilation

Natural ventilation of a building relies on driving forces based on exterior environmental conditions. In cross-ventilation the air is moved laterally through the building driven by a pressure differential between the windward and leeward side of the building. The amount of air passing through interior spaces is higher with larger pressure differentials. Pressure losses of openings and other obstacles along the path of the air flow limit the air flow rates.

Air flow through the building can also be induced by buoyancy forces where warm indoor air rises to upper openings in the building from where it is expelled and replaced by cooler outdoor air through lower openings in the envelope.

The energy advantage of naturally induced space ventilation is obvious since no mechanical equipment must be used to induce the pressure driving forces. On the negative side natural driving forces are intermittent and therefore naturally ventilation cannot provide continuous space ventilation. In addition, natural ventilation allows warm outdoor air to enter the building thereby potentially increasing the indoor air temperature.

A.4.4. Cooling Effect of Moving Air

A beneficial and very cost-effective thermal performance mechanism is the cooling effect of moving indoor air. Air moving over the body of occupants provides increased heat loss and therefore cooling to the occupants. This cooling effect, however, is not contributing to the cooling of the indoor space, it only helps occupants to regulate their individual heat balance within the indoor environment. The cooling effect of increased air speed will be discussed later in this report.

A.4.5 Performance Parameters Considered for this Study

Tables A.4.5.1 through A.4.5.3 show pertinent building performance parameters used in the present report of mechanical and natural ventilation, and air movement through leakage in the envelope, respectively:

Table A.4.5.1: Performance parameters for mechanical ventilation			
Type of building performance aspect	Description and/or value used in present study		
Type of mechanical ventilation	<p>Pertinent performance design parameters are:</p> <table border="1"> <tr> <td>Configuration of fan</td> <td>Mechanical ventilation can occur through exhaust, supply or a balanced fan configurations; the exhaust fan creates a lower pressure indoors than outdoors and air is sucked into the space through openings; the supply fan pressurizes indoor spaces and air is expelled through openings; the balanced fans configuration provides the pressure driving forces for both the exhaust and supply, and the indoor spaces are</td> </tr> </table>	Configuration of fan	Mechanical ventilation can occur through exhaust, supply or a balanced fan configurations; the exhaust fan creates a lower pressure indoors than outdoors and air is sucked into the space through openings; the supply fan pressurizes indoor spaces and air is expelled through openings; the balanced fans configuration provides the pressure driving forces for both the exhaust and supply, and the indoor spaces are
Configuration of fan	Mechanical ventilation can occur through exhaust, supply or a balanced fan configurations; the exhaust fan creates a lower pressure indoors than outdoors and air is sucked into the space through openings; the supply fan pressurizes indoor spaces and air is expelled through openings; the balanced fans configuration provides the pressure driving forces for both the exhaust and supply, and the indoor spaces are		

Table A.4.5.1: Performance parameters for mechanical ventilation		
Type of building performance aspect	Description and/or value used in present study	
		neither pressurized or applied with a reduced pressure relative to the outside
	Electric power demand	The supply and exhaust fan configurations typically consume equal amounts of electric energy, whereas the balanced fan configuration requires more fan energy
	Suitability for Energy recovery	The balanced fan configuration is used in energy recovery systems
Air movement rates	Code required air flow rates	Minimum air flow rates are mandated by the applicable standard, here ASHRAE 62.2, with the year 2013 selected for the present investigation.
Energy recovery capacity	Sensible heat recovery	Sensible heat recovery requires heat exchange, typically with a surface-to-air heat exchanger. The process involves exchanging of sensible heat energy between the cool discharged indoor air and warm outdoor air supply; the performance metric is the sensible recovery efficiency.
	Latent heat recovery	Latent heat recovery requires mass exchange preferably by means of a membrane air-to-air exchanger. The process involves exchanging moisture between the cool and dry discharged indoor air and warm and moist outdoor air supply; the performance metric is the latent recovery efficiency

Table A.4.5.2: Performance parameters for natural ventilation		
Type of building performance aspect	Description and/or value used in present study	
Operation of natural ventilation	Pertinent performance design parameters are:	
	Time of open operable windows	The time when operable windows are indeed open; the time can be set by the simulation software and can vary between 3 and 7 days per week.
	Occupant intervention	Outdoor climatic conditions can affect the occupant's inclination to open or close operable windows; a maximum outdoor humidity set-point value controls opening of the windows
Openings to allow natural ventilation	Windows	The higher the fraction of operable windows the higher is the natural ventilation efficiency

Table A.4.5.3: Performance parameters for air leakage		
Type of building performance aspect	Description and/or value used in present study	
Exterior driving force	Pertinent performance design parameters are:	
	Exposure to exterior wind movement	High exterior wind flow that impinges on the facade creates higher pressure differential than smaller wind flow; the so-called shelter coefficient indicates how the building is shielded by adjacent buildings and structures against wind movement; a high shelter coefficient indicates not shielding
Level of leakiness of the building envelope	Tested air changes ACH	The level of leakiness is tested with blower doors under a specified differential pressure, most commonly the pressure differential between interior and exterior is held at a constant 50 Pa for the duration of the blower door testing. The amount of air changes per house (ACH) measures gives an indication of the actual air changes

A.5 Space Cooling

Space conditioning is synonymous with space cooling, although space conditioning includes both cooling and ventilation. Under space cooling indoor heat is rejected to the outdoor environment by some mechanical cooling system.

A.5.1 Importance for Building Performance - Heat and Moisture Removal

Cooling equipment perform important functions as they control sensible and latent loads in the buildings. The control of both types of thermal loads is important to achieve acceptable indoor thermal comfort.

The sensible cooling occurs by rejecting the indoor heat, contained in the air or in building material and other indoor objects, to the outside by providing actively cooled surfaces, typically cooling coils. In all-air systems cold air is recirculated indoors and the cold air absorbs sensible heat. The air is then flowing over the cooling coils thereby rejecting heat from the indoor air. In so-called hydronic systems indoor heat is directly transferred to a working fluid that transports the heat to the outside.

Besides sensible heat, latent load removal from interior spaces is of essential importance to control the level of humidity. As the indoor air is cooled the relative humidity level increase unless humidity is removed from the air. Conventional removal of indoor moisture is by means of below dew point cooling coils, where the moisture in the air condenses, and thus is removed from the air.

A.5.2 Cooling Equipment Technologies

There are several cooling equipment technologies available for use in the residential homes market, including, central AC, split systems, window unit, and portal AC systems. Each technology has its specific and optimal application. One of the basic differences between the cooling technologies is if they supply the indoor environment with fresh outdoor air. Central AC systems typically have outdoor air supply integrated in their ducted air distribution whereas the other AC technologies do not. These other technologies only remove sensible and latent loads from the indoor air, without providing fresh outdoor air. The different cooling technologies have inherent efficiency characteristic, which is a result of their working process.

A.5.3 Ratings (EER, COP, SEER)

The efficiency of the AC system in rejecting heat from indoor spaces is measured by the amount of heat removed in relationship to prime energy used for the heat removal process. There are several different metrics used to express this relationship, including the following:

- EER = Energy Efficiency Ratio; ratio of the cooling capacity in BTU per hour to power in put in watts; BTU/h / Watts; for example, a 10,000 BTU/h AC-unit consumes 1,5 kW or 1,400 Watts; The EER rating is $10,000 \text{ BTU/h} / 1400 \text{ watts} = 7.1$ EER. Higher EER values indicate higher efficiency.
- SEER = Seasonal Energy Efficiency Ratio; is the energy efficiency of the AC-system during the cooling season at varying outdoor temperature. The SEER has the same dimensions as the EER but the SEER rating for the same equipment is a higher value than the EER. A typical conversion is $\text{EER} = 0.875 * \text{SEER}$

- COP = Coefficient of performance; the ratio of useful cooling to work required for cooling; for example, a 20 tons (nominal) AC system consumes 12 kW, $20(\text{tons}) * 12,000 \text{ BTU/h/ton} / 10 \text{ kW} * 3414 \text{ BTU/kW} = 0.5 \text{ (COP)}$.
- kW / ton (ref) Ratio is a direct expression of efficiency

A.5.4 Performance Parameters Considered for this Study

Table A.4.5.1 shows pertinent building performance parameters of cooling equipment used in the present report:

Table A.5.4.1: Performance parameters for cooling equipment and appurtenances		
Type of building performance aspect	Description and/or value used in present study	
Central AC units	Pertinent performance design parameters are:	
	Rated cooling capacity	AC-system sizing of cooling capacity in accordance to ACCA manual J; the present project used the auto sizing function of the BEopt software
	Efficiency rating	Efficiency is given in SEER; where the number of stages and work process of the compressor significantly affect the SEER rating
	Type of condenser	Either air cooled or water cooled; the AC-system used in the present study were air cooled
	Cooling fan power	The power required by the condenser cooling fan for air cooled compressors
	Supply fan power	The required power to drive the supply air fans
	Sensible heat ratio	The ratio of sensible heat to total heat removed at the nominal rated capacity; typical range between 0.7 and 0.9
Room AC units	Rated cooling capacity	AC-system sizing of cooling capacity in accordance to ACCA manual J; the present project used the auto sizing function of the BEopt software
	Efficiency rating	Efficiency is given in EER
	Sensible heat ratio	The ratio of sensible heat to total heat removed at the nominal rated capacity; typical value is 0.65

Table A.5.4.1: Performance parameters for cooling equipment and appurtenances		
Type of building performance aspect	Description and/or value used in present study	
Mini spilt system	Rated cooling capacity	AC-system sizing of cooling capacity in accordance to ACCA manual J; the present project used the auto sizing function of the BEopt software
	Efficiency rating	Efficiency is given in SEER
	Sensible heat ratio	The ratio of sensible heat to total heat removed at the nominal rated capacity; typical range between 0.7 and 0.8

A.6 Domestic Water Heating

The supply of heated water is an important energy service to occupants.

A.6.1 Importance for Building Performance

The theoretical energy demand for heating of water is determined by the mass of water, the specific heat and the temperature difference between the municipal water supply and the desired water supply temperature. The actual energy demand incorporates energy losses associated with the heater and distribution losses.

A.6.2 Types and Performance of Water Heating Systems

The following categories of water heaters are typically found in residential houses and these systems have been used for the building performance analysis of the present study:

- Storage water heaters (tank); most commonly used domestic water heater; the system has a tank with integrated heater; the system can be either electric or gas; losses are heat losses of the water storage tank
- Tankless water heater; the system provides instantaneous or on-demand hot water by the water flowing over heating elements; the system can be either electric or gas; requires high electric power supply
- Solar water heater used the solar radiation as heat source

Heat losses are associated with the distribution of hot water through the building. Insulating the distribution pipes lowers heat losses.

Electric water heaters have a higher heating efficiency, expressed as energy factor, than gas water heater. Electric water heater, however, consume significantly more source energy than gas water heaters.

A.6.3 Performance Parameters Considered for this Study

Table A.6.3.1 shows pertinent building performance parameters of cooling equipment used in the present report:

Table A.3.3.1: Performance parameters for domestic water heating		
Type of building performance aspect	Description and/or value used in present study	
Water heater	Pertinent performance design parameters are:	
	Fuel type	Either electricity or gas
	Rated efficiency	Measured in energy factor; describing how much site energy is converted to heat energy contained in the water
	Water consumption of occupant	Standard demand calculated by BEopt and based on the number of bedrooms
	Set point	Water temperature that triggers the water heater; typically, around 120 to 130 F
Water distribution	Pipe material	Either metal (copper) or plastic (pex)
	Pipe insulation	Rated R-value of pipe insulation
	Recirculation	Forced circulation, reduces the time hot water arrives at the point of demand
Solar water heaters	Size of solar panel array	Given in size of collector area of the system
	Tank storage and insulation	Storage of heated water; given in gallons capacity; rated tank insulation in R-value
	Heat exchanger effectiveness	Rated efficiency of transfer of heat between working fluid and water
	Water pump power demand	Power demand of the recirculating water pump

A.7 Lighting

Lighting is an essential energy service to occupants. Lighting provide comfort and safety. Lighting can be provided to interior spaces by electric (artificial) light or by daylighting.

A.7.1 Importance for Building Performance

Electric lighting requires a significant portion of the overall electric demand of the building. The efficiency of converting electricity to visible light and the efficient supply of lighting to the location of use are key component of energy efficient lighting sources.

New LED and CFL lighting technologies have ushered in significant improvements of energy efficiency over the conventional incandescent light sources.

A.7.2 Replacement of Electric Lighting with Daylighting

Replacing electric lights with natural light, or daylighting, reduces electricity demand in the building. Daylighting is depended on the number, sizes and orientation of windows. Increased window area can, however, increase the heat flux into interior spaces. There are newer technologies which provide natural light enter interior spaces through light domes or fiber optic conduits.

A.7.3 Benefits to Indoor Environmental Comfort

Replacing electric lighting with daylighting causes improvement to occupant comfort. Humans typically prefer daylighting and external views provided by windows. Some type of electric light also improves indoor comfort by changing the temperature and color of the light sources.

A.7.4 Performance Parameters Considered for this Study

Table 3.7.4.1 shows pertinent building performance parameters of lighting equipment used in the present report:

Type of building performance aspect	Description and/or value used in present study	
Type and distribution of lighting sources	Pertinent performance design parameters are:	
	Lighting options	Compact fluorescent (CFL), light emitting diode (LED), linear fluorescent (LFL), incandescent (Inc);
	Fraction of types used	Portions of types of lighting; in percent for all four types
	Hardwired	Portion of the types of lighting hardwired
	Plug loads	Portion of the types of lighting as plug loads
Efficiency	Efficacy	Ratio of light output (lumens) to electric power input; this determines how much energy is used to produce the desired level of visible light

A.8 Appliances

Major appliances represent a significant portion of the energy demand of the building.

A.8.1 Importance for Building Performance

Major appliances provide important functions to the living conditions and comfort. Major appliances include the following:

- Refrigerator
- Cooking range
- Dishwater
- Clothes washer
- Clothes dryer

A.8.2 Performance parameters considered for this study

Table A.8.2.1 shows pertinent building performance parameters of major appliances used in the present report:

Type of building performance aspect	Description and/or value used in present study	
Refrigerator	Annual electric energy use	Depending on the configuration of the freezer and energy factor of the unit different annual energy usage were considered
	Schedule of usage	Standard schedules were considered and energy efficiency due to set point
Cooking range	Annual electric or gas energy use	Depending on the type of the stove, energy factor and fuel source (electricity or gas), different annual energy usage were considered; cooking ranges can either be electric or gas driven
	Schedule of usage	Standard schedules and levels of usage were considered
Dishwasher	Annual electric energy use	Depending on the type of the dishwasher and energy factor
	Schedule of usage	Standard schedules and levels of usage were considered

Table A.8.2.1: Performance parameters for major appliances		
Type of building performance aspect	Description and/or value used in present study	
Clothes washer	Annual electric energy use	Depending on the type of the clothes washer and energy factor different annual energy usage were considers
	Schedule of usage	Standard schedules and levels of usage were considered
Clothes dryer	Annual electric or gas energy use	Depending on the type of clothes dryer, energy factor and fuel source (electricity or gas), different annual energy usage were considered; clothes dryers can either be electric or gas driven
	Schedule of usage	Standard schedules and levels of usage were considered

A.9 Miscellaneous Demands

Miscellaneous energy demands considered are plugs loads.

A.9.1 Importance for Building Performance

While miscellaneous demand increases the utility of the building of the and the comfort of occupants, these demands can represent a significant portion of the overall energy consumption in the building.

While types of miscellaneous demands have significantly varying power requirements, the frequency of usage combined with numbers of miscellaneous demands can render even relatively low power types of miscellaneous demands as significant energy consumption in the building.

A.9.2 Performance Parameters Considered for This Study

Table A.9.2.1 shows pertinent building performance parameters of plug loads used in the present report:

Table A.9.2.1: Performance parameters for Miscellaneous demands		
Type of building performance aspect	Description and/or value used in present study	
Plug load	Pertinent performance design parameters are: For the present study only plug loads were considered as miscellaneous demands. A standard annual electric energy demand provided in BEopt was used:	
	Annual electric energy use	Defined as a multiplier of a standard BEopt plug load annual demand
	Schedule of usage	Standard schedules were considered and energy efficiency due to set point

A.10 Photovoltaic Power Generation at the Building

Photovoltaic energy generation is the essential factor to achieve net-zero energy performance or to significantly lower the required grid energy supply to buildings.

There are, however, implications of PV-based power generation at the building that go beyond the boundary of the single building. These aspects include effects of the grid electricity supply and the energy costs charged by the utility. Electricity generation by the PV system at the building and that is fed to utility grid lowers the capacity factor of the power plants and alters the typical daily demand function of the grid supply. During days with favorable climatic conditions PV electricity generation from many building roofs in a region can provide a significant portion of electric energy to the electric utility grid, thereby replacing fossil fuel generated energy from the power plant. But since solar radiation is intermittent, during unfavorable climatic conditions as well as during the off-daylight hours, buildings must draw their full demand from the grid. Consequently, the capacity factor of power plants can vary considerably.

At this point it is assumed that there is not significant storage capacity for on-site PV generated electric energy. For the following discussion only, factors of the building are considered, but the wider consequences of PV-generation and larger grid implementation of net-zero energy buildings is explicitly acknowledged.

A.10.1 Importance for Building Performance

While the energy consumption in the building is not affected by the fact that the PV-system produces electricity, PV generated power decreases the net energy demand that is required from the utility. The energy balance is performed over a period, typically a year.

A.10.2 Performance Parameters Considered for this Study

Table 3.8.2.1 shows pertinent building performance parameters of major appliances used in the present report:

Type of building performance aspect	Description and/or value used in present study	
PV System capacity	Pertinent performance design parameters are:	
	Size of the PV system	The size of the PV is described by the installed capacity. This is typically determined by the number of PV panels. The available roof size presents a natural limitation on how much PV capacity can be installed.
	System losses	These are system losses and degradation factors; other than inverter losses; defined as a fraction of the name plate capacity of the panels
	Inverter efficiency	The efficiency of the inverter; defined as a percentage
	Capacity factor	The capacity factor is the fraction of the electric power that the system generates to the energy that the system would produce when generating electricity 24/7
PV panel orientation	Azimuth	The azimuth of the PV system on the roof; expressed as degrees measured from due South
	Tilt	The absolute and angle of tilt relative to the horizontal, with 0 degree equal to horizontal

A.11 Site and Source Energy Performance

As discussed in Section 2 the environmental impact of energy consumption is associated with source and not site energy consumed by building. The source/site ratios and carbon factors used in the present study are as follows:

Type of energy used at the building (site)	Source/site ratio	Carbon factor [lbs/kwh]
Electricity	3.150	1.53 lbs carbon per kWh
Propane	1.150	15.7 lbs carbon per gal

A.12 Energy Costs - Utility Rates Considered for the Study

The default energy costs rates that were provided in BEopt for Hawaii are \$0.30 per kWh and \$8.00 per month for fixed charges for electricity and \$2.58 per gallon for propane as fixed costs were used for the present study.

APPENDIX B – BUILDING PERFORMANCE PROCESSES BENCHMARKED IN STUDY

Authored by Manfred Zapka

Appendix B presents discussions of selected procedures of the present investigation and specific aspects of energy performance of selected building technologies. The objective of Appendix B` is to provide the reader with relevant findings on generic topics of building performance. The different topics discussed in Appendix B provide background information on procedures and assumption used for the analysis of three example buildings, which is presented in Section 3. The discussions of relevant procedures and assumptions prior to the analysis of the three example houses in Section 3 provides a better understanding and appreciation of important application of building simulation, physics principles and financial performance used in the present study.

B.1 Global Parametric Analysis

The present study considered a wide range of building technology, operations and outfitting parameters. These multiple parameters, in combination and support of each other, can provide energy efficient as well as cost-effective building designs.

B.1.1 Approach

The BEopt building simulation software, which was used for the present study, provides 16 option categories of building technology, construction and operational schedules. Each of these 16 option categories has subcategories which themselves have up to 30 options, from which the proposed design was be described for the simulation.

Table B.1.1: Fifteen option categories in BEopt

No.	Option categories in BEopt
1	Building (site specific conditions)
2	Walls
3	Ceiling/Roofs
4	Foundation / Floors
5	Thermal Mass
6	Windows & Doors
7	Airflow
8	Space Conditioning
9	Space conditioning schedules

APPENDIX B BUILDING PERFORMANCE PROCESSES BENCHMARKED IN STUDY

No.	Option categories in BEopt
10	Water Heating
11	Lighting
12	Appliances & Fixtures
13	Appliance and fixture schedules
14	Miscellaneous
15	Miscellaneous schedules
16	Power generation (onsite)

Within the various option categories BEopt provides wide ranges of generic options, which reflect building technology, construction and operational presently in use in the building industry and with different ranges of energy efficiency. The options present poor, medium and good energy performance. In such a way the BEopt options provide a suitable range of options to choose from in order to describe buildings with different energy efficiency.

One of the first steps in the simulation process of the present project was to understand the quantitative contributions of option categories regarding their energy performance expressed as simulated annual energy consumption. For each relevant option category, options were selected that represented the highest, lowest and medium energy performance of the measures provided by BEopt. This project phase was called “Global Parametric Analysis”.

Work on the Global Parametric Analysis commenced with the creation of a generic residential house which was constructed in BEopt by using a software’s default option set. The default option set provided by BEopt reflects a standard building based on the Building America’s House Simulation Protocols.

Using the generic residential building the “parametric” software feature in BEopt was used to select representative options (e.g. highest, lowest and medium energy performance of the measures) in one option category while leaving the default selection in the other option categories unchanged. As an illustration, Figure B.1.1.1 shows multiple options selected for the “Wood Stud” category.

Option	<input type="checkbox"/> R-Assembly [h-ft ² -R/Btu]	<input type="checkbox"/> Cavity Insulation Type	<input type="checkbox"/> Cavity Insulation Nominal R-value [h-ft ² -R/Btu]	<input type="checkbox"/> Cavity Insulation Installed R-value [h-ft ² -R/Btu]	<input type="checkbox"/> Cavity Install Grade	<input type="checkbox"/> Cavity Depth [in]	<input type="checkbox"/> Insulation Fills Cavity	<input type="checkbox"/> FR
1) None								
2) Uninsulated, 2x4, 16 in o.c.	4.0					3.5	False	
3) Uninsulated, 2x6, 24 in o.c.	4.1					5.5	False	
4) R-7 Fiberglass Batt, 2x4, 16 in o.c.	9.3	fiberglass batt	7.0	7.0	1	3.5	False	
5) R-11 Fiberglass Batt, 2x4, 16 in o.c.	10.9	fiberglass batt	11.0	11.0	1	3.5	True	
6) R-13 Fiberglass Batt, 2x4, 16 in o.c.	11.9	fiberglass batt	13.0	13.0	1	3.5	True	
7) R-15 Fiberglass Batt, 2x4, 16 in o.c.	12.7	fiberglass batt	15.0	15.0	1	3.5	True	
8) R-19 Fiberglass Batt, 2x6, 24 in o.c.	16.0	fiberglass batt	19.0	17.3	1	5.5	True	
9) R-21 Fiberglass Batt, 2x6, 24 in o.c.	17.7	fiberglass batt	21.0	21.0	1	5.5	True	
10) R-13 Cellulose, 2x4, 16 in o.c.	11.9	cellulose	13.0	13.0	1	3.5	True	

Figure B.1.2.1 – Parametric Case with Multiple Options Selected

Following this procedure, BEopt parametric investigations proceeded for each representative option category. Typically, 3-5 options from each option category were considered. Following initial scoping the options with the highest, lowest and medium energy consumption were identified. As an example, for the wall insulation selecting “uninsulated”, “R-13 Fiberglass Batt”, and “R-30 Fiberglass Batt” as insulation options, represented the lowest, medium and best option.

The results of simulations run for each relevant option category provided the amount of source energy (MMBtu/a) consumed by the building, for each of the three selected options. The resulting difference for the highest and lowest source energy value was calculated, and the difference was referred to as the “target variable”. The higher the “target variable” the more of an effect had the option category on the overall energy performance of the building. By performing this analysis for all relevant option categories, an assessment of the relative contribution of the option category on the overall energy performance of the building was obtained.

It is important to note that choosing the extreme, e.g. best and poorest, energy performing options in the simulation software created a somewhat “exaggerated” spread. When looking at more realistic, will mean design-relevant or “practical” options, the differences between two realistic options would not be as large as the target variable using the extreme.

B.1.2 Report on Initial Findings

Figure B.1.2.1 shows example results obtained in the parametric simulation runs for four option categories. Figure B.1.2.1 shows the name of the option category and the highest and lowest resulting energy consumption of the entire building, the difference between max. and min. being the “target variable”. Figure B.1.2.2 shows a comparison of the differences.

Wood Stud - Fiberglass Batt Insulation			Air Conditioning - SEER Value		
	Energy use [MBTU/year]			Energy use [MBTU/year]	
Uninsulated	165.8		SEER 13	161.7	
R-15	156.1		SEER 18	139.4	
R-30	155.6		SEER 24.5	118.8	
Max	Min	Difference	Max	Min	Difference
165.8	155.6	10.2	161.7	118.8	42.9

Figure B.1.2.1:
Annual energy consumption for four selected option categories

Source Energy Use (MMBtu/yr.)

Window Type		
	Energy use [MBTU/year]	
Clear, Double Paned	170.3	
Low-E Double Paned	157.3	
Low-E Triple Paned Argon Insulation	158.3	
Max	Min	Difference
170.3	157.3	13

Ceiling Fans (x6)		
	Energy use [MBTU/year]	
Standard	156.4	
Premium	147.6	
Premium, Smart, 4 deg	119.2	
Max	Min	Difference
156.4	119.2	37.2

APPENDIX B BUILDING PERFORMANCE PROCESSES BENCHMARKED IN STUDY

	Max Energy Difference [MBTU/year]
Variable	
Wall Insulation	10.2
SEER Value	42.9
Window Type	13
Ceiling Fans (x6)	37.2

Figure B.1.2.2: End results for four selected option categories

Upon completion of the global parametric analysis for the generic building design additional building design alternatives were tested. Figure B.1.2.3 illustrates the results of an early test run. The results in Figure B.1.2.3 suggest that option categories differ in their quantitative contribution to the overall energy performance of the building. The high-level breakdown of the sensitivity of the selection of options in option categories on the effect to the overall energy performance helped gauging an understanding of how the contributions of option categories compared.

2	* Plug Loads	46.1
3	Mechanical Ventilation	31.4
4	* Room AC	26.4
5	Central AC	16.7
6	* Mini-Split Heat Pump	12.5
7	* Cooling Set Point	11.1
8	Solar Water Heating	7.7
9	* Window Areas	5.9
10	* Unfinished Attic	5.2
11	Lighting	4.2
12	* Exterior Finish	2.1
13	* Water Heater	1.8
14	Steel Stud	1.6

Figure B.1.2.3: Example of results of a global parametric analysis

The results of a global parametric analysis shown in the figure depicts one of several parametric investigations that evaluated the contribution of option categories on the overall energy performance of the building.

The results of the global parametric analysis suggested that improvements of active space conditioning equipment had a more significant effect on the energy consumption than passive means of envelope improvements, and even lighting.

The fact that plug loads had such a significant effect on energy consumption provided the rationale to use plug loads as one of the main parameters in describing the simulation models for existing houses.

Determining the contribution of different BEopt option categories to energy efficiency performance of the proposed building design supported the project work. A high level understanding what option category is likely to produce the largest improvements allowed focus on these option categories for subsequent simulation analysis.

B.2 Ventilation and Air Movement in Buildings

This section shows benchmarking of higher rates of mechanical ventilation and their effect on the indoor air temperature. The motivation for the analysis presented in this section was to approximate a whole house fans (WHF) equivalent ventilation process, which results in high air changes in the house.

B.2.1 Background

Hawaii's climate allows houses without air conditioning to utilize natural ventilation as the primary source of temperature control. The typical climate in Hawaii is never cold enough to require a heating system, and, as has been shown by many naturally ventilated houses in Hawaii, with proper design, home owners frequently choose not to use AC but instead opt for natural ventilation.

Initial simulation results and the literature suggested that for naturally ventilated homes the amount of air that moves between the indoors and outdoors provides a means of control of the indoor thermal conditions. The basic principle is air moving through the building acquires heat from the indoor spaces and rejects the indoor heat to outside by convection. The same principle is valid to remove humidity from the indoor space; but the effect of increased ventilation on humidity control is not discussed in this present project.

The two governing parameters of the indoor heat rejected by means of moving air through the indoor spaces is the amount of air mass passing through the spaces and the temperature difference between the indoor and the outdoor air. The basic equation of heat acquired and then conveyed by the moving air is:

$$Q = M * c * \Delta (T) \text{ (eq. B.2.1.1)}$$

Where:

Q = Heat acquired and then conveyed by the air passing through the spaces [BTU]

M = Mass of the air [lbs]

C = heat capacity of air [BTU/(lbs*F)]

Delta T = Temperature difference between indoor T_i and outdoor T_o

With C being considered a constant equation B.2.1.1 suggests the following:

- The more outdoor air moves through the indoor spaces the higher the heat removed from the spaces

- The higher the temperature difference between outdoor and indoor air, e.g. delta T, the more heat is removed with a constant air flow rate.
- As the temperature difference between outdoor and indoor temperature decreases the mass of air passing through the spaces must increase to remove the same amount of heat.
- No heat can be removed by the air passing through spaces when the difference between indoor and outdoor temperature is zero
- If the outdoor air temperature is higher than the indoor temperature no heat is removed from the space, but heat is added.

In many cases the rate of air movement driven by natural external conditions or the so-called internal stack effect is insufficient to remove enough heat to lower the indoor promote indoor comfort. In such cases, a so-called whole house fan (WHF) is one way of obtaining more comfortable indoor temperature without air conditioning. A WHF is a large exhaust fan, typically located in the attic that pulls air up from the indoor spaces and pushes it out through vents in the roof or attic area. As the hot air from the living space is pulled into the attic, the pressure decreases in the living spaces which draws fresh outdoor air into the house via open fenestrations such as doors and windows or other openings in the envelope.

In this way, a WHF can remove heat to approach but not attain the outdoor conditions. The greater the airflow, the closer the indoor conditions match the outdoor conditions. One limitation is that a WHF cannot be used to decrease the indoor temperature or humidity to below that of the outdoors.

B.2.2 Approach

For this investigation a generic test house was constructed in BEopt. The BEopt option of mechanical ventilation was used to simulate the effect of an “equivalent” WHF. The mechanical ventilation option in BEopt determines the ventilation based on the required ventilation rate of the ASHRAE 62.2 standard. While the ventilation rate per AHSRAE 62.2 were well below typical ventilation rates of WHFs, multipliers of the basic mechanical ventilation were used to significantly increase the ventilation rates.

Four air flow rates were selected and applied to the simulation:

Multiplier (fraction) of ASHRAE 62.2 (2013 base) selected in BEopt	Resulting air flow rate [cfm]
1 = baseline	100
10	1000
22	2200
40	3900

For each of the four simulation runs, with the selected air flow rate, hourly data of the indoor temperature was obtained. The outdoor temperature was the same for all four cases. The difference between the indoor and outdoor temperature was obtain on an hourly basis. Figures B.2.2.1 shows the hourly data for the 2,200-cfm test case.

The difference between indoor and outdoor temperature was calculates for each data point. One probability density function was developed for each simulation run by creating 10 data bins (width = 2.5 F) and calculating the number of percentage of data in the bin relative to the total number of data

points. Figure B.2.2.2 shows the probability density for the difference of indoor and outdoor temperature on an hourly basis for the entire year. A first order moment was applied to the results of all the 10 bins to obtain the centroid. The centroid was the representative difference between the indoor and outdoor temperatures for the specific run. The centroid is given in degrees F, relative to the axis of 0-degrees difference of indoor and outdoor temperatures. Figure B.2.2.3 shows the results of the analysis of this section.

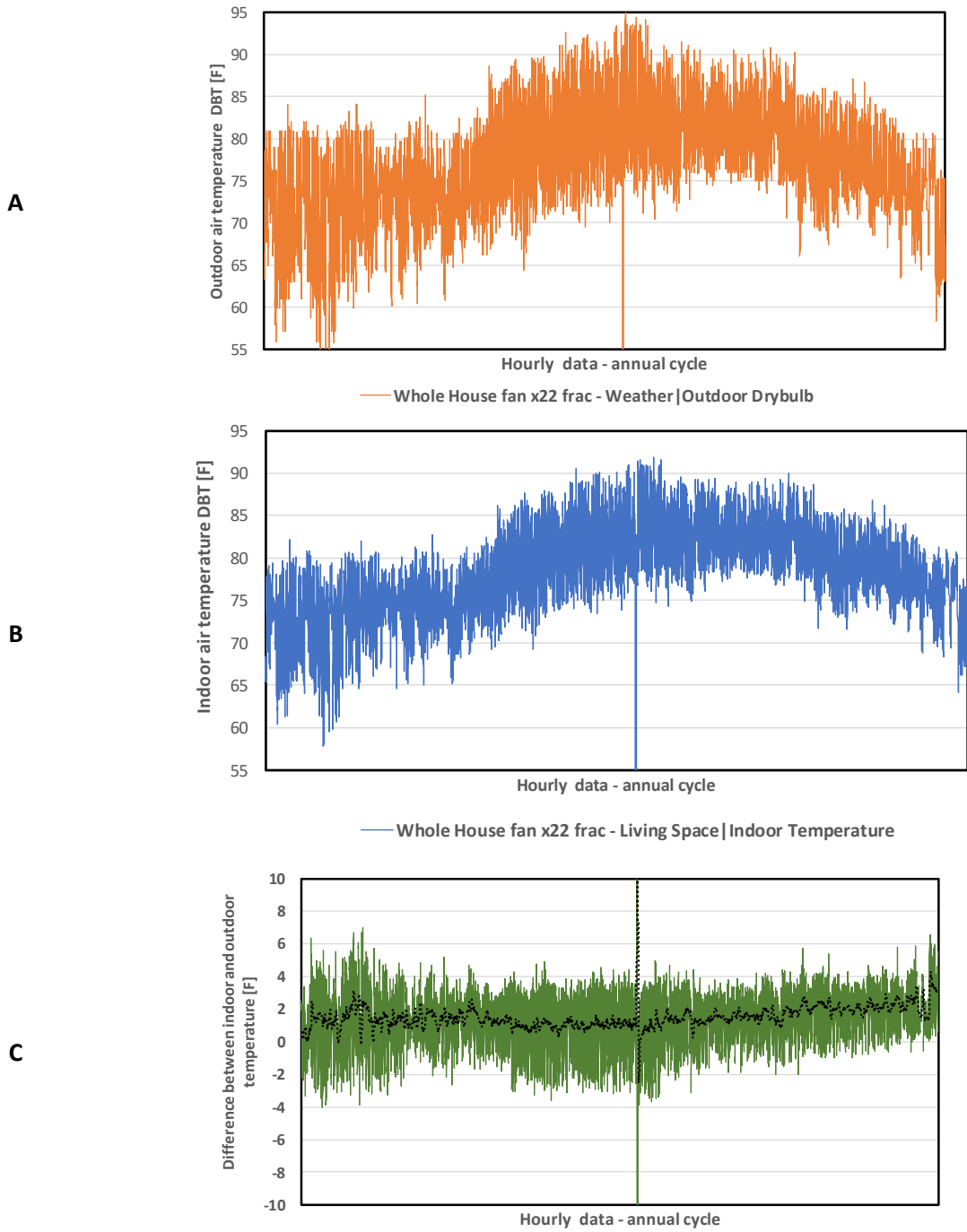


Figure B.2.2.1: Hourly data for outdoor (A), indoor (B) and difference between outdoor and indoor (C) temperature for increase air flow; case of 2,200 cfm

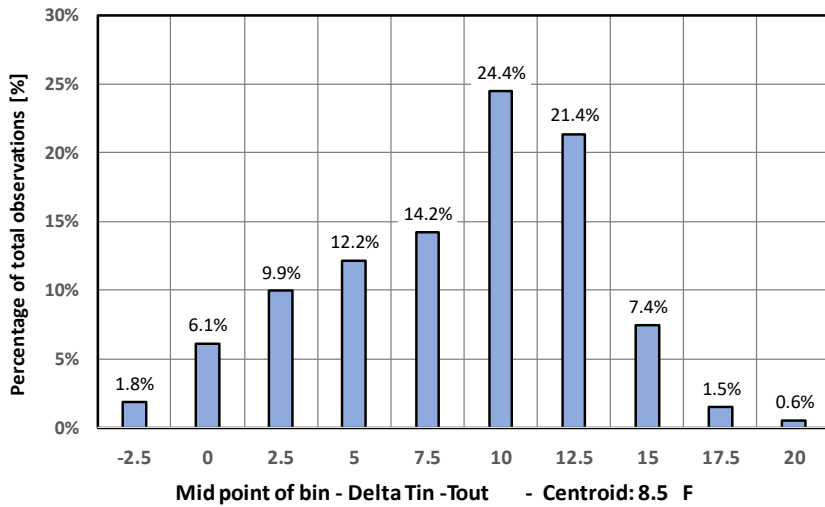


Figure B.2.2.2: Example probability density of temperature differential between indoor and outdoor air temperature for hourly data

Table B.2.2.1: Calculated centroids for increase ventilation simulation

No.	Air flow rate [cfm]	Centroid [F]
1	100	8.5
2	1000	4.0
3	2200	2.8
4	3900	2.0

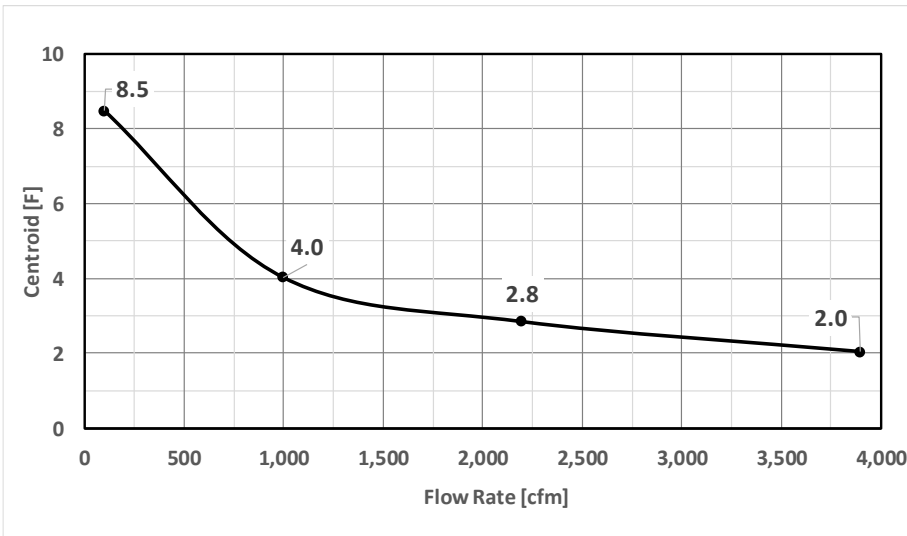


Figure B.2.2.3:
Calculated centroids for
increase ventilation
simulation

B.2.3 Discussion of Performance of Increased Ventilation

The following assumptions were used:

- The objective of the simulations presented in this section was to illustrate how the magnitude of air flow rate of outside air through the indoor spaces affects the indoor temperatures.
- No schedules for the mechanically induced air flow were used. This means the ventilation was continuous, even during the night, when the indoor space did not receive radiant solar heat.
- The difference between indoor and outdoor temperature served as the indicator of the effectiveness of controlling the indoor temperatures.
- The smaller the difference between outdoor and indoor temperature the more responsive is the system to control the indoor temperature.
- More detailed analysis is required to properly model a whole house fan, including operational schedule and the control of the fan.

- The results of the investigation suggest that increasing flow rates of outdoor air through the indoor space decreases the difference between indoor and outdoor temperature. Thus, with larger air flow rates the indoor temperatures can approach the outdoor.
- There is a diminishing return with higher air flow rates when the temperature difference, and therefore the capacity to control indoor temperature conditions, decreases.
- The simulation does not attempt to model a whole house fan, since a more detailed analysis would be required for such an investigation.

B.3 Effect of Efficiency of Space Cooling Equipment

This section investigates the effect of efficiency of the mechanical cooling equipment on energy demand of the building. Parametric building energy simulations were conducted with changing SEER ratings of the same installed cooling capacity, while all other building performance options remaining the same.

B.3.1 Background

For air-conditioned homes, cooling is one of the largest portions of annual energy consumption. To mitigate energy use and cost, one of the most important factors for an air conditioning system is the energy efficiency of the heat pump. There are two main standards of measuring an air conditioner's (AC) energy efficiency. These are the Energy Efficiency Ratio (EER) and the Seasonal Energy Efficiency Ratio (SEER). Both values are calculated by correlating the amount of heat (measured in BTU) removed from the space by the electrical power consumption (measured in watts). As a rule of thumb, the higher the EER and SEER value, the more energy efficient the AC system is. The difference between EER and SEER is that the EER is calculated using constant environmental factors while SEER uses scenarios that are normalized using seasonal conditions.

The present guidelines for energy efficiency suggest a minimum allowable SEER rating of 14. However, a higher SEER rating is recommended to mitigate large energy consumptions and energy costs.

B.2.2 Simple Payback Analysis

The energy performance and first cost (purchase price) of AC equipment with the same cooling capacity but with different efficiencies (e.g. SEER) is shown in Figure B.2.2.1 and B.2.2.2, respectively.

APPENDIX B BUILDING PERFORMANCE PROCESSES BENCHMARKED IN STUDY

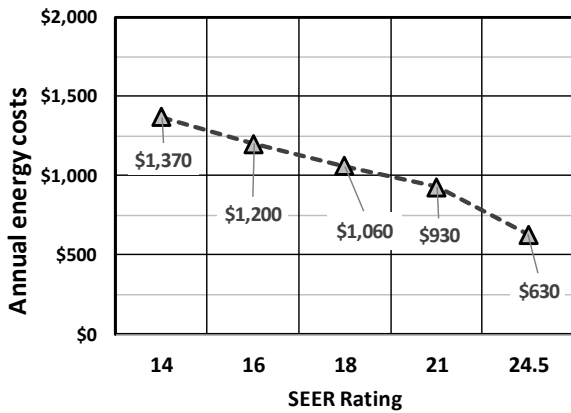


Figure B.2.2.1: Energy performance of cooling system with varying SEER

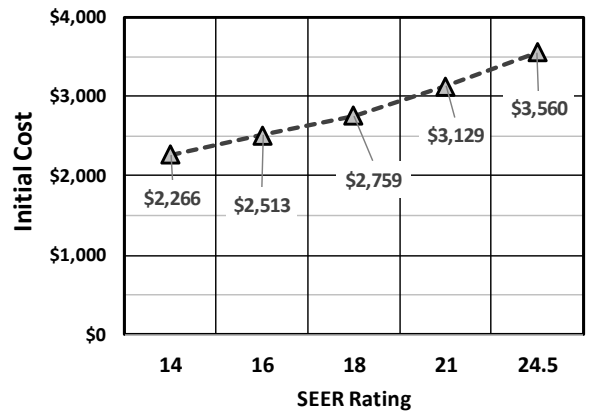


Figure B.2.2.2: Initial costs of cooling system with varying SEER; using BEopt costs

The scoping of the differences in energy costs and initial costs of the five AC units with SEER from 14 to 24.5 suggested that a simple payback could be applied. The calculation of simple payback used additional cost and the energy savings for more efficient AC-units, relative to the base case. Figure B.2.2.3 shows the annual energy savings relative to the lowest performing AC-unit with SEER value of 14. Figure B.2.2.4 shows the additional initial costs which had to be spent in addition for the lowest performing AC-unit with SEER value of 14. Table B.2.2.1 and Figure B.2.2.5 show the results of the simple payback analysis.

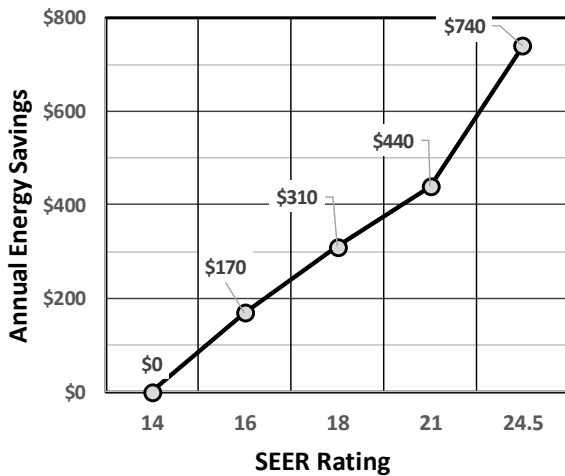


Figure B.2.2.3: Energy cost savings relative to the SEER-14 AC-unit

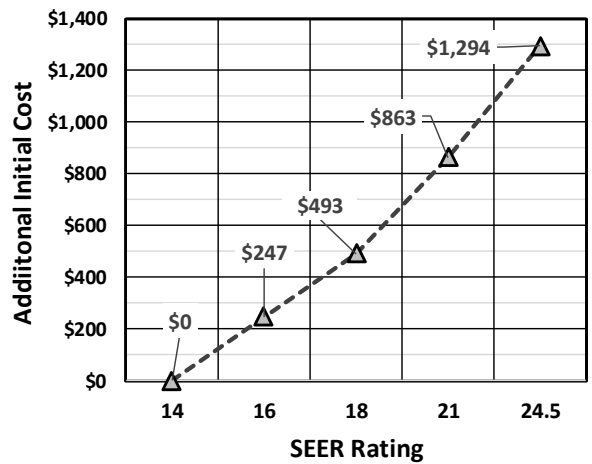


Figure B.2.2.4: Additional initial costs relative to the SEER-14 AC-unit

SEER Value	Additional Initial Cost [\$]	Annual Savings [\$]	Years for Payoff
14	\$0	\$0	N/A
16	\$250	\$170	1.5
18	\$490	\$310	1.6
21	\$860	\$440	2.0
24.5	\$1,290	\$740	1.7

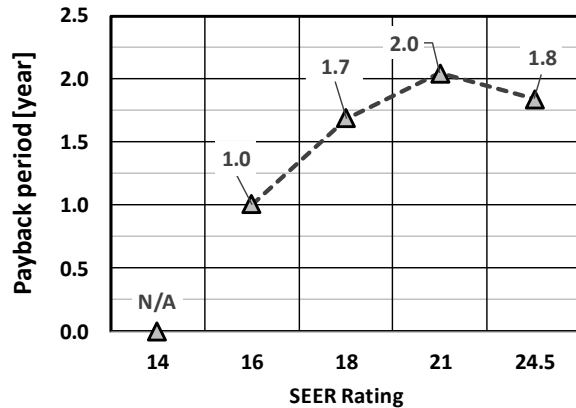


Table B.2.2.1: Results of payback analysis

Figure B.2.2.4: Results of payback analysis

A simple payback analysis of five AC-units was conducted where the five AC-units which had different energy efficiencies. The results show a simple payback of either equal or below 2 years, which make the investment in more energy efficient AC-units very cost attractive. In addition, the use of more energy efficient AC-units significantly lowers the electricity and energy consumption, and thereby decreases the environmental impact of AC equipment with the same installed cooling capacity.

B.4 Cooling Effect of Moving Indoor Air and Effectiveness of Ceiling Fans

The use of ceiling fans is an effective way to create increased air speed in indoor spaces. There is a cooling effect associated with increase air speed where the cooling effect represents the rejection of body heat from the occupants. The air temperature in the indoor spaces remains basically unchanged since there is no heat added to or rejected from the spaces, due to the ceiling fan operation. Minor additions of heat due to friction and the heat produced by the ceiling fan motor were neglected at this point.

B.4.1 Background

Elevated air speeds are being used to increase the allowable operative temperature under the applicable ASHRAE 55 Standard. This cooling effect is also described in the technical and scientific literature.

Figure B.4.1.1 illustrates an ASHRAE endorsed approach to determine the amount the operative temperature can be increase by air speed, where the increase air speed causes a sensible and latent heat loss of the skin. Figure B.4.1.1 shows the correlations between the air speed and the increases by which the operative temperature can be increased, thus illustrating the cooling effect of the increased air flow rates. The figure indicates combinations of different combination of radiant and convective indoor conditions.

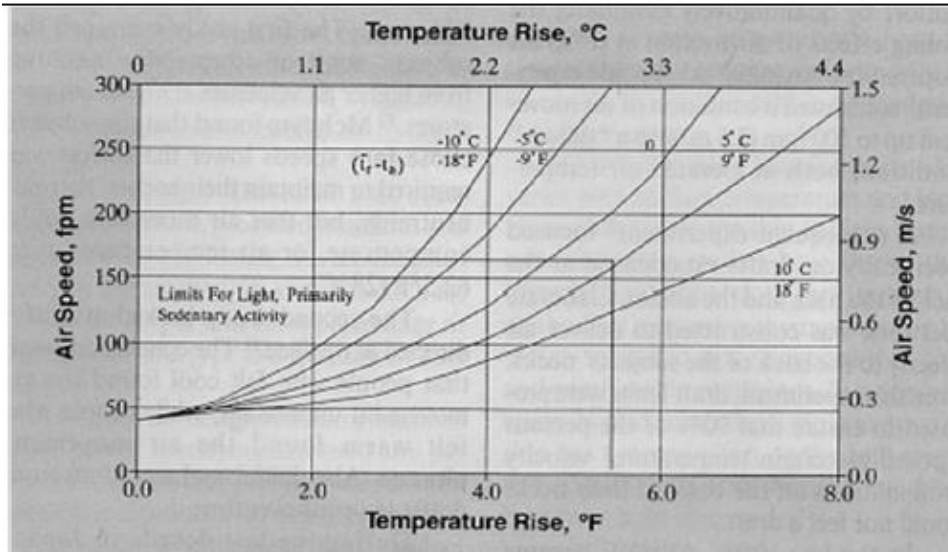


Figure B.4.1.1: Air speed required to offset increased air and radiant temperatures

Source: Addendum D to ANSI/ASHRAE Standard 55-2004, Thermal Environmental Conditions for Human Occupancy

The use of increased air speed is endorsed by ASHRAE 55 for fully conditioned as well as for ventilated indoor spaces.

- Conditioned spaces: Figure B.4.1.2 shows acceptable ranges of operative temperature and average air speed for the 1.0 and 0.5 clo comfort zones at humidity ratio 0.010. The humidity ratio of 0.010 is equal to thermal conditions of 76F and RH 50%, which is a preferred thermal condition for actively conditioned spaces.
- Natural ventilated spaces: ASHRAE 55 allows an increase in acceptable operative temperature limits in occupant-controlled naturally conditioned spaces by means of increase air speeds.

Table B.4.1.1 and Figures B.4.1.2 and B.4.1.3 show the acceptable temperature increases.

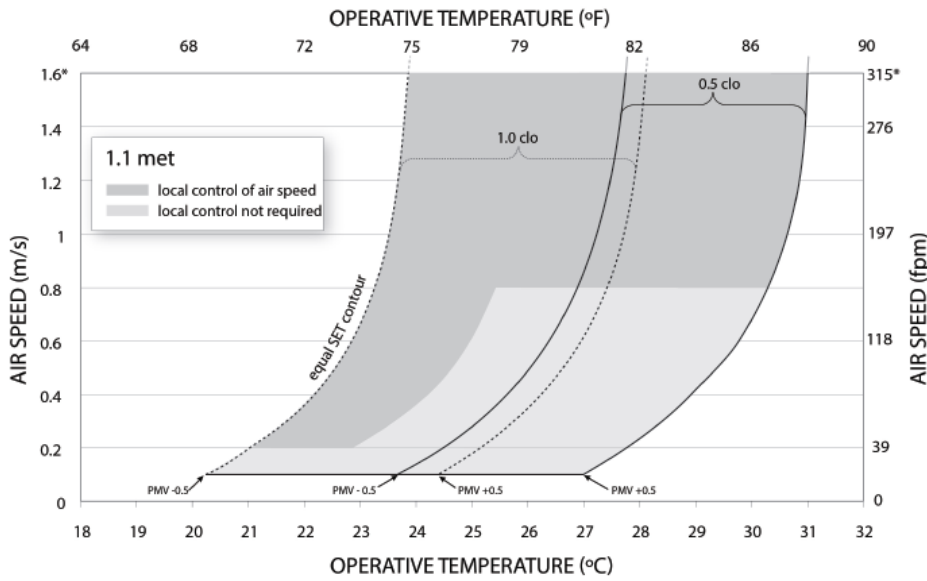


Figure B.4.1.2: Air speed required to offset increased air and radiant temperatures

Table B.4.1.1: Increases in Acceptable Operative Temperature Limits in Occupant-Controlled Naturally Conditioned Spaces (ASHRAE 55, Table 5.4.2.4)

Average Air Speed V_a 0.6 m/s (118 fpm)	Average Air Speed V_a 0.9 m/s (177 fpm)	Average Air Speed V_a 1.2 m/s (236 fpm)
1.2°C (2.2°F)	1.8°C (3.2°F)	2.2°C (4.0°F)

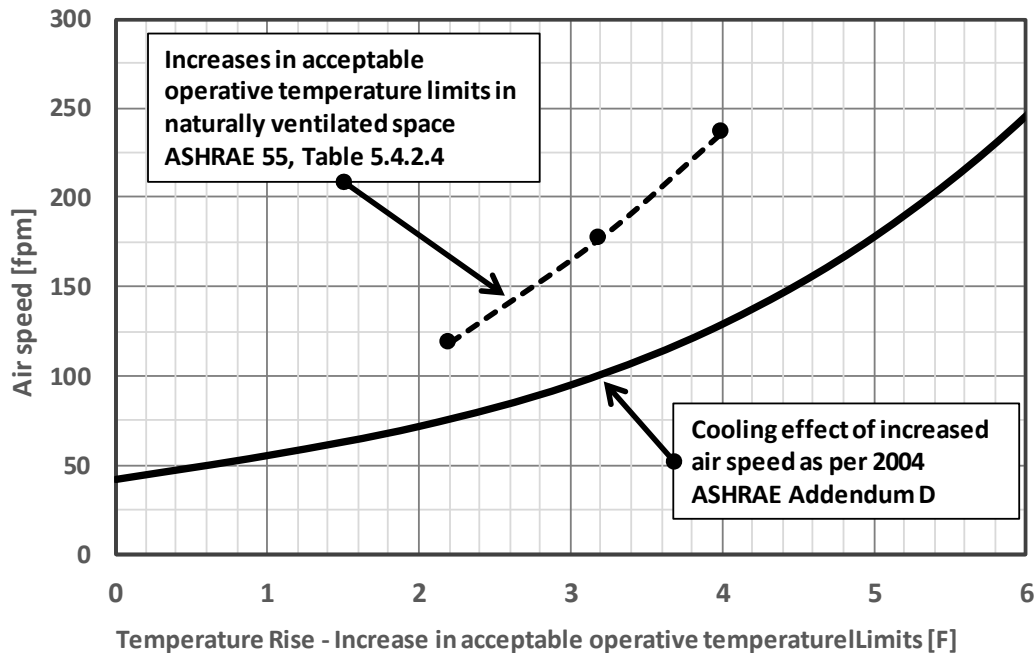


Figure B.4.1.3: Increases in Acceptable Operative Temperature Limits (source as indicated)

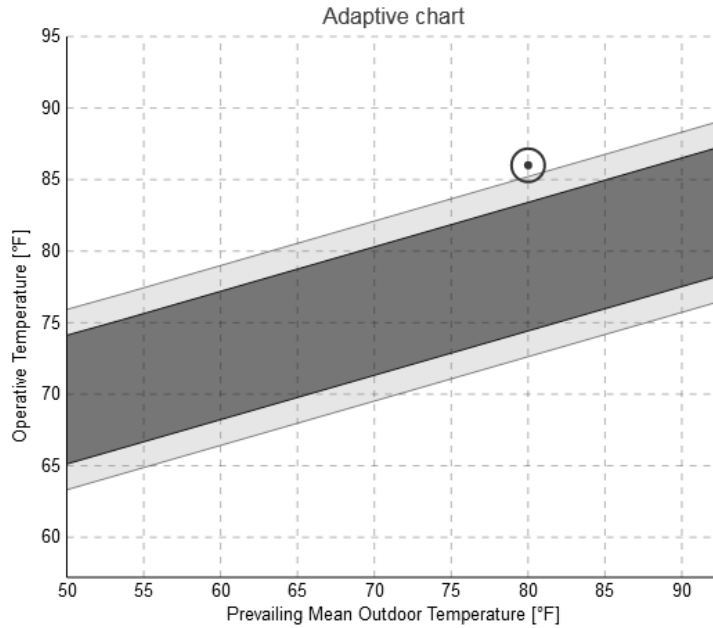
B.4.2 Acceptability of Increased Air Speeds in Naturally Ventilated Spaces

As shown in Figure B.4.2.1 ASHRAE 55 allows an increase in acceptable operative temperatures in naturally ventilated spaces. The magnitude of the increases is a function of the air speed. In naturally ventilated space the ASHRAE 55 adaptive comfort standard applies. Figure B.4.2.1 shows the adaptive comfort standard for (a) without air speed and (b) with air speed, and a resulting increase in allowable operative temperature. With the same operative temperatures but different air speeds, Case A with an air speed below the threshold does not comply with the ASHRAE 55 standard, whereas Case B with an air speed of 118 fpm does comply.

While there is no maximum air speed specified in the ASHRAE 55, the readiness of occupant to accept increased air speeds is an important comfort issue. Figure B.4.2.2 shows the results reported by Candido et al. (2011) for air movement acceptability limits and thermal comfort in hot humid climate zones. Figure B.4.2.2 suggests that occupants in hot humid climates can readily accept higher air speeds to obtain thermal comfort. The authors describe the broader theory of alliesthesia and the physiological role of pleasure due to air movement increment. For air movement acceptability of 80% (V80) and 90% (V90) Figure B.4.2.2. suggests minimal air velocities depending on the prevailing operative temperatures.

The functional relationships delineated in Figures B.4.1.2 and B.4.2.2 were cross referenced to construct a correlation of acceptability of air speed and operative temperatures in natural ventilated spaces. Figure B.4.2.3 shows the resulting increase of air speeds and acceptable operational temperatures as a function the operative temperatures. Figure B.4.2.4 shows the upper 80% acceptability limits for the

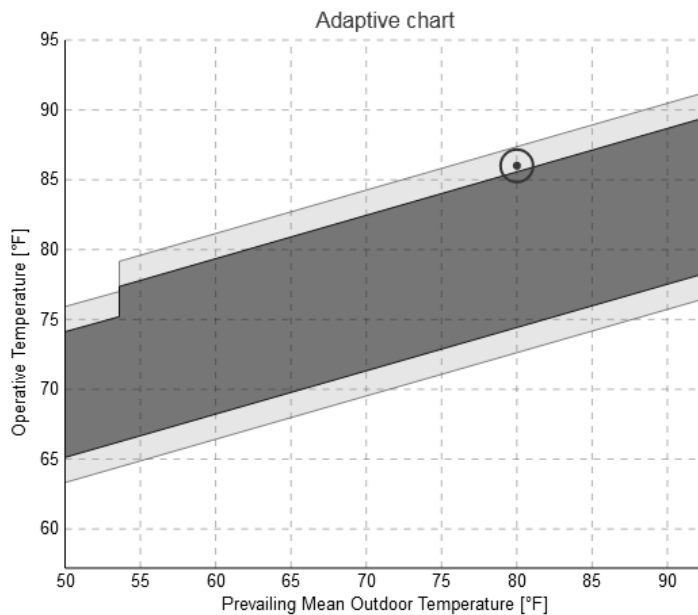
adaptive comfort standard with allowable and acceptable increases in operative temperature due to increased air speeds. Figure B.4.2.5 compares the minimum air movement acceptability of 80% (V80) with three increased air speeds as stated in the ASHRAE 55 standard.



Adaptive comfort conditions – Case A:

- Operative temperature 86 F
- Prevailing mean outdoor temperature 80 F
- Air speed below threshold

X Does not comply with ASHRAE Standard 55-2017



Adaptive comfort conditions – Case B:

- Operative temperature 86 F
- Prevailing mean outdoor temperature 80 F
- Air speed 118 fpm

✓ Complies with ASHRAE Standard 55-2017

Figure B.4.2.1: Adaptive comfort standard – the same operative temperature but different air speeds result in one different compliance to the ASHRAE 55 standard (source CBE)

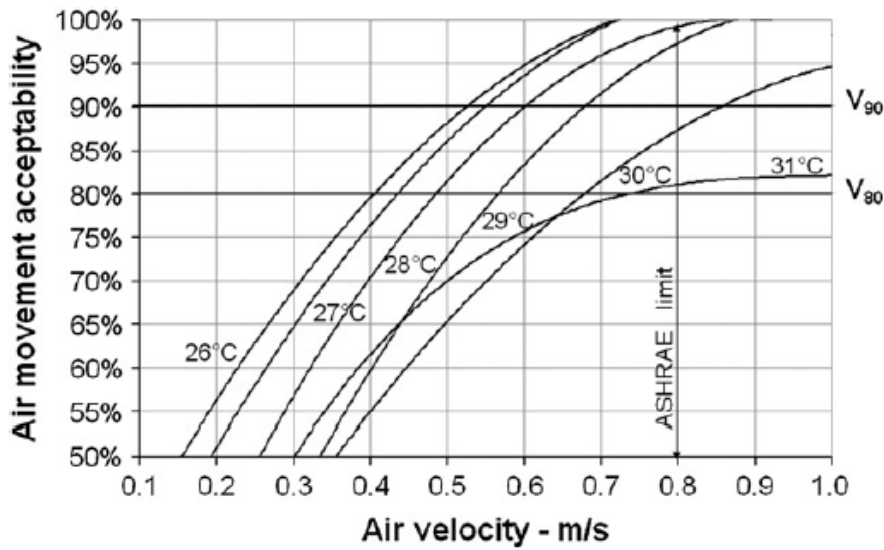


Figure B.4.2.2: Air movement acceptability and operative temperature as a function of air velocity

Source: C. Candido, et. al (2011) "Air movement acceptability limits and thermal comfort in Brazil's hot humid climate zone"

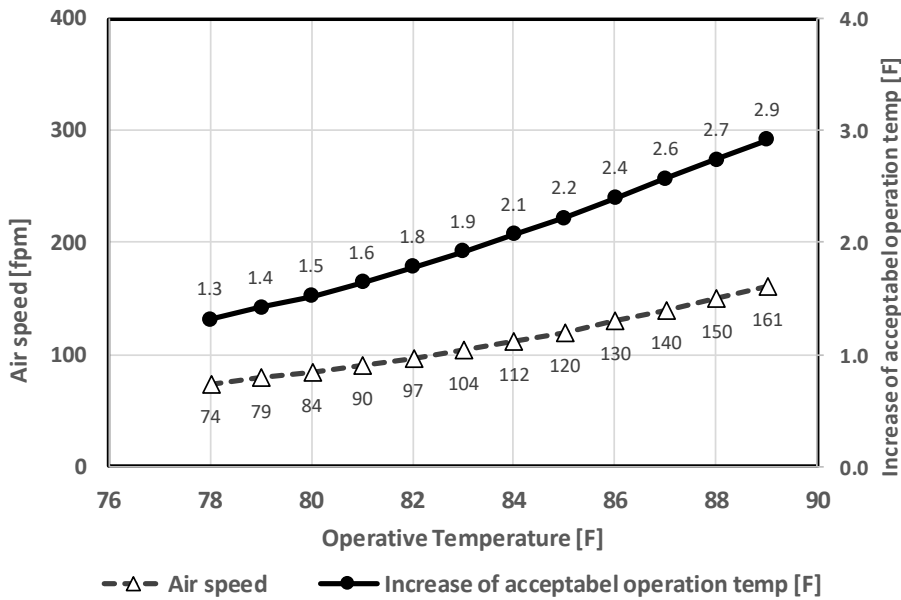


Figure B.4.2.3: Upper 80% acceptability limits for the adaptive comfort standard with allowable and acceptable increases in operative temperature due to increased air speeds

Note: the air speeds are minimum air speeds preferred by 80% of the occupants

Source: C. Candido, et. al (2011) "Air movement acceptability limits and thermal comfort in Brazil's hot humid climate zone"

APPENDIX B BUILDING PERFORMANCE PROCESSES BENCHMARKED IN STUDY

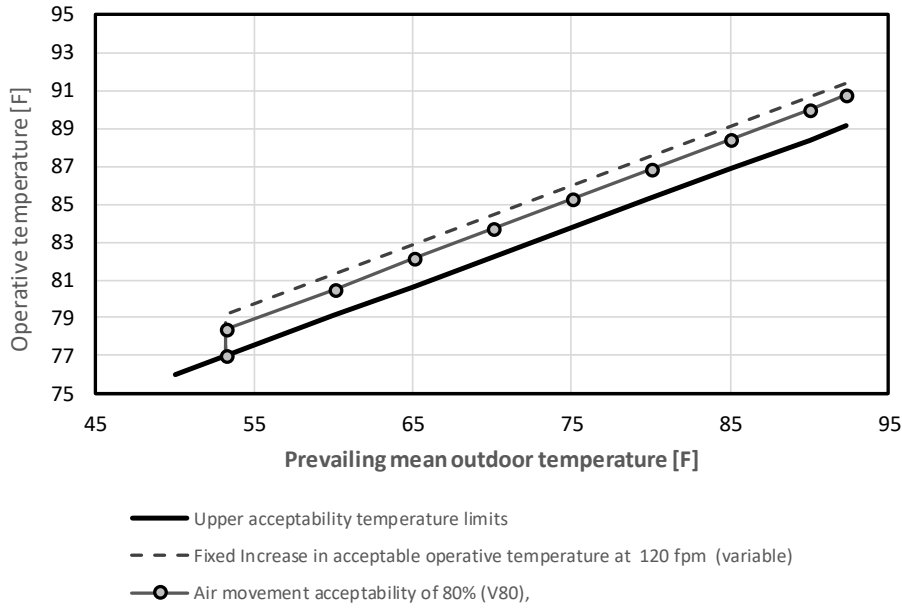


Figure B.4.2.4: 80% acceptability limits for the adaptive comfort standard with allowable and acceptable increases in operative temperature due to increased air speeds

Note: the air speeds are minimum air speeds preferred by 80% of the occupants

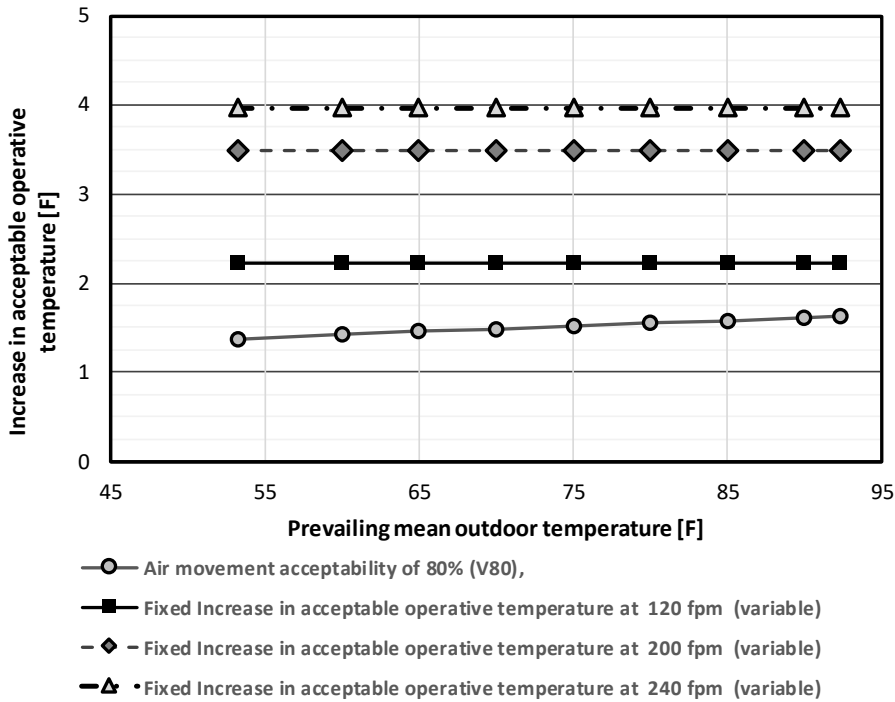


Figure B.4.2.5: compares the minimum air movement acceptability of 80% (V80) with three increased air speeds as stated in the ASHRAE 55 standard.

Note: the air speeds are minimum air speeds preferred by 80% of the occupants

B.4.3 Discussion and Conclusions

The result of our analysis underlines the premise that increase air speed has an additional cooling effect for occupants as air moves over the body causing sensible and latent heat losses.

The ASHRAE 55 standard provides guidance for increased air speeds to be used in space with and without mechanical cooling. A higher air speed increases acceptable operative temperature.

While ASHRAE 55 provides no guidance on what magnitude increases in air speed is acceptable by occupants under the adaptive comfort standard.

The findings of a quoted technical paper evaluated the acceptance of air speed in naturally ventilated spaces in hot and humid climate. The technical paper provides guidance on the minimum air speed accepted by 80% of the occupants.

Using a cross reference of the ASHRAE 55 and the report cited the present investigation concluded that air speeds listed in the ASHRAE 55 are above the minimum air speeds preferred by 80% of the occupants.

Increased air speeds, preferably created by ceiling fans, provide an effective cooling effect for occupants, where the magnitude of the cooling effect increases with increased air speeds. Since increases in acceptable operative temperatures can increase the temperature set points in conditioned spaces ceiling fans can significantly reduce energy used for space cooling. Research in what operational mode of the ceiling fan is perceived for indoor thermal comfort favorably is ongoing.

B.5 Air Leakage - Sensitivity of Cooling Energy to Leakiness of the Envelope

This section discusses the effect of air tightness of the building envelope on the cooling energy demand. A BEopt parametric simulation investigation was carried out for a generic test 2-story air-conditioned house where the air leakage rate, expressed as air changes per hour (ACH), was varied for building alternatives while the remainder of the simulation input settings remained constant.

B.5.1 Background

Air leakage in this case is defined as unintentional exchange of air between outdoors and indoors due to improper sealing windows, doors, or any other penetration in a building envelope.

Air leakage is determined for buildings by blower doors testing, which is carried out by applying a specific pressure differential between exterior and interior air. Under standard test procedure openings such as windows, doors, dampers, and other known and intentional openings in the envelope must be closed or temporarily sealed. The blower door is fitted into one of the doors and the indoor spaces is pressurized, in the case of positive pressure testing.

Because of the pressure differential air that is pumped into the indoor spaces under a pressure escapes the building through unintentional openings. The typical pressures differentials that are applied are 25 or 50 Pascal (Pa); other pressure differentials can also be applied if found advantageous. The standard annotation of air changes measured under standard conditions is ACH₅₀, for ACH measured at a 50 Pa pressure differential.

With a constant pressure applied the volume of the air supplied to the indoor spaces, and therefore the same amount of air leaking from the building, is measured. A standard correlating function is applied to tested air changes under the increase pressure differentials to obtain the actual air leakage rate; since the pressure differentials at actual houses is typically significantly smaller than under the blower door testing.

The higher the ACH value, the leakier the building, or, expressed differently, the higher the infiltration rate. For naturally ventilated houses this is of less concerns than for air-conditioned homes, where more cooling energy must be used to remove the sensible and latent heat that enters the house through leaks. The amount of additional required cooling energy is higher for leakier houses, or house with higher ACH values

For this parametric simulation a typical 2-story air-conditioned home was used. All sources of external air supply such as open windows or mechanical exhaust systems were set to zero to validate the effect caused by air leakage.

It should be noted that leaks in the envelope also have a significant effect on humidity performance. But in the present analysis only effects on energy consumptions are discussed.

B.5.2 Results

The results of the analysis are presented in Table B.5.2.1. The range of the ACH-values were ACH 2 to 14. The ACH 2 and ACH 14 represent extremes of air tightness in building design. The value of ACH 5 is a value that should not be surpassed in the applicable energy code. The energy and energy cost savings were calculated relative to the building design alternative with the smallest air change rate value, ACH 2.

		14 ACH	11 ACH	8 ACH	5 ACH	2 ACH
Cooling energy	kWh/a	6,040	5,880	5,700	5,490	5,360
Cooling energy savings	kWh/a	0	160	340	550	680
Cooling costs	\$/a	\$1,812	\$1,760	\$1,710	\$1,650	\$1,610
Cooling energy costs savings	\$/a	\$0	\$52	\$102	\$162	\$202

Table B.5.2.1: Results of the parametric simulations using varying ACH values

Figure B.5.2.1 illustrates the projected energy cost savings that can be achieved with increasing tightness of the envelope.

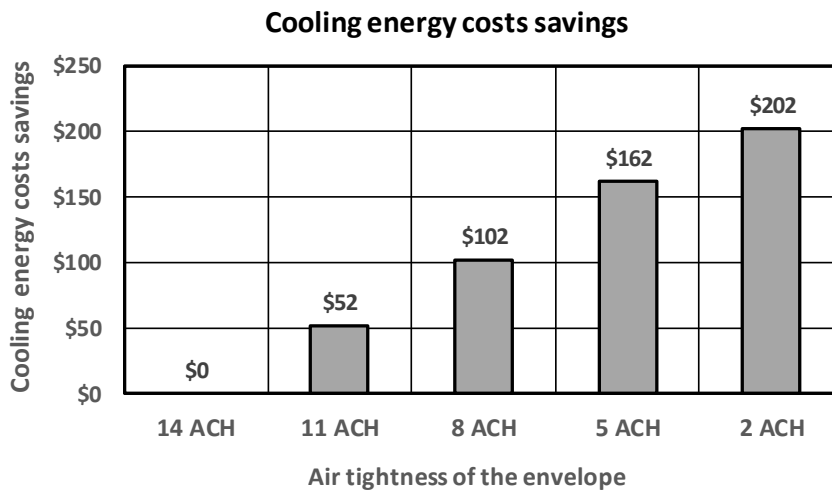


Figure B.5.2.1: Results of the parametric simulations using varying ACH values

The energy savings were expressed using the benchmark of ACH 14. This means an ACH 14 envelope leakage rate causes a savings in cooling energy of \$202 relative to an ACH 2 leakage rate.

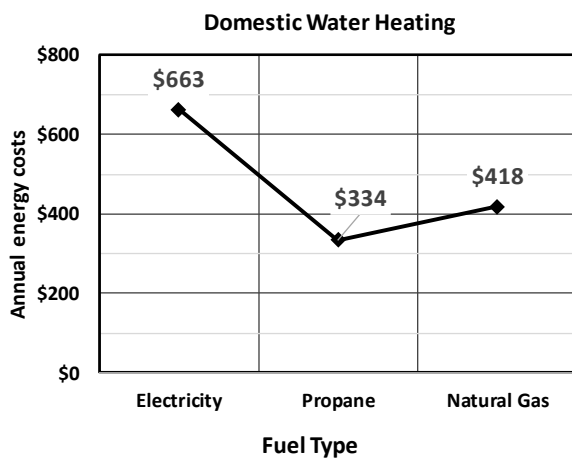
The parametric building simulation analysis in this section suggest that under the assumptions used in the present building simulation the airtightness of the envelope has only a limited effect on the cooling energy consumption and related energy costs. With higher air tightness the savings increase, but do not reach significant levels.

B.6 Domestic water heating – Cost Evaluation and Source Energy Considerations

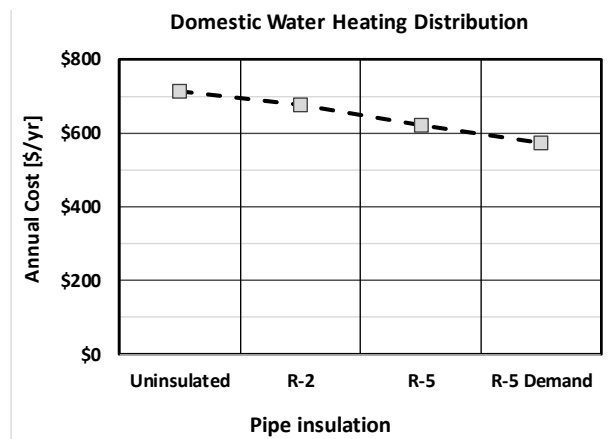
This section presents financial and source energy considerations for various domestic water heating systems.

B.6.1 Financial Performance of Domestic Water Heating Systems

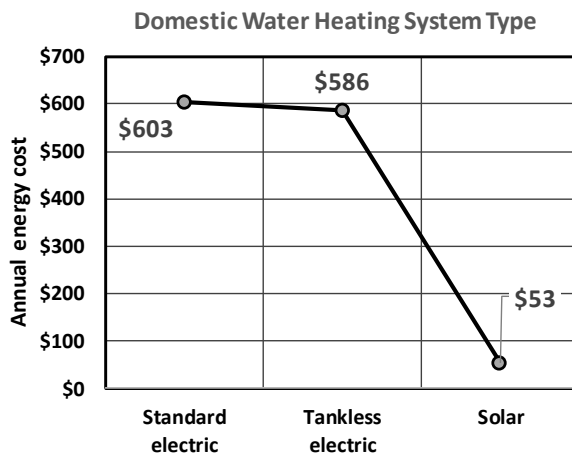
The BEopt simulation program was used to compare energy costs of several domestic hot water system components. For the simulation’s standard options for the water heater and distribution were selected. The following shows how selections of fuels, distribution piping and type of water heater can affect energy costs. Figure B.6.1.1 (a) through (c) shows energy cost sensitivity to three aspects of domestic water heaters.



(a) Cost variation per Fuel type



(b) Cost variation per distribution pipe insulation



(c) Cost variation per water heater type

Figure B.6.1.1: Energy cost sensitivity to three aspects of domestic water heating

The annual energy costs are the cost for the water heater.

B.6.2 Financial Assessment of a Generic Solar Water Heater System

The financial assessment in Figure B.6.1.1. (c) indicates that solar water heaters have an attractive energy costs per year. While solar water heating systems represent significant upfront investments, the financial benefits are only realized over a longer time-period time. Therefore, it is important to assess the long-term financial performance rather than the annual financial performance.

A Net Present Value (NPV) assessment was performed for a generic solar heating system to gain a basic understanding of the long-term return of investment of solar systems. The assumption made in the NPV assessment used common first and recurring costs, efficiencies, and predicted energy savings. These assumptions are listed in Table B.6.2.1:

Assumptions	
Δ Water Temp:	45° F
Occupancy:	# Bedrooms + 1
Water Usage:	*
SHW Heater Cost:	\$7,200
Maintenance:	\$400 / 2 years
Repair:	\$2000 / 10 years
Price of kWh:	\$0.30
Time period	15 years
All water heated with solar	
* calculated per 2014 Building America House Simulation Protocols	

Table B.6.2.1: Assumptions used for the NPV assessment of a generic solar heating system

Two discount rates, 3% and 6%, were used to reflect typical discount rates of residential home owner. The net present value (NPV) analysis was conducted for five different cases as shown in Table B.6.2.2, and the final net present value for all five cases is depicted in Figure B.6.2.1.

# Bedrooms	# Occupants	NPV	
		3% Discount Rate	6% Discount Rate
1	2	-\$3,900	-\$4,400
2	3	-\$2,800	-\$3,500
3	4	-\$1,200	-\$2,200
4	5	\$300	-\$1,000
5	6	\$1,900	\$300

Table B.6.2.2: Results of the NPV analysis

NPV values refer to cash flow at the end of 15 years, refer to Table B.6.2.1

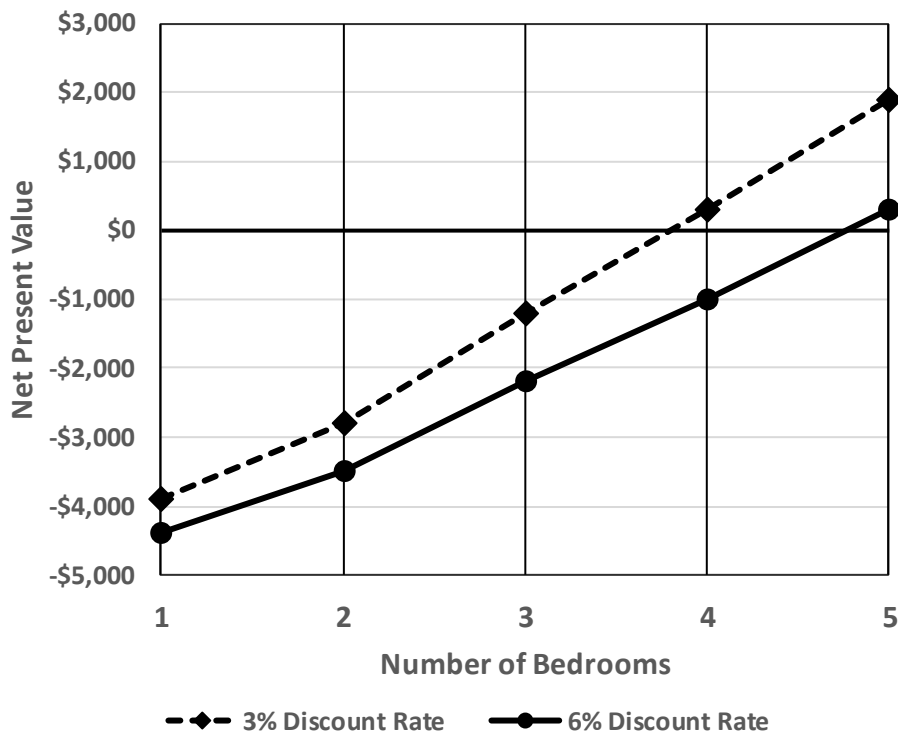


Figure B.6.2.1: Results of the NPV analysis

A net present value (NPV) assessment was conducted to assess the long-term financial performance of a generic solar water heating system. The NPV analysis used generic assumptions, including standard consumption of hot water, and therefore this NPV analysis portray results of a generic nature. Furthermore, the NPV analysis did not consider incentive payments. The results suggest the important consideration that the long-term positive return is not guaranteed for lower house occupancy. The analysis presented in this section suggested that with the long-term positive NPV is only achieved by having large number of occupants, in the case presented in this section above 5 bedroom or 6 people occupying the house.

B.7 Energy Savings Through Cooling Set-Point Variations

Varying the cooling set-point alters the energy demand on the cooling equipment, since with higher cooling set-points the space cooling equipment operates at a lower capacity and/or at a lower frequency as with lower cooling set-points. Therefore, it can be reasoned that keeping the indoor spaces at a higher temperature results in energy savings.

Set-points are usually adjusted by the building owner or operator to represent the prevailing thermal preferences of occupants. In general, cooler indoor temperatures are typically preferred in the hot and humid climate of Hawaii, as occupants can adjust their thermal comfort experience in a cooler indoor environment by increasing their clothing insulation, which means wearing thicker clothing. On the contrary, while keeping the indoor temperature at a higher temperature, occupants have little individual intervention of adjusting their thermal comfort experience if they feel too hot. The main individual intervention in this case would be to provide a cooling effect by means of a ceiling fan and/or to wear clothing with smaller insulation, e.g. “lighter clothing”.

A parametric study was performed with BEopt to identify the effect of varying the cooling set-point on the energy demand of the cooling equipment. The parametric study used a generic 1,200-sqft test house that was fully air conditioned by means of a medium efficient SEER split system. Cooling set-points were varied between 72°F to 80°F, with an increment of 2°F, plus the IECC minimum design condition of 75°F as an additional set point. The cooling equipment capacity was based on 75°F interior temperature, as recommended by the 2015 IECC energy code.

Figure B.7.1 shows the annual site energy demands of the generic test house as a function of different cooling set-points. Figure B.7.2 shows the annual electricity demand for the cooling equipment and the cooling fans combined as a function of different cooling set-points. Figure B.7.3 shows the energy demand for the cooling system as a percentage change relative to the 2015 IECC 75°F design condition.

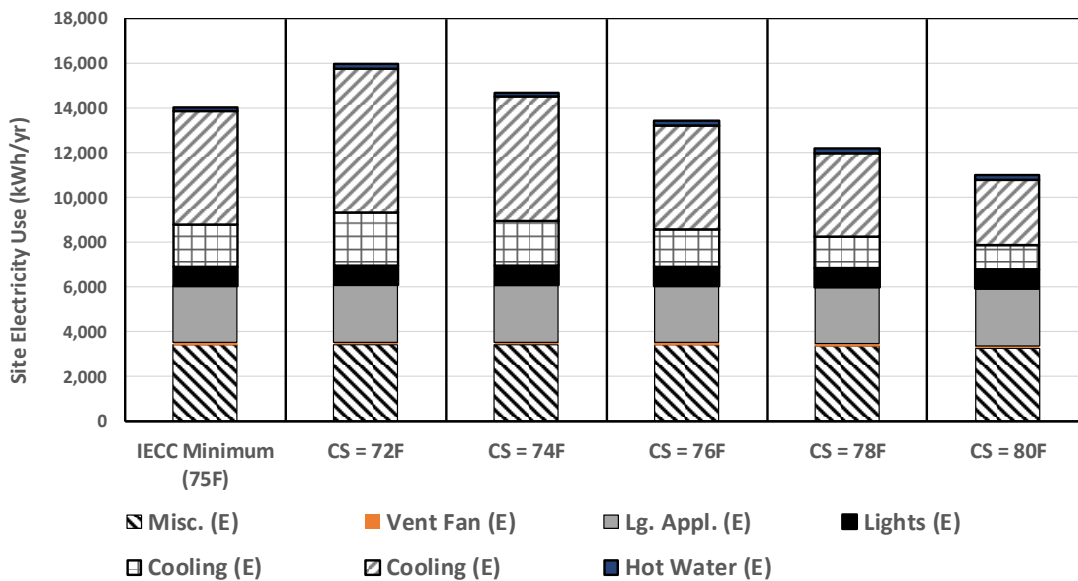


Figure B.7.1: Whole house energy demand of generic test house as a function of varying cooling set-points

APPENDIX B BUILDING PERFORMANCE PROCESSES BENCHMARKED IN STUDY

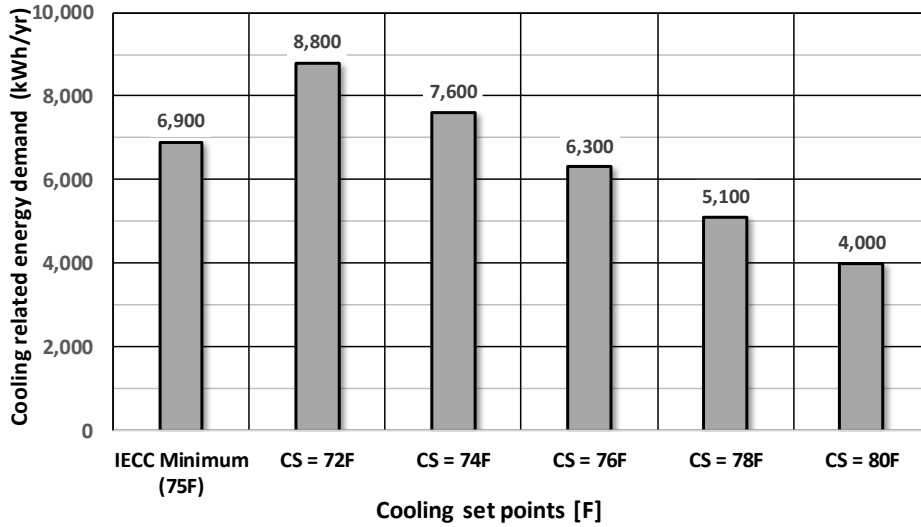


Figure B.7.2: Whole house energy demand of generic test house as a function of varying cooling set-points

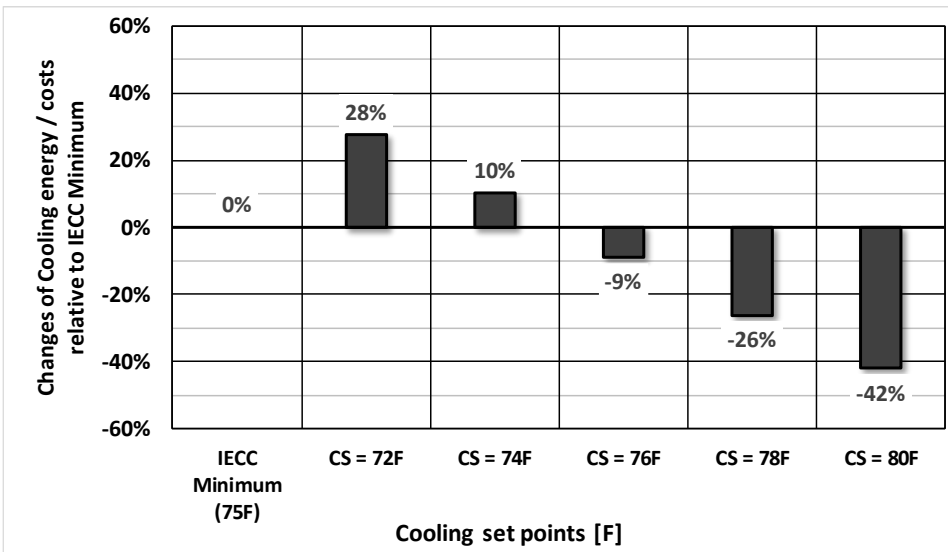


Figure B.7.2: Whole house energy demand of generic test house as a function of varying cooling set-points

The baseline was a 75 F cooling set-point

The results of the parametric cooling set-point study suggest that the selection of cooling set-points has a significant effect on the energy demand of the cooling system. When compared to the 2015 IECC design requirement of a minimum 75°F cooling set-point, an 80°F cooling set-point could save energy for the cooling system of up to 42%, under the assumptions of the generic test case. On the other hand, lowering the cooling set point to 72°F would incur an energy penalty of about 30%. It must be noted that the parametric study used generic and not optimized cooling equipment, nor did the parametric study address possible implications on dehumidification performance of the cooling equipment. But the basic premise indicated by these results underlines that significant energy can be saved by increasing the cooling set point. An effective remedy for occupants to provide individual cooling in indoor spaces with higher cooling set points is the use of ceiling fans. Therefore, a combination of increasing the cooling set-point and ceiling fans represents an attractive energy efficiency measure.

B.8 Contribution of Selection of Efficient Appliances

Appliances represent a significant portion of the energy use in residential buildings. The readiness of the house owners' occupants to purchase energy efficient appliance has therefore a significant impact on the overall energy performance. This section discusses the energy performance and the financial costs of different types of refrigerators. First costs, or purchase price, has a significant influence on what appliances are bought.

Main types of appliances include, clothes washers and dryers, stoves, dishwasher and refrigerators. Refrigerators were chosen to represent the energy and financial performance of appliances since their operation is the least affected by personal behavioral choices; since refrigerators are required to run constantly.

B.8.1 Type of Refrigerators Considered for the Analysis

Three types of refrigerators were considered, those with side-by-side, bottom and top freezers. A wide range of refrigerators products available from retailers in Hawaii was assembled for an energy and cost comparison. Table B.8.1.1 Illustrates the list of top-freezer refrigerators considered for this analysis. The list in Table B.8.1.1 shows typical consumer brands that were identified, as well as options of appliances that were provided by BEopt for the energy performance simulations.

Top-freezer Refrigerator				
Brand	Model	Capacity (ft³)	Price	Elec Use [kWh/yr]
Consumer products				
GE	GIE16GSHSS	15.5	\$729.00	428
GE	GTS16DTHBB	15.5	\$449.00	382
Samsung	RT18M6215SR	17.6	\$699.00	448
Insignia	NS-RTM18SS7	18	\$499.00	362
Whirlpool	WRT348FMEW	18.2	\$699.00	455
GE	GIE21GSHSS	21.2	\$1,259.00	480
Samsung	RT21M6215SG	21.2	\$899.00	478
Samsung	RT21M6215SR	21.2	\$849.00	478
LG	LTCS24223S	23.8	\$999.00	501
Frigidaire	FFTR1821TS	18	\$499.00	404
Whirlpool	WRT311FZDW	20.5	\$599.00	436
Frigidaire	FFTR1814TW	18.1	\$449.00	404
Whirlpool	WRT311FZDB	20.5	\$599.00	436
Maytag	MRT118FFFM	18.1	\$699.00	411
Equivalent refrigerators provided as option in Beopt				
BEopt	11 (EF=15.9)	18	\$611.00	480
BEopt	12 (EF=17.6)	18	\$619.00	434
BEopt	15 (EF=19.9)	18	\$629.00	384
BEopt	16 (EF=20.4)	18	\$859.00	374
BEopt	17 (EF=21.9)	18	\$975.00	348

Table B.8.1.1: Sample list of refrigerators considered for this analysis.

APPENDIX B BUILDING PERFORMANCE PROCESSES BENCHMARKED IN STUDY

Figures B.8.1.1 through B.8.1.2 show a comparison of energy performance and purchase price (first cost) for consumer product top-freezer refrigerators and generic BEopt options top-freezer refrigerators, respectively. In Figure B.8.1.1 the consumer products considered depict a ranked energy performance from best to worst. Figure B.8.1.1 also shows that the purchase price of these consumer products is not directly correlated with the energy performance of the appliances. Figure B.9.1.2, on the other hand, shows the BEopt equivalent refrigerators types, where the increasing energy performance is directly correlated with a higher purchase price.

The data suggests that BEopt assumes higher first cost, for a “better machine” with a better energy performance. This is a trend that seems to be intuitive and is used for the simulation; but this trend is not reflected in the actual data for evaluated refrigerators currently available from retailers in Hawaii.

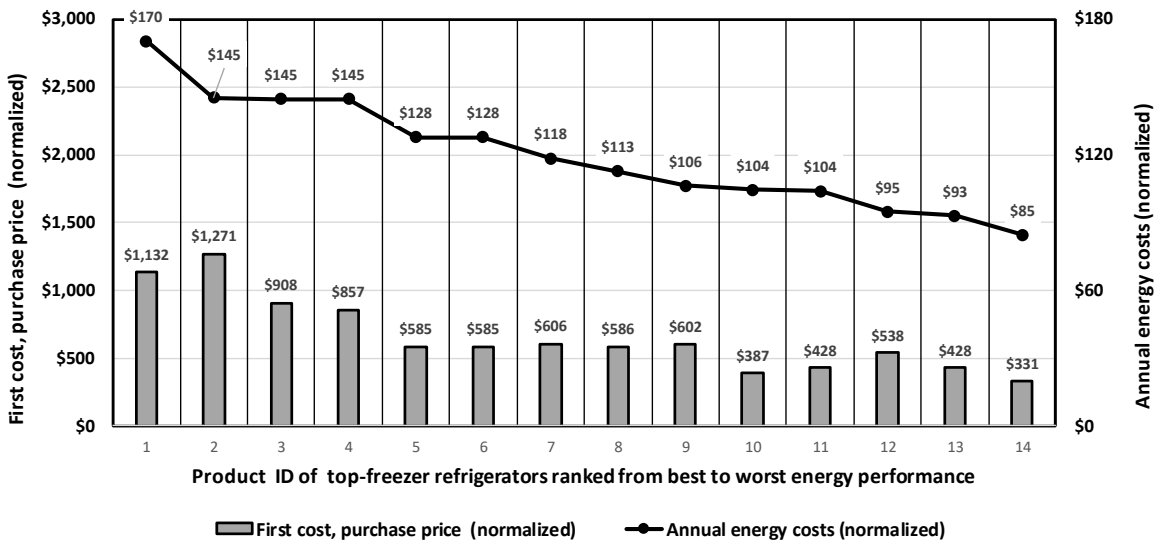


Figure B.8.1.1: Energy performance and purchase price (first cost) for consumer product top-freezer refrigerators

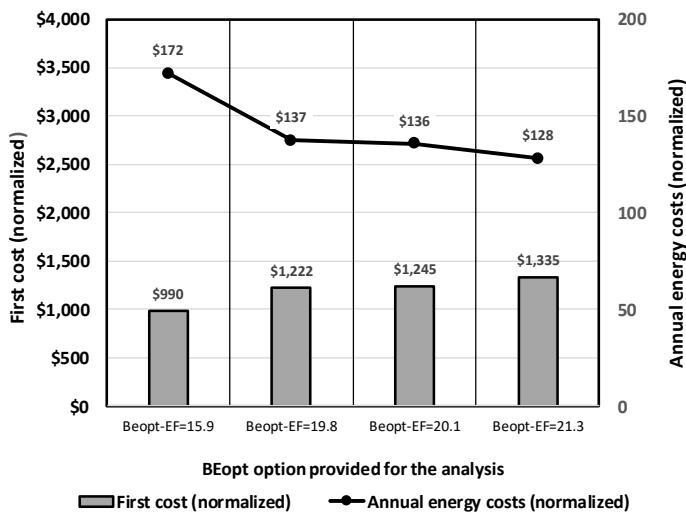


Figure B.8.1.2: Energy performance and purchase price (first cost) for generic BEopt options top-freezer refrigerators

A comparison of common consumer refrigerators and the refrigerator options that are provided in the BEopt simulation software showed that the first costs (purchase price) of the consumer products did not correlate with the energy performance of the appliance type. In other words, for consumer products the best energy performers evaluated were not always the most expensive and vice versa. For the BEopt default options for refrigerators this cost trend does not apply and for the appliance options used in the BEopt simulation the more energy efficient appliance options are also the more expensive to purchase.

B.8.2 Net-Present Value Assessment for Appliances

A net-present value (NPV) analysis was performed, using generic input value and disregarding inflation and fuel cost escalation. Thus, the NPV analysis is on the conservative side.

The NVP assessment was performed for the three refrigerator types, side-by-side, bottom and top freezers. Table B.8.2.1 shows the average energy and cost assumptions that were used in the NPV analysis. Figure B.8.2.1 shows the comparison of the average first costs and annual energy costs for the three types of refrigerators. Figure B.8.2.2 shows the unit energy costs for the three refrigerator types. The comparison of unit energy costs is created since the three types of refrigerators have inherent different internal volumes.

Refrigerator type	Average numbers				
	First cost [\$]	Energy use [kWh/a]	First cost Normalized [\$/(kWh/a)]	Energy use Normalized [(kWh/a) /cbf]	Energy use annual cost [\$/a]
Side-by-side	\$1,300	620	\$2.13	24.8	\$190
Bottom-freezer	\$1,200	520	\$2.40	20.0	\$160
Top-freezer	\$660	400	\$1.60	19.0	\$120

Table B.8.2.1: Average energy and cost assumptions that were used in the NPV analysis.

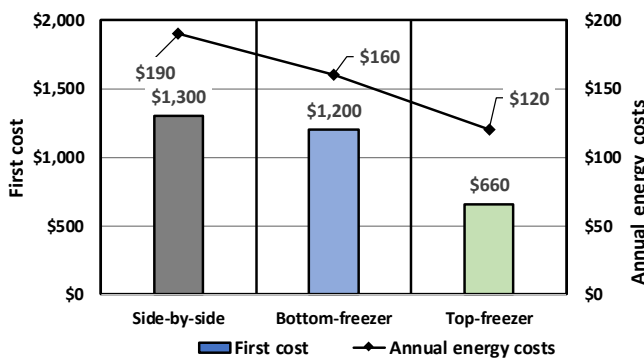


Figure B.8.2.1: Comparison of the average first costs and annual energy costs for the three types of refrigerators

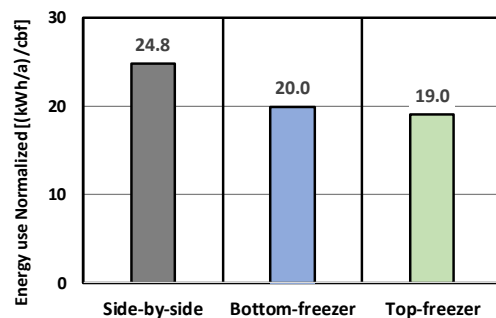


Figure B.8.2.2: Unit energy costs for the three refrigerator types

APPENDIX B BUILDING PERFORMANCE PROCESSES BENCHMARKED IN STUDY

The discount rates of 3% and 6% were used for the NPV assessment of the three refrigerator types.

From the list of each of the three refrigerator types three groups were selected, the top-performers, the low-performers and an average of all products. These three “performers” represented the best, the worst and average energy performance, respectively. Table B.8.2.2 and Figures B.8.2.3 through B.8.2.5 show the results of the NPV analysis.

Refrigerator type	NPV		NPV		NPV	
	All products		Top performers		Low performers	
	3%	6%	3%	6%	3%	6%
Side-by-side	-\$3,570	-\$3,150	-\$3,150	-\$2,800	-\$3,680	-\$3,190
Bottom-freezer	-\$3,110	-\$2,750	-\$2,710	-\$2,450	-\$3,700	-\$3,250
Top-freezer	-\$2,090	-\$1,830	-\$1,500	-\$1,300	-\$2,890	-\$2,560

Table B.8.2.1: Results of the NPV analysis

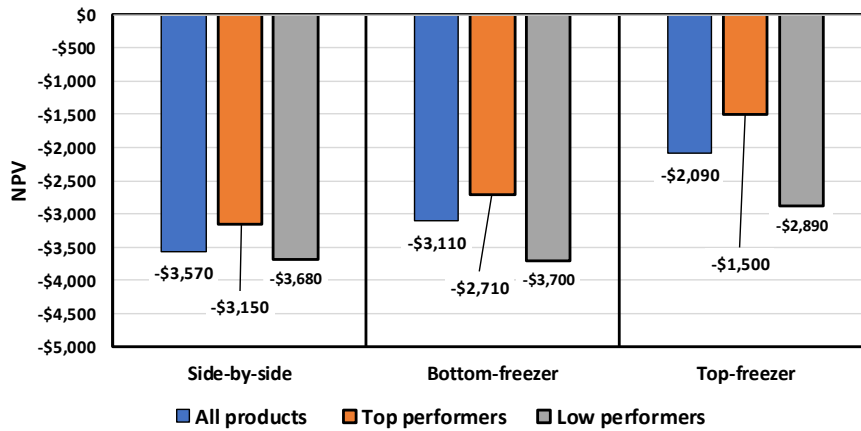


Figure B.8.2.3: Results of the NPV analysis

Discount rate of 3%

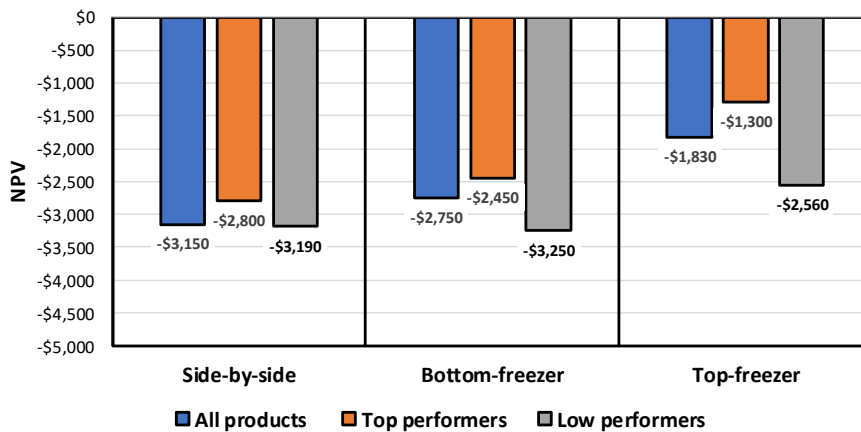


Figure B.8.2.4: Results of the NPV analysis

Discount rate of 6%

APPENDIX B BUILDING PERFORMANCE PROCESSES BENCHMARKED IN STUDY

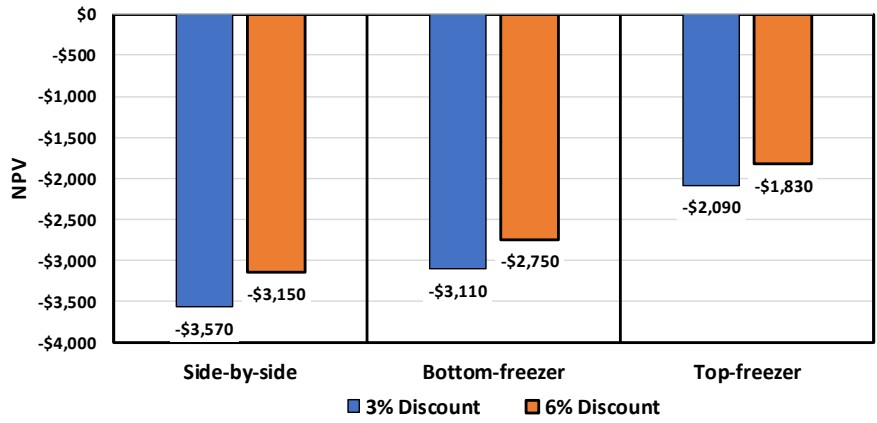


Figure B.8.2.5: Results of the NPV analysis

Overall average numbers

B.9 Generic Performance Parameters of Photovoltaic Site Energy Generation

A parametric study was carried out with the BEopt simulation program to investigate the three principle design parameters for photovoltaic (PV) installations on residential buildings. The parametric study used a generic residential house design. The three BEopt design parameters for the simulation of the PV system performance and which were changed in this study were as follows:

- Size of the PV system
- Azimuth of the PV panels
- Tilt angle of the PV panels

Varying the three PV system parameters was done using absolute design considerations and constraints of the roof geometry of the generic house designs were not considered.

B.9.1 Example Sizing of the PV System Capacity and Net-Zero Energy Performance

The size of the installed PV system capacity determines how close the house design approaches net-zero performance. Figure B.9.1.1 shows a correlation of the size of the PV power generating capacity with the actual electric energy generated and the example energy demand of the generic house design. Figure B.9.1.2 shows the net-zero energy performance of the PV-sizing design example depicted in Figure B.9.1.1. The percentages indicated in Figure B.9.1.2 illustrate the magnitude of net-zero energy achieved by the design example in Figure B.9.1.1. In the case depicted in Figure B.9.1.1 a minimum PV-capacity of 7 kW must be installed to achieve basic net-zero energy performance.

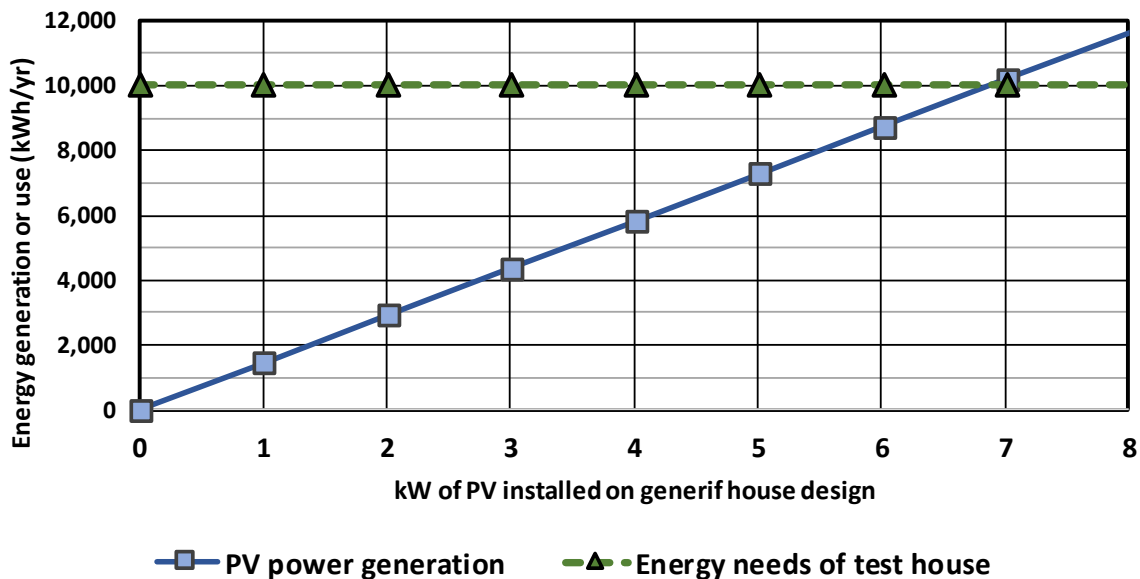


Figure B.9.1.1: PV power generation capacity correlated to generic house design energy requirements

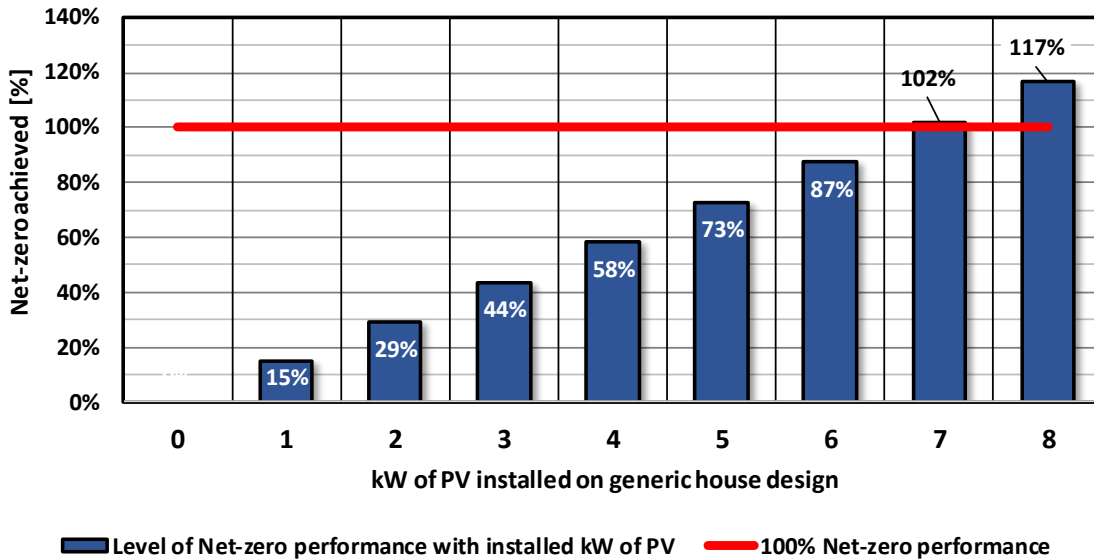


Figure B.9.1.2: Net-zero energy achieved for the PV-sizing example depicted in Figure B.9.1.1

The example electric energy generation performance would indicate a capacity factor of 17%, where the capacity factor is the ratio of the energy generated versus the potential energy generated if the generation would have happened at name plate capacity. In our example 1,450 kWh/yr generated by a 1 kW PV panel divided by the potential 8,760 kWh energy generated by the same panel, is calculated as 17%.

B.9.2 Effect of PV Panels Tilt Angle on Energy Generation

Figure B.9.2.1 defines the tilt angle used in this parametric study.

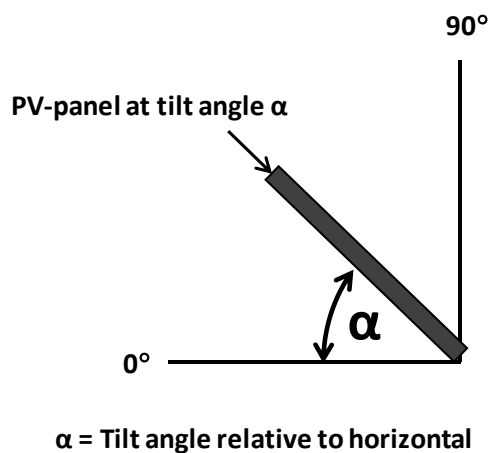


Figure B.9.2.1: Definition of tilt angle of the PV-panels

Figure B.9.2.2 shows the energy generation in kWh per day per 1 kW of PV power installed correlated with tilt angles of the panel. Figure B.9.2.3 indicates how energy generation performance of the PV-system correlated against the tilt angles relative to the maximum energy generation, which in Figure B.9.2.2 was at a 20-degree tilt angle.

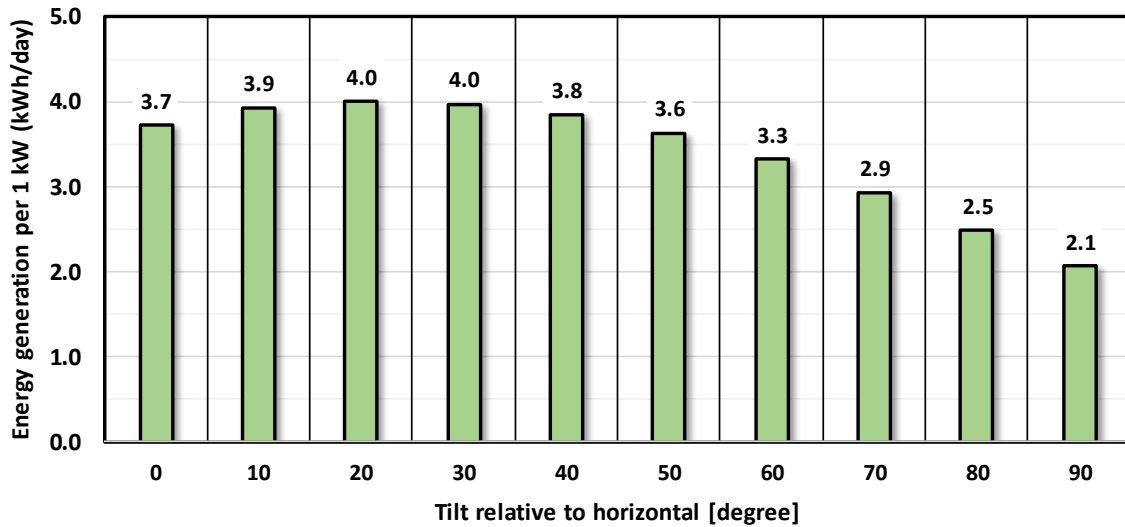


Figure B.9.2.2: energy generation in kWh per day per 1 kW of PV power installed correlated with tilt angles of the panel

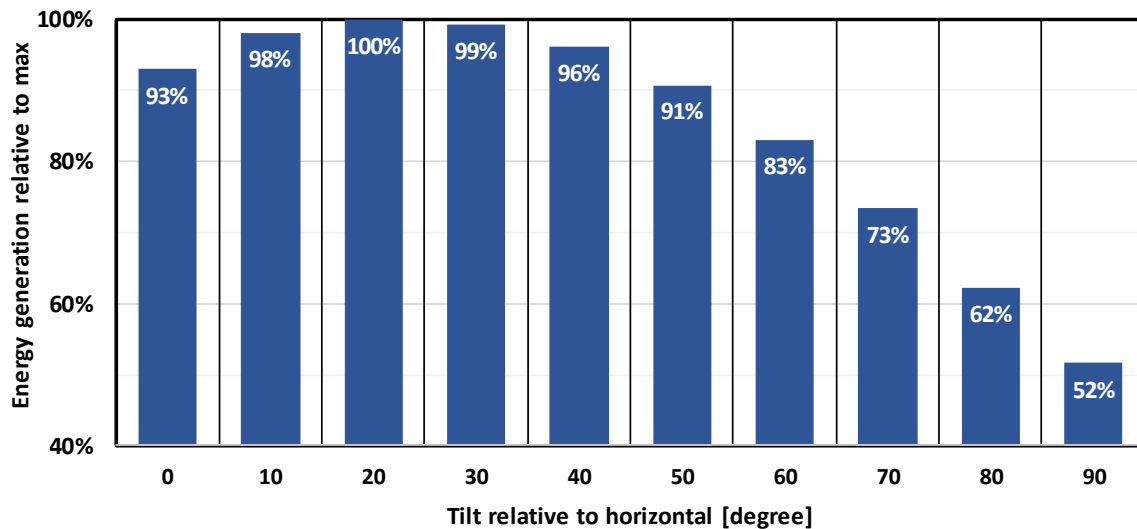


Figure B.9.2.3: Energy generation performance correlated against the tilt angles relative to the maximum energy generation, which in Figure B.9.2.2 was at a 20-degree tilt angle

B.9.3 Effect of the Orientation of PV-Panel

Figure B.9.3.1 illustrates the definition of the orientation of the PV-panels, or azimuth, used in BEopt.

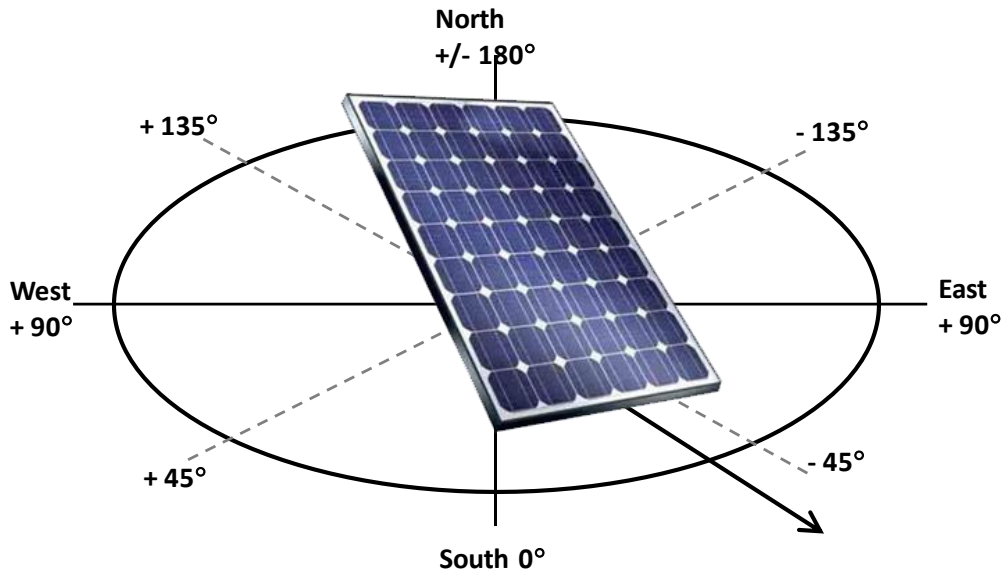


Figure B.9.3.1: Definition of the orientation of the PV-panels, or azimuth, used in BEopt.

Figures B.9.3.2 and B.9.3.3 indicate the correlation of energy generation capacity of PV panels and orientation of the PV panel. Figures B.9.3.2 shows the average daily energy generated by a 1-kW panel for a 20-degree tilt and a 0-degree tilt angle. Figure B.9.3.3 shows the percentage of energy generated when compared to the maximum energy generated by the panel oriented to the South.

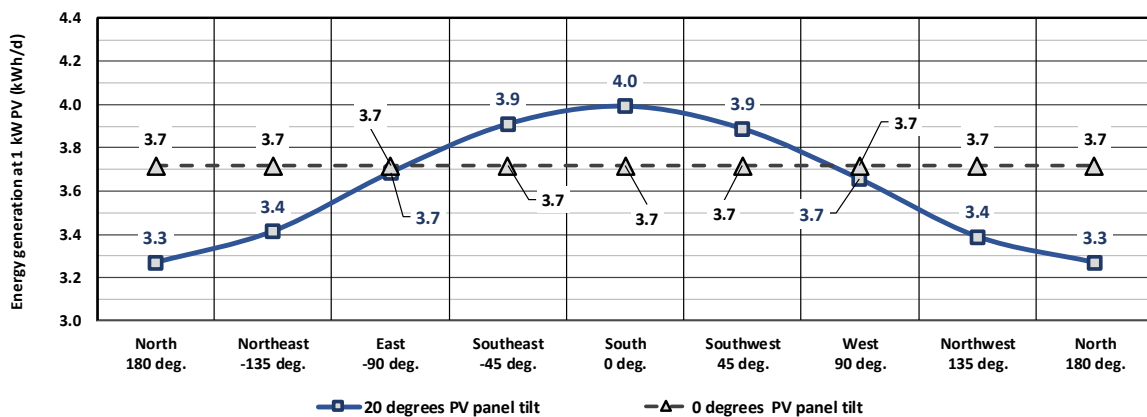


Figure B.9.3.2: Daily energy generated by a 1-kW panel for a 20-degree tilt and a 0-degree tilt angle

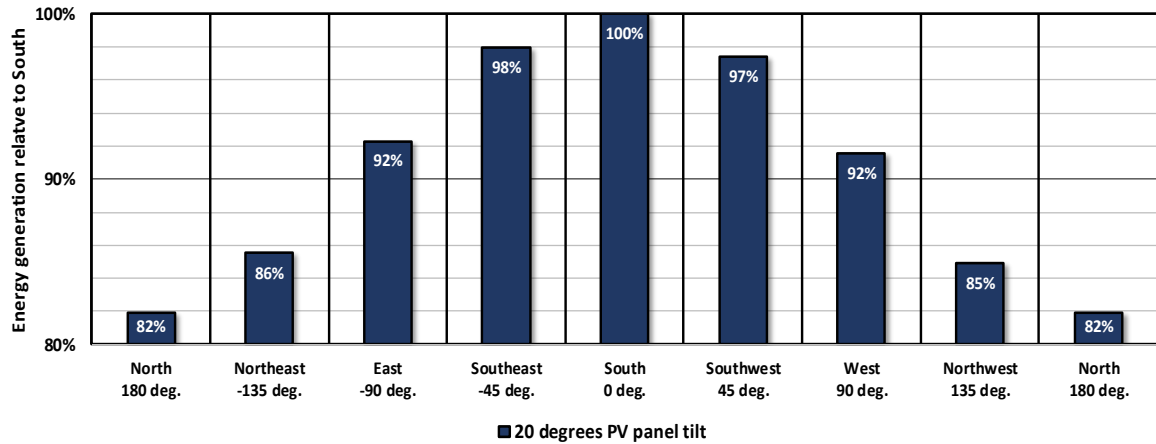


Figure B.9.3.3: percentage of energy generated when compared to the maximum energy generated by the panel oriented to the South.

B.9.4 Effects of Combined PV-Panel Orientation and Tilt on Energy Generation

Figure B.9.4.1 shows the definition of the combined orientation of the PV-panels, or azimuth, and tilt, as defined in BEopt.

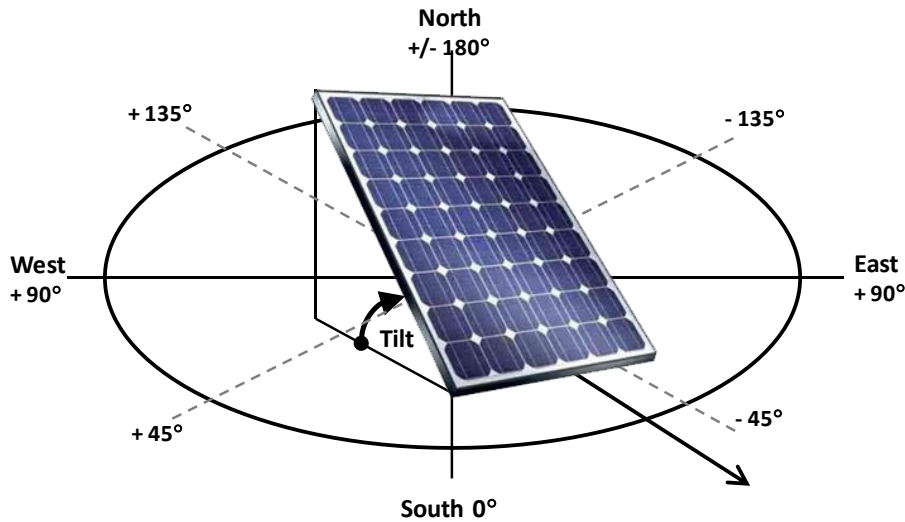


Figure B.9.3.1: Definition of the combined orientation of the PV-panels, or azimuth, and tilt, as used in BEopt.

Figure B.9.4.2 and Table B.9.4.1 shows the daily energy generation potential of a normalized 1-kW PV panels with different orientation and tilt angles. The numbers were calculated by using a generic BEopt model with absolute azimuth and tilt angles.

Table B.9.4.1: Daily predicted Electric energy production of a 1-kW PV panel, using BEopt.

	North 180 deg.	Northeast -135 deg.	East -90 deg.	Southeast -45 deg.	South 0 deg.	Southwest 45 deg.	West 90 deg.	Northwest 135 deg.	North 180 deg.
Tilt angle	Site Energy Generation (kWh/d) for 1 kW PV capacity installed								
0	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7
10	3.6	3.6	3.8	3.9	3.9	3.9	3.7	3.6	3.6
20	3.3	3.4	3.7	3.9	4.0	3.9	3.7	3.4	3.3
30	2.9	3.1	3.6	3.9	4.0	3.8	3.5	3.1	2.9
40	2.5	2.8	3.4	3.7	3.8	3.7	3.3	2.8	2.5
50	2.1	2.5	3.2	3.5	3.6	3.5	3.1	2.5	2.1

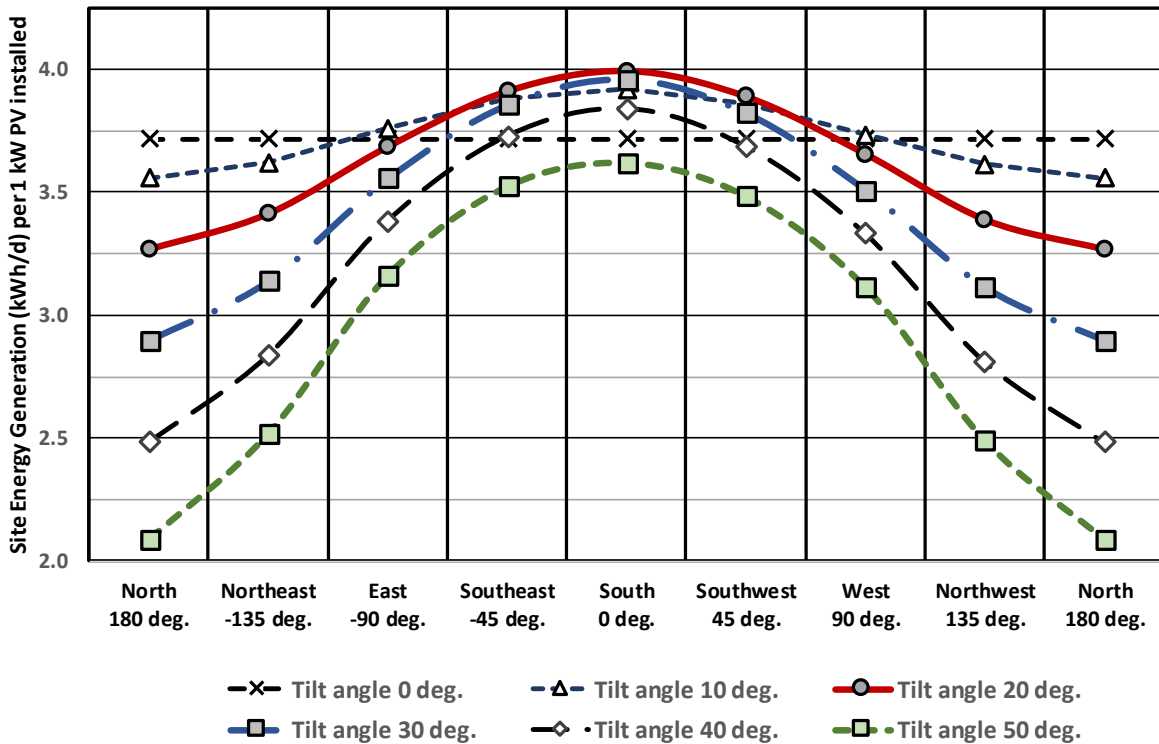


Figure B.9.4.1: Table B.9.4.1: Daily predicted Electric energy production of a 1-kW PV panel, using BEopt.

The result of the parametric study investigating the energy production potential by PV-systems as a function of panel orientation and tilt indicated the significant effect of orientation and tilt on the system performance. The performance of the PV system was calculated using the BEopt software using generic input parameters and local weather conditions as represented by the TMY file for the project site.

B.9.5 Benchmarking PV Generation Potential Using PV-Watts and BEopt

The assessment of PV generation using a generic test house configuration, which was described in this Sections B.9.1 and B.9.4, used BEopt software to quantify the electric energy production by the PV-system. For the assessment of the Net-zero performance of the Sample Houses 2, 3 and 8 in Section 5.3 through 5.5 the web-based PV-Watts application was used.

A comparison of PV-energy production rates, assuming the same tilt and orientation, was performed using the BEopt and the PV-Watts software applications. The results of the comparison of the calculated PV-generation rates for a 1-kW capacity between BEopt and PV-Watts is presented in Table B.9.5.1. Figure B.9.5.1 shows the percentage of PV-generation rates of PV-Watts relative to BEopt. Figure B.9.5.1 indicates that the PV-generation rates that were calculated with PV-Watts were consistently larger than the rates calculated with BEopt. Both BEopt and PV-Watts describe the sizes of the PV system in kW DC.

BEopt provides default input calculation variable values for the efficiency of different PV-panels, system losses and inverter efficiency, where the values system losses and inverter efficiency can be changed from the default values. The PV-Watt application, on the other hand, provides a wider range of input variables and the ability to change all default values. The results shown in Table B.9.5.1 and Figure B.9.5.1 represent results of calculation using default values in both BEopt and PV-Watts.

Table B.9.5.1: Comparison of the calculated PV-generation rates for a 1-kW capacity using BEopt and PV-Watts

Tilt	PV Watts				Beopt			
	North	East	South	West	North	East	South	West
Direction used in program >>>	0	90	180	270	-180	-90	0	90
degrees	kWh/year per 1 kW				kWh/year per 1 kW			
0	1,560	1,560	1,580	1,580	1,360	1,360	1,360	1,360
20	1,350	1,540	1,640	1,490	1,190	1,350	1,460	1,330
40	1,020	1,400	1,590	1,370	910	1,230	1,400	1,220
degrees	kWh/day per 1 kW				kWh/day per 1 kW			
0	4.3	4.3	4.3	4.3	3.7	3.7	3.7	3.7
20	3.7	4.2	4.5	4.1	3.3	3.7	4.0	3.6
40	2.8	3.8	4.4	3.8	2.5	3.4	3.8	3.3
degrees	Percent results PV-Watts > BEopt				N/A			
0	15%	15%	16%	16%				
20	13%	14%	12%	12%				
40	12%	14%	14%	12%				

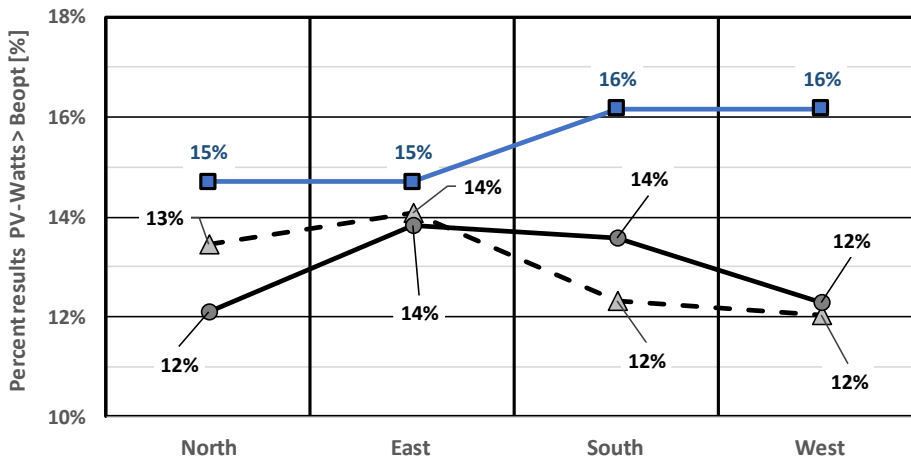


Figure B.9.5.1: Percentage of PV-generation rates of PV-Watts relative to BEopt

The comparison of the PV-generation values calculated with the software applications BEopt and PV-Watts indicate a consistently higher achievable energy generated by the PV-Watts application. The divergence of the calculated energy generated by the PV-system could be caused on the different range and control of calculation input variables, where PV-Watts offers more control of inputs.

B.10 Site and Source Energy Performance - Sensitivity of Energy Factors on GHG Emissions

This section discusses the effect of energy conversion process in the power plants and losses in the power grid on the environmental impact as a function of energy use in the building. For the following discussion of environmental impacts from water heaters only fossil fuel-based electricity generation was considered, thus water heating with solar water heater or electricity generated from renewable energy were not considered.

For the cases of fossil fuel-based water heating applications, which are still representing most domestic water heating applications, heating of water occurs, when chemical energy contained in fuel is transformed to heat energy. This burning of fuel causes the release of carbon dioxide as the carbon atoms in the fuel combine with free oxygen in the air. Electric water heaters are responsible for carbon release through the burning of fossil fuel in the power plant where the electricity is generated.

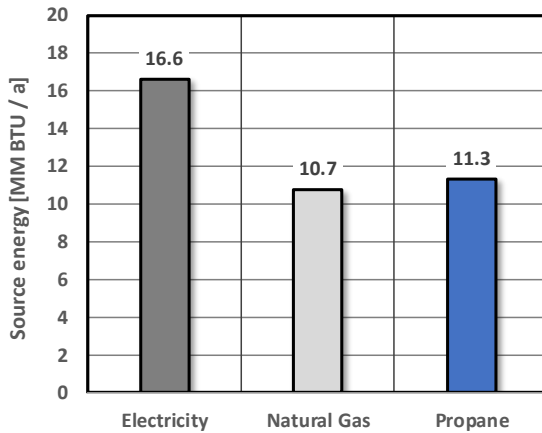
A BEopt simulation was run of a generic test house with electric, natural gas and propane water heaters to evaluate the amount of carbon that is release. The same amount of water was heated in each of the three cases. The results are depicted in Table B.6.3.1 and Figure B.6.3.1 (a) through (c).

APPENDIX B BUILDING PERFORMANCE PROCESSES BENCHMARKED IN STUDY

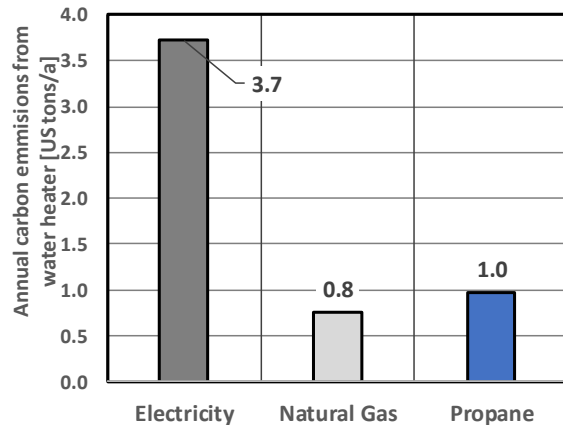
Table B.6.3.1: Results of source energy analysis

Hot water heater type [fuel]	Energy factor [-]	Source energy MMBTU/a	Source/Site Ratio [-]	Carbon Factor		Carbon Factor normalized		Annual carbon emissions from water heater	
					unit		unit	US ton/a	
Electricity	0.92	16.6	3.2	1.5	lb/kWh	4.48E-04	lbs/BTU	3.7	100%
Natural Gas	0.59	10.7	1.1	14.2	lb/therm	1.42E-04	lbs/BTU	0.8	20%
Propane	0.59	11.3	1.2	15.7	lb/gal	1.73E-04	lbs/BTU	1.0	26%

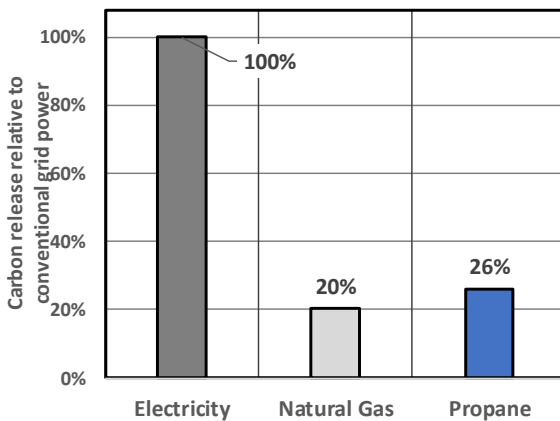
The results indicate that while electricity has the largest site energy factor, and therefore best site energy performance, grid supplied electricity has a significantly larger environmental impacts in form of carbon emission. Therefore, water heaters that consume fuel on the site to heat water are more environmentally friendly than their electric counterparts.



(a) Source energy



(b) Carbon emissions (absolute)



(c) Carbon emissions (relative to grid electricity)

Figure B.6.3.1: Results of source energy and carbon footprint analysis

APPENDIX C – COMPLETE RESULTS OF ALL SIMULATIONS

Table C.1. Site energy (MMBtu) for all simulations for House 3, the fully air-conditioned house.

Components	Options	Misc.	Large Appliances	Vent Fan	Lights	Cooling /fan	Cooling	Hot Water	Sum	Change from IECC 2015
IECC 2015	House #3 IECC 2015 minimally compliant	8.29	8.7	0.37	2.95	6.07	16.61	0.58	43.57	0.0%
Wood wall insulation h-ft ² °F/Btu	R-15	8.29	8.7	0.37	2.95	6.04	16.54	0.58	43.5	-0.2%
	R-20	8.29	8.7	0.37	2.95	5.99	16.39	0.58	43.3	-0.7%
	R-25	8.29	8.7	0.37	2.95	5.95	16.28	0.58	43.1	-1.0%
Exterior finish	Fiber-cement light color absorptivity = 0.3	8.29	8.7	0.37	2.95	5.66	15.51	0.58	42.1	-3.5%
	Vinyl light color absorptivity = 0.3	8.29	8.7	0.37	2.95	5.66	15.49	0.58	42.0	-3.5%
	Aluminum light color absorptivity = 0.3	8.29	8.7	0.37	2.95	5.66	15.49	0.58	42.0	-3.5%
	Wood light color absorptivity = 0.3	8.29	8.7	0.37	2.95	5.66	15.48	0.58	42.0	-3.5%
Roof material	White metal absorptivity = 0.3	8.29	8.7	0.37	2.95	5.75	15.71	0.59	42.4	-2.8%
	Light color metal absorptivity 0.6	8.29	8.7	0.37	2.95	5.96	16.3	0.58	43.2	-1.0%
	Galvanized Steel	8.29	8.7	0.37	2.95	6.05	16.55	0.58	43.5	-0.2%
Ceiling insulation	R-40	8.29	8.7	0.37	2.95	6.05	16.56	0.58	43.5	-0.2%
	R-50	8.29	8.7	0.37	2.95	6.04	16.53	0.58	43.5	-0.3%
	R-60	8.29	8.7	0.37	2.95	6.03	16.51	0.58	43.4	-0.3%
Radiant barrier	Double sided	8.29	8.7	0.37	2.95	5.9	16.15	0.58	42.9	-1.4%
Window area as % of conditioned floor area	13%	8.29	8.7	0.37	2.95	5.97	16.33	0.58	43.2	-0.9%
	11%	8.29	8.7	0.37	2.95	5.87	16.06	0.58	42.8	-1.7%
	9%	8.29	8.7	0.37	2.95	5.75	15.73	0.58	42.4	-2.8%
Window U-value Btu/h-ft ²	0.4	8.29	8.7	0.37	2.95	6.09	16.65	0.58	43.6	+0.1%
	0.3	8.29	8.7	0.37	2.95	6.11	16.7	0.58	43.7	+0.3%
Window overhangs	2' all stories	8.29	8.7	0.37	2.95	6.01	16.44	0.58	43.3	-0.5%
	3' all stories	8.29	8.7	0.37	2.95	5.92	16.21	0.58	43.0	-1.3%
Lighting	100% LED	8.29	8.7	0.37	2.84	6.06	16.59	0.58	43.4	-0.3%
Cooling	SEER 16	8.29	8.7	0.37	2.95	3.58	15.81	0.58	40.3	-7.6%
	SEER 18	8.29	8.7	0.37	2.95	3.29	14.19	0.58	38.4	-11.9%
	SEER 21	8.29	8.7	0.37	2.95	3.29	12.03	0.58	36.2	-16.9%
	SEER 24.5	8.29	8.7	0.37	2.95	1.16	9.05	0.58	31.1	-28.6%
Exhaust	ASHRAE 62.2 2013, ERV 70% sensible recovery 48% total recovery efficiency	8.29	8.7	1.48	2.95	5.99	16.35	0.58	44.3	+1.8%
	ASHRAE 62.2 2013, HRV, 70% sensible recovery 20% total recovery efficiency	8.29	8.7	1.48	2.95	6.15	16.81	0.58	45.0	+3.2%
Ceiling Fans	5 Premium fans	9.37	8.7	0.37	2.95	6.16	16.84	0.58	45.0	+3.2%
	5 Premium fans occupancy sensors +4°F setpoint	8.54	8.7	0.37	2.95	3.93	10.85	0.58	35.9	-17.6%
Appliances	Combined energy efficient appliances	8.29	5.68	0.37	2.95	5.93	16.24	0.56	40.0	-8.1%
Recommended	Combined strategies	8.67	5.68	0.37	2.84	0.5	4.35	0.57	23.0	-47.3%

Table C.2 Site energy (MMBtu) for all simulations for House 8, the partially air-conditioned house.

Components	Options	Misc.	Large Appliances	Vent Fan	Lights	Cooling/ fan	Cooling	Hot Water	Sum	Change from IECC 2015
IECC 2015	House #8 IECC 2015 minimally compliant	10.9	8.7	0.24	3.68	0.31	8.38	0.58	32.79	0.0%
Wood wall insulation h-ft ² °F/Btu	Fiberglass batt R-15	10.91	8.7	0.24	3.68	0.3	8.07	0.58	32.48	-0.9%
	Open cell spray foam R-20	10.93	8.7	0.24	3.68	0.29	7.87	0.58	32.29	-1.5%
	Fiberglass batt R-25	10.92	8.7	0.24	3.68	0.29	7.99	0.58	32.40	-1.2%
Interzonal wall	R-19	10.9	8.7	0.24	3.68	0.31	8.36	0.58	32.77	-0.1%
	R-21	10.9	8.7	0.24	3.68	0.31	8.36	0.58	32.77	-0.1%
Exterior finish	Fiber-cement, light color absorptivity = 0.3	10.87	8.7	0.24	3.68	0.29	7.67	0.58	32.03	-2.3%
	Vinyl, light color absorptivity = 0.3	10.87	8.7	0.24	3.68	0.29	7.67	0.58	32.03	-2.3%
	Alum. light absorptivity = 0.3	10.87	8.7	0.24	3.68	0.29	7.66	0.58	32.02	-2.3%
	Wood, light color absorptivity = 0.3	10.88	8.7	0.24	3.68	0.29	7.66	0.58	32.03	-2.3%
Roof material	White metal	10.88	8.7	0.24	3.68	0.29	8.12	0.59	32.50	-0.9%
	White or cool colors absorptivity = 0.3	10.88	8.7	0.24	3.68	0.29	7.66	0.58	32.03	-2.3%
	Galvanized steel	10.87	8.7	0.24	3.68	0.29	7.67	0.58	32.03	-2.3%
Ceiling insulation	R-35	10.9	8.7	0.24	3.68	0.31	8.35	0.58	32.76	-0.1%
	R-40	10.9	8.7	0.24	3.68	0.31	8.31	0.58	32.72	-0.2%
	R-45	10.9	8.7	0.24	3.68	0.31	8.29	0.58	32.70	-0.3%
Radiant barrier	Double sided	10.9	8.7	0.24	3.68	0.31	8.25	0.58	32.66	-0.4%
Window area as % of conditioned floor area	18%	10.88	8.7	0.24	3.68	0.32	8.45	0.58	32.85	+0.2%
	20%	10.86	8.7	0.24	3.68	0.32	8.51	0.58	32.89	+0.3%
	25%	10.84	8.7	0.24	3.68	0.33	8.64	0.58	33.01	+0.7%
Window SHGC	0.2	10.87	8.7	0.24	3.68	0.31	8.2	0.58	32.58	-0.6%
	0.15	10.86	8.7	0.24	3.68	0.3	8	0.58	32.36	-1.3%
Eaves	2'	10.89	8.7	0.24	3.68	0.31	7.92	0.58	32.32	-1.4%
	3'	10.88	8.7	0.24	3.68	0.3	7.71	0.58	32.09	-2.1%
Lights	100% LED	10.89	8.7	0.24	3.34	0.31	8.34	0.58	32.40	-1.2%
Cooling	36 kBtu/unit SEER 16.5	10.9	8.7	0.24	3.68	0.31	7.08	0.58	31.49	-4.0%
	12 kBtu/unit SEER 18	10.9	8.7	0.24	3.68	0.35	6.98	0.58	31.43	-4.1%
	36 kBtu/unit SEER 20	10.9	8.7	0.24	3.68	0.31	5.81	0.58	30.22	-7.8%
Natural ventilation	50% openable window 100% open 0.0115 Max outdoor air humidity	10.59	8.7	0.24	3.68	0.3	8.14	0.58	32.23	-1.7%
	50% openable window 100% open 1.0 Max outdoor air humidity	10.07	8.7	0.24	3.68	0.26	8.05	0.58	31.58	-3.7%
Ceiling Fans	5 Premium fans 50% efficiency	9.18	8.7	0.24	3.68	0.31	8.17	0.58	30.86	-5.9%
	50% coverage 2 fans, occ sensor +4°F setpoint	8.09	8.7	0.24	3.68	0.21	4.94	0.58	26.44	-19.4%
	100% coverage 5 fans, occ sensor +4°F setpoint	8.48	8.7	0.24	3.68	0.22	4.98	0.58	26.88	-18.0%
Appliances	Combined energy efficient appliances	10.88	5.68	0.24	3.68	0.31	8.16	0.55	29.50	-10.0%
Recommended	Combined strategies	7.99	5.68	0.24	3.34	0.08	1.4	0.57	19.3	-41.1%

Table C.3 Site energy (MMBtu) for all simulations for House 2, the naturally ventilated house. Many options were tried that were investigated for thermal comfort improvements and they did not affect energy use.

Components	Options	Misc.	Large Appliances	Vent Fan	Lights	Hot Water	Sum	Change from IECC 2015
IECC 2015	House #2 IECC 2015 Tropical Zone minimally compliant	7.14	6.91	0.06	1.82	0.75	16.7	0.0%
Wood wall insulation h-ft ² °F/Btu	Fiberglass batt R-7	7.14	6.91	0.06	1.82	0.75	16.7	0.0%
	Fiberglass batt R-13	7.14	6.91	0.06	1.82	0.75	16.7	0.0%
Wood wall insulation h-ft ² °F/Btu	Fiberglass batt R-19	7.14	6.91	0.06	1.82	0.75	16.7	0.0%
Wall Sheathing	R-5 XPS	7.14	6.91	0.06	1.82	0.75	16.7	0.0%
	R-10 XPS	7.14	6.91	0.06	1.82	0.75	16.7	0.0%
	OSB, R-5 XPS	7.14	6.91	0.06	1.82	0.75	16.7	0.0%
	OSB, R-10 XPS	7.14	6.91	0.06	1.82	0.75	16.7	0.0%
Ext. finish	Alum, Light	7.11	6.91	0.06	1.82	0.75	16.7	0.0%
	Fiber-cement, light color absorptivity = 0.3	7.11	6.91	0.06	1.82	0.75	16.7	0.0%
	Vinyl, light color absorptivity = 0.3	7.11	6.91	0.06	1.82	0.75	16.7	0.0%
Ceiling insulation	Roof, R-30, Unvented	7.13	6.91	0.06	1.82	0.74	16.7	0.0%
	Ceiling, R-19, Vented	7.13	6.91	0.06	1.82	0.74	16.7	0.0%
Attic insulation	Fiberglass batt R-19 at ceiling, vented	7.13	6.91	0.06	1.82	0.74	16.7	0.0%
Rad. barrier	Double sided	7.14	6.91	0.06	1.82	0.75	16.7	0.0%
Eaves	2 ft	7.14	6.91	0.06	1.82	0.74	16.7	0.0%
Window area as % of finished floor area	House 2 Windows (15.7%)	7.14	6.91	0.06	1.82	0.75	16.7	0.0%
	House 2 + Door (17.6%)	7.14	6.91	0.06	1.82	0.75	16.7	0.0%
Window U-value Btu/h-ft ²	0.63	7.14	6.91	0.06	1.82	0.75	16.7	0.0%
	0.37	7.12	6.91	0.06	1.82	0.75	16.7	0.0%
Window type	Low E, 2, Non-M, Arg	7.14	6.91	0.06	1.82	0.75	16.7	0.0%
	Low E, 2, Ins, Air	7.14	6.91	0.06	1.82	0.75	16.7	0.0%
Window schedule	Windows closed 9 am-5pm	7.18	6.91	0.06	1.82	0.75	16.7	0.0%
Int. Shading	S = 0.7, W = 0.7	7.18	6.91	0.06	1.82	0.75	16.7	0.0%
	S = 0.3, W = 0.3	7.18	6.91	0.06	1.82	0.75	16.7	0.0%
Ceiling Fans	3 Premium fans with occupancy sensors	6.12	6.91	0.06	1.82	0.75	15.7	-6.2%
Water heater	Electric, tankless	7.12	6.91	0.06	1.82	4.84	20.8	+24.3%
	Solar hot water with premium electric backup	7.13	6.91	0.06	1.82	0.58	16.5	-1.2%
Hot water distribution	Trunk & branch, R-5 timer	7.13	6.91	0.06	1.82	1.20	17.1	+2.5%
Lighting	100% LED	7.14	6.91	0.06	1.75	0.75	16.61	-0.5%
Appliances	Combined energy efficient appliances	7.13	4.40	0.06	1.82	0.72	14.1	-15.4%
Recommended	Combined strategies	6.10	4.40	0.06	1.75	0.46	12.8	-23.5%