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Evaluation of Model Results and Measured Performance of Net-Zero Energy Homes in Hawaii

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Evaluation of Model Results and Measured Performance of Net-Zero Energy Homes in Hawaii

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ABSTRACT

The Kaupuni community consists of 19 affordable net-zero energy homes that were built within the Waianae Valley of Oahu, Hawaii in 2011. The project was developed for the native Hawaiian community led by the Department of Hawaiian Homelands. With high electricity prices in Hawaii, integrating energy efficiency and renewable energy to the design are critical to minimize energy cost. The energy features included in these all-electric homes were chosen using hourly energy modeling with building energy optimization (BEopt) software by the National Renewable Energy Laboratory (NREL). An optimization algorithm was applied to find the combinations of energy efficiency and renewable energy measures to achieve net-zero energy performance at least cost.

The community includes a mix of one-story and two-story homes ranging from 1,306 to 1,616 square feet and is located in a relatively hot region of Oahu with low winds. Each home is equipped with high-efficiency windows, architectural shading, well-insulated walls and roof, light-colored roofing, SEER-16 air conditioning, solar water heating, high-efficiency appliances and lighting, and a 6.37 kW photovoltaic system. Whole-house electricity consumption and indoor temperature has been monitored for all homes since their construction.

This paper presents a comparison of the modeled and measured energy performance of the homes. Over the first year of occupancy, the community as a whole performed within 1% of the net-zero energy goals. The data show a range of performance from house to house with the majority of the homes consistently near or exceeding net-zero, while a few fall short of the predicted net-zero energy performance. The impact of building floor plan, weather, and cooling set point on this comparison is discussed. The project demonstrates the value of using building energy simulations as a tool to assist the project to achieve energy performance goals. Lessons learned from the energy performance monitoring have had immediate benefits in providing feedback to the homeowners, and will be used to influence future energy efficient designs in Hawaii and other tropical climates.

INTRODUCTION

Located in the Waianae Valley on the southwest side of the island of Oahu, the Kaupuni community consists of 19 all-electric 1-story (1,306 ft^2, 3 BR) and 2-story (1,616 ft^2, 4 BR) affordable homes. With high electricity prices in Hawaii (Oahu residential electricity rates averaged \$0.35/kWh over the period of this study), integrating energy efficiency and renewable energy to the design are critical to minimize energy cost. The goal of net-zero energy performance was chosen in early design charrettes for this project. During these charrettes, the decision was also made to include air conditioning for the homes. Although many homes on Oahu are naturally ventilated with no space conditioning system, the Waianae valley is on the leeward side of the Waianae mountain range and has little access to the trade winds available in many other parts of the island. For example, the annual average wind speed in the Typical Meteorological Year (TMY) weather data for Honolulu is 4.8 m/s, but the average wind speed measured in the Waianae valley during the test period was only 1.6 m/s.

Recognizing that air conditioned homes would require larger, more costly photovoltaic (PV) system, the team decided to minimize cooling loads and design around a modest cooling set-point of 76° F.

By combining shading, high-performance windows, well-insulated walls and ceiling, light-colored roofing, solar water heating, a high-efficiency air conditioning system, and a rooftop PV system, these "net-zero energy" homes were designed to generate as much energy as they consume each year. The homes were completed and occupied in the spring of 2011 (HCEI 2010). Their energy performance was monitored from August 2011 to August 2012. This report summarizes the measured performance of the homes and compares these results to modeled performance. To protect the privacy of the homeowners, in this report each Kaupuni home is referred to by a randomly assigned house number. Each house number refers to the same home throughout the report, but it is not related in any way to the address or lot number of that home.

DESIGN RECOMMENDATIONS BASED ON ENERGY MODELING

With the designated goal of net-zero energy with a 76° F cooling set-point and a preliminary architectural design completed, energy models of the homes were created using BEopt building energy optimization software, version 0.9. BEopt was developed by the National Renewable Energy Laboratory with support from the U.S. Department of Energy and is available free of charge (Christensen, et.al, 2006). BEopt used the DOE2 and TRNSYS simulation engines to model the energy performance of a home in optimization, parametric, or design mode. The least-cost efficiency and solar option package needed to achieve the project goals were found by using BEopt in optimization mode. In optimization mode the user chooses a variety of possible energy-efficiency options, and BEopt finds the least-cost combination of options for each energy savings level up to net-zero energy. TMY2 weather data for Honolulu was used for the simulations. Although it is recognized that the weather in the Waianae valley can differ from Honolulu, TMY2 data for the Waianae valley was not readily available. To simulate the effect of occupant behavior on energy consumption, BEopt implemented the occupant assumptions published in the 2008 Building America Research Benchmark (Hendron, 2008). This benchmark uses available national data on occupant behavior to provide reasonable assumptions for typical occupants. As we shall see, actual occupant behavior varied substantially. The results of the optimization modeling for the 1-story model are shown in Figure 1.

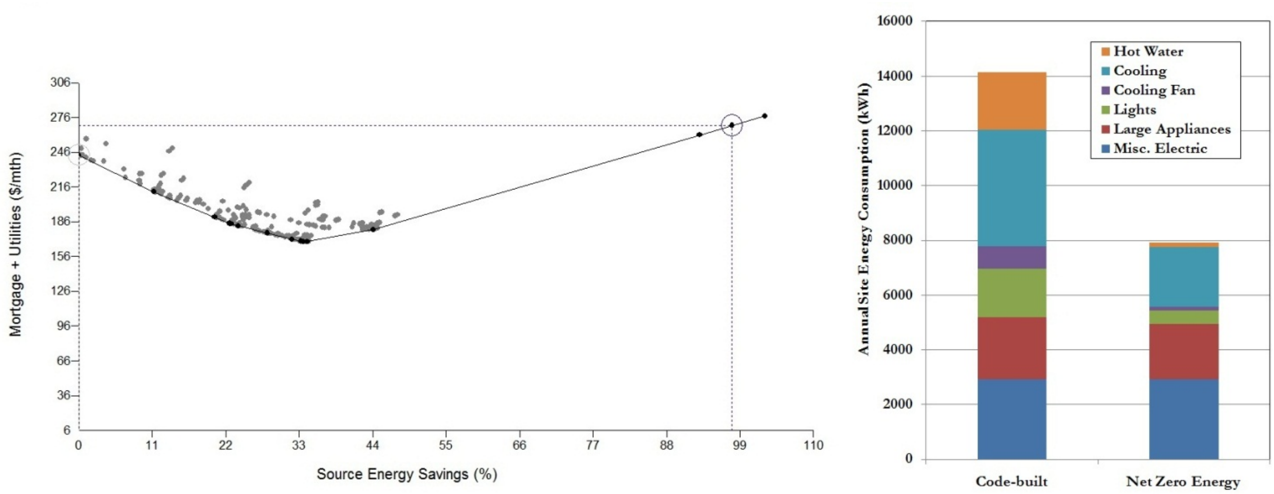

Figure 1 BEopt optimization results for the 1-story home model. On the left, each point represents a full year of hourly energy simulation for a unique package of efficiency and solar options. The points along the lower line are the least-cost option packages. The bar chart on the right shows the energy consumption comparison for the code-built (Hawaiianized IECC 2006) and net-zero energy homes.

Based on the BEopt results, a list of recommended energy features was provided to Group 70, the architectural firm for the project. For simplicity, a single set of recommendations for both the singe-story and 2-story homes was provided.

Most of these features were implemented in the actual homes. A few were left out or modified based on concerns with cost or ease of building integration. A list of the recommended and as-built features is presented in Table 1.

Table 1. Recommended and As-Built Home Energy Features

Energy Feature	Recommended	As-Built
Roofing	Light-colored asphalt singles	As recommended
Attic insulation	R30 at the ceiling plane	As recommended
Lighting	100% CFL	As recommended
Air conditioning	SEER 18 ductless mini-splits	SEER 16 ducted central
Appliances	Energy Star™ appliances	As recommended
Wall insulation	R11 batts with 1" exterior foam	R11 open-cell spray foam
Water heating	Solar water heater with electric backup	As recommended
Window type	Low-e, low SHGC throughout	As recommended
PV system size	6.0 kW rated peak AC output	6.37 kW rated peak output

MEASURED HOME PERFORMANCE

The hourly total electricity consumption and PV production were measured by the Hawaii Electric Company (HECO) with support from the Electric Power Research Institute (EPRI). An internet-connected whole-house meter capable of measuring hourly average total electricity consumption and total PV production was installed in each home. Data was collected from at least August 18, 2011 through August 14, 2012. In addition, the temperature and relative humidity next to the thermostat was measured by NREL on an hourly basis using stand-alone battery-operated loggers. The ratio of the total PV production to total consumption for each home is shown in Figure 2.

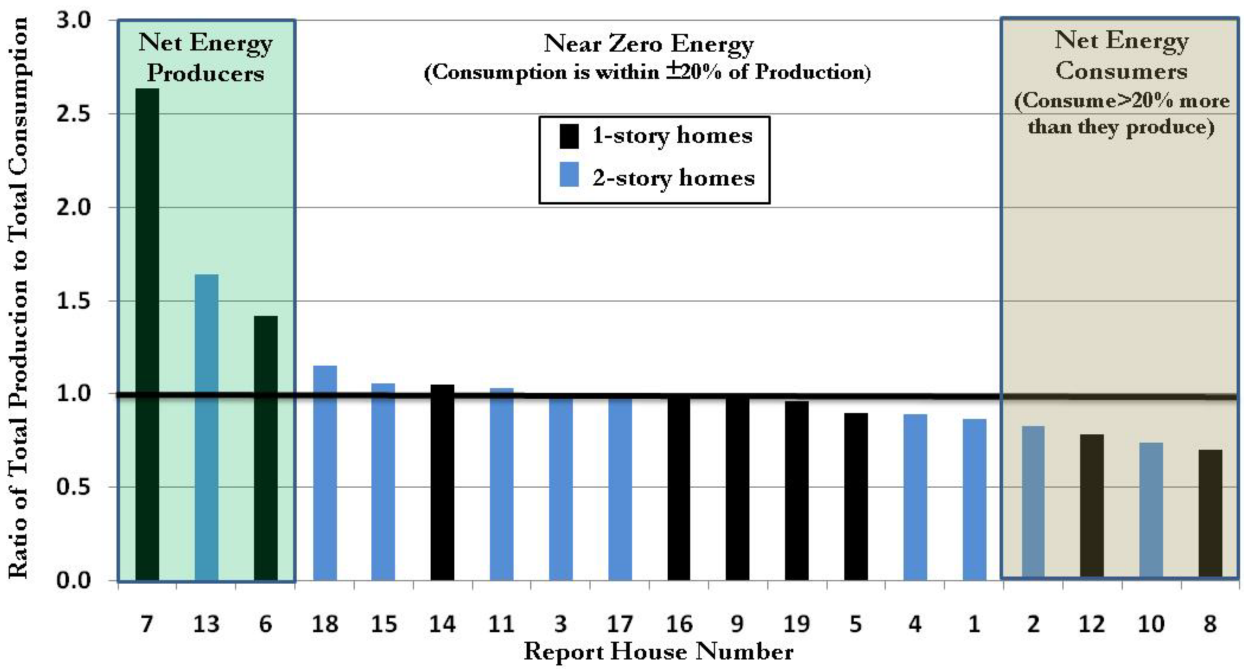

Figure 2 Annual net energy performance of each home (1.0 = exactly net zero energy).

Overall, the community came within 1% of the net-zero energy target. The total PV production for all 19 homes was equal to 99% of the total consumption for the year of study. However, only six of the homes in the community were within

5% of the net-zero target individually – most were either net-energy producers or consumers. Most of the homes fell within 20% of the net-zero energy target. In the extreme, house 7 consumed so little that the PV production was more than 2½ times the consumption.

All homes were equipped with the same 6.37 kW-rated PV system – somewhat larger than the 6.0 kW system recommended based on modeling. The installed PV panels are slightly larger than those used for the roof design, forcing three homes to have several panels facing north. In addition, the layout of the development required the home design to be rotated 90 degrees on seven lots. The roof pitch is low (~18 degrees), so the reduction in PV output for these off-south PV panels is reasonably small. The average daily PV production over the year of study for each home is shown in Figure 3. The average daily PV production varied from house-to-house by less than 10% – from a low of 26.9 kWh/day (capacity factor (CF)=17.6) to a high of 29.7 kWh/day (CF=19.4). Therefore, the large house-to-house variation in net energy is clearly mostly due to variations in consumption rather than variations in PV production.

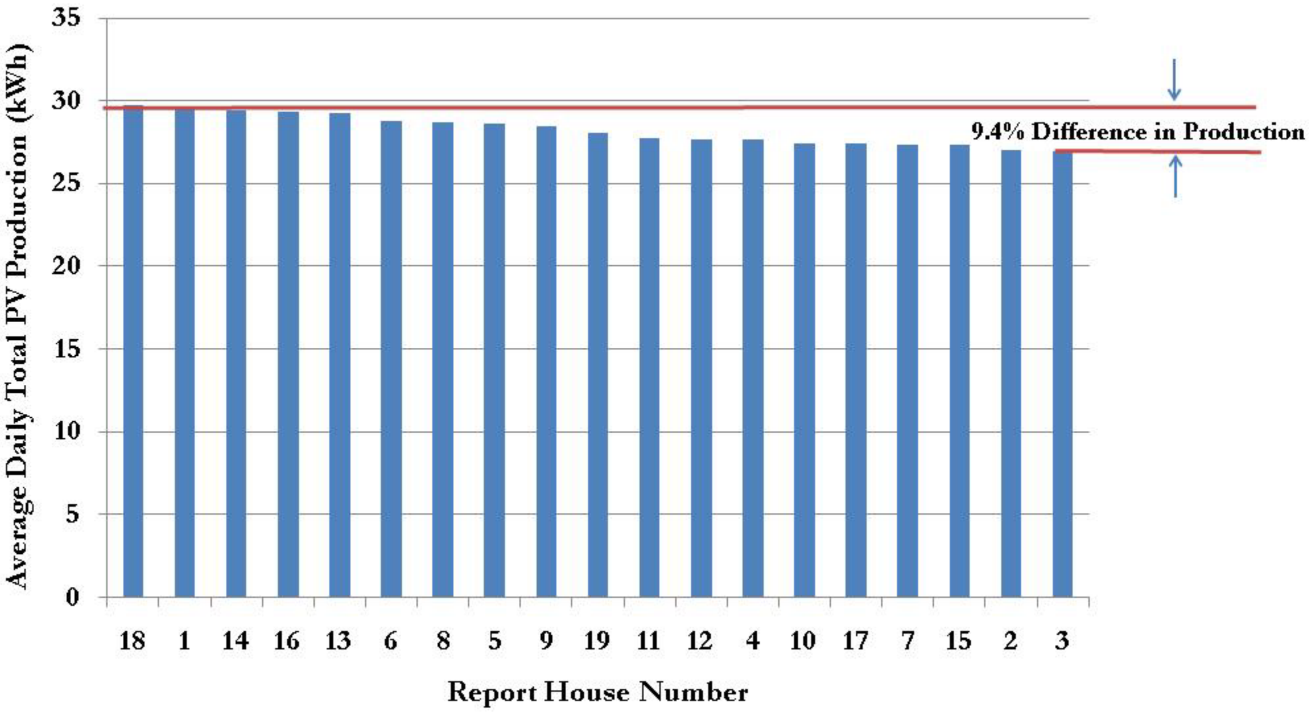

Figure 3 Daily average PV production from each home.

The average daily electricity consumption over the year of study for each house is shown in Figure 4. The house-to-house consumption varied by nearly a factor of four. The coefficient of variance (the standard deviation divided by the mean) for the community is 25%. This variation may seem higher than expected in a community of homes built at the same time with the same energy efficiency features, but similar variation has been seen is several other new home projects (Aldrich 2012, Osser and Kerrigan 2012, Norton, et.al. 2008, BIRA 2007, BSC 2000). It is interesting to note that any consumption differences between smaller one-story and larger two-story home are lost in the variation due to different numbers and behavior of occupants. The difference in net-energy performance seen in Figure 2 is nearly completely due to the difference in consumption patterns of different occupants.

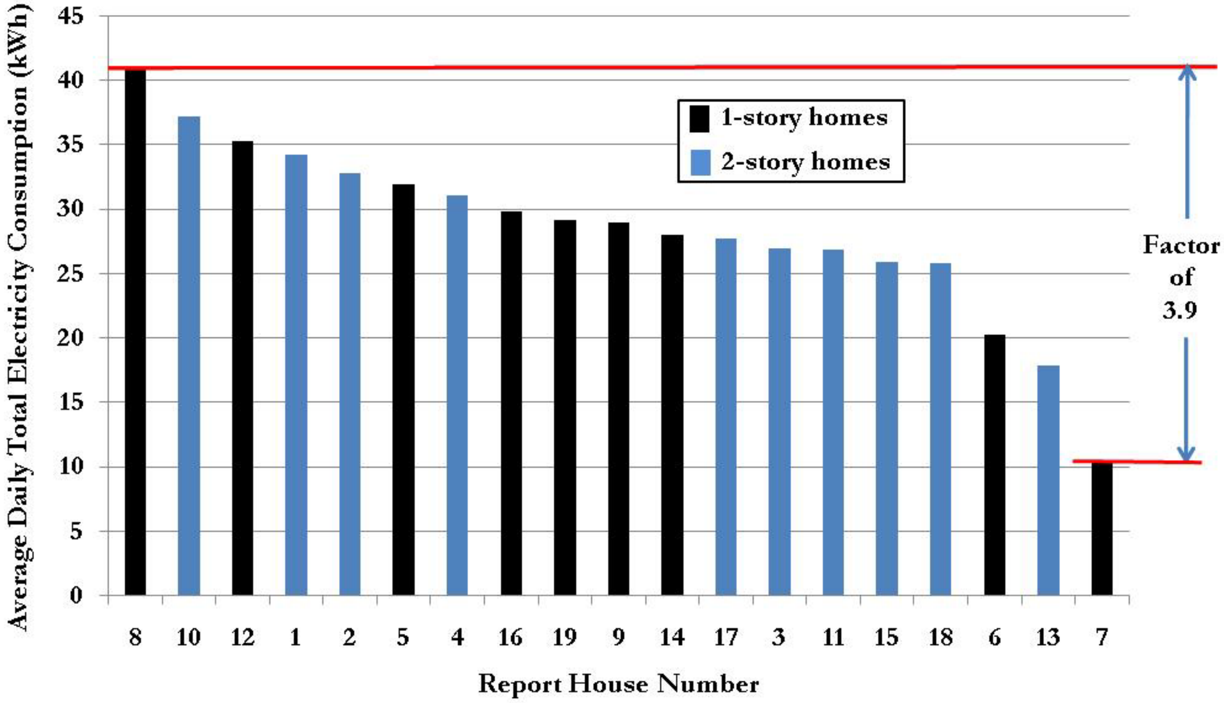

Figure 4 Average daily total electricity consumption from each house.

Lessons learned from the energy performance monitoring has had immediate benefits in providing feedback to the homeowners, and will be used to influence future energy-efficient designs in Hawaii and other tropical climates. The performance data from these homes will be presented in more detail in an upcoming NREL technical report, which will be available through the NREL publications website (http://www.nrel.gov/publications).

MODELING THE HOMES AS BUILT

To make a fair comparison between modeled and measured results for this paper, the home models created for design assistance were refined to more closely reflect the homes as they were actually built and operated. The geometry, window areas, cooling equipment, insulation, and PV sizing were modified to represent finished homes. The cooling set point was modified to reflect the actual measured average indoor temperature of 23.8° C (74.8° F) – somewhat lower than the 24.4° C (76° F) assumed for the design recommendations. Other than the cooling set point, standard occupant assumptions were used in all models. A summary of these additional modeling runs is given in Table 2.

Table 2. Additional modeling done to better represent the homes as they were actually built

Model #	Weather Data	Cooling Set Point	BEopt Version	Simulation Engine(s)
1	Honolulu TMY3	24.4 C (76 F)	BEopt 0.9.04 Beta	DOE2.2-47g, TRNSYS
2	Honolulu TMY3	23.8 C (74.8 F)	BEopt 0.9.04 Beta	DOE2.2-47g, TRNSYS
3	Waianae actual	23.8 C (74.8 F)	BEopt 0.9.04 Beta	DOE2.2-47g, TRNSYS
4	Waianae actual	23.8 C (74.8 F)	BEopt 1.3	DOE2.2-47g, TRNSYS

The Honolulu weather file was modified with weather data for the actual test period in the Waianae Valley. In addition, the as-built models were recreated in an improved version of BEopt that incorporates an updated set of occupant assumptions – The Building America House Simulation Protocols (Hendron and Engebrecht 2010).

The Waianae Intermediate School is about 1 km (0.6 mi) from the Kaupuni community and has a weather station with publically accessible data (HECO 2012). Waianae data for dry bulb temperature, wind speed, and solar radiation during the study period was used to replace those values in the Honolulu TMY3 data to create the "Waianae actual" weather file. The solar radiation data required for the TMY3 files was calculated from the radiation on the plane of the PV modules at the school. The cooling degree days for the Waianae weather file (2,566, base 18° C) were remarkably similar to the Honolulu TMY3 weather file (2,524, base 18° C). The daily average horizontal global radiation was also similar between the two files (Waianae: 5,551 Wh/m^2; Honolulu TMY3: 5,346 Wh/m^2). The big difference between the weather files is the annual average wind speed (Waianae: 1.6 m/s; Honolulu TMY3: 4.8 m/s). The modification of the Honolulu TMY3 file was intended to include available microclimate data but does not represent the complete actual weather. The replacement of the Honolulu TMY3 weather with the measured Waianae data had only a small effect on the predicted annual consumption and PV production of the homes.

The predicted annual consumption for each of the refined models is shown along with the actual house-by-house consumption in Figure 5.

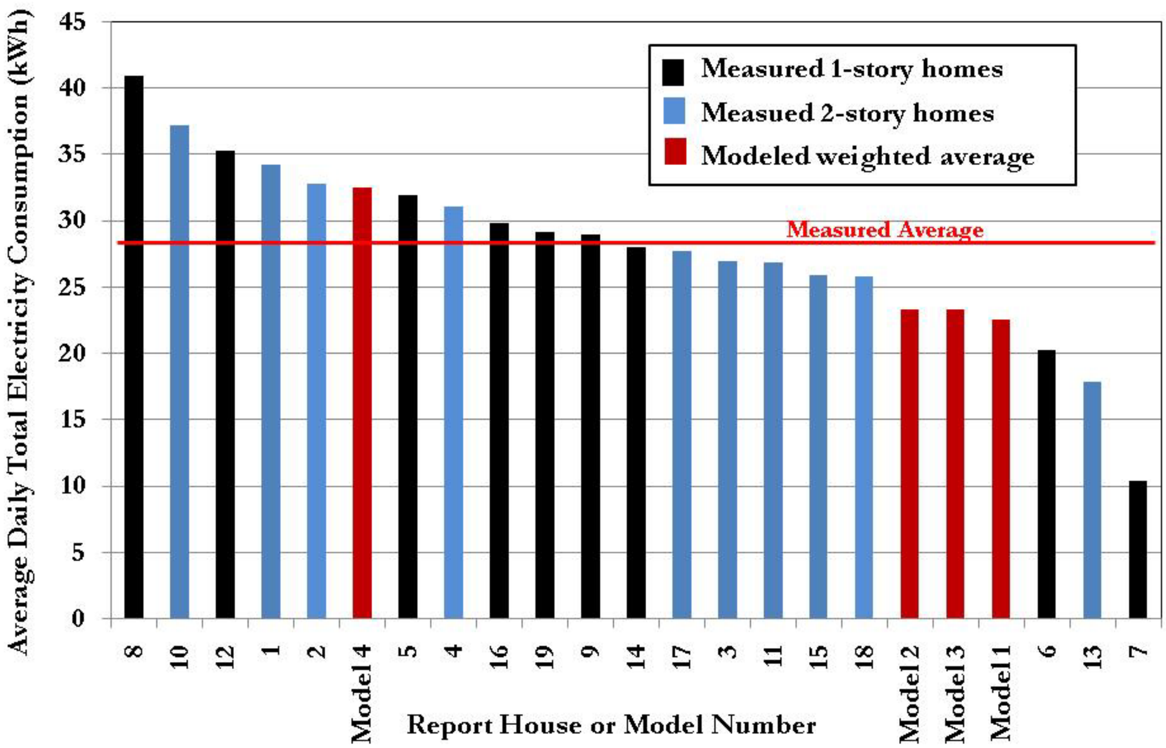

Figure 5 Measured and modeled daily total electricity consumption

All modeled consumption results are within the home-to-home range of measured consumption. Although the change in cooling set point and weather data had some effect on predicted consumption, all BEopt 0.9 models predicted annual consumption below the measured average by about 19%. In contrast, Model 4 recreated in BEopt 1.3 predicted consumption above the measured average by about 14%. Most of the difference in predicted energy use between the earlier and current versions of BEopt lies in the simulated cooling and air handler energy use.

The average daily PV production predicted was 24.4 kWh (CF=16.2) for Model 3 and 25.3 kWh (CF=16.8) for Model 4. These predictions are both shy of the measured average of 28.2 kWh/day (CF=18.7). Although the BEopt options library includes many specific PV modules, the modules used in Kaupuni were not available and a generic c-si type module model was used. The models also include a derate factor of 15% when predicting PV output. This derate factor includes effects such as losses due to the inverter efficiency, wiring, diodes, connections, and soiling (PVWatts 2012). The actual derate factor may be different than the modeling assumption. The module type and default derate factors may account for the models' under-prediction of PV output. The most refined and up-to-date simulations (Model 4) with the 15% default derate predict that the community would fall short of the net-zero energy goal by over 20%.

DISCUSSION

The use of modeling to provide design guidance for the Kaupuni project proved very effective. The community of homes built incorporating this guidance came within 1% of the net-zero energy goal. However, any single home may deviate significantly from the expectations based on simulations. The variation in behavior and choices of different occupants has a profound effect on energy use in residential buildings. Because of this, comparison of modeled results to a *single* occupied home may be a futile exercise. It is hard to imagine capturing all of the inputs needed to characterize the quirks of actual occupant behavior to an acceptable level of accuracy. For every simulation generated in this study there were homes in the community that matched the simulated consumption fairly well and others that differed dramatically. For example, if this project had been only one occupied home – house 2, then one might have lauded the accuracy of Model 4 that predicted the consumption with less than 1% error. In contrast, if the only occupied home in the study had been house 7, one might have thought there was some egregious error in Model 4 causing it to miss the actual consumption by more than a factor of three. This level of mismatch between a model using standard occupant assumptions or even one with some assumptions (like cooling set point) tuned to the actual occupants should not be surprising considering the range of energy use variation seen in communities of identical homes. Comparing modeled to average measured energy performance in a large sample of occupied homes may provide a more meaningful assessment of modeling accuracy.

There are many possible explanations for the difference between the modeled and measured community average consumption at Kaupuni. The difference between the actual and TMY data does not seem to be a significant contributor to the difference between modeled and measured use in this project. The sample size for the Kaupuni study was fairly small – 19 homes. This sample size may not be large enough to represent typical behavior, so the actual energy use is a function of the individuals who happened to purchase homes in the community. In addition, the occupant behavior in the unique climate and culture of Oahu may vary substantially from the national data upon which the modeling inputs were based. The BEopt program provides a pick list of energy-efficiency measures – in some cases, the exact measure implemented was not available and the closest option was chosen. For example, the configuration of solar water heating systems used in Hawaii does not exactly match any of the options available in BEopt. BEopt also provides a geometry tool to quickly create the home geometry. The exact roof geometry and window sizes could not be reproduced with the BEopt geometry tool. As mentioned earlier, some homes were built with differing orientations. The observed difference in modeled and measured average consumption is likely to be the net effect of many factors but is not large enough to reduce the usefulness of the model for guiding design decisions.

Understanding modeling accuracy requires a careful consideration of possible sources of errors and the development of methodologies to disaggregate these potential sources (Polly 2011, Polly, et. al. 2011, Roberts, et. al. 2012, Judkoff and Neymark 2006). It may be necessary divide and conquer – studying algorithm accuracy in laboratory studies and unoccupied instrumented homes and studying occupant input assumption accuracy statically in large samples of occupied homes. It is clear from this study that occupant behavior and choices can have as large an effect on the energy consumption as the energy efficiency measures incorporated in the home. As we build more efficient homes, the relative importance of occupant behavior is likely to increase. Although sensitivity of water heating and space conditioning to use and set points may be reduced with more efficient enclosures and equipment, the relative contribution of highly variable appliance and miscellaneous electric loads to total energy use increases substantially. This argues for a greater investment in understanding the variety of occupant behavior and developing more sophisticated ways to incorporate their effects on energy consumption. Despite the differences between modeled results and measured performance, it is important to emphasize that the overall result has been that the community as a whole is performing near net zero during the first year of occupancy.

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