

# **Simulation versus Reality: *Comparing a small residential building's performance simulation to its Post-Occupancy-monitored operational performance***

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## **Abstract**

Between spring 2019 and fall 2020, a team of 10 architectural students developed, designed, and built a 70 m<sup>2</sup> Accessory Dwelling Unit named the Kunga ADU. The project was designed for a wheelchair-bound former Tibetan refugee mother of a larger family. Supported by faculty, community partners, and the author as the Design+Build program founder and director, the project's goals included aspects of social justice, accessibility, and high-performance design at affordable cost, the latter to be proven through methods of Post-Occupancy Monitoring. During the project's design phase, iterative energy simulations and explorations on a physical model led to a simulated performance increase of 44% above the baseline code standard building for the location, achieved through a 71% reduction of the building's heating load, and a 40% reduction in required cooling demand. Given the opportunity to install a modular, custom-designed Post-Occupancy Monitoring for the electric-only project, this paper investigates the differences between the simulated energy-performance results versus the actual, 26-month Post-Occupancy monitored operational energy consumption of the building, to answer the question of how reliable the specific energy performance simulation was compared to the building's actual energy performance during occupancy.

Keywords: Design+Build process, Building Simulation, Post-Occupancy Monitoring, Resilient Building Design, Affordable High-Performance housing, Envelope Component Performance

## **1. Introduction**

The Kunga ADU was the inaugural project of a newly created, academic-led Design+Build Salt Lake (D+BSL) program at the School of Architecture, University of Utah, where students design, develop, and construct affordable, 40-50% above code-standard performing small residential buildings within given budgets. Within the program, students are given opportunities for leadership roles throughout all design, permitting, and construction phases [1]. The program is part of the School's graduate curriculum and teaches participating students in an immersive process about design, simulation, administration, permitting procedure, and the physical construction of a building, focusing on the building design, construction, and administration, and engaging students "into the realities and exigencies of the construction industry," which "encourages a more lateral relationship between ideas on paper and nuts and bolts on-site" [2]. Simultaneously, the program offers opportunities for interdisciplinary applied research in the field of resilient building design, components, and system performance. It furthermore contributes to the communities we live and work in by creating affordable case-study homes for low-income clientele in underserved areas within the region, thus engaging students in community service and creative projects to promote cultural diversity and sustainability.

Within the D+BSL studio setting, learning objectives include a practical-oriented architectural education. This exposes students to all players in a real-world small-scale project and involves them in every step of project development from the first sketch to the final building occupancy, with the goal that participants understand and experience the immediate impact of their architectural activities on the built environment and the actual building. The main studio outcome is the successful design, permitting, construction, and documentation of a small-scale residential project. Additional student involvement opportunities are given through the project's Post-Occupancy research, data analysis, and documentation through papers and conference presentations.

## 2. Design Process

As described in more detail in a previous paper, the holistic Kunga ADU design process required students to apply processes of complex thinking and a collaborative and interdisciplinary group approach where the sum of all efforts was more important than everyone's individual outcome, which presented a welcome divergence from the individual studio project work mostly found in the regular academic architectural studio setting. The cluster of several design+build classes included a combination of iterative design and research, and precedent and fabrication assignments of increasing complexity. The holistic and interdisciplinary design process integrated the client, engineers, and other professionals from the early beginning and allowed that at all project phases a cross-section of students and faculty would engage with the supportive entities in a meaningful way [3]. Different from a purely hypothetical studio project, a design+build project needs to fulfill extracurricular guidelines and constraints, including code requirements and schedules outside academia that are set by the supporting engineers or the jurisdiction. At the time of designing the Kunga ADU, Salt Lake City's Planning and Building department had just begun to allow the design of ADUs within its city limits; the project being only the second-ever permitted ADU at that time resulted in a lot of uncertainty among the building officials about the application of specific codes. Another challenge was the long permitting times that the project required: the initially necessary Low-Impact permit took roughly 3 months and created the base for the further design process during the summer of 2019; the subsequent building permit took another 3 months, even though the project was only 70 m<sup>2</sup> in size. With the timeline not controllable by the design team, the group decided to take the risk of prefabricating the entire building in wall and roof panels and components on the School's shop yard and in parallel to the permitting process, hoping no bigger changes would be required by the time the permit was finally granted in mid-November 2019. Once the permit was obtained, the entire structure was disassembled and moved to the actual site within three days, where demolition, footing, and foundation work had already been prepared in parallel.



*Figure 1: The Kunga ADU in Salt Lake City, Utah*

The building's actual design process was embedded in between the two permitting phases and took roughly eight weeks. Design drivers were client needs and programming, but also site and code constraints and requirements, which left only a small portion on the parcel to place the building in the back of the property. Further key aspects included accessibility, visual connection to the main house, a strong focus on the building's south-facing orientation, and appropriate daylighting studies to enhance passive solar heat gain and glare control as well as allowing the vigilant placement of all windows. Other determinants included building cost,

component, and system research, iterative Sefaira energy simulations for five different envelope and system scenarios, and a passive-to-active design approach emphasized by the author [4]. The applied method of choice that led to better building energy performance comprised of a site and program-driven design as close to the Passive House (PH) Standard as the budget would allow. This included strategies of passive solar heating in a heating-dominated winter climate, integrated fixed shading devices to protect the building from direct solar radiation during the hot summer months in the arid semi-desert environment of Salt Lake City, increased envelope component performance, thermal-bridge-free construction, a Passive House Standard air infiltration rate of 0.6 ACH50, and the installation of a whole-house Heat Recovery Ventilation system HRV. The flat property allowed for a fully insulated and thermal-bridge-free shallow slab foundation that could be easily constructed by the student team [5, 6]. An HVAC Active Building Compact Core ABCC designed by the author and assembled by the student team was optimized for the building's predicted energy and component performance.

The Kunga ADU project constitutes the fourth project for which the author applied a Post-Occupancy Monitoring mechanism. Having realized discrepancies between the simulated and therefore predicted energy consumption of these high-performance residential buildings and their actual Post-Occupancy performance in the past, the design and construction team of the Kunga ADU was given the opportunity to develop and install an updated, easily scalable Post-Occupancy Monitoring system as part of the research that accompanied the design+build and Post-Occupancy phase of the overall Kunga ADU project scope. The new system was integrated into the ABCC, which allows setting the originally simulated performance results in direct correlation to the actual building performance data under occupancy.

### **3. Simulation Tools and Methods**

For simplicity of use and software availability in the academic setting of the project, the team utilized Sefaira Energy and Daylighting simulation software that was plugged into the SketchUp 3D model developed during the design process. Additional tools included the online U-value, moisture control, and heat protection calculator Ubakus [7] as well as the Passive House Planning Package PHPP spreadsheet version 8.5 [8]. Throughout the design process, the project went through five performance and simulation iterations, during which research and quantitative optimization methods were applied to optimize envelope components for their best possible performance at given budget and spatial constraints. As a baseline, details from the publication "Passive House Details" [5, 6] and construction details from the Field of Dreams Eco-Community [9] were analyzed and categorized for feasibility by the students, to be then calculated and simulated in Sefaira, PHPP, and Ubakus software to identify envelope component performance values in the subsequent step. Before further proceeding, each step was then discussed and agreed on within the entire team and in direct feedback with the clients.

The Passive House performance standard was used as a general guideline and complemented by the inclusion of an optimized HVAC core as the project's active component, even though it was clear from the onset that the small project would not fulfill the stringent standard due to the many project constraints. Only the combination of the two standards – Passive to Active - allowed the team to reach optimized results by cautiously gauging the requirements of both systems against each other and fulfilling the aspired comfort and performance goals at the given budget and the project's limited space, where thicker exterior walls would have taken away from the available interior net area at the given maximum building footprint. The project's cubical appearance was also derived from a surface area to volume (A/V) ratio optimization process, during which the team experienced the challenges of optimizing a very small building's A/V and form factor, as described in Lewis "PHPP Illustrated" [10]. Based on the building's external surface area of 264 m<sup>2</sup> and internal conditioned Treated Floor Area TFA of 70 m<sup>2</sup>, the result was an A/V value of 3.88, which is below an optimal PH performance value of 3.0 or lower. This suboptimal value is due to the existence of a generous, double-story air space above the living room in the house, which was a programmatic desire by the client and presents an architectural and daylighting gem in a spatially rather minimized building configuration. Furthermore, the air space is also necessary to reach the project's future caregiver gallery located above the main bedroom.

The simulation method applied to each performance and simulation iteration began with the determination of a specifically chosen component combination's U and R-value, using the Ubakus online calculator and PHPP's R-Value tab. Once optimized for its performance, durability, moisture behavior, and contribution to greenhouse

gases, those values were summarized in an Excel spreadsheet. In the next step, the original architectural 3D SketchUp model was optimized for energy and daylighting simulation, which included rebuilding the simple volume as a single-pane surface model and attaching component entities in the Sefaira plugin. Entities comprised of walls, roof, floor, operational and fixed glazing, and shading entities. Even though not necessary for energy simulation, the students also added interior walls to run daylighting studies in parallel. To start the initial benchmark process, the location and function of the building needed to be added, to allow the software to utilize the correct TMY 3 data, which were derived from Salt Lake International Airport for the ADU's location. Sefaira, in its simplified plug-in version, only allows for a preset fan coil unit and central plant as a residential building's HVAC system, which equals a standard forced air system. This preset can only be changed in the online version once the building has been optimized in the plug-in version and is being exported to the Sefaira online portal.

Defining all preliminary criteria enables Sefaira to automatically populate a building's code-standard model properties. For Utah, the baseline consisted of the ASHREA 90.1 – 2013 version for the time the building was designed in 2019, and once this first simulation is run, the software produces the building's designed-to-local-code performance baseline. The result was an Energy Use Intensity (EUI) of 34 kBTU/ft<sup>2</sup>/year, as shown in Figure 2 on the left-hand side, and based on a single-person occupancy of the small unit.

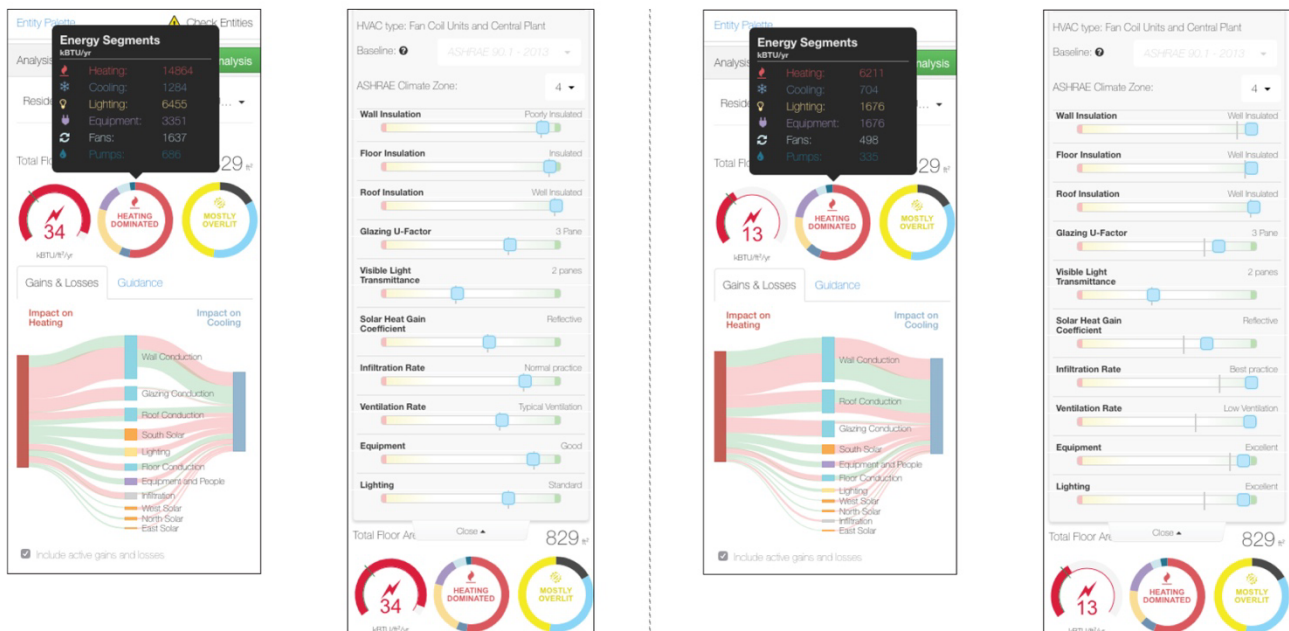


Figure 2: The Kunga ADU performance shown as code-standard baseline (left) and optimized (right)

In the next step, the software's model properties were changed to the chosen component's values, which included better R-values for walls, roofs, windows, floors, better equipment, lighting sources, and others. For each component version, the results were documented, to allow for a final comparison and therefore decision on component assembly and choice. To determine the actual component assembly and combination, additional aspects of buildability by an inexperienced student team, budget considerations, and spatial constraints played a role in combination with the best model performance. Based on all parameters, the team decided on a 2x6" standard framed wall system filled with 140 mm cellulose insulation, an additional 50mm rigid foam layer on the outside, a fully insulated concrete shallow-slab-on-grade floor that uses a frost skirt EPS foam insulation perimeter and a rigid 200 mm geofoam insulation to the ground, and a roof assembly that consists of an overall 435 mm insulation. The resulting performance values are depicted in Figure 3. The utilized windows had an imperial U-factor of 0.26 BTU/h\*ft<sup>2</sup>/yr.

Total Floor Area = 830.00 sq. ft.			Total Floor Area = 830.00 sq. ft.		
Wall	R-13	ft <sup>2</sup> *h*°F/BTU	Wall	R-29	ft <sup>2</sup> *h*°F/BTU
Slab/Floor	R-18	ft <sup>2</sup> *h*°F/BTU	Slab/Floor	R-30	ft <sup>2</sup> *h*°F/BTU
Roof	R-32	ft <sup>2</sup> *h*°F/BTU	Roof	R-49	ft <sup>2</sup> *h*°F/BTU
Glazing U-Factor	0.35	BTU/ft <sup>2</sup> *h*°F	Glazing U-Factor	0.26	BTU/ft <sup>2</sup> *h*°F
Visible Light Transmittance	0.42		Visible Light Transmittance	0.42	
SHGC	0.40	SHGC	SHGC	0.28	SHGC
Infiltration Rate	0.39	cfm/ft2	Infiltration Rate	0.06	cfm/ft2
Ventilation Rate	0.22	cfm/person	Ventilation Rate	2.75	cfm/person
Equipment	0.50	W/ft2	Equipment	0.25	W/ft2
Lighting	0.97	W/ft2	Lighting	0.25	W/ft2

Figure 3: Component performance values: Code-standard (left), as build (right)

The chosen version to be further investigated resulted in an Energy Use Intensity of 13 kBtu/ft<sup>2</sup>/year, which constitutes a roughly 60% better performance than the code standard version in the Sefaira plug-in software. Experiences with the software from the past though showed that these initial results are rather on the very optimistic side, which is the reason why, in the final simulation step, the already optimized building model is uploaded into Sefaira's more precise online version.

The online portal allows for considerably more precise component input, including numerical R-value input, different performance and solar heat gain coefficient data for each building orientation, manual HVAC system selection, and many more. It furthermore allows for a direct comparison of different cases by cloning a setup, allowing for changes, and directly documenting the differences in performance and energy consumption against the previous case(s) (Figure 4).

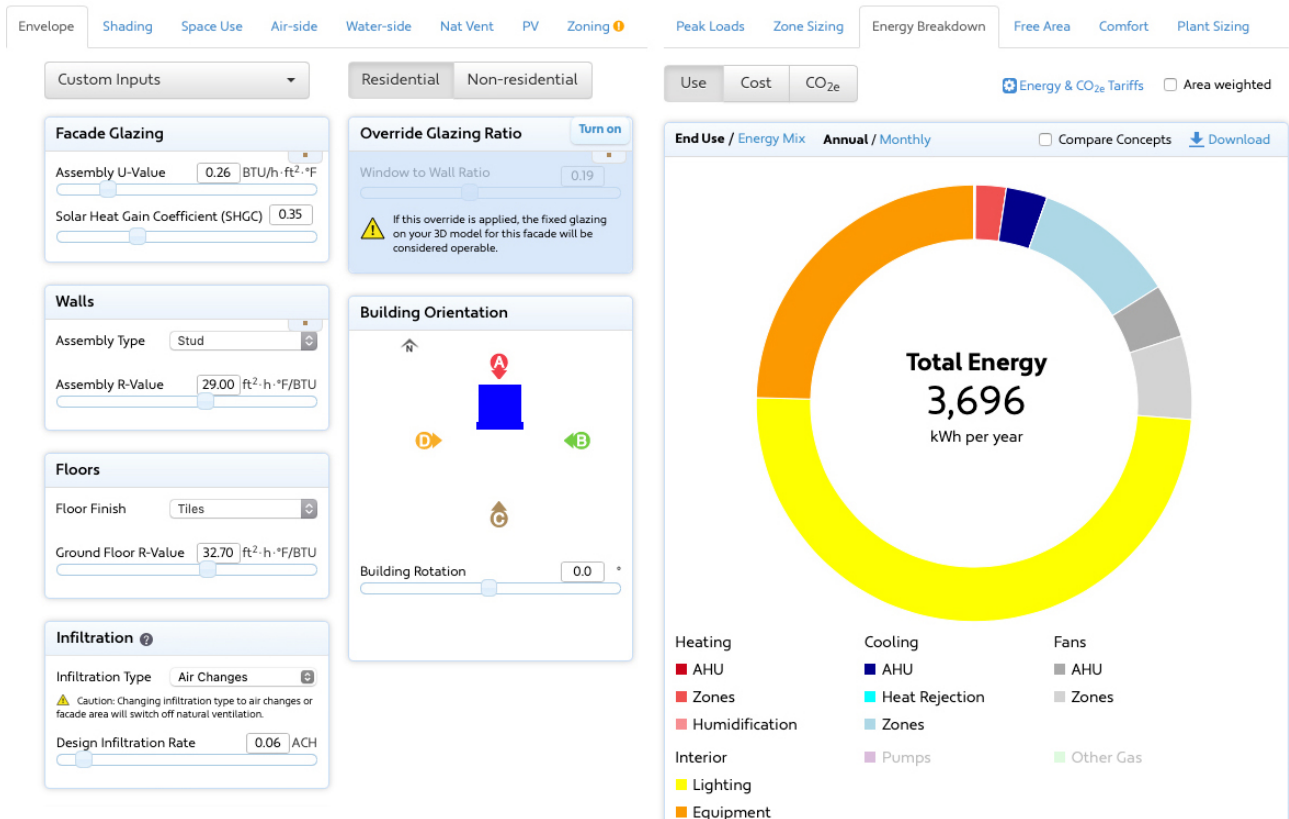


Figure 4: Optimized model in the Sefaira Online Software version

Further investigation and optimization of the Kunga ADU resulted in a predicted total energy consumption of 3,696 kWh per year, compared to a consumption of 8,811 kWh for the code baseline scenario. As for the project's Energy Use Intensity and as depicted by the software, this constitutes a 44% increase over the original baseline (Figure 5).



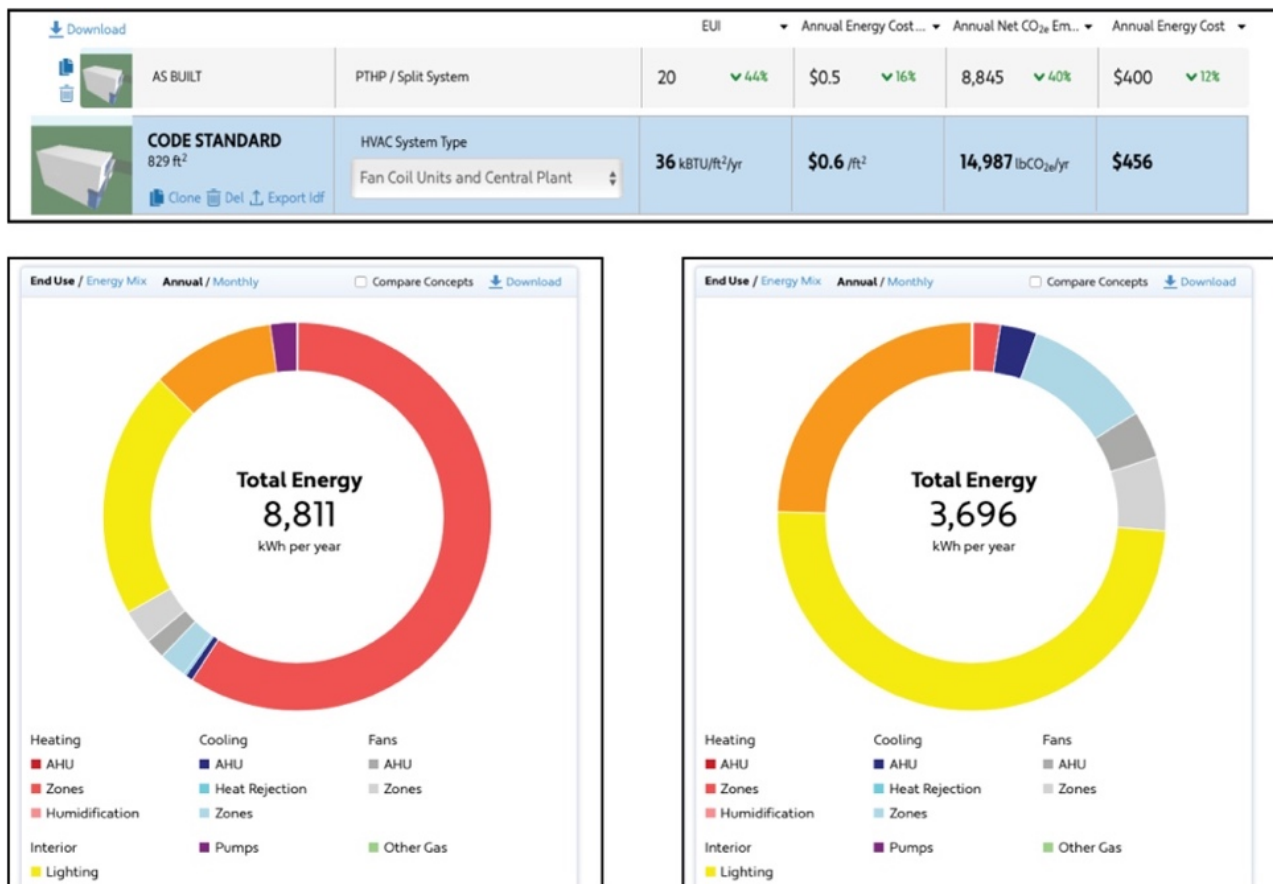


Figure 5: Sefaira energy Performance designed at local code standard (left) and as-designed (right)

#### 4. Monitoring Tools and Methods

Post-Occupancy Monitoring POM assesses a building's actual performance after occupancy. It usually includes systematic data collection for building performance, resource consumption, indoor environmental quality, or user satisfaction. As a tool, POM is critical to better understanding utilized design measures, applied building systems, and energy performance standards to give valuable feedback to architects, building owners and operators, engineers, and policymakers by identifying areas where a building does not perform as intended or does not meet occupants' needs. This allows for targeted improvements that can be made Post-Occupancy or can be considered in future projects, helping to improve our built environment and future building policies. Despite being a powerful tool, POM is not widely practiced in the US and EU, and where applied it usually lacks standardized protocols, which leads to difficulties to compare results across different studies [11]. This is one of the reasons why the Kunga ADU team developed its own modular POM system, consisting of scalable, modular off-the-shelf components that were assembled in conjunction with the building's ABCC. A feasible line of products was found at a manufacturer that provides all components necessary to monitor different scales of buildings of different functions, including the all-electric Kunga ADU to document its electricity and water consumption via an online portal that allows easy access to all data collected [12].

The monitoring system was tested and up and running on March 16, 2021, about 6 months after initial building occupancy. Even though POM is still ongoing, the period analyzed for this paper is limited to the time frame between March 16, 2021, to June 18, 2023, which constitutes about 27 months or exactly 824 days. For the data analysis, a simple spreadsheet was programmed, which automatically calculates the energy use for radiant heating and DHW, as well as the percentage of the energy of each consumer in relation to the whole-house electric energy consumption.

The following values were constantly monitored and recorded throughout the POM period: 1. 240-volt whole house electric energy consumption, tapped at the major incoming electric lines before the electric meter and

breaker box; 2. 240-volts on-demand Domestic Hot Water DHW and hydronic heating water consumption tapped at the electric on-demand hot water heater; 3. 240-volt Heat Recovery Consumption, tapped at the HRV; 4. Water consumption for: 4.1 Whole house cold water consumption, tapped at the main incoming water line; 4.2 hydronic heating water consumption, tapped at the ABCC core pump board; 4.3 DHW hot water consumption, tapped at the DHW water line between the on-demand hot water heater and the house's DHW consumer faucets; 5. 120-volt pump board electric consumption tapped at the incoming electric line to the ABCC pump board; 6. 240-volt Mini Split electric consumption for heating and cooling, tapped centrally at the outside compressor, which also feeds the mini split heads inside the building (Figure 6).

Because the on-demand hot water heater provides both hot water for DHW and the radiant heating pipes in the concrete floor, the different consumptions were identified by separately measuring the amount of hot water for the radiant heating system (4.2) and the DHW (4.3) and calculating the percentage through the spreadsheet formula.

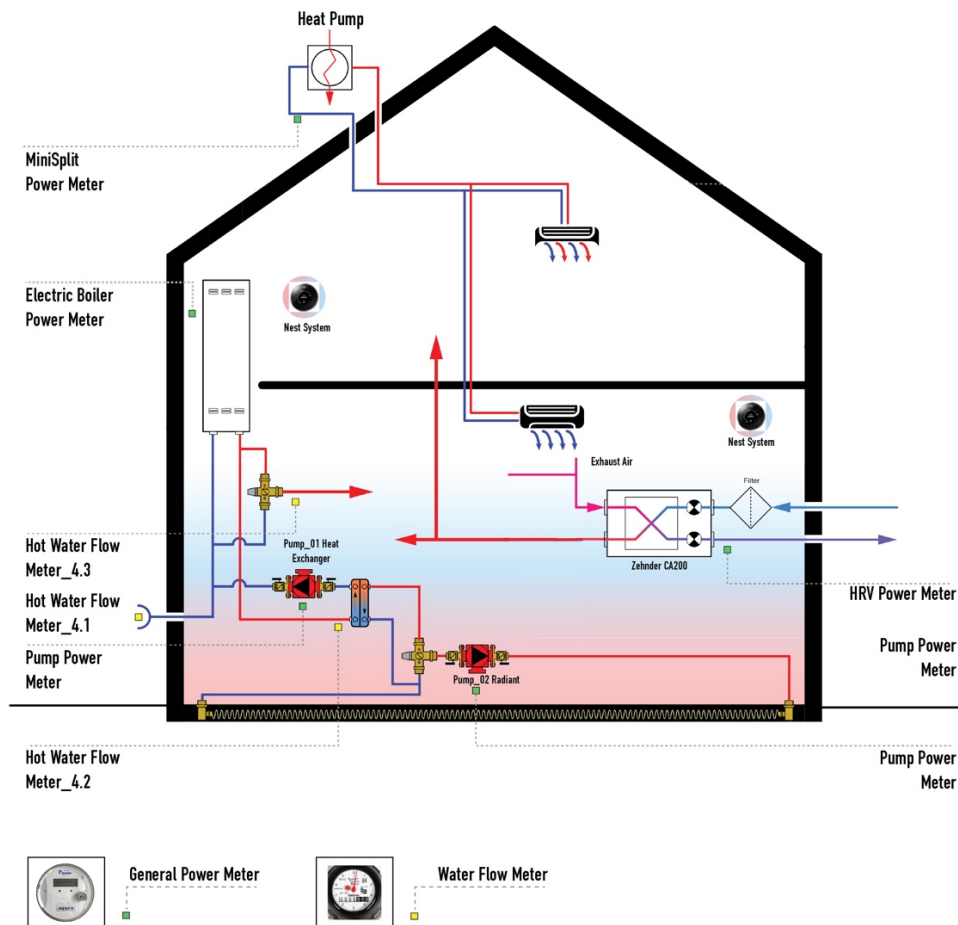


Figure 6: Data points and devices diagram

In the actual monitoring setup, an Omnimeter Pulse v.4 is the modular minicomputer that collects data depending on the attached metering device (Figure 7). Two different metering devices were chosen to record all required data: several SCT-013-200 Current Transformers, which measure electric currents and consumption, and can simply be 'clicked' around an electric wire, and three  $\frac{3}{4}$ " Hot Water Meter SPWM-075, which pulse-measures the amount of water flow. Additional gas flow meters are also available but were not part of this specific, all-electric ADU monitoring setup. For each data point, the system requires its own Omnimeter computer, which is then wired in series to other devices and finally connect to a small radio device that wirelessly transfers the data to the online Push2 device, which is installed in the client's main house and through which data becomes available in real-time through the manufacturer's Internet portal.

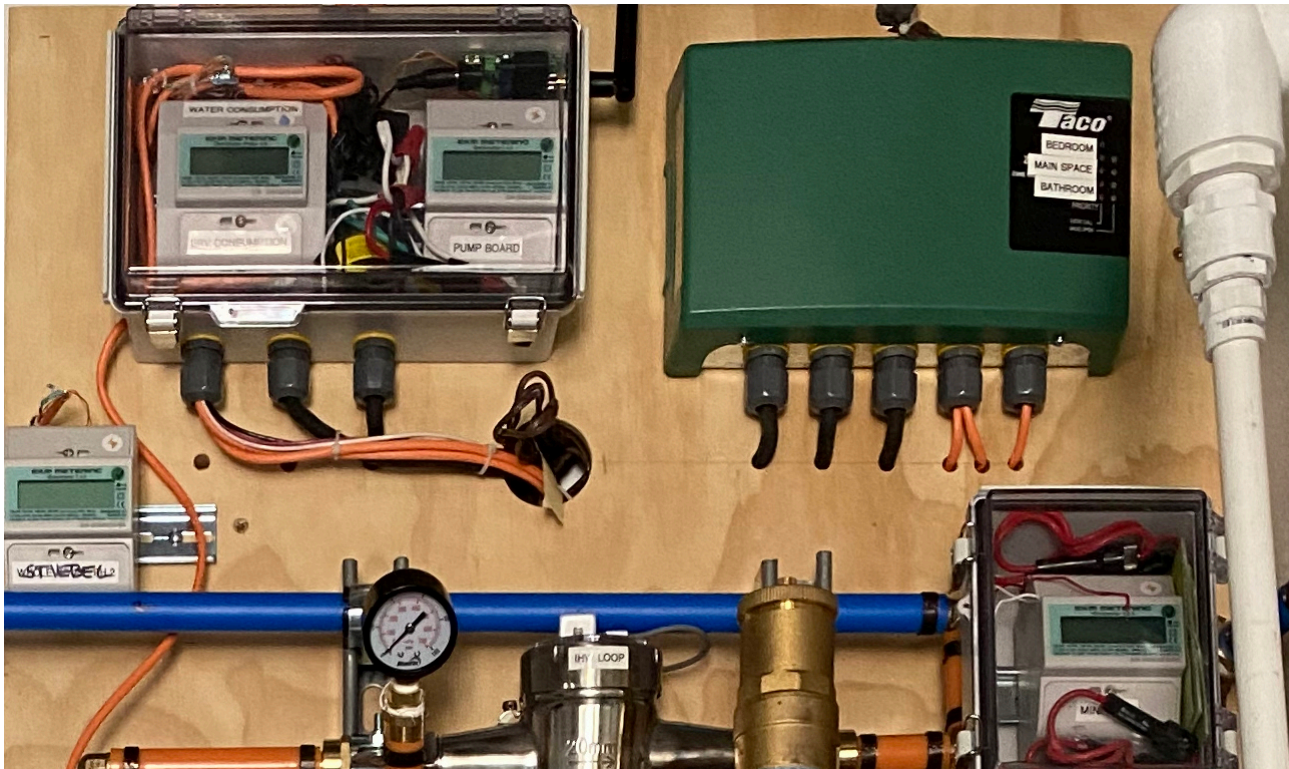


Figure 7: Omnimeter Pulse v.4 computers, CTs, and flow devices integrated into the KUNGA ABCC

Wherever possible, all metering devices were integrated directly into the house's electric and HVAC system; one Omnimeter box had to be installed in the living room, and another one on the roof next to the mini split compressor.

## 5. Post-Occupancy Monitoring results

During the POM period to date, consumption data was transferred from the POM interface into the spreadsheet every two weeks. The data clearly shows the amount of energy drawn by each component, allowing a separation between the different functional components as described above under 4. As expected, energy consumption differed by component depending on the season and different user behavior and occupancy. To obtain the average energy consumption per year, and thus make the data comparable to the simulated Sefaira results, the overall POM period data was then divided by the number of overall monitoring days and multiplied by 365. The result is the annual energy consumption in kWh, either for the entire building or for each component group in the setup.

During the first year, the team additionally used the data to educate the client about their user behavior and to finetune the different system components. As an example, it became evident that it would be more efficient to use hydronic heating only to just bring up the temperature in the concrete floor to the desired comfort level; to then use the Minisplit in its heating function to heat the air in the spaces. The coefficient of performance COP of the on-demand electric hot water heater is at 0.98, whereas the COP of the mini split is usually above 3.0, depending on the outdoor temperature, which explains that, if only the radiant system would be used, the amount of energy utilized for heating was almost three times higher.

To make the POM data comparable to the simulated data, some of the groups of POM consumers had to be re-grouped as shown in Table 1 below. Only the whole-house energy is directly comparable between the two data sets; heating, cooling, fans, pumps, etc. had to be regrouped to become approximately comparable. In any case, the absolute numbers do not change, but this method makes it a little bit more difficult to analyze the research outcome.



	Component	Simulated kWh	POM Measured kWh	Difference
1.	Whole House Energy	3,696	7,928	+4,232
2.	Heating	89	4,423	+4,334
3.	Equipment & DHW	908	552	-356
4.	Lighting	1,824	2,083	+259
5.	Pumps & HRV	376	357	-19
6.	Cooling	499	513	+14

*Table 1: Consumption comparison between simulated and actual POM consumption, with higher POM consumption values shown in red, and lower shown in blue*

When analyzing the final energy consumption data compared to the simulated date, it becomes evident that the Kunga ADU uses more than twice as much energy as originally predicted. Averaged over the entire POM period, the home uses 4,232 kWh more per year than expected (7,928 kWh/yr POM versus 3,696 kWh/yr simulated). The lion's share of this considerably higher consumption can be found in heating energy alone, which is outside the ordinary and expected, whereas cooling, pumps, and HRV fans are very close to the original predictions, lighting consumption is 259 kWh above the predicted value, and equipment and DHW consumption is 356 kWh lower than predicted, with those smaller discrepancies falling within expectations.

## 6. Conclusion

As a result, one could conclude that, in the case of the Kunga ADU, the energy simulations very much failed to predict the building's actual energy performance, which is generally true. This tendency towards a considerably higher energy consumption was first detected in early 2022, when the author, who is used to some discrepancies between simulated and POM performance results, and two of the original design team members decided to interview the building occupant, to find out about her general satisfaction with the building, but also to possibly detect inconsistencies in building usage or other matters to better understand the considerable divergences. The interview was finally conducted in March 2023, after the project went through a winter that fell among the 10 wettest and coldest winters since the beginning of weather records in 1895, which also meant that the passive solar heat gain during that period was compromised due to a lack of direct sunlight during the winter months [13].

During the meeting with the client, the interviewers were made aware of some considerable deviations from the original simulation case, which all fall in the category of user behavior, and explained the large consumption differences at least to some extent. First and foremost, the team learned that the house, different from its simulated occupancy, was occupied by a family of four with two parents and two young children, who moved in before the POM period began. The family is directly related to the original wheelchair-bound client, who continued to stay in the main house. The team also learned that the occupants heat the house to 72°F during the winter months, also evident through the Nest smart thermostat data that document set temperatures, which is 4°F or 2°C warmer than simulated, and thus explains additional energy use. The recorded data also shows that the occupants, after the first winter, fell back to using only the radiant heat for winter heating, which requires considerably more heating energy due to the system's lower efficiency. Finally, the occupants told the team that, on sunny winter days it is somewhat hard to predict how much passive solar heat gain the building will obtain, therefore they have many days where they overheat the house during the morning hours, to then flush out the excessive amount of afternoon heat by simply opening the building's main southern door.

The evidence of those discrepancies only offers partial answers to the problem of a very inaccurate simulation prediction in the Kunga ADU case, but they also show how important the consideration of user behavior is, and how unpredictable the latter is especially in residential buildings, where individual user behavior can often change and is almost impossible to predict, especially if the building occupant is a different one or not known when simulating a building. Predicted in commercial or institutional architecture, user behavior is much more foreseeable, thus will be more reliable when it comes to a building's simulated versus actual performance.

It must be noted though that the Sefaira software, during the actual design process of the Kunga ADU, was a

very helpful tool since it created real-time immediate results that would be used to identify a change in the building's setup or in its actual components toward a better or worse efficiency. Taken in relation to the design case, the application of the different software tools enhanced the building's performance, at least on the hypothetical side.

In conclusion, the Kunga ADU case shows how important POM is to detect discrepancies – without monitoring, the issues would have gone undetected or only recognized by the occupants in unexpectedly higher energy bills, and there would have been no results that teach a design team how to enhance a future building design. It also shows that, for better applicability and comparability of different cases, POM protocols need to be created to provide guidance in the utilization of such methods and tools.

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