ENGINEERING

SPARC

U.S. Department of Energy
Solar Decathlon 2021

The SPARC House has the ambitious goal of being a model for sustainable, attainable living in cold climate mountain communities, while being a fully functional and durable home for up to four people on day one of occupancy. The design response demonstrates how available processes, materials, and technologies can be combined to create low-risk, affordable solutions for immediate response to our global energy and climate crises.

The result is rooted not in complex technology but rather in process. A performance based design-build approach was used to align expectations of critical stakeholders, identify design alternatives, and to move through each step of the design-build process with a focus on performance goals.[1]

The non-negotiable, performance goals agreed upon in conceptual design are described in Table 1.

Since the performance goals were wide reaching and interconnected, they could not be considered in isolation. As a first step to find an integrated solution, design charrettes with stakeholders were held and a software tool, Building Energy Optimization Tool (BEopt), was used to find the set of passive and active systems optimal for zero energy at typical construction costs of a small home. The BEopt analysis helped confirm the solution set to include a high performance envelope, daylighting, natural ventilation, cold-climate-air-source heat pumps, an energy recovery ventilator (ERV), and, high efficiency appliances. An iterative design process was used to ensure each system specification would not negatively impact other project goals. In addition, quantitative analysis was performed on the final design using the Modelica Language to verify zero energy plus performance of the final construction documents. This tool was specifically selected to allow for future analysis of the building as a grid-integrated all-electric home.[2] [3]

Performance Goals	Non-negotiables	Design response
Sustainability	The house must consider the health and safety of current and future occupants/community	All-electric house prepared for deeper controllability and integration into an electrifying grid; made of healthy materials
Performance	The house must produce more energy over the course of one year than it consumes	Form; layering of passive and active systems; high efficiency active systems
Attainability	The house must be an affordable option for permanent residents of Fraser	Panelization; accessory dwelling unit (ADU); prioritization of envelope and building systems in budget allocation
Resilience	The house must be durable under the extreme snow and cold conditions of ASHRAE climate zone 7, and it must be an all-electric, grid-integrated house	Continuous thermal and vapor envelopes; thermal storage; thermal resistance and some thermal capacitance, automatic demand response; battery
Community	The house must serve to strengthen the local community of Fraser	ADU; comfortable all-electric living supporting local go-electric utility campaign

Table 1: SPARC House non-negotiable performance goals and design response

In parallel to equipment and material cost considerations, a design for mountain towns must consider labor costs and tight construction timelines during a short summer building season. To address these barriers, a prefabricated, panelized construction method was selected. The SPARC House was initially constructed in a Denver warehouse and transported as a set of partially-closed panels to the Fraser build site. Working in a climate-controlled indoor environment allowed for panel construction to commence in early spring and for a weather barrier to be applied before being transported to Fraser. The detailed solution of the energy systems and construction methods that enabled the house to achieve all of the non-negotiable goals are described below.

PASSIVE SYSTEMS

The approach to the passive system design of the SPARC House allowed heat gain from solar radiance and solar power generation through site-specific positioning of three volumes. The envelope design limited the active system load by reducing infiltration, a common goal of many passive houses. Additionally, heat loss through the envelope was targeted with high R-value insulation, low U-factor windows, and combined use of selected window openings for views, daylighting, and natural ventilation.

Massing and orientation

Specifically, the site's setback lines required the foundation to be oriented 45-degrees off-axis. Initially, a southwest orientation was considered to align solar panel generation to projected late-day peak utility demand. However, shading from existing trees and regular afternoon storms required a southeast orientation to maximize energy production.

Within the square footprint, the modules were positioned with two on the lower level and one on the upper north side. The stacked modules create the main house while the attached module is the ADU. The ADU will receive significant direct insolation, which is beneficial on the exterior for electricity generation and will aid in snowmelt on the shallower 3:12 ADU roof pitch. In the winter, the lower modules will receive the least amount of direct insolation but will have the higher internal load contribution due to higher typical occupant density, cooking, and electronics use. The upper main module will have the highest hourly heat loss and gain, primarily due to windows. Cross ventilation will allow for summer cooling of the second story space.

The windows were strategically placed to allow for cross ventilation, views and daylight, with an average window-to-wall ratio of no more than 20% on each of the full facades. The north wall has only two small windows for ventilation to maintain its thermal integrity. The glazing specification on each facade was tuned by orientation, however the SHGC and U-factor was kept low in all cases. Passive solar as a holistic heating strategy was not employed due to the small size and air tightness of each module and potential for overheating.

The awning windows meant for natural ventilation, daylight, and views of peaks have a solar heat gain coefficient (SHGC) of 0.22, while the southeast windows near seating and sleeping spaces have a SHGC of 0.27. All windows are quadruple-lite and are the lowest U-factor available for the product used and operation style, ranging from 0.11 for the fixed windows to 0.16 for the sliding glass door. Fiberglass frames and triple seals were included for thermal integrity and durability of the windows over time in the harsh climate.

Relative hourly heating load per module

	Sensible + latent heat gain	Sensible heat loss
ADU	30% *(without site context)*	30%
Lower main	34% *(without site context)*	29%
Upper main	36%	41%

Figure 2: Relative hourly heating load per module

To allow for additional solar shading and weather protection, the windows were recessed midway in the thick exterior walls, while maintaining functional horizontal space on the interior sill. Windows represent one of the primary shifts of budget to the envelope. High performance windows were used because they are critical to energy performance and costs in cold climates, while providing views and a sense of spaciousness for the occupants living within a small footprint design. Costs were

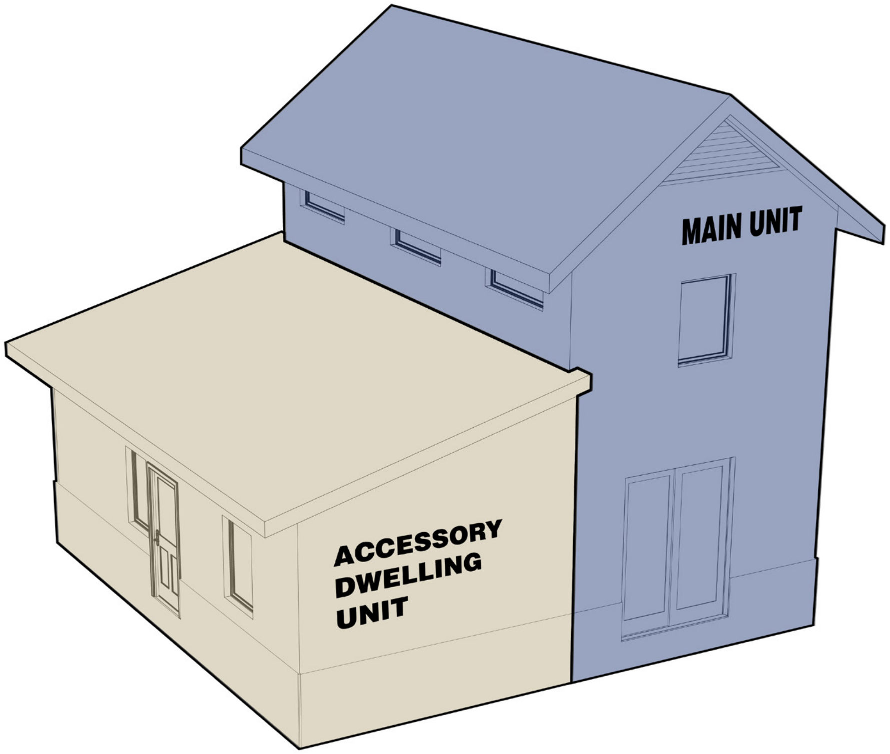

Figure 1: Volumetric division of ADU and Main Unit

Figure 3: High performance windows

controlled by limiting window size variation and by not using custom shapes, styles, or operating characteristics.

A gable roof was used on the main house, with a shed roof on the ADU. The height of the walls and roof were set to maximize ceiling height while accounting for transportation load size restrictions from Denver to Fraser. The main gable roof has a pitch of 9:12 to encourage snow shedding to maintain solar panel production. The lower shed roof pitch of 3:12 allowed for placement of windows on the upper main module for cross ventilation. This roof can be reached with a snow rake for snow removal as needed. The modules were placed in the square footprint of the SPARC House site but can be shifted in other instances to create space for shielding outdoor equipment from wind or to create separate outdoor space for the main and ADU residents.

The attics of both modules under a roof are vented. This allowed for the use of wool batt insulation as the primary insulation to be used next to all living spaces. Additionally, venting allows for a cool roof, limiting potential for ice damming. In order to allow for annual inspection of moisture buildup and batt compression, each attic was equipped with entry points. The attic doors were insulated, sealed, and placed away from bathrooms to prevent vapor movement through the hatches.


Figure 4: SPARC House showing roofs, PV, and outdoor minisplit units

Construction Methods

Panelized construction was selected due to its potential for fast production, low material waste, and high-quality fabrication results.[4] The specific panel style used was based on the “Best” wall described by architect, Greg La Vardera.[5]

The “Best” wall uses common building materials, in this case 2x8s for framing, which allow for ease of construction while providing additional capacity for insulation compared to a typical home. (The SPARC House design achieved R-42 for the walls and R-59 for the roof.) The SPARC House demonstrates the innovative practice of prefabricating a “Best” wall assembly in partially closed form. To date, most panelized construction uses open panels, with just the wood framing transported to the site. This allows for onsite inspection of the structure prior to the addition of insulation or weather and vapor barriers. In contrast, the SPARC House panels were filled with the wool batt insulation and closed with the vapor/air barrier on the interior and weather resistive barrier on the exterior before leaving the warehouse. Application of batt insulation in the warehouse can allow for tight fits, without compression, and securing at the top of panels to limit sagging over time. Extra laps of barrier material were left on each panel to allow for wrapping during panel setting, creating the continuous air barrier between walls, modules, and floors. Since the local authority having jurisdiction must inspect the structure, prefabrication in a different location can prove problematic. To mitigate this, the town was included in the planning conversations and a plan was created for remote inspection through photographs. The process at large was successful although lessons were learned about how to detail the barriers in the warehouse to prevent the need for onsite rework.

During prefabrication in the warehouse, a laser guide was used to show nailing patterns on the sheathing and a mechanical table was used to flip the panels, which were primary tools for decreasing production time and increasing production quality. After completion, the panels

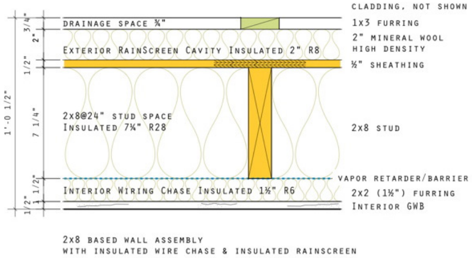

Figure 5: The “Best” wall design

were transported to Fraser and assembled on site in just two days, one day for wall panel setting and one day for roof trusses.

Envelope layers

The separate and continuous enclosures for weather protection, vapor transport, and insulation was the primary strategy used to create a high performance, durable envelope for a cold climate. Disaggregated weather and vapor barriers were part of a multilayer approach to reduce moisture accumulation in the walls and roof, a particular concern in Fraser where much of the precipitation has the potential to refreeze and expand under crevices in the envelope. This is even more pertinent when moisture accumulation in roof and attic spaces go unnoticed in dry climates and mold or fungus accumulates, leading to costly repairs. The air barrier used (ProClima Intello Plus) is considered an “intelligent” vapor barrier because it prevents vapor from entering the wall cavity and entering the attic, keeping moisture created in the house, inside the vapor shell. The weather barrier (ProClima Solitex Mento) keeps bulk moisture outside of the wall assembly. In typical dry Colorado conditions, the envelope will dry in an outward direction and interior moisture accumulation will be maintained at appropriate levels with mechanical ventilation. However, if moisture accumulates in the wall assembly and on the vapor barrier during high exterior humidity conditions or due to condensation, the material can let moisture through to allow drying of the wall assembly toward the interior. This flexibility is useful for a house with small spaces and with insulation inside the wall cavities versus all continuous exterior.

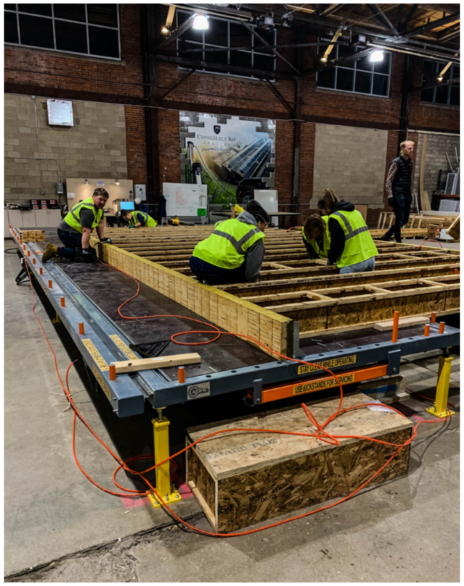
Figure 6: The CU Boulder Team working at Simple Homes’ factory


Figure 7: SPARC House panels on truck


Figure 8: Crane placing panel on floor box

To preserve the continuous air barrier, the SPARC House design included a 2x8 wall framing and horizontal furring strips to create an MEP chase outside of the continuous air barrier. (During construction the use of the 2x2 furring strip chase for electrical conduit was vetoed at the discretion of the electrical inspector. Under this interpretation of the electrical code a similar method of construction could be used with a 2x4 wall framing and 2x4 furring strip to create a larger chase. Due to time and budget constraints construction of the SPARC House continued with electrical conduit running through the main wall framing although the number of punctures created in the weather barrier is unideal. However, the chase is a viable solution, perhaps with the use of Romex, which was corroborated by experienced architects and the project electrician.)

In addition to the energy performance and durability of the envelope layers, the materials used also exhibit low global warming potential through the use of limited foams and adhesives. Materials that contribute to good indoor environmental quality were selected such as no-VOC


Figure 9: ProClima Solitex Mento on house

paint and sheep's wool insulation at the interior wall, which is an antibacterial and a low mold growth option.

ACTIVE SYSTEMS

HVAC System

The HVAC system for the SPARC House used a solution that affected both energy costs and carbon emissions.[6] The solution consisted of three outdoor heat pump units ("mini splits"), electric radiant baseboards, and an ERV. Mini split systems, which provide heating and cooling through heat exchange with the outdoor air, are an energy efficient option for extreme climates. Because the mini split system does not provide ventilation, energy is saved by recyclinging pre-conditioned air. When ventilation is necessary to evacuate air from the house the ERV uses an air-to-air energy exchange to retain the humidity of the exhaust air and pre-condition supply air. This preconditioning occurs in both winter and in the summer, and in the latter case can assist natural ventilation by reducing the latent load introduced on rare humid days. By providing three individual mini split units SPARC is able to maintain three thermal zones, naturally divided by the three main living spaces (the ADU, lower main living area, and upper main work and sleep area), which further eliminates excess heating and cooling. For example, when the ADU is unoccupied, the heating setpoint of that zone can be reduced in order to save power.

Figure 10: In-set window and wall layers

Figure 11: Air barrier lining interior

In order to improve the efficacy of the mini split system, and to limit refrigeration line runs, the outdoor unit was located on the south and east facades of the house. Because the heat pump relies on the effective outdoor air temperature (a combination of the Ambient Air Temperature and the Mean Radiant Temperature), placing them in sunny locations will allow the heat pumps to operate even when the ambient temperature is below the cutout temperature. Additionally an ERV was specified to retain some latent heat in the house. ERVs, rather than the more common Heat Recovery Ventilation (HRV) use a direct air-to-air heat exchange to preserve humidity that is built up in the exhaust air. Moisture retention was an integral part of achieving thermal comfort in accordance with the ASHRAE Standard 55 guidelines, a guideline useful for ensuring adequate HVAC design.

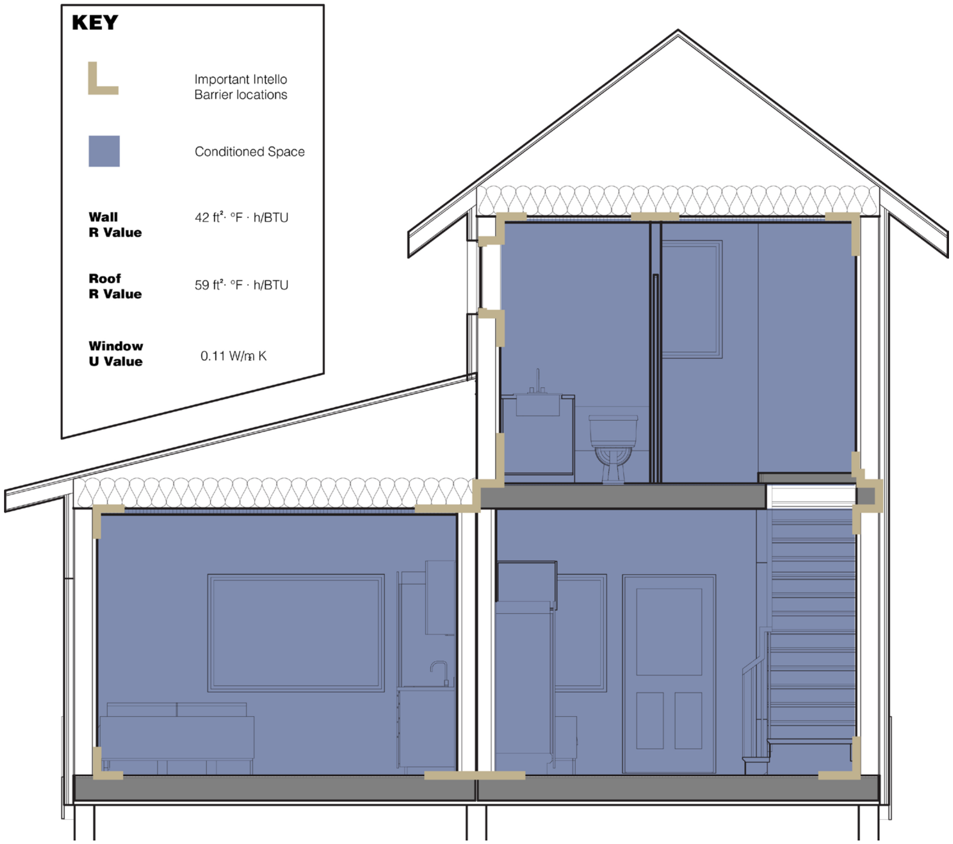

Figure 12: SPARC House section view showing critical vapor barrier wrap points

The ERV was selected for cost, efficiency of a passive defrost approach, and size. The Renewaire EV Premium M product sits on the ceiling of the small mechanical room, out of range of electrical panel clearances. It is approximately two-to-three times less expensive than a top-of-the-line alternative, which would not pay back for more than 30 years with an estimated energy cost improvement of $50/year. These alternative systems achieve higher efficiency mainly through preheat and defrost cycles that allow the ERV to deliver air at comfortable temperatures in the coldest of temperatures. Instead, in the selected system, outdoor air from the Renewaire ERV, which is expected to be 45 degrees Fahrenheit as a worst case scenario, is introduced near the indoor units of the heat pump, and away from occupant sitting locations. Placing the air vents next to the indoor units encourages conditioning of outdoor air before it reaches the occupants. Additionally, the ERV pulls air from the crawl space to put slight depressurization on the attic to prevent moisture accumulation and allow crawl space to be ventilated without need for additional resistance heater as would be the case with direct outside air.

Figure 13: ERV on ceiling of mech room

Mini split systems are naturally limited in their ability to exchange heat with the outdoor air when the outdoor air drops significantly. The Mitsubishi mini split systems installed in the SPARC House maintain 70% heating capacity at -13 degrees Fahrenheit, which is expected to occur for only nine hours per year. During extreme conditions electric radiant backup heat is designed to maintain 46% of the heating load, maintaining a temperature close to 40 degrees Fahrenheit, and this is not accounting for the still available, just reduced heating capacity of the heat pumps. The resistance heaters are installed in strategic locations to improve comfort. For example, a kickspace unit is used in the lower main unit where occupants will largely be walking and standing in the nearby kitchen. Cove units are used in bedrooms instead of baseboards for better form factor from heater to bed. The electric resistance was locked out for use during the heat pump’s typical operating temperatures.

Figure 14: Wet core and systems diagram

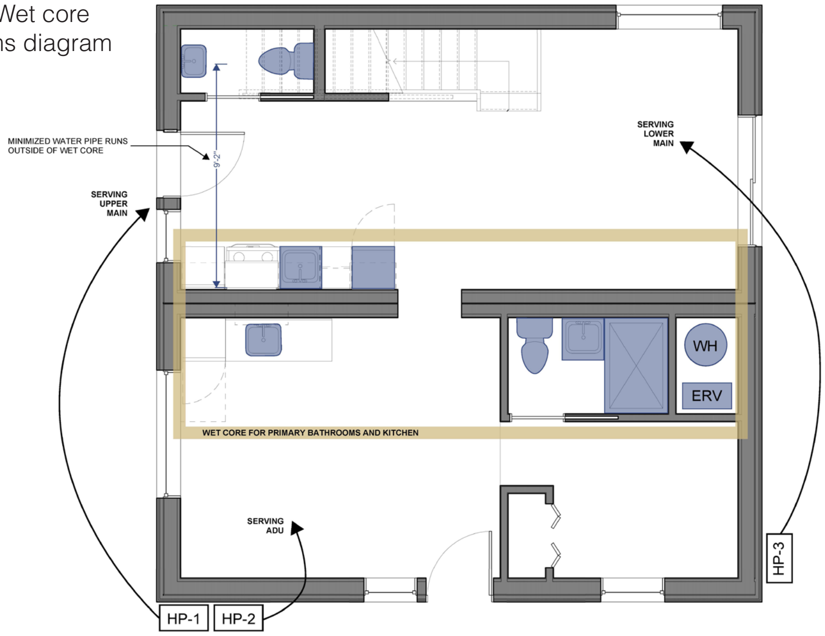

Figure 15: Outdoor mini split

Water Heater

The use of thermal energy storage in tanked water heaters was the primary driver in selecting a water heater. While a heat pump water heater was considered to lower the electricity consumption of the water heater, in a heating dominated climate using a heat pump to pull heat from the living space would drive up the HVAC cost of the house and introduce noise and cool air next to the ADU bedroom. Therefore, a 50-gallon resistive electric water heater by A.O. Smith was used. Since water heater tanks typically have very low energy loss through the tank walls, hot water will increase the demand response flexibility of the SPARC House. Automatic demand response was integrated into the unit using a SkyCentrics CTA-2045 module, which offered connectivity via the Home Energy Management System described below.

Lighting

The hardwired electric lighting scheme consisted of an ambient layer of warm but efficacious light at the living and working areas of the house. Recessed downlights in the lower main area and ADU provide ambient lighting for movement through the space, and near the main kitchen and ADU kitchenette. Additional undercabinet lighting at the kitchens reduces shadows on working surfaces. The downlights were placed only in areas where recessing the luminaries did not penetrate an air barrier. A soffit was installed in the ADU for this purpose. Sconces with diffuse, luminous surfaces and distribution onto nearby walls provide surface lighting near living spaces for the dual purpose of functional lighting and to suggest warmth near the seating areas. A sconce mounting was used specifically to enable mounting in the wall's electrical chase instead of in the ceiling, which would require penetration and sealing of the continuous air barrier. Throughout the house, light colored surfaces and mirrors compliment the surface illumination to create a sense of spaciousness in the small footprint. Each unique luminaire type in the house, in each module, was put on its own lighting control zone so that each space can have a range of lighting scenes. This contributes to a unique function and feel of the zone needed at specific times of day. This helps the small footprint meet a range of space needs. The equipment was specified as WAC's 90 lumens per watt luminaire efficacy options, which guarantees high efficacy over time relative to screw base, plug-in options. The lighting control intent is manual-on with automatic-off at regularly scheduled times of day through the Home Energy Management System in coordination with the Lutron Caseta wireless wall switches and controllable relays. The off times coincide with high daylight hours, as well as midnight to offer a reset to all-off status of luminaires in the house.

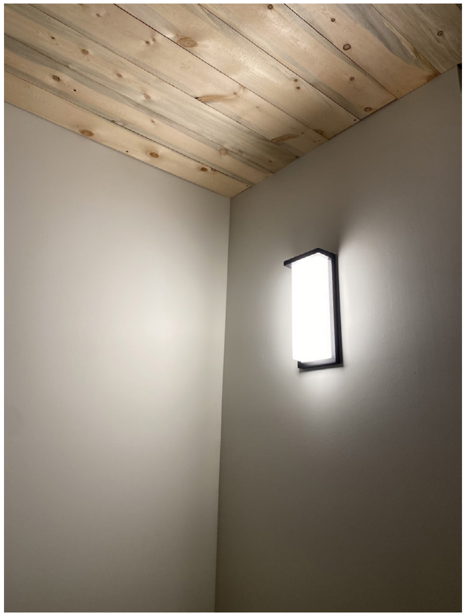

Figure 16: Electric lighting in the house

Auxiliary Appliances

Home appliances such as cooktops, washing machines, and dishwashers meet or exceed Energy Star standards. Through careful selection of appliances, the SPARC House showcases not only the low energy cost of these appliances, but also practical improvements over their conventional counterparts. In the main kitchen, the induction cooktop provides even heat supply, faster cook times, and lower residual heat than gas powered or conventional stoves. The heat pump dryer, for example, removes the need for ventilation penetrations on the north facade and prevents moisture in the closet, which could move into the walls and attic. Even though heat pump based appliances are generally discouraged in heating dominated climates, the additional demand of a dryer was determined to be very little compared to the potential losses created by puncturing the north wall. Additionally, the use of the dryer can be timed to prevent noise and cooling near the master bedroom.

Smaller plugs loads are integrated into the Home Energy Management System through the use of smart plugs. Two smart plugs in the main suite, and two smart plugs in the ADU may be scheduled to provide the owner with additional functionality (i.e. timers on lamps) or can be remotely shut off at arbitrary times for demand response.

Home Energy Management System

All major components of the SPARC House active systems are integrated with a Home Energy Management System (HEMS) for both typical daily operation and demand response when requested by the local utility. High demand systems such as the heat pumps, electric radiant cove heaters and the domestic water heater are integrated for the purpose of demand response, while lighting and appliance monitoring are added for occupant comfort.

Currently, bi-directional flow to and from electric vehicles is limited due to utility restrictions and/or UL listing of equipment. When available, it is the preferred solution to energy storage for the SPARC House so that the batteries in the car can serve a dual purpose gvein the limited conditioned space to place a home battery. As a demonstration aspect of the house, and as a feasible path forward for other houses and owners, a temporary battery will be installed in partnership with a solar plus storage installer in the Rocky Mountain Region who is actively working with manufacturers and home owners on currently viable solutions. As part of the demonstration, the recommended integration of the battery in the HEMS and suggested control algorithm for the battery is described below.

Under normal operating conditions the SPARC House should be able to maintain all conventional loads specified by the homeowners. However, during periods of demand response the home must be able to automatically respond to utility requests while maintaining occupant comfort. In order to achieve an automated response, the HEMS will rely on the open-source Home-Assistant (HASSIO) platform which integrates many commercially available IoT devices through manufacturer provided application programming interfaces (APIs). HASSIO was selected over other commercial Building Automation System protocols such as BACnet because smart devices with open APIs are more broadly available for residential applications. Additionally, the open-source platform does not require annual/integration fees and it enables the homeowners to add controllable systems over time as devices, selected for initial costs, are replaced with integrated WiFi capability.

During a period of requested demand response the HEMS will schedule loads as determined by their importance in keeping

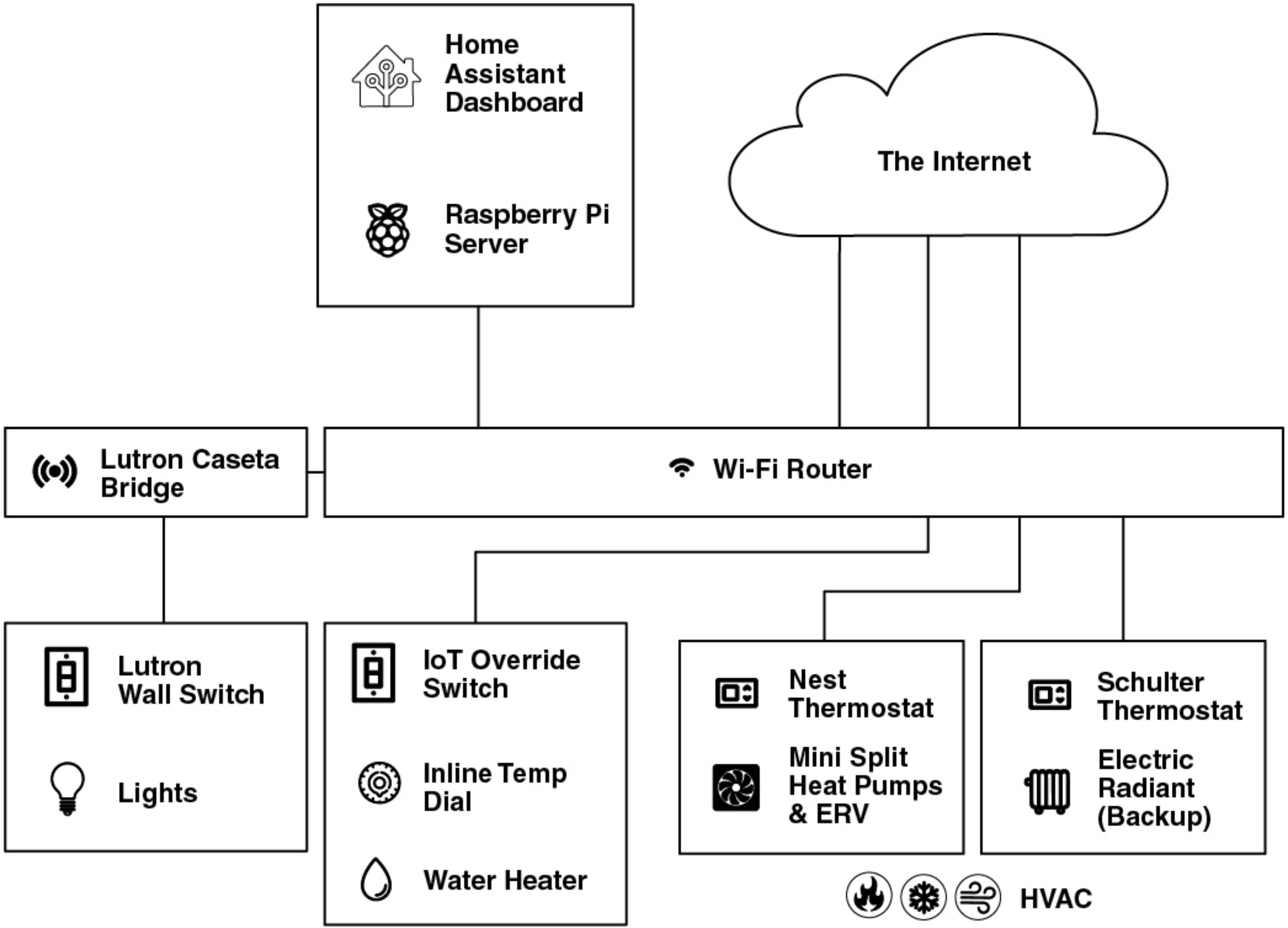

Figure 17: Controls diagram

the home comfortable and their energy consumption.

Loads in the SPARC House are shed as follows:

1. Domestic water heater

2. Zone air thermal loads

3. Lighting

4. Auxiliary plug loads

Thermal loads are shed first since they act as energy storage and the temperature drop will not be immediately noticeable. In particular, the domestic water heater (DHW) takes the lowest priority in load scheduling due to the low probability of hot water demand during a demand response period. Higher priority loads that would be used in emergencies (i.e. minimal lighting and heating to maintain the lowest acceptable temperature) will only be overridden when the house experiences a power outage since they will be immediately noticeable. For a more in depth review of how the Building Automation System is used for demand response and grid-islanding capabilities we refer to the Resilience section.

Energy Performance

The combination of passive strategies, efficient active systems, and twenty four solar panels enables the home to produce more energy than it consumes over the course of one year. A Nissan Leaf at 10,000 annual driving miles is included in the energy consumption. The energy production is from Trina panels and a SolarEdge inverter, with power optimizers on each of two differently oriented strings. The home energy model, with modifications for as-built assumptions shows the following expected total energy consumption, production, and annual net production.

Conclusion

A performance-based design-build process allowed for the SPARC House non-negotiable engineering goals to be achieved; system options were compared and evaluated relative to the five goals starting in concept design and ongoing through occupancy. The resulting house is a viable, all-electric house for mountain communities prepared for deeper grid integration and controllability over time. The passive systems and materials create a healthy, livable indoor space that, when layered with the efficient cold climate heat pumps, ERV, and efficient appliances, will produce more energy than it consumes on an annual basis. With the rental income of the ADU, the house is attainable, not for all, but with a combined household income of less than $73,000, which is under the median household income in Colorado.7 The cost considerations of the construction method, prioritizing cost toward the energy systems and envelope, using currently available equipment, and evaluating each equipment purchase shows that an attainable, zero energy plus house is possible.

	Baseline (kWh)	**SPARC House (kWh)**
HVAC	4,996	2,196
Hot Water	3,970	2,203
Lighting	906	7,80
MELs	5,217	3,645
Electric Vehicle	NA	2,681
PV Production	NA	11,826
Net Energy	15,089	-321

Table 2: Annual energy consumption

Figure 18: SPARC House after completion of the roof

Endnotes

1. Deru, M. and Torcellini P (2004). Improving Sustainability of Buildings Through a Performance-Based Design Approach, presented at World Renewable Energy Congress VII and Expo, Denver, Colorado. CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy04osti/36276.pdf
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Energy Modeling of a Zero Energy Plus, Cold-Climate, Residential Building

CU Boulder Solar Decathlon
SPARC House

Report Context

The following report provides the energy modeling assumptions, inputs, and results for the CU Boulder Solar Decathlon SPARC House. The project report was completed by team member, Angelique Fathy, in partial fulfillment the project pathway to a Master of Science Degree in Department of Civil, Environmental and Architectural Engineering. The content shown in blue text reflects as-built conditions of the Solar Decathlon house. These updates are added to the Means and Methods section.

Abstract

Many zero energy (ZE) homes are being constructed, but few are analyzed on the energy performance of each system component being used. The purpose of this report is to investigate the complex physical systems of a ZE design in Boulder, Colorado in terms of energy performance to demonstrate zero energy before construction. More specifically, the miscellaneous electric loads, domestic hot water (DHW) system, heating, ventilation and air conditioning (HVAC) system, and electrical system, including a solar photovoltaic (PV) system and battery storage unit, are modeled to demonstrate that the annual energy generated is greater than or equal to the annual energy consumed. The energy performance of each system is predicted using the modeling software tool called Modelica and was compared against the modeling software tool called BEopt to provide confidence in both approaches. It was found that the building design, in both models, demonstrated the home to be not only zero energy but also net-positive. The miscellaneous electric loads in both models proved to be the highest, while the HVAC system had the greatest disparity in load between the models. Moreover, a cost analysis of the ZE design is compared to that of code requirements, and different occupant behavior profiles are analyzed. In terms of cost, the ZE design showed a 41% annualized energy cost saving compared to code standards in Boulder, Colorado. The occupant behavior study showed that in a ZE design, good occupant behavior plays a factor in the annual energy usage by reducing consumption by 8%, and in terms of peak demand, good occupant behavior has little effect.

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1. Introduction

This report evaluates the cost-benefit of different energy efficiency (EE) and renewable energy (RE) technologies and assesses the energy performance for a zero energy (ZE) home designed for a design-build competition held by the U.S. Department of Energy (DOE) called the Solar Decathlon 2020 Build Challenge. A team of students attending the University of Colorado Boulder have defined a home to demonstrate that both affordability and sustainability can go hand in hand. The home will be built and tested in Fraser, Colorado. The tests on the house will demonstrate the concept of resilience in several ways, including: grid islanding capability, battery storage, and on-site energy generation. Therefore, the importance of a cost-benefit analysis of different measures can help assess the optimal design in terms of affordability. Furthermore, energy simulation tools can provide insight to system selection from energy performance results.

1.1 Purpose of the Study

In this study, a ZE design is modeled and evaluated for optimal economic and energy benefits. The purpose of this study was completed to justify the design considerations, such as the construction materials and operations for the final build. The research aims to answer the following questions:

1) What is the cost-optimal design for a ZE building in comparison to that of code requirements?
2) Does a full model of all the complex physical systems chosen, show the home to be ZE?

1.2 Scope of the Study

The research to be completed within the scope of this study is based on the purpose and is broken into three steps. The first step is the cost and energy analysis of a ZE home in comparison to that of code standards. An optimization tool named BEopt is used to model the home to define several building construction features and energy efficiency measures to obtain a ZE design. Such measures included higher insulation values, different temperature setpoints, more efficient heat pumps, etc. Good occupant behavior in the ZE design is also studied in the energy analysis comparison. The second step consists of modeling the designed house in an equation-based, object oriented language called Modelica to build out each of the system models within the home. The energy consumption and generation, as well as peak demand, will be evaluated. The last step will be comparing the two tools used to justify the results.

2. Literature Review

This review explores what a ZE building is and how modeling tools can evaluate the energy performance and thermal comfort to optimize the design before construction begins. First off, there are many ways to define ZE in the context of buildings. The term zero energy describes the measure in which energy is reduced through efficiency gains such that the balance of energy is met by renewables. The National Renewable Energy Laboratory (NREL) defines a ZE building as "an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy" [1]. The building's energy load is compared to the energy generated by renewables to understand the site energy usage. However, site energy usage is not a good metric to compare buildings which use mixed energy types or buildings with on-site generation [1]. Since the design uses a PV system for on-site energy generation, source energy will be calculated to assess the relative efficiencies. This is when the modeling tool BEopt is most helpful. It can convert the different types of energy into the same unit thereby converting site energy usage to source energy usage. Otherwise, the extra step of using source energy conversion factors would need to be utilized and calculated. Although for this design, the energy used is only electricity so an energy conversion factor is not needed.

Furthermore, BEopt compares the economic performance of EE measures with that of renewable energy generation to find an optimum combination. The algorithm accounts for the relationships between the EE measures until the price of the left over EE measures is greater than the price of PV. This is ultimately the optimal design to reach ZE. This overarching method is the same way A precedent study concludes the greatest cost effectiveness. Parker [2] presents a study of annual performance data on residential projects in North America with very low energy where he further mentions that before the consideration of renewable energy sources, EE measures need to be accounted for first. Cost effectiveness is more greatly achieved through EE measures than the use of renewables. Once the appliances, construction materials, and PV capacity are optimized, the energy performance is calculated. However, minimizing the building energy demand also includes encouraging better than standard occupant behavior [2]. There is a direct correlation to reducing total energy use by influencing energy efficient behaviors. Many studies look at the economics of EE measures and energy performance, but rarely discuss occupant behavior. This study will address this challenge.

Furthermore, while BEopt presents the energy performance and energy cost analysis of the ZE build, the equation-based, object-oriented language of Modelica allows for close examination of how each of the energy systems within a home is coupled with the power grid. Each of the systems and its components within the home is subject to fine tuning when it comes to control design and evaluation. Smart control technologies can have immense effects on efficient operation of the ZE home [3]. To the authors knowledge, limited work and research has been done on these interactions using Modelica for residential homes of small scale in cold, dry climates. He et al [4] presents a community perspective of these energy interactions, specifically the ground source heat pump, of ZE homes and offices in Florida, but it does not examine one specific residential home nor is the study located in a cold, dry climate. Tumminia et al [5] studies the energy interaction of a ZE residential home by introducing a wide range of on-site generation and storage systems, but does not look into how the energy systems within the home itself play a factor. This report will introduce the optimal design of the ZE home in Modelica which will include the multiple sub-systems for energy generation and consumption. Smart control logics will be implemented to some systems to better understand the effects on efficient operation as well. Using this software, not only can annual energy performance be examined but also the dynamic pattern and interactions between the energy systems. This creates the ability for controllability and stability of the systems to mimic real-world operating characteristics.

3. Means and Methods

3.1 BEopt

The program used to model the home that was designed by the University of Colorado students for the Solar Decathlon challenge during the construction phase is Modelica, while the program used to select the systems in the design during the schematic phase is BEopt. BEopt is a computer program software that uses a sequential search technique to automate the process of finding optimal building designs along the path to ZE [6]. A cost comparison analysis can be calculated relative to a reference. In this case, the reference model follows code standards for climate zone five by using the 2015 International Energy Conservation Code (IECC) [7]. Within the software, the inputs include building geometry, photovoltaic system parameters, economic parameters and energy saving options. Once an optimization has been run, the outputs include the optimal and near optimal designs along the path to achieve ZE, as well as a defined cost associated with the selected options from the input. It is important to note the inputs are selected from predefined options.

The building geometry parameters for the input include the floor area, number of stories, wall height, number of bed and baths, and roof characteristics. The inputs in the model built for the report are presented in Table 1. The building geometry rendered is shown in Figure 1.

Table 1: BEopt building geometry

Floor Area [sqft]	1568 (as-built: 1176)
Number of Stories	2
Wall Height [ft]	9
Number of Bed and Baths	2 Beds, 2 Baths
Roof Type	Gable
Roof Pitch	9:12 (as-built: 9:12 and 3:12 mix)
Roof Structure	Truss, Cantilever

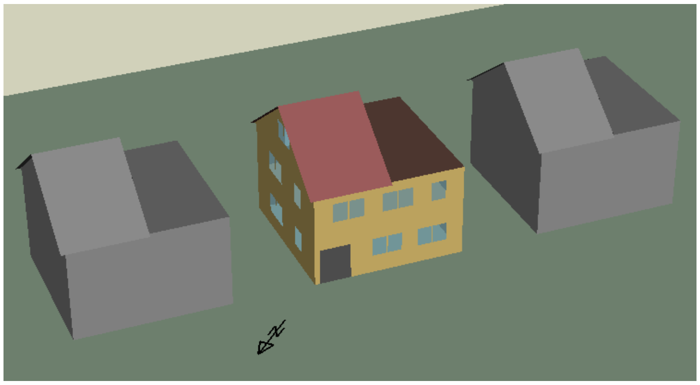


Figure 1: BEopt rendered ZE design

The photovoltaic system parameters include the module type, size, cost, inverter efficiency, system losses, tilt and azimuth. The specified options in the model are in Table 2. A maximum of 6 kW was chosen due to the limiting factor of the available roof area. The maximum PV size was chosen based on the rule of thumb of 1 kW per 125 square feet.

Table 2: BEopt PV system parameters

Module Type	c-si
Size	6 kW (as built: 7.68 kW)
Cost [$/W]	$2.91
Inverter Efficiency	0.96
System Losses	0.14
Tilt	40 (as built: 9:12 and 3:12)
Azimuth	South (as built: southeast)

The economic parameters used for the cost analysis of different designs include the analysis period, inflation and discount rate, and utility rate. The inputs are shown in Table 3.

Table 3: BEopt economics

Project Analysis Period [years]	30
Inflation Rate [%]	2.4
Discount Rate, Real [%]	3.0
Average Utility Rate [$/kWh]	0.1198

As for the energy saving options, BEopt provides different EE and RE options to select from and are divided into eight categories: building, envelope, windows and shading, equipment, appliances and lighting, and renewables. Combinations of the selected options within each category is used in the optimization process. For the optimization conducted, the selected options within the categories are shown in Table 4.

Table 4: BEopt energy saving options

Building	Building	● **Orientation:** Southwest (as-built: southeast) ● **Neighbors:** Left/Right at 15ft
Envelope	Walls	● **Wood Stud:** R-15 Fiberglass Batt., 2x4, 16 in. oc; R-21 Fiberglass Batt., 2x6, 24 in. oc (as-built: R-34 wool batt) ● **Wall Sheathing:** R-5, XPS (as-built: R-8 rockwool) ● **Exterior Finish:** Wood, Light
	Ceiling/Roofs	● **Finished Roof:** R-60, Closed Cell Spray Foam, 2x10 (as-built: R-59 wool batt) ● **Roof Material:** Metal, Light
	Foundation/Floors	● **Slab:** 2 ft, R10, Exterior XPS (as-built: crawl space)
	Thermal Mass	● **Floor Mass:** Wood Surface ● **Exterior Wall Mass:** ⅝ in. drywall ● **Partition Wall Mass:** ½ in. drywall ● **Ceiling Mass:** ⅝ in. drywall (as-built: wood)
	Airflow	● **Air Leakage:** 3ACH50 (as-built preliminary tests with no drywall and prior to leaks identified and fixed: 2.8 ACH) ● **Mechanical Ventilation:** 2013, ERV, 70% ● **Natural Ventilation:** Year-Round, 3 days/wk; Year-Round, 7days/wk
Windows and Shading	Windows and Doors	● **Window Areas:** 15%, F25, B25, L25, R25 ● **Windows:** Low-E, Double, Insulated, Air, M-Gain; Low-E, Double, Insulated, Argon, H-Gain ● **Door Area:** 40 ft2 ● **Doors:** Wood ● **Eaves:** 1 ft
Equipment	Space Conditioning	● **Electric Baseboard:** 100% Efficiency ● **Mini-Split Heat Pump:** 12 kBTUh, SEER 26, HSPF 11.5; 9 kBTUh, SEER 30, HSPF 12.5
	Space Conditioning Schedules	● **Cooling Setpoint:** 75F; 76F ● **Heating Setpoint:** 67F; 68F; 69F
	Water Heating	● **Water Heater:** HPWH, 50 gal, in confined space (as-built: 50 gal electric tank) ● **Distrubrition:** R-2, TrunkBranch, PEX

Appliances and Lighting	Lighting	● **Lighting:** 20% LED; 40% LED; 60% LED; 80% LED; 100% LED; 100% LED, Low Efficacy (as-built: manual-on, scheduled off, for daylighting and nighttime efficiency)
	Appliances and Fixtures	● **Refrigerator:** EF 17.6; EF 19.9; EF 21.9 ● **Cooking Range**: Electric (as-built: induction) ● **Dishwasher**: 290 Rated kWh ● **Clothes Washer:** EnergyStar ● **Clothes Dryer:** Electric (as-built: heat pump) ● **Hot Water Fixtures:** 20.8 gal/day ● (as-built: expected 30 gal/day total water use) ● (as-built: expected 2,681 kWh/year electric vehicle (EV) use)
	Miscellaneous	● **Plug Loads:** 1905 kWh/yr
Renewables	Power Generation	● **PV System:** 1 kW; 2 kW; 3 kW; 4 kW; 5 kW; 6 kW (as-built: 6.5 kW) ● **PV Azimuth:** South (as-built: southeast) ● **PV Tilt:** 40 degrees (as-built: 3:12 and 9:12)

3.2 Modelica

Modelica is a model-based engineering tool and is used to model the different systems within the designed house. Modelica is used over other simulation tools due to its capability to model complex systems containing mechanical, electrical and thermal components. Unlike BEopt, Modelica tailors to different systems and designs rather than predefined systems. Also, due to having different layers to create the systems, Modelica quickly identifies errors in the model thereby reducing debugging time.

To better understand the selected systems used in the designed home, a physical description of each system must first be analyzed before implementation in Modelica. The systems in the home include the domestic hot water, the HVAC system, which takes into account the thermal zones and building envelope, and the electrical, which looks into how all the loads interact. The sections below describe the physical model chosen for each system.

3.2.1 DHW System

The DHW system chosen for design is a fifty gallon Sun Bandit® Solar Hybrid Electric Universal Water Heater (see appendix for specification as as-built specification). For modeling purposes, the system uses only the electric heater to heat up the tank. A schematic shown in Figure 2 describes the physical model. In this schematic, it can be understood that the fifty gallon DHW tank receives water from the city pipes at roughly 45 F and supplies greater than 105 F water to the sink, which replicates the appliances located throughout the house. To heat up the water in the tank, the electric heater is controlled by a temperature sensor. The sensor makes sure the water in the tank is at the proper temperature at which the tank can supply the sink hot water.

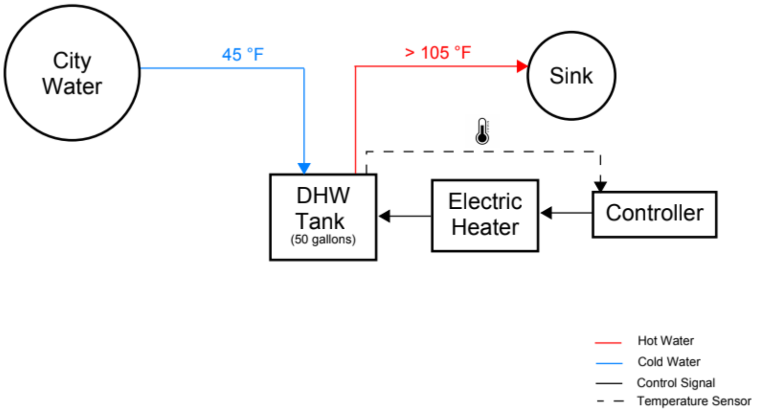


Figure 2: Domestic hot water schematic

A basic off-the-shelf electric tank was used for the house for purposes of initial cost (approximately $3,000 for the solar hybrid version versus approximately $700 for a basic electric tank not directly connected to RE). A secondary RE system was not needed. Additionally, an electric resistance versus heat pump option was used because it was more appropriate for the location in the house and climate (e.g., heat pump version could increase noise and decrease thermal comfort in the ADU bedroom adjacent to the mechanical closet, and the heat pump version could increase potential for nearby pipe freezing in critical loads scenarios).

3.2.2 HVAC System

The overall HVAC system takes into account the thermal zones, the building envelope and the types of systems used.

3.2.2.1 Thermal Zones

Understanding which zones are heated, cooled and ventilated, as well as the thermal bridging between the zones, brings insight into the size and type of systems to be used. A schematic of the thermal zones is seen in Figure 3. This schematic shows the floor plan layout of the designed home and the allocated thermal zones. On the first floor there are two thermal zones while on the second floor there is one. Window-to-wall ratios and door-to-wall ratios are calculated for each thermal zone as well as ceiling and roof insulation values. A wall-to-wall connection can be seen between thermal zone one and thermal zone two. A ceiling-to-floor connection can be seen between thermal zone three and thermal zone one.

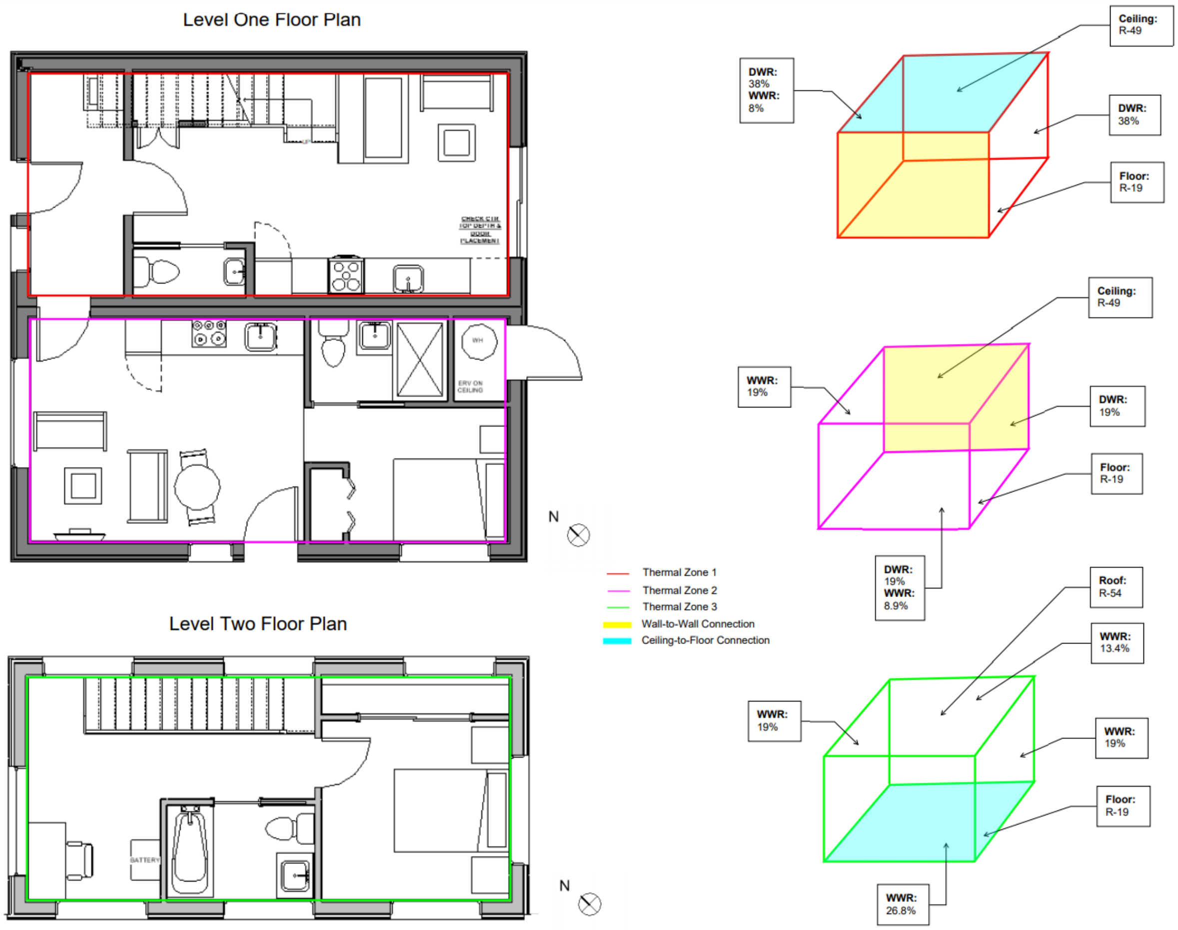


Figure 3: Thermal zone schematic (The mud room, common main and ADU entry, was eliminated and main kitchen and half bath moved in as-built house. Initial plan attempted to keep all services on the demising wall near the mechanical room.)

3.2.2.2 Building Envelope

The building envelope also plays a role in the HVAC system selection. Specifically, the materials of the building envelope can affect the heating and cooling loads. A schematic of the designed building envelope with the construction materials used is shown in Figure 4. The insulation values for the roof, walls, floors and foundation is listed. The window and door types are listed as well including the dimensions and locations. The U-factor and solar heat gain coefficient (SHGC) for the window types are mentioned too.

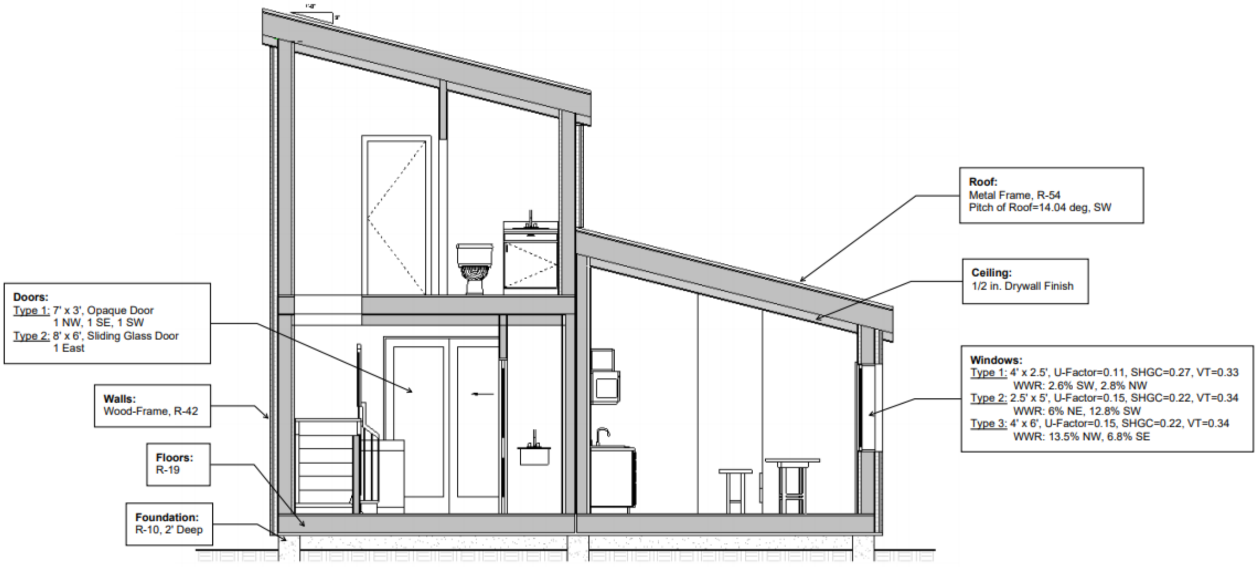


Figure 4: Building envelope schematic (The double shed roof was considered for PV generation but returned to a gable in the permit set for the purposes of reducing north wall height, interior air volume, and aesthetics.)

3.2.2.3 HVAC

After taking into account the thermal zones and building envelope, the type of HVAC system selected for the design of the house consists of minisplit systems for heating and cooling needs and an energy recovery ventilator (ERV) for ventilating needs. Figure 5 presents each of the zones and the corresponding equipment and setpoints necessary to heat, cool and ventilate each space.

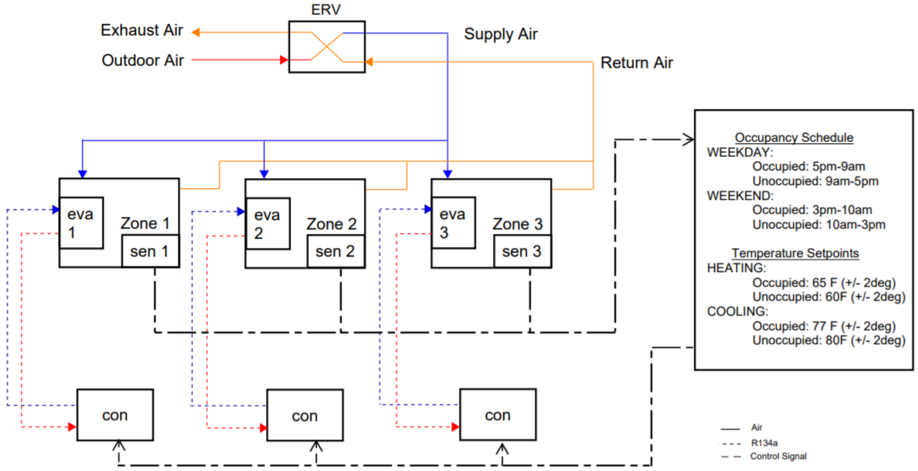


Figure 5: HVAC schematic (cooling mode)

For heating and cooling, this physical model shows how each zone has a minisplit system as presented by an evaporator and condenser. Each evaporator is connected to its own condenser accounting for a one to one, indoor to outdoor, ratio. A thermostat, represented by a sensor, is placed in each zone as well. This sensor controls the minisplit, or in terms of the schematic the condenser, for each zone and is on a time-based occupancy schedule. This means if the space is occupied or unoccupied based on time, the room setpoint changes. The setpoints depend on the season (heating or cooling) and the occupancy schedule depends on the time of day. For the setpoints, there is a deadband that the temperature should meet. The chosen minisplit for design is a 9 kBtuh with a heating seasonal performance factor (HSPF) of 12.5 and a seasonal energy efficiency ratio (SEER) of 30.5 (See the appendix for as-built specification).

While Figure 5 shows how the ERV is connected to the thermal zones, Figure 6 shows the physical model of how the air loop works inside an ERV. The system transfers both heat and moisture from one air stream to another. The heat from the return air is transferred to the incoming fresh, outdoor air by a heat exchanger. The purpose of the heat exchanger is to ensure the space retains heat or cold depending on season and weather. The process saves energy by pre-heating or pre-cooling the outdoor air to a relatively close temperature of the inside space by mixing the air streams in the heat exchanger. Ultimately, this system was chosen for design since less energy is required to condition the fresh air. (In the as-built house, no electrical resistance pre/post-conditioning is installed. See the appendix for equipment specifications.)

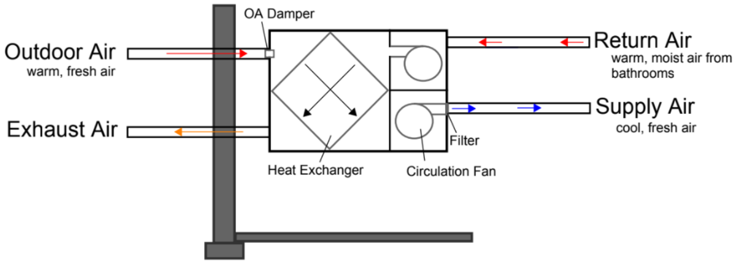


Figure 6: ERV schematic (cooling mode)

3.2.3 Electrical System

The designed house is supplied by two main power sources: the grid and a 6.5 kW PV system. The house also has its own 13.5 kWh battery storage system in which the house can serve as its own source of electricity if a power outage were to exist. (A home battery is to be installed for demonstration purposes for the Solar Decathlon competition but not a permanent feature of the home. No battery option was found that was formally tested for performance, durability, and safety at Fraser's elevation of 8,573 feet; and the likely near-term ability of the owners to use bi-directional flow from a purchased electric vehicle limits is value of a separate home battery in this instance.) These sources supply electricity to the miscellaneous electric loads, like the equipment and appliances, the HVAC system and the DHW system. A control exists where the battery and PV can supply the electrical demand and if there is excess generation from the PV, it can charge the battery. Figure 7 presents the physical model of the electrical connection between the supply and demand.

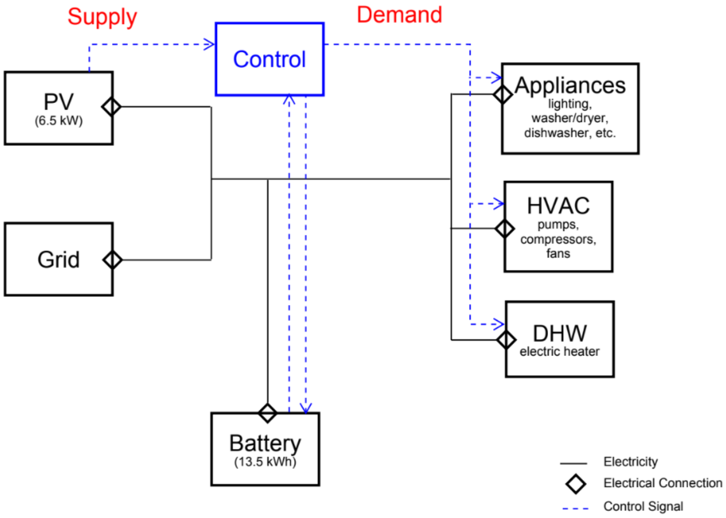


Figure 7: Electrical schematic (The as-built home demonstrates control using Home Assistant for load management and automatic demand response. The system serves as a platform for future integration of other building systems not integrated for the purposes of demonstration.)

4. Results and Analysis

4.1 BEopt

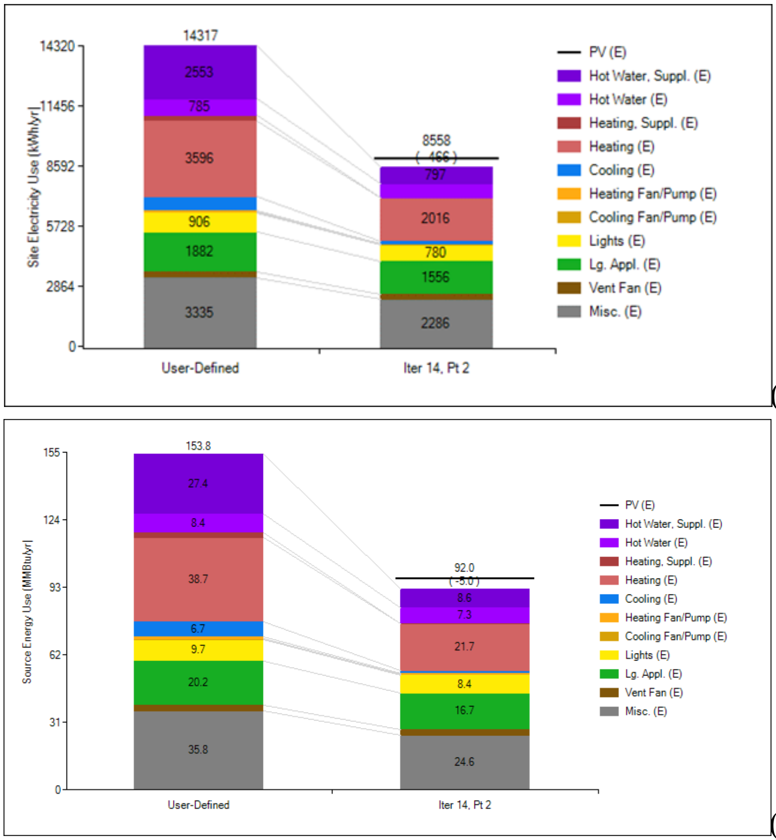
4.1.1 Energy Performance

To determine the energy performance of a house, the annual electricity consumption and peak demand can be found. A baseline house, following code standards, was simulated first in BEopt to get the hourly annual electricity usage for a typical build in Boulder, Colorado. Then, an optimization on the baseline was conducted to find a ZE design. The optimization introduced different EE options for the HVAC, lighting and appliance efficiencies. An RE option, such as rooftop PV, was also included in the optimization. Table 5 presents the differences between the selected measures in the baseline model and the optimized ZE design. The initial costs are also presented.

Table 5: BEopt inputs for models

			Code Standards	ZE
Envelope	Walls	Wood Stud	R-13 Fiberglass Batt., 2x4, 16 in. oc ($5983)	R-21 Fiberglass Batt., 2x6, 24 in. oc ($6385)
	Ceiling/Roof	Finished Roof	R-30C Fiberglass Batt., 2x8 ($1870)	R-60 Closed Cell Spray Foam, 2x10 ($6192)
	Thermal Mass	Exterior Wall Mass	½ in. Drywall ($1529)	⅝ in. Drywall ($1694)
		Ceiling Mass	½ in. Drywall ($1019)	⅝ in. Drywall ($1129)
	Airflow	Natural Ventilation	Cooling Months Only, 7 days/wk	Year-Round, 7 days/wk
Windows and Shading	Windows/Doors	Windows	Clear, Double, Non-metal, Air ($7285)	Low-E, Double, Insulated, Air, M-Gain ($11,602)
Equipment	Space Conditioning	Mini-Split Heat Pump	9 kBtuh, SEER 19, HSPF 9.8 ($5072)	9 kBtuh, SEER 30, HSPF 13.5 ($5613)
	Space Conditioning Schedules	Cooling Setpoint	74 F	76 F
		Heating Setpoint	70 F	67 F
Appliances and Lighting	Lighting	Lighting	100% CFL ($73)	100% LED ($187)
	Appliances and Fixtures	Refrigerator	EF = 15.9 ($612)	EF = 19.9 ($629)
		Dishwasher	318 Rated kWh ($879)	290 Rated kWh ($959)
		Clothes Washer	Standard ($590)	Energy Star ($662)
		Hot Water Fixtures	41.6 gal/day	20.8 gal/day
	Miscellaneous	Plug Loads	2858 kWh/yr	1905 kWh/yr
		Extra Refrigerator	EF = 15.9 ($612)	EF = 19.9 ($629)
Renewables	Power Generation	PV System	NA	6 kW, South, 40 degrees ($17,460)

Figure 8 presents the annual energy usage comparison of the code standard design versus the ZE design. Since the building has on-site energy, the source energy usage is also presented to confirm the design is ZE as defined by NREL. The site electricity use for the baseline build is 14,317 kWh/yr while the ZE build is 8,558 kWh/yr. This concludes that the ZE shows better energy performance by reducing the annual energy consumption by 40%.



(a)

(b)

Figure 8: Site energy usage (a) and source energy usage (b) of code standards design vs. ZE design

After an optimized design was found, better than standard occupant behavior was also analyzed to see the effects in the energy performance. In BEopt, occupant behavior is based on usage of the appliances. The energy efficient occupant behavior is introduced by changing the usage of the appliances from typical use to 80% usage. Table 6 presents the energy use changes in the appliances.

Table 6: BEopt inputs for ZE design with EE behavior

			ZE - Standard Behavior	ZE - EE Behavior
Appliances and Lighting	Appliances and Fixtures	Cooking Range	417 kWh/yr	333 kWh/yr
		Dishwasher	69.2 kWh/yr	55.4 kWh/yr
		Clothes Washer	29.1 kWh/yr	23.3 kWh/yr
		Clothes Dryer	1.0 Energy Multiplier	0.8 Energy Multiplier
	Miscellaneous	Plug Loads	1905 kWh/yr	1429 kWh/yr

Figure 9 presents the site electricity usage for the ZE design with better than standard occupant behavior. The site electricity usage for this case is 7,875 kWh/yr.

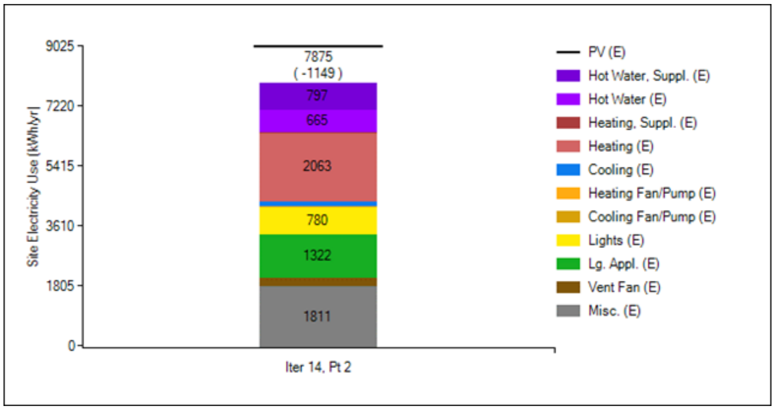


Figure 9: Site energy usage of ZE design with good behavior

The annual energy consumption of good occupant behavior in comparison to the ZE design with standard occupant behavior shows a 7.98% reduction. While this reduction is low, it still proves that there is a direct correlation to reducing the energy use, in terms of annual consumption, by influencing energy efficient behaviors.

Furthermore, the load duration curves in Figure 10 presents the peak demand of the three designs: code standard, ZE, and ZE with good occupant behavior. The peak demand is highest with code standards at 10.22 kW/yr and lowest with a ZE design with good occupant behavior at 8.70 kW/yr. The ZE design at standard behavior has a peak demand of 8.80 kW/yr.

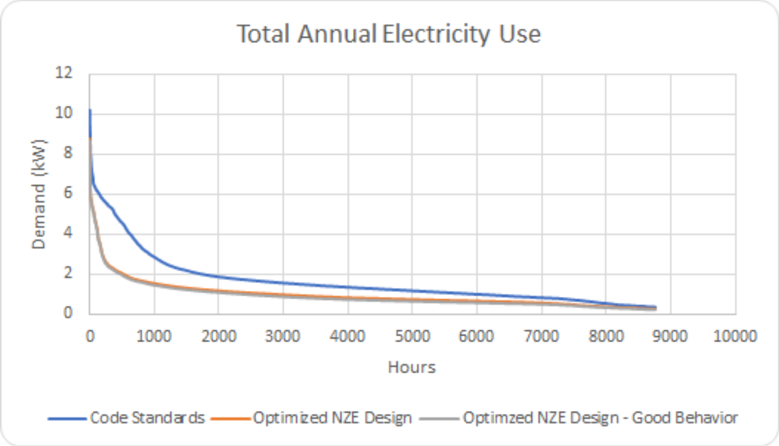


Figure 10: Load duration curves

When comparing the peak demand of the ZE design with standard occupant behavior to that of code requirements, a 13.89% reduction is found. Meanwhile, when comparing the peak demand for the ZE design with standard occupant behavior to that with better than standard occupant behavior, there is barely a reduction.

4.1.2 Energy Cost Analysis

BEopt helped to further assess an energy cost analysis. Figure 11 presents the optimization curve conducted in BEopt to find the ZE design and the associated annualized energy costs. The optimization curve ultimately defines the path to ZE extending from the base case of the code-compliant home. A ZE building results in 100% energy savings. This can be seen as the last point in the figure. From point one, better known as the base case, EE measures (i.e. improvements in R-values, HVAC SEER, etc.) are applied, as mentioned previously in the report, thereby reducing the energy use. An annual cost optimum occurs at the second to last point on the figure. However, ZE is not yet achieved. From that point on, a rise in energy cost is seen due to the marginal cost of saved energy equaling the cost of producing PV energy. In other words, the energy savings to achieve ZE is solely a result of adding PV capacity.

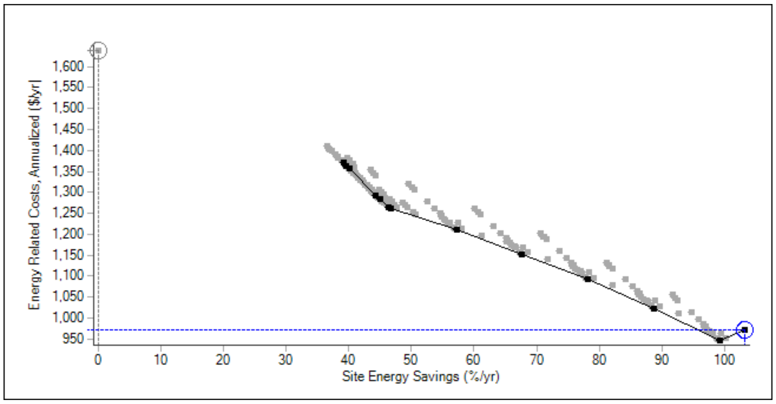


Figure 11: BEopt optimization curve

Table 7 investigates the cost breakdown results more closely. The ZE design, although a higher initial cost of $27,235 or 35% more, the annual savings is worth the investment. In terms of savings, there is a 41% savings and in terms of energy use there is a 103% site energy use savings. This means the ZE design is not zero energy but actually net-positive since it produces 3% more energy than it consumes. The ZE design also presents a higher total present value of $83,197, again presenting itself as the better investment.

Table 7: Energy cost analysis of code standards design vs. ZE design

Point	**Site Energy Savings [%/yr]**	**Energy Related Costs, Annualized [$/yr]**	**Total Present Value [$]**	**Total Initial Cost [$]**
Code Standards	0	1638.28	53,408	51,302
ZE	103.25	971.47	83,197	78,537

4.2 Modelica

4.2.1 DHW System

The DHW system is built in Modelica by following the physical model schematic as presented in the previous section. Figure 12 presents the schematic in Modelica. The hot water tank volume is fifty gallons with a height of forty-eight and a half inches and insulation thickness of two inches, which follows the specification listed for the Sun Bandit® Solar Hybrid Electric Universal Water Heater (see the appendix for as-built specification). To run the simulation, the terminal is connected to the grid to supply the electric heater with electricity and the sink is represented by the schedule bus, which is connected to a constant mass flow rate mimicking the hot water use from appliances. The amount of water the house uses per day is set to a constant 0.00284 kg/s, or roughly 2.7 gallons per hour.

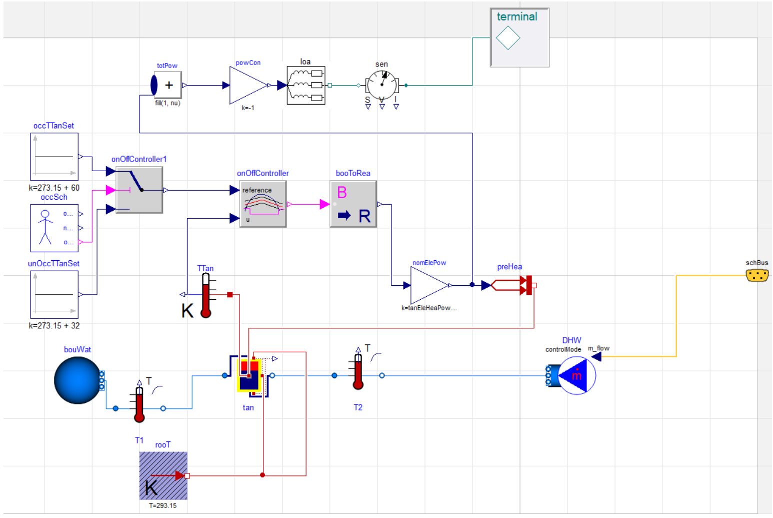


Figure 12: Modelica schematic of domestic hot water

City water enters the tank at a constant 68 F throughout the year, under the assumption the piping is very well insulated. The water in the tank undergoes a heating process by an electric heater. The control for the heater states the water in the tank needs to be at 106 F (315.15 K), with a deadband of two degrees, during the occupied hours of 8AM-9AM and 6PM-8PM. This is to ensure the supply water to the appliances is at that temperature. When the house is unoccupied, the water tank temperature is set to a low limit temperature of 86 F (303.15 K). Figure 13 shows the tank reaching and maintaining setpoint during occupied hours for a one day period. During unoccupied hours, the tank temperature is seen to not fall below the low limit threshold.

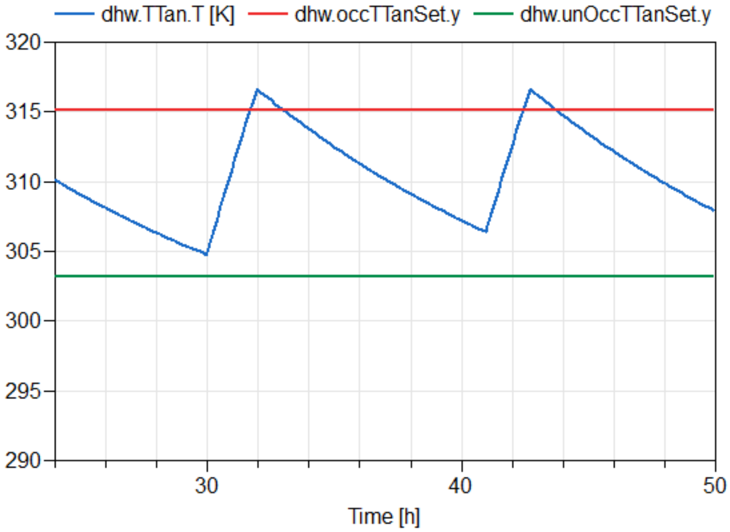


Figure 13: DHW reaching and maintaining setpoint

Figure 14 shows the control logic of the electric heater for a one day period. To get the tank to reach setpoint during occupied hours, a two hour startup time is needed in the morning and a one hour startup time is needed in the evening. At 6AM the electric heater is seen to turn on, and at 8AM the electric heater is seen to turn off due to reaching setpoint. The electric heater does not turn on again until 5PM due to the space being unoccupied. In the evening, it stays on for one hour until it reaches setpoint at 7PM. It does not turn on again until the following morning. This logic repeats for every day of the year. Since hot water is only used for three hours daily, the total gallons used per day is 8.1.

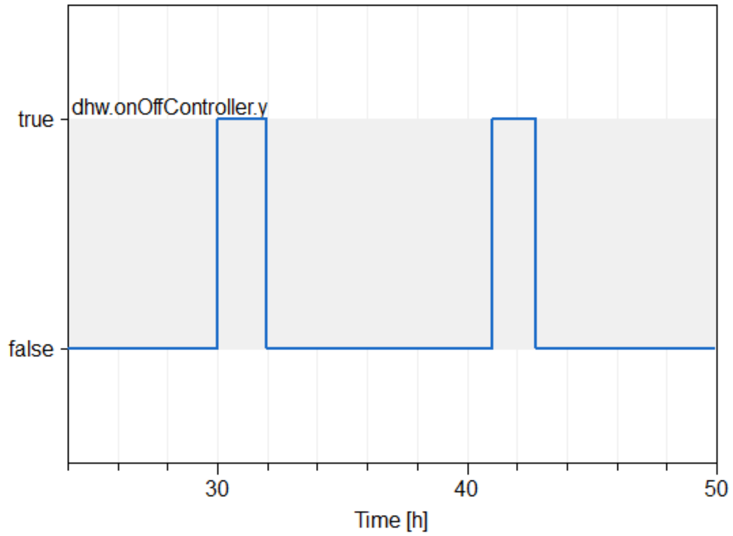


Figure 14: DHW control logic

4.2.2 HVAC System

4.2.2.1 Thermal Zones and Building Envelope

Before the HVAC system can serve the loads of the thermal zones, the zones themselves need to be created within Modelica. The models follow their corresponding thermal zone and building envelope schematic as previously mentioned in the report. Figure 15 presents this model in Modelica.

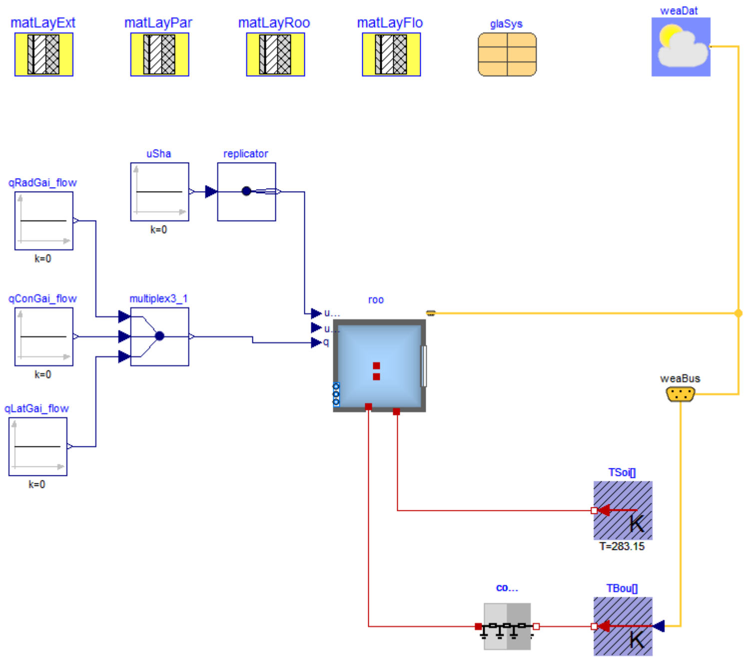


Figure 15: Modelica schematic of a thermal zone

Each thermal zone is connected to a weather bus with data for Boulder, Colorado. It is also connected to a prescribed soil temperature to simulate the heat transfer from the foundation to the room. Each thermal zone has different construction materials for the exterior walls, partition walls, roof/ceiling, and floors. Table 8 presents the materials used for each construction of each zone. The actual design is used for reference in the material choices for the model simulation, and the two can be compared.

Table 8: Construction materials for thermal zones

Thermal Zone 1, 2	
Ceiling:	
Material Used in Construction:	**Material Used in Model:**
¾” Plywood	Plywood
9 ½” TJI	Plywood
½” Plywood	Plywood
Floor:	

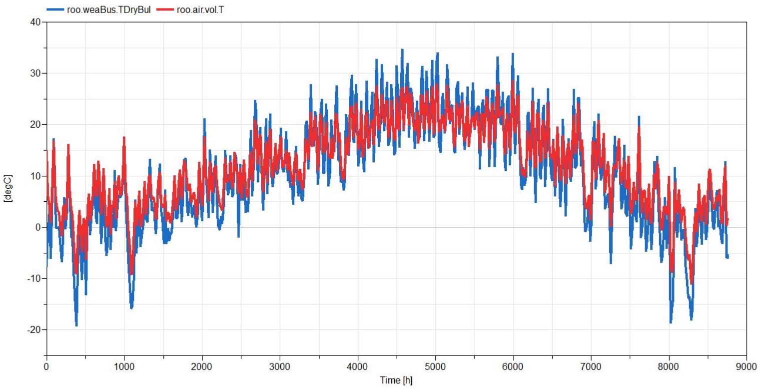
Material Used in Construction:	**Material Used in Model:**
¾” Plywood	Plywood
9 ½” TJI	Plywood
Foundation Wall	Concrete
Exterior Walls: (R-42 total for insulation layers only)	
Material Used in Construction:	**Material Used in Model:**
Beetlekill Pine Siding	Plywood
¾” Air Gap	Negligible
Weather Resistive Barrier	Negligible
2” Comfortboard (Wool Insulation), R-8	Insulation Board
½” Plywood	Plywood
7.5” Batt. Insulation, R-27	Insulation Board
Vapor Barrier	Negligible
2” Batt. Insulation, R-7	Insulation Board
½” Gypsum	Gypsum Board
Partition Wall:	
Material Used in Construction:	**Material Used in Model:**
½” Gypsum	Gypsum Board
1 ½” Air Gap	Negligible
½” Plywood	Plywood

1 ½” Air Gap	Negligible
½” Gypsum	Gypsum

Thermal Zone 3	
Roof: (R-54 total for insulation layers only)	
Material Used in Construction:	**Material Used in Model:**
1 ½” Metal Roof	Steel
Weather Resistive Barrier	Negligible
⅝” Plywood	Plywood
9” Batt Insulation, R-33	Insulation Board
Vapor Barrier	Negligible
3 ½” Batt Insulation, R-13	Insulation Board
1 ½” Gypsum	Gypsum Board
Floor:	
Material Used in Construction:	**Material Used in Model:**
¾” Plywood	Plywood
9 ½” TJI	Plywood
½” Plywood	Plywood
Exterior Walls: (R-42 total for insulation layers only)	
Material Used in Construction:	**Material Used in Model:**

Beetlekill Pine Siding	Plywood
¾” Air Gap	Negligible
Weather Resistive Barrier	Negligible
2” Comfortboard (Wool Insulation), R-8	Insulation Board
½” Plywood	Plywood
7.5” Batt. Insulation, R-27	Insulation Board
Vapor Barrier	Negligible
2” Batt. Insulation, R-7	Insulation Board
½” Gypsum	Gypsum Board

The weather file for Boulder, Colorado in Modelica resulted in January 17th being the coldest day and July 10th being the hottest day. Each of the thermal zones was simulated for a year to project the indoor air temperature of the space without an HVAC system installed. In Figure 16, the plots of each of the zones are shown.



(a)

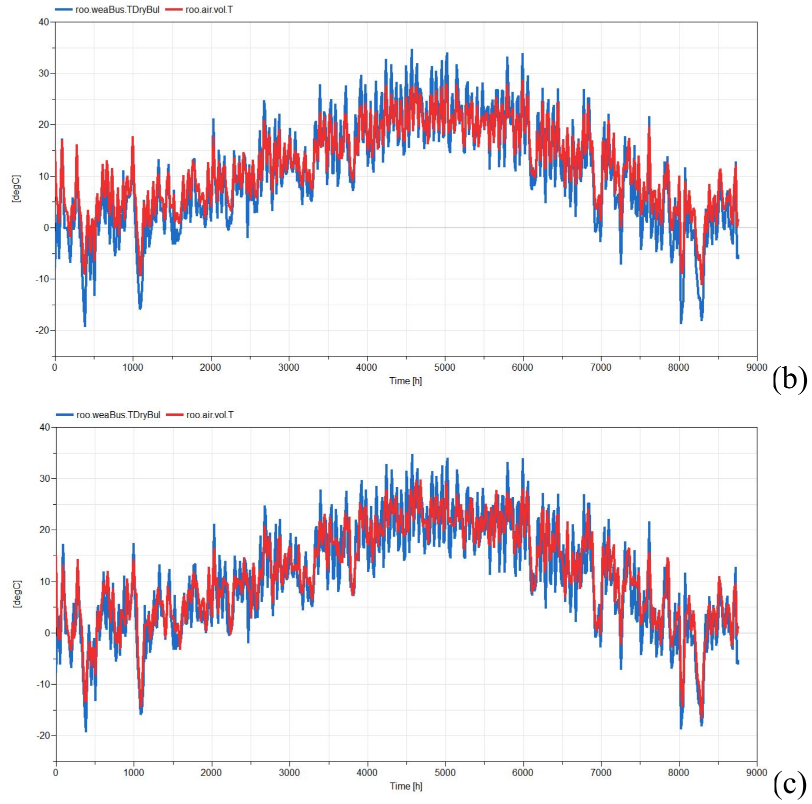


Figure 16: Yearly indoor and outdoor temperatures for (a) thermal zone 1 (b) thermal zone 2 and (c) thermal zone 3

For all three thermal zones, the coldest indoor day was seen on December 12th at 7AM. Meanwhile the hottest indoor day was seen on September 7th at 5PM for thermal zones one and two and July 14th at 11PM for thermal zone three. This can be seen in Table 9 as well.

Table 9: Coldest and hottest day for thermal zones

	Coldest Day	Hottest Day
Thermal Zone 1		
	Dec. 12 @ 7 AM	**Sept. 7 @ 5 PM**
Indoor Air Temperature [C]	-11.22	28.68
Indoor Air Temperature [F]	11.80	83.62
Thermal Zone 2		
	Dec. 12 @ 7 AM	**Sept. 7 @ 5 PM**
Indoor Air Temperature [C]	-11.23	28.78
Indoor Air Temperature [F]	11.79	83.81
Thermal Zone 3		
	Dec. 12 @ 7 AM	**Jul. 14 @ 11 PM**
Indoor Air Temperature [C]	-16.70	29.76
Indoor Air Temperature [F]	1.94	85.56
Thermal Zones 1-3		
	Jan. 17 @ 1:30 AM	**Jul. 10 @ 2:25 PM**
Outdoor Drybulb Temperature [C]	-19.35	34.76
Outdoor Drybulb Temperature [F]	-2.83	94.56

4.2.2.2 HVAC

Now that the thermal zones are created, the HVAC system, consisting of the minisplit systems and the ERV, can be connected and analyzed. The top layer of the minisplit and ERV in connection with the zones is shown in Figure 17. The minisplit is built first and then the ERV is added on.

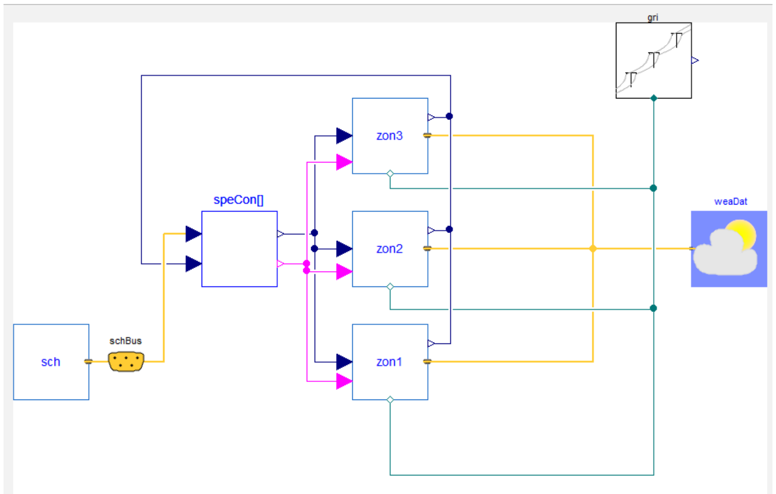


Figure 17: Top level model of HVAC system

The three minisplits serving each thermal zone is controlled by an occupancy schedule. The occupancy schedule is dependent on the time of day during a weekend and weekend and on whether the system is in heating or cooling mode. For instance, during a weekday in cooling mode, the schedule states for the hours of 5PM to 9AM, the switch is on to maintain a temperature of 77 F. Otherwise, the switch is off and should state unoccupied and maintain a temperature of 80 F. The schedule is also attached to a constant mass flow rate of 0.00284 kg/s to mimic the hot water usage. The model for the occupancy schedule is constructed as Figure 18 shows.

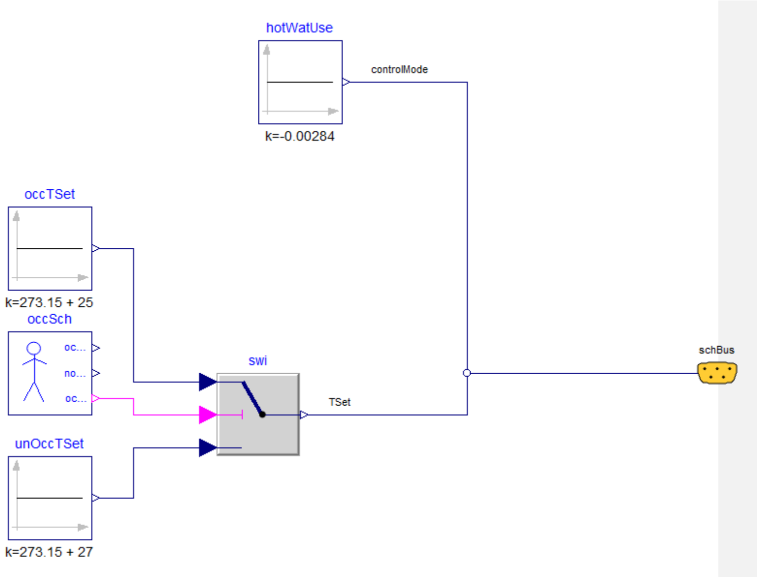


Figure 18: Occupancy schedule schematic (cooling mode)

In a top level model of the HVAC system, the schedule is seen to be connected to the speed controller of the minisplit heat pump. The heat pump speed controller consists of a switch that maintains the setpoint of the occupancy plus or minus two degrees. The switch also controls if the heat pump of the minisplit should be on or off. This layer can be seen in Figure 19.

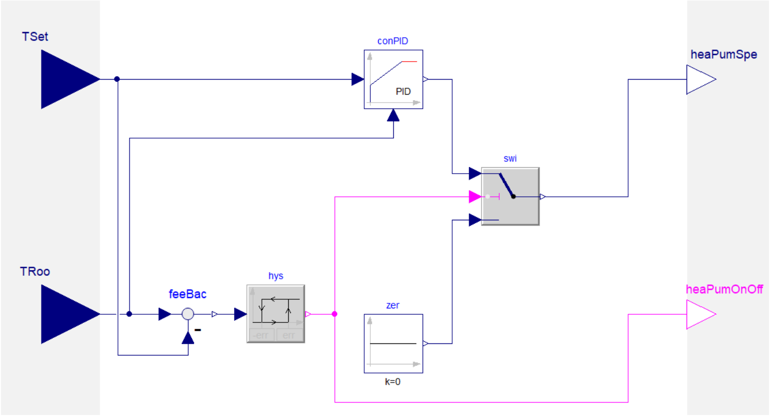


Figure 19: Speed controller of minisplit heat pump

By looking at the top layer again, connected to this speed controller are the minisplits in each of the thermal zones. For simulation reasons, the minisplit is represented by a variable speed direct expansion coil during cooling season and a heating coil during heating season. The evaporator and condenser are located in both these coil components. The difference is shown in Figure 20. Inside the presented thermal zone layer, the control of the heat pump speed controller can be more closely analyzed. The switch that turns the system on and off is connected to a fan that simulates the flow of air to room while the deadband is connected to the minisplit directly.

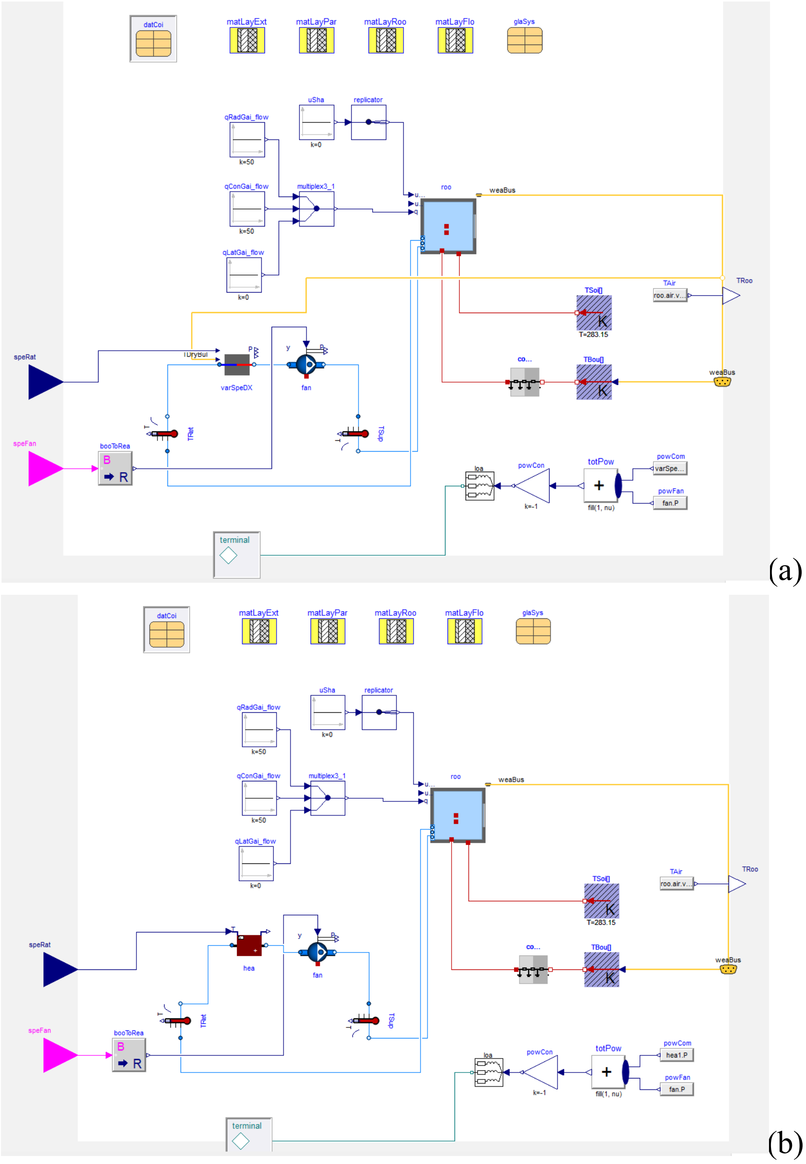


Figure 20: Thermal zone with minisplit during cooling (a) and heating (b)

After running the simulation during the hottest day, July 10th, for each of the thermal zones, under the assumption it falls on a weekday, the minisplit is seen to follow the occupancy schedule pattern as mentioned previously. Figure 21 shows the supply temperature to the zones, as well as the room temperatures, return temperatures and outdoor temperatures during cooling mode. The thermal zones can be seen to be 77 F (25 C) during occupied hours and 80 F (27 C) during unoccupied hours.

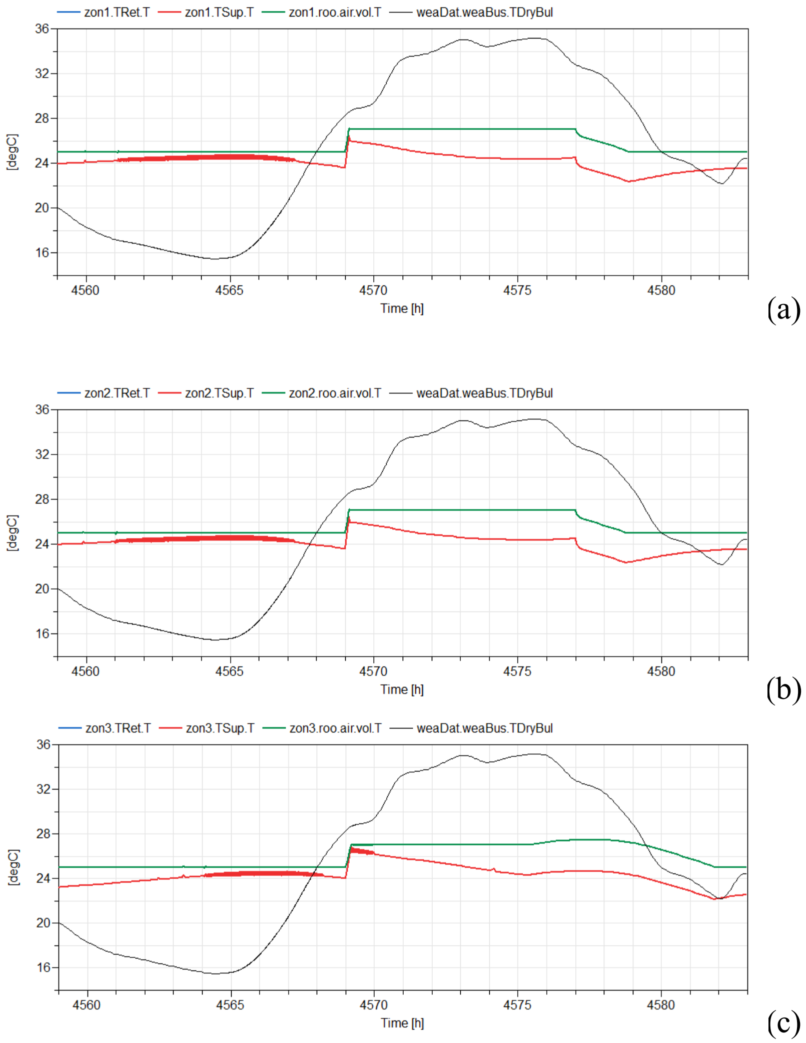


Figure 21: Temperatures in thermal zone 1 (a), 2 (b) and 3 (b) during weekday in cooling mode

In heating mode, the occupancy schedule changes. Now the schedule states for the hours of 5PM to 9AM, the switch is on to maintain a temperature of 65 F (18 C). Otherwise, the switch is off and should state unoccupied and maintain a temperature of 60 F (16 C). A deadband of two degrees is still set in place. Figure 22 shows the supply temperatures, room temperatures, return temperatures and outdoor temperatures during the coldest day on January 17th for the three zones, under the assumption it falls on a weekday again. The thermal zones can be seen to be to follow the set occupancy schedule.

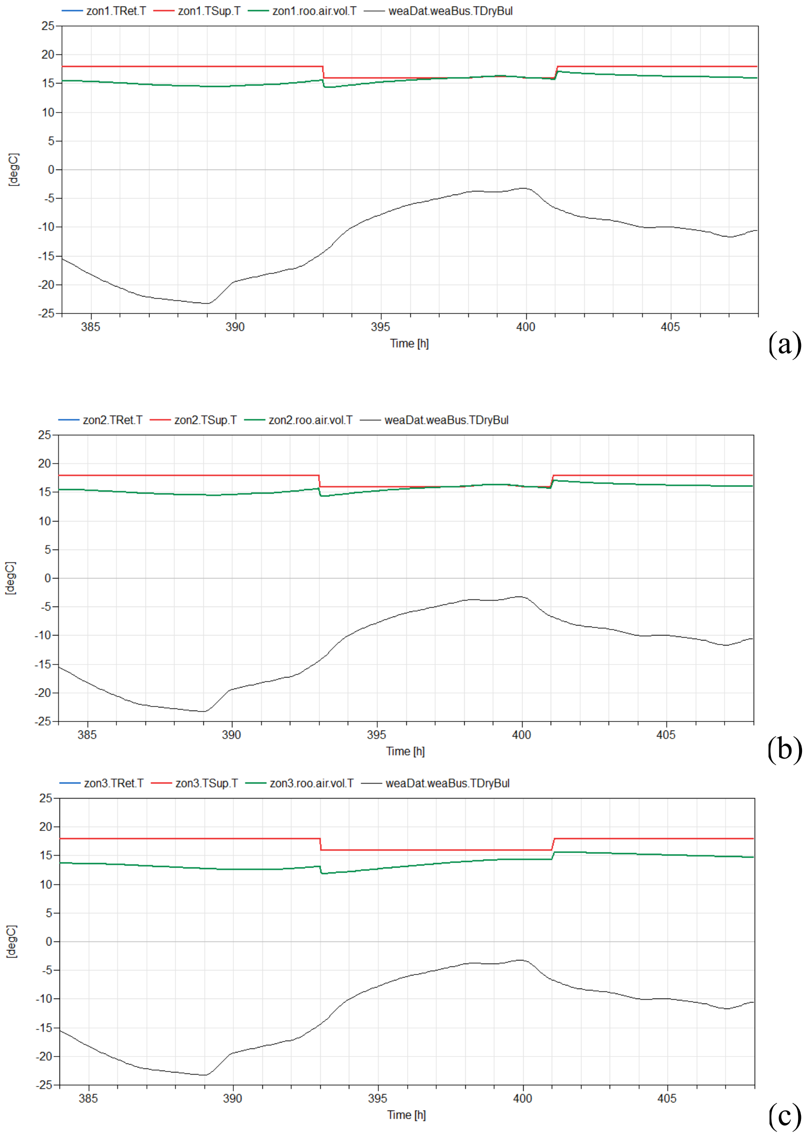


Figure 22: Temperatures in thermal zone 1 (a), 2 (b) and 3 (b) during weekday in heating mode

Now that the heating and cooling component of the HVAC system is built, the ventilating component is added on. Inside the thermal zone layer, the ERV is attached to the fan that blows air into the zone. The schematic is seen in Figure 23. The ERV is modeled as a heat exchanger component in Modelica which follows the physical schematic as mentioned in a previous section.

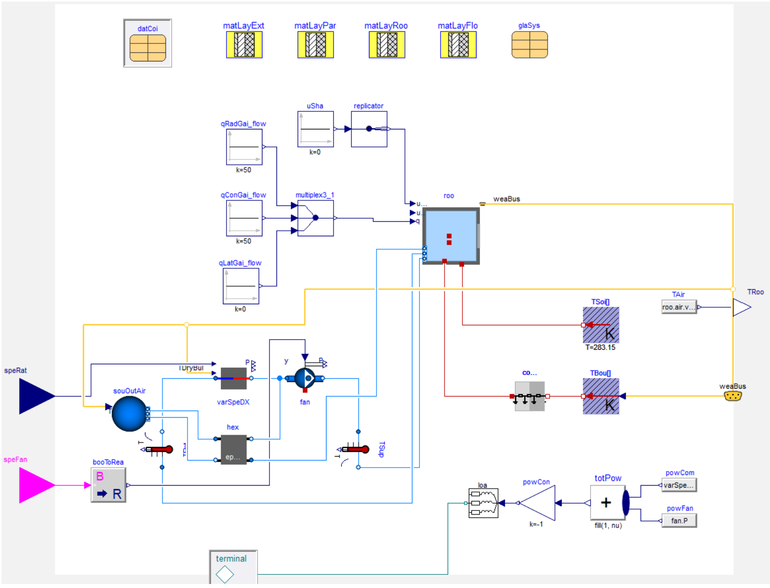


Figure 23: Thermal zone with minisplit and ERV

To show that the ERV is functioning, or in other words the zone is being ventilated, Figure 24 shows that the total mass flow rate of the fan into the thermal zone includes both the minisplit and the ERV. The simulation takes place over a seven hour period on July 10th.

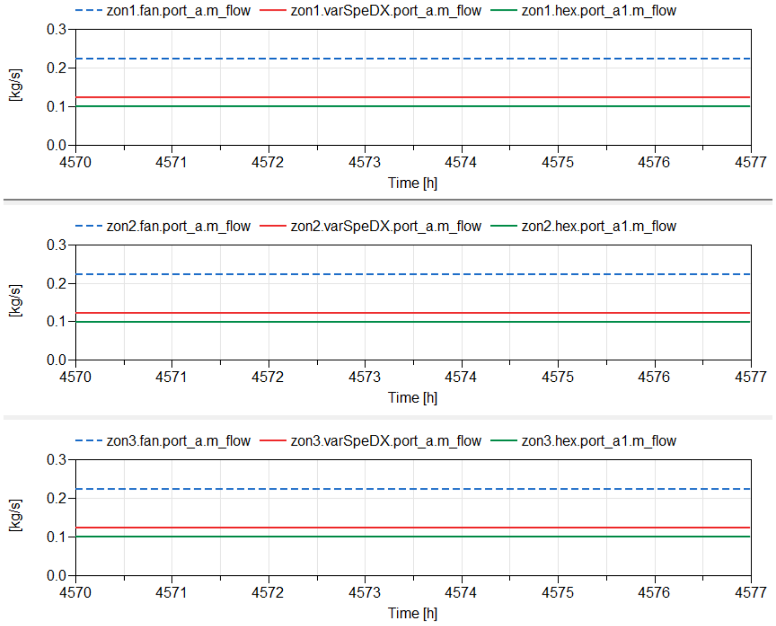


Figure 24: Mass flow rate of fan by ERV and minisplit systems for thermal zones

The volumetric flow rate of the minisplit for each zone is 200 CFM which amounts to a mass flow rate of 0.12 kg/s, which is shown in the figure above for each zone. For the ERV, the total volumetric flow rate is 475 CFM. Therefore, for each zone, the volumetric flow rate is 158 CFM which amounts to a mass flow rate 0.1 kg/s. The conversion from volumetric flow rate to mass flow rate is completed by multiplying by volumetric flow rate by the density of air which is 1.3 kg/m^3. For each zone in the graph above, the fan proves to flow a total of 0.22 kg/s, which is the flow rate of both the minisplit and the ERV. Thereby the model shows the zones are in fact being ventilated, as well as in this case cooled.

4.2.3 Electrical System

The last step in the Modelica modeling process is connecting all the zones with the miscellaneous electric loads and the DHW system. The PV system is also connected to ensure zero energy status by the energy power balance represented as the mathematical expression of $E_{PV}-E_{load}=0$. This states that the generation of the PV system must be equal to the power consumed by all the loads from the building over the course of a year. E_{load} consists of the miscellaneous electric loads, HVAC from the three thermal zones, and the DHW system. If the equation results in a negative number, this means extra power must be supplied from the grid during the year. While if the equation results in a positive number, this means there is excess power being generated at times during the year. In other words, a negative number means the building is not zero energy, and a positive number means the building is net-positive. The top layer of the model is displayed in Figure 25.

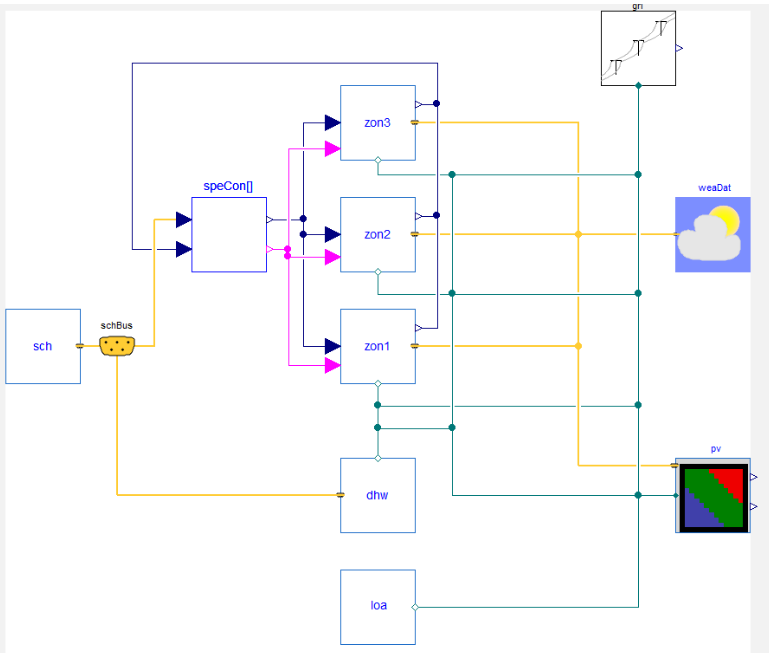


Figure 25: Top level model of connected systems

The dataset for miscellaneous electric loads is based off of the Building America House Simulation Protocols and uses the building characteristics for a low load residential home in Boulder, CO [8]. The annual hourly load profile has a minimum of 290 Watts and a maximum of 1076 Watts. An hourly load profile for one day of the dataset is shown in Figure 26. The power of the load is negative which means the power is being consumed.

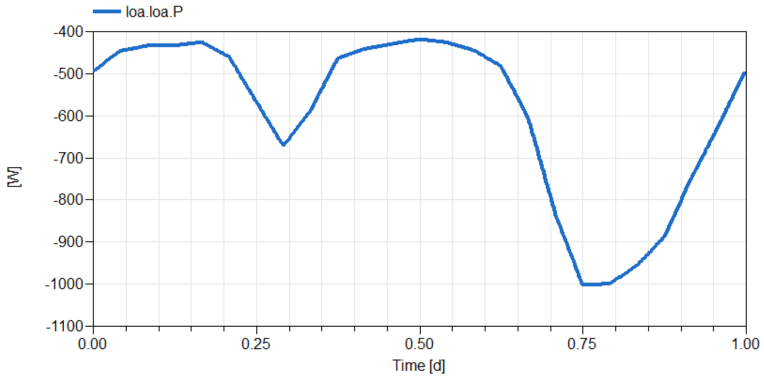


Figure 26: Hourly miscellaneous electric loads profile

For the building HVAC loads, the hourly load profiles from the three thermal zones on July 10th is shown in Figure 27. The maximum HVAC power consumed for thermal zone one, two and three on that day respectively are 1683, 1681, and 1685 Watts respectively. The annual hourly load profile of the combined loads has a minimum of 612 Watts and a maximum of 5127 Watts.

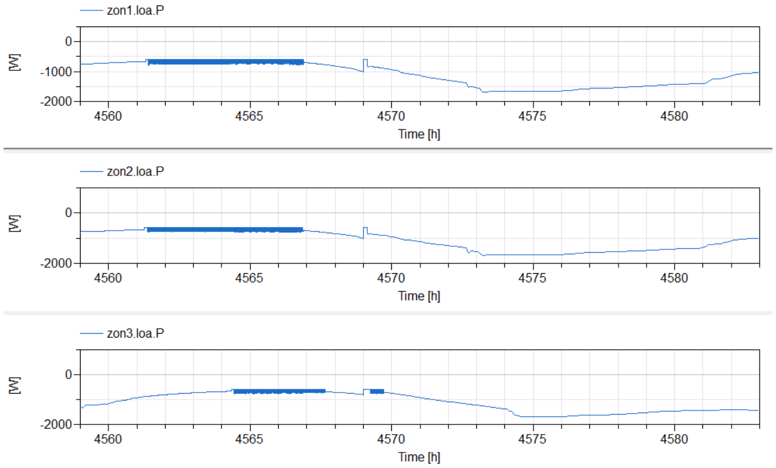


Figure 27: HVAC loads for thermal zones

The hourly load profile of the DHW system for July 10th is shown in Figure 28. The maximum power consumed in 1500 Watts. The power is seen to turn on and off, which follows the control logic prescribed to it as mentioned in a previous section. The annual hourly load profile has a maximum power usage of 1500 Watts as well since this is the maximum power rating of the chosen DHW system.

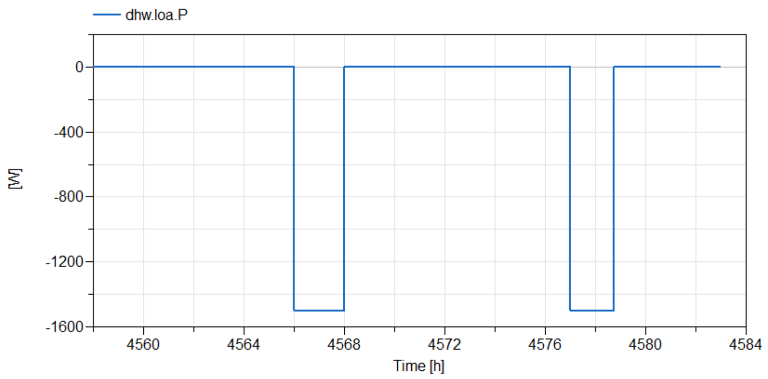


Figure 28: Power of DHW

To prove the energy balance equation, PV is added to the Modelica model as a source of generation. The inputs for the PV system are shown in Table 10.

Table 10: Modelica inputs for PV system

Parameters		**As-built modification**
Area of PV [m2]	36	24 panels as specified in the appendix
Module Conversion Efficiency [9]	0.204	Panel efficiency 19.3%; DC to AC size ratio: 1.01; Inverter and power optimizer efficiency: 98%
AC Conversion		
Power Factor	0.8	
Efficiency of DC/AC Conversion	0.8	
Orientation		
Surface Tilt [deg]	40	8 panels at 9:12; 16 panels at 3:12
Latitude [deg]	40.015	
Surface Azimuth [deg]	45	135

The power generated by the system for the days of July 9th and 10th are shown in Figure 29. The power of the system is positive to show generation rather than consumption. The maximum power generated for those days is 6595 Watts. The annual hourly load profile has a maximum power of 6449 Watts which is generated on June 18th.

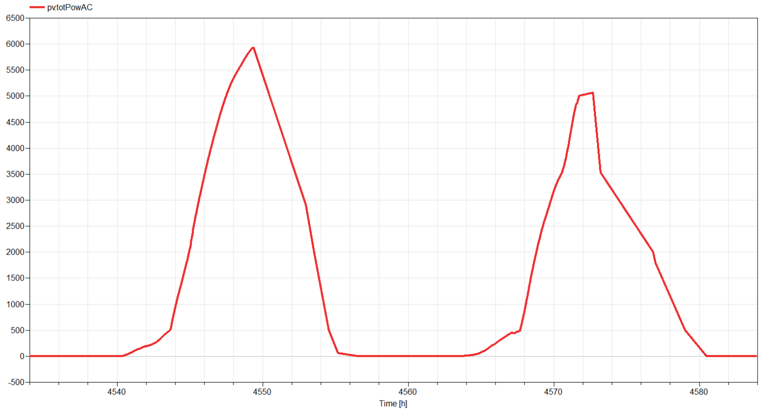


Figure 29: PV power generation on July 9th and 10th

For the competition, the building not only has to be zero energy but also has to prove resilience. Therefore, a battery storage system is in the design for the capability of being off-grid. Another Modelica model includes the addition of a battery storage system. The top layer model is presented in Figure 30. The battery storage unit is sized at 13.5 kWh. The parameters used for the battery in model is presented in Table 11.

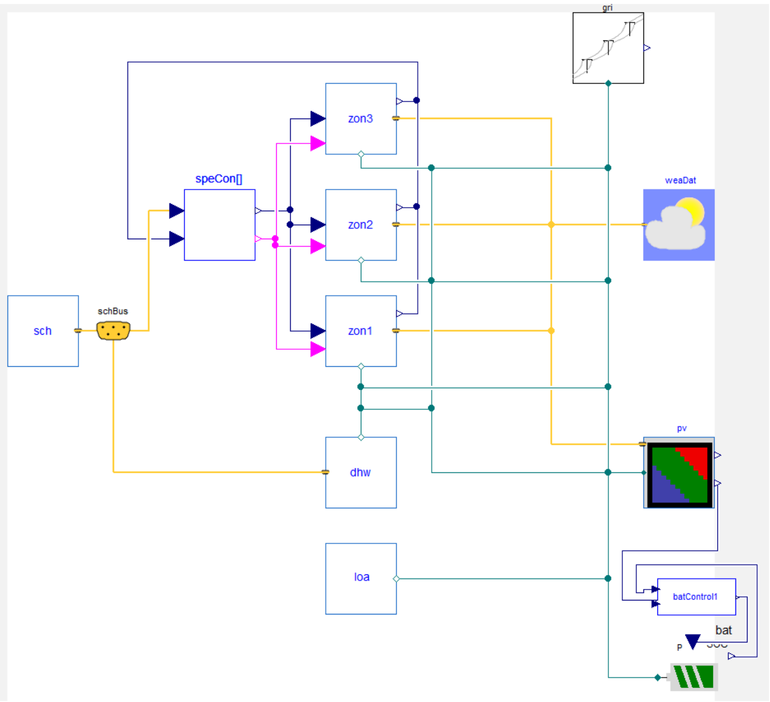


Figure 30: Top layer of connected systems with battery storage system

Table 11: Modelica inputs for battery storage system

Parameters	
Efficiency during charging	0.9
Efficiency during discharging	0.9
Initial charge	0.1
Size [kWh]	13.5
Nominal voltage [V]	120
AC Conversion	
Power factor	0.9
Efficiency of DC/AC conversion	0.95

The battery has a control logic in place as shown in Figure 31. The logic of the charge and discharge times of the battery is controlled by the power generation from the PV. The battery is told to begin charging when the PV power generated is greater than or equal to 2000 Watts and to continue charging until the SOC reaches full. The logic then says to hold that charge until the PV power generation reduces to 500 Watts or less. When the PV power is 500 Watts or less, the battery is told to begin discharging until the SOC is empty. The charging and discharging power is assumed to be controlled at a constant value of 3500 Watts**.**

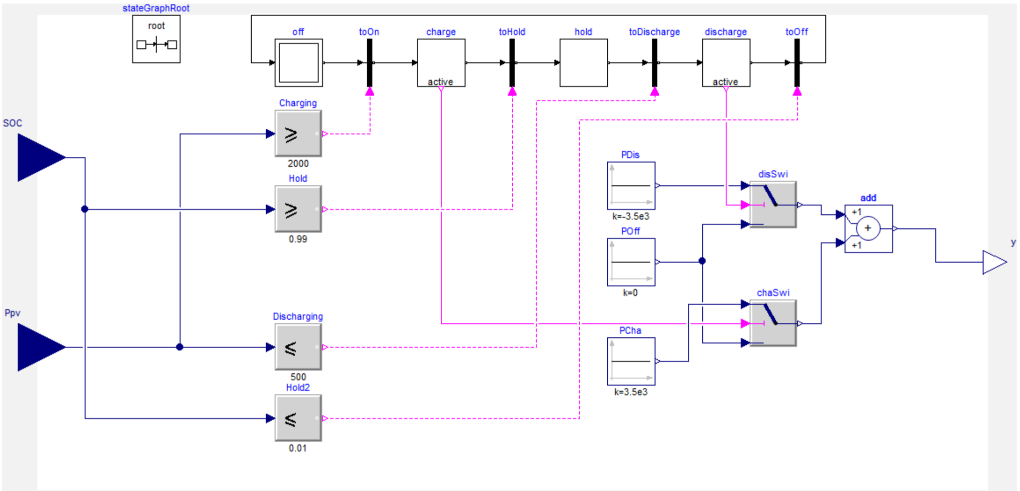


Figure 31: Battery control logic

Figure 32 shows the SOC of the battery on July 10th. The initial SOC can be seen as 0.1, or 10% full. The battery begins charging at 10AM until full at 2:15PM. The battery begins discharging at

8PM until empty at 11:15PM. This is consistent with when the PV power generation reaches 2000 Watts and 500 Watts for the day.

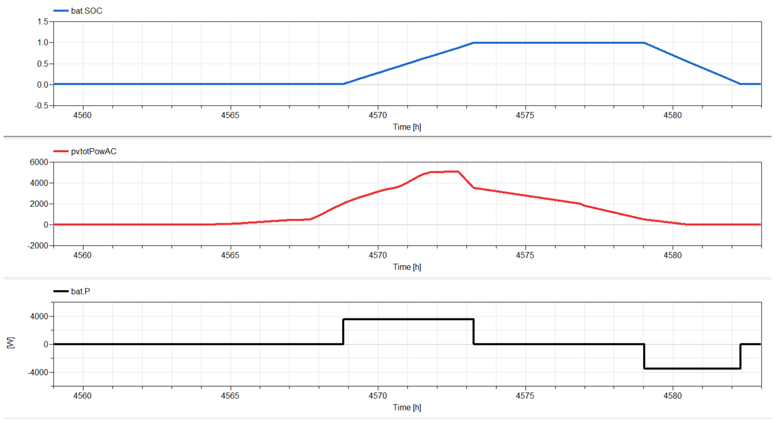


Figure 32: Battery SOC and power in relation to PV generation

The PV generation for July 10th is presented in Figure 32 above, and it can be seen to reach 2000 Watts at 10AM and 500 Watts at 8PM which again is consistent with when the battery begins to charge and discharge. Figure 32 also presents the battery power draw when charging and discharging. It can be seen that the battery is pulling the needed power of 3,500 Watts.

It is important to remember that the definition of a ZE building specifies that the annual energy delivered to the building must be on-site renewable energy. While a battery storage system isn't considered a renewable energy, it can help distribute building loads more evenly throughout the day as well as reduce peak power demands of the building itself. Figure 33 presents the load duration curve of the model with and without a battery storage system. The peak demand is in fact higher without a battery at 9.74 kW/yr and lower with a battery at 6.81 kW/yr.

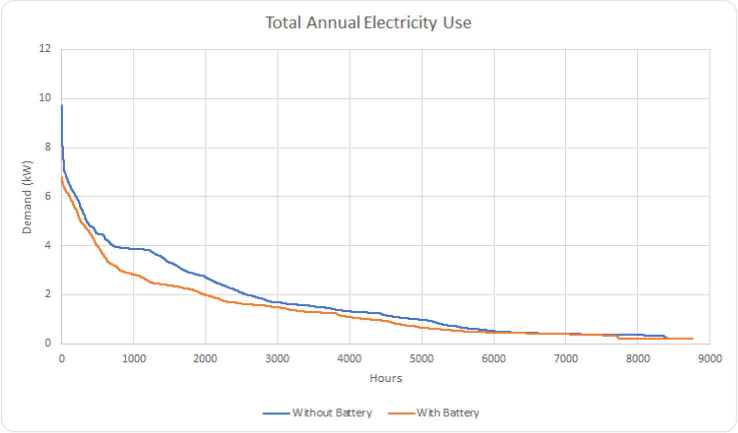


Figure 33: Load duration curve with and without battery storage system

4.3 Zero Energy Evaluation

Now to figure out if the house is zero energy, the mathematical equation as mentioned earlier is $E_{PV}-E_{load}=0$. Again, E_{load} can be broken into the miscellaneous electric loads, the HVAC load of each of the thermal zones and the load of the DHW system over the course of a year. To clarify, the equation can look as such: $E_{PV}-(E_{Misc.Elec.Loads}+E_{HVAC,1,2,3}+E_{DHW})=0$. The energy usage, or production, for each of these systems is presented in Table 12. Energy is the power used over a period of time, therefore the energy is calculated by interpolating the power data of the Modelica model for each system for every hour of the year and summing up the loads to get the annual energy. This is used to ensure the building is annually zero energy.

Table 12: Modelica annual energy generation/use

E_{PV} [kWh]	$E_{Misc.Elec.Loads}$ [kWh]	E_{HVAC1} [kWh]	E_{HVAC2} [kWh]	E_{HVAC3} [kWh]	E_{DHW} [kWh]	E_{Load} [kWh]
9668.49	4424.61	1319.66	1230.90	1209.46	1305.98	9490.61
$E_{PV}-E_{load}$ [kWh]				177.88		

The proof of zero energy by the use of the energy balance equation provides the answer that the complex systems chosen for the home is enough to make it considered a ZE building. Interestingly enough, since the energy balance equation has a positive number, the building is actually net-positive. This means the building produces more energy than is consumed. The excess energy produced by the PV system is 177.88 kWh/yr.

Furthermore, the annual electricity bill can be calculated. Following the residential rate plan in Boulder, CO [11], the general pricing and time-of-use (TOU) pricing is compared. Table 13 presents that with the installed PV, the annual electricity bill is cheaper with TOU pricing.

Table 13: Annual electricity bill

	General	TOU
Cost [$]	1509.87	1466.44

4.4 Model Verification

To verify the results, the Modelica model's annual energy use and peak demand is compared to the BEopt model. The greatest disparity found in the energy use is the HVAC energy, which ultimately affected the overall energy balance. Table 14 presents the annual energy use of each system, as well the disparity between the two, in comparison to the BEopt model. The Modelica model's HVAC system uses 71.24% more energy than the BEopt model. This made the total consumption in the Modelica model to be 10.92% higher than the BEopt model. Since the annual energy generation is higher than the energy consumed for both models, excess energy is produced. Therefore, both models prove to not only be zero energy but also net-positive. However, the Modelica model only produces an extra 177.88 kWh/yr while the BEopt model produces an extra 467.64 kWh/yr. The other systems in each program fall under roughly a 10% difference.

Table 14: Program comparison of annual energy generation/use

	BEopt	Modelica	Disparity [%]	Adjustment for as-built house
PV [kWh]	9023.68	9668.49	7.15	4,107 (upper) + 7,719 (lower) [1]
Miscellaneous Electric Loads [kWh]	4886.85	4424.61	-9.46	4425 (house) + 2,681 (EV)
HVAC [kWh]	2195.81	3760.02	71.24	2196 [2]
DHW [kWh]	1473.38	1305.98	-11.36	2203 [3]
Total Consumption [kWh]	8556.04	9490.61	10.92	11,505
Energy Balance [kWh]	467.64	177.88	-	321

1 Calculated from PVWatts Calculator with system efficiencies described in Table 10

2 Average of the two model results. The higher kWh value from Modelica is higher than a hand-calculation (conservative heating and cooling loads calculated according to Manual J, no controls, and no expected efficient occupant use) with ERV fan, and heat pump heating and cooling energy use. It is therefore assumed that the BEopt analysis sets a more appropriate expectation of actual performance.

3 Based on 30 gal/day use determined by current use patterns of homeowners. This can be compared to an expected baseline of 50 gal/day of a typical house of 3 [] . Tenant education will allow the savings to be applied to the ADU and main house.

It is important to note the dissimilarities made in the models which affected the disparity between the two programs. First off, the building geometry between the two models is different as presented in Table 15. The BEopt model has a 25% higher floor area than the Modelica model.

Table 15: Program comparison of building geometry

	BEopt	Modelica
Wall Height [ft]	9	9
Floor area [ft2]	1568	1175
Volume [ft3]	14,112	10,575

Moreover, Table 16 presents the differences in the building characteristics. The high disparity in the HVAC loads are due to the fact that the HVAC loads in the Modelica model are dependent on the systems themselves as well as the thermal zones. The contrast in the ERV system is that the BEopt model has a lower ventilation rate than the Modelica model. As for the minisplit system, the Modelica model has a higher SEER value but lower HSPF than the BEopt model. In terms of energy efficiency, a higher HSPF is better in colder climates [10]. This means the chosen system in the BEopt model is more efficient. This is also noted as the COP in which the BEopt model also has a higher value. Additionally, a contrast seen for the thermal zone models are the R-values and material type of the construction used. For instance, while the R-value for the wall is greater in the Modelica model, the R-value in the finished ceiling and roof is lower than the BEopt model. Also, the setpoints and occupancy schedule made for the thermal zones affect the HVAC loads. The Modelica model has a lower setpoint during heating and a higher setpoint during cooling than the BEopt model, which should reduce the total load, but considering the fact of the high ventilation rate and lower thermal mass and R-values, these may be part of the reason why the Modelica model has a higher total HVAC load. Furthermore, the PV generation in the Modelica model is greater than the BEopt model perhaps due to the larger size of the PV system. The DHW system in the Modelica model is smaller than the BEopt model perhaps due to hot water fixture usage being 61% lower. It is important to mention BEopt has a prescribed value for these characteristics while Modelica allows for inputs that match the final design.

Table 16: Program comparison of building characteristics

			BEopt	**Modelica**
Envelope	Walls	Wood Stud	R-21	R-42
	Ceiling/Roof	Finished Ceiling/Roof	R-60	R-49/R-54 (as-built: R-59 for 75% of area)
	Thermal Mass	Exterior Wall Mass	⅝ in. Drywall	½ in. Drywall
		Ceiling Mass	⅝ in. Drywall	½ in. Drywall
	Airflow	Air Leakage	3ACH50	(as-built: < 1.5 ACH expected based on initial tests)
		Mechanical Ventilation	270 CFM	475 CFM (as-built: planned 120 CFM operation)
Windows and Shading	Windows/Doors	Windows	Low-E, Double, Insulated, Air	Low-E, Double, Insulated, Air (as-built: quad-lite)
Equipment	Space Conditioning	Mini-Split Heat Pump	9 kBtuh, SEER 30, HSPF 13.5, COP 3.13	9 kBtuh, SEER 30.5, HSPF 12.5, COP 2.73 (as-built: COP 2.16 at 5 degrees and 4.50 at 47 degrees)

	Space Conditioning Schedules	Cooling Setpoint	76 F	77 F
		Heating Setpoint	67 F	65 F
	DHW	Tank Volume	50 gal	50 gal
Appliances	Fixtures	Hot Water Fixtures	20.8 gal/day	8.1 gal/day (as-built: 30 gal/day total home)
Renewables	Power Generation	PV System	6 kW, South, 40 degrees	6.5 kW, South, 40 degrees (as-built: see Table 10)

With the annual energy use and the square footage, the energy use intensity (EUI) is calculated for each model. Table 17 presents the results. The EUI is lower with the BEopt model.

Table 17: Program comparison of annual EUI

	BEopt	**Modelica**	**Disparity [%]**
Peak Demand [kBTU/ft2]	18.62	27.56	38.72%

In terms of peak demand, the peak demand of the Modelica model without a battery storage system is 10.7% higher than the BEopt model as shown in Table 18. Since the BEopt model did not include a battery storage system, the peak demand of the Modelica model with a battery storage system cannot be compared.

Table 18: Program comparison of annual peak demand

	BEopt	**Modelica**	**Disparity [%]**
Peak Demand [kW/yr]	8.80	9.74	10.7%

5. Conclusion

Using BEopt, a cost-optimal design for a ZE home, in comparison to that of code standards in Boulder, Colorado, uses many different energy saving options. For instance, higher R-value insulation and thicker drywall are used for the building envelope. Also, more efficient windows and equipment are used as well as the addition of a PV system. Using this program, the optimized ZE design compared to code standards proves to be 40% lower in annual energy consumption and 14% lower in annual peak demand. In terms of cost, the ZE design has a 35% higher initial cost value but shows 41% savings annually from energy related costs. Ultimately, the ZE design presents itself as the better investment due to having a higher total present value of $83,197.

Using Modelica, the proof of zero energy by the use of the energy balance equation provides the answer that the complex systems chosen for the home is enough to make it considered a ZE building. With only the PV system attached as the renewable energy source, the building produces more energy than is consumed annually. An excess of 178 kWh/yr is generated by the PV system. In comparison to the BEopt model, the Modelica model has a higher load for the HVAC system thereby increasing the total energy consumed and offsetting the overall energy balance. While the energy balance of both models proves zero energy, the Modelica model generates less excess energy than the BEopt model.

The design of the house also includes a battery storage system. The 13.5 kWh battery storage system for the home shows a reduction in the peak power demand. In the Modelica model, the building without a battery has an annual peak demand of 9.74 kW/yr. With a battery in place, the model shows an annual peak demand 30% lower at 6.81 kW/yr. A comparison of the peak demand against the BEopt model is completed as well. The peak demand of the Modelica model without a battery is 10% higher than the BEopt model at 8.80 kW/yr. Since the BEopt model does not include a battery storage system, the Modelica model with one is not compared.

6. Future Research

There are myriad opportunities for future research that could be explored. For instance, a further study on behavior analysis can be looked into using BEopt. Currently, the energy performance of typical and good behavior in a ZE home are compared to code standards for Boulder, Colorado, but the energy performance of bad behavior and different locations can be compared as well. Further study on carbon emission reductions of each of these scenarios can also be analyzed.

Using Modelica, future research may include testing the home with other alternative energy sources. The model currently consists of a PV system and a battery storage unit, however this can be replaced with other sources of energy such as wind or hydrogen fuel cells for instance. Otherwise, modifications on the current alternative energy sources, i.e. changing the type, size and efficiency of the PV system, can be tested for the effects on energy performance too. The battery storage system control logic can be worked on to prove resilience per competition guidelines as well.

Furthermore, the model can also be duplicated to present a community rather than a single building. In this case, the energy performance and cost analysis can be studied on a community scale. Studies on communities of ZE homes is currently limited and this may shine a light on if distributed energy resources in a community of ZE homes is cost-effective and efficient.

Lastly, since the ZE design will be built in real life, actual testing of the building after construction will be conducted. This can be used to verify the model and test if the building is in fact zero energy plus by collecting the energy data after one year of the home being occupied.

7. References

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8. Appendices

2015 IECC Code Standards for Climate Zone 5:

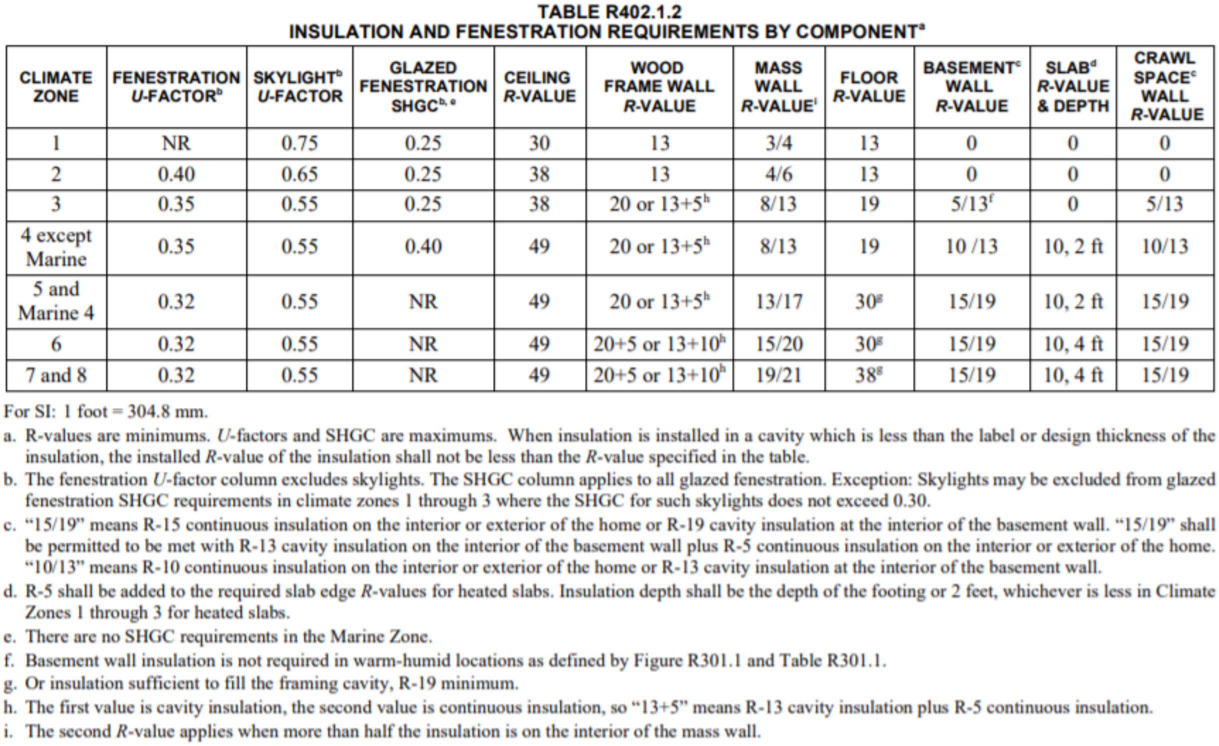

TABLE R402.1.2
INSULATION AND FENESTRATION REQUIREMENTS BY COMPONENT[a]

CLIMATE ZONE	FENESTRATION *U*-FACTOR[b]	SKYLIGHT[b] *U*-FACTOR	GLAZED FENESTRATION SHGC[b, e]	CEILING *R*-VALUE	WOOD FRAME WALL *R*-VALUE	MASS WALL *R*-VALUE[i]	FLOOR *R*-VALUE	BASEMENT[c] WALL *R*-VALUE	SLAB[d] *R*-VALUE & DEPTH	CRAWL SPACE[c] WALL *R*-VALUE
1	NR	0.75	0.25	30	13	3/4	13	0	0	0
2	0.40	0.65	0.25	38	13	4/6	13	0	0	0
3	0.35	0.55	0.25	38	20 or 13+5[h]	8/13	19	5/13[f]	0	5/13
4 except Marine	0.35	0.55	0.40	49	20 or 13+5[h]	8/13	19	10 /13	10, 2 ft	10/13
5 and Marine 4	0.32	0.55	NR	49	20 or 13+5[h]	13/17	30[g]	15/19	10, 2 ft	15/19
6	0.32	0.55	NR	49	20+5 or 13+10[h]	15/20	30[g]	15/19	10, 4 ft	15/19
7 and 8	0.32	0.55	NR	49	20+5 or 13+10[h]	19/21	38[g]	15/19	10, 4 ft	15/19

For SI: 1 foot = 304.8 mm.

a. R-values are minimums. *U*-factors and SHGC are maximums. When insulation is installed in a cavity which is less than the label or design thickness of the insulation, the installed *R*-value of the insulation shall not be less than the *R*-value specified in the table.

b. The fenestration *U*-factor column excludes skylights. The SHGC column applies to all glazed fenestration. Exception: Skylights may be excluded from glazed fenestration SHGC requirements in climate zones 1 through 3 where the SHGC for such skylights does not exceed 0.30.

c. "15/19" means R-15 continuous insulation on the interior or exterior of the home or R-19 cavity insulation at the interior of the basement wall. "15/19" shall be permitted to be met with R-13 cavity insulation on the interior of the basement wall plus R-5 continuous insulation on the interior or exterior of the home. "10/13" means R-10 continuous insulation on the interior or exterior of the home or R-13 cavity insulation at the interior of the basement wall.

d. R-5 shall be added to the required slab edge *R*-values for heated slabs. Insulation depth shall be the depth of the footing or 2 feet, whichever is less in Climate Zones 1 through 3 for heated slabs.

e. There are no SHGC requirements in the Marine Zone.

f. Basement wall insulation is not required in warm-humid locations as defined by Figure R301.1 and Table R301.1.

g. Or insulation sufficient to fill the framing cavity, R-19 minimum.

h. The first value is cavity insulation, the second value is continuous insulation, so "13+5" means R-13 cavity insulation plus R-5 continuous insulation.

i. The second *R*-value applies when more than half the insulation is on the interior of the mass wall.