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

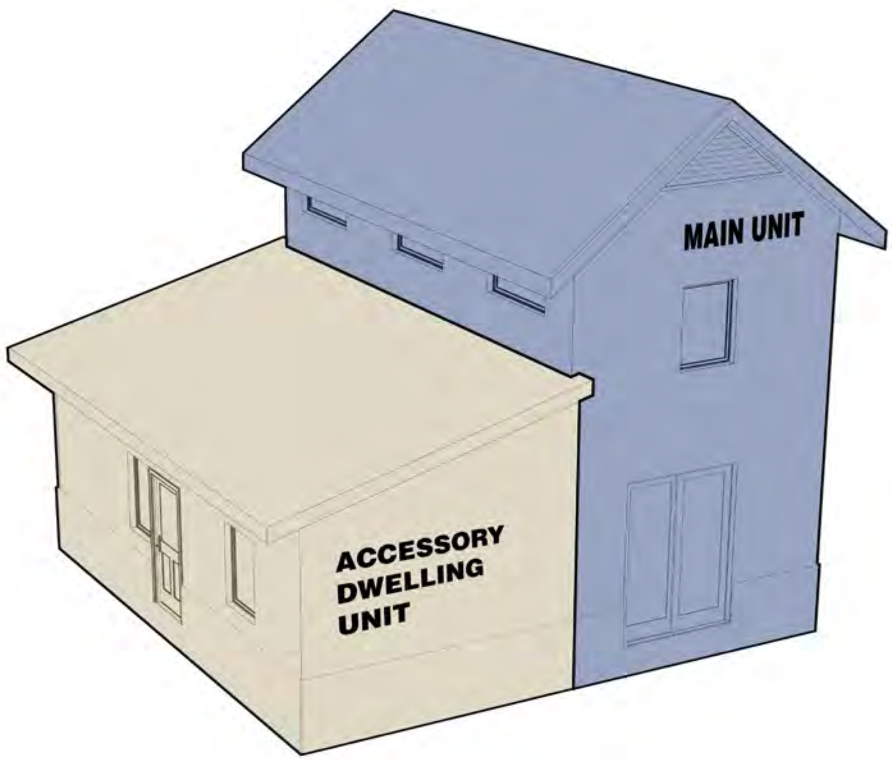

Figure 1: Volumetric division of ADU and Main Unit

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

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

away from bathrooms to prevent vapor movement through the hatches.

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

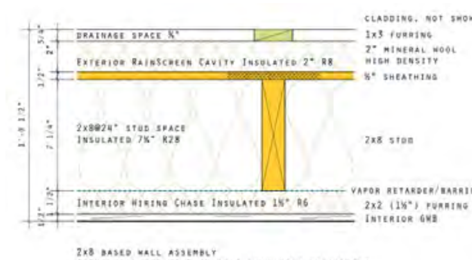

Figure 5: The "Best" wall design

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

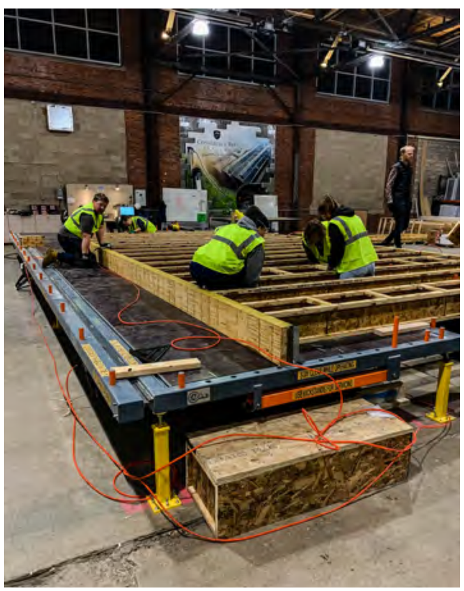

Figure 6: The CU Boulder Team working at Simple Homes' factory

Figure 7: SPARC House panels on truck

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

Figure 8: Crane placing panel on floor box

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.

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.

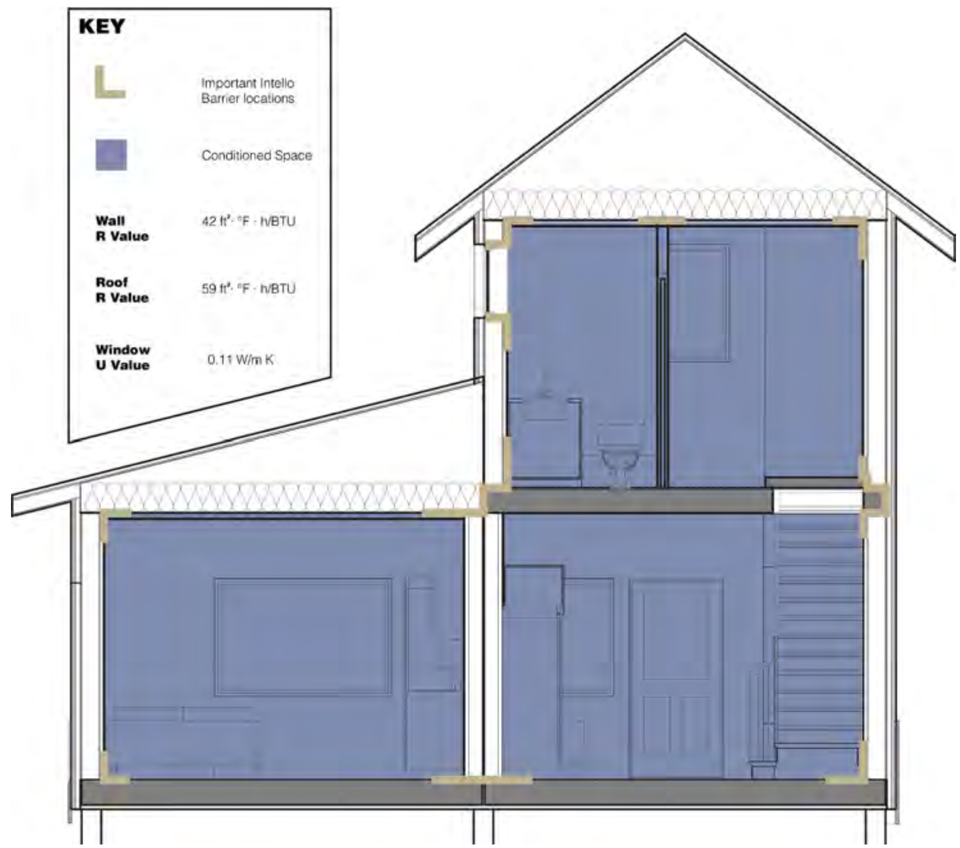

Figure 12: SPARC House section view showing critical vapor barrier wrap points

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

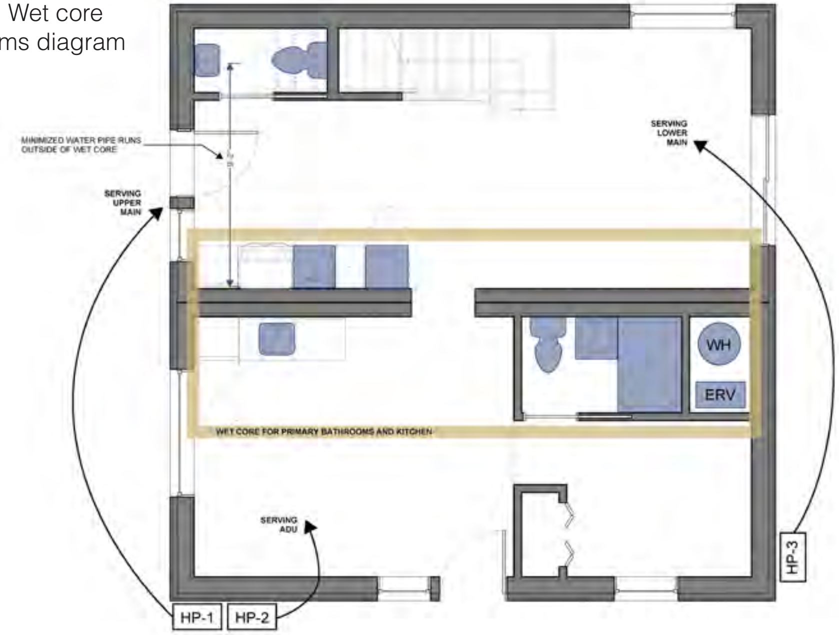

Figure 15: Outdoor mini split

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

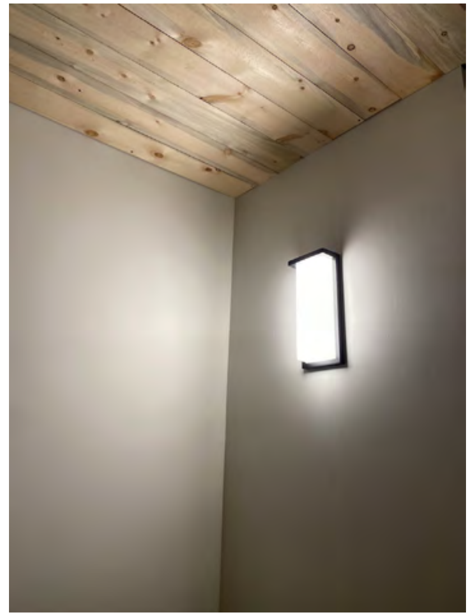

Figure 16: Electric lighting in the house

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.

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

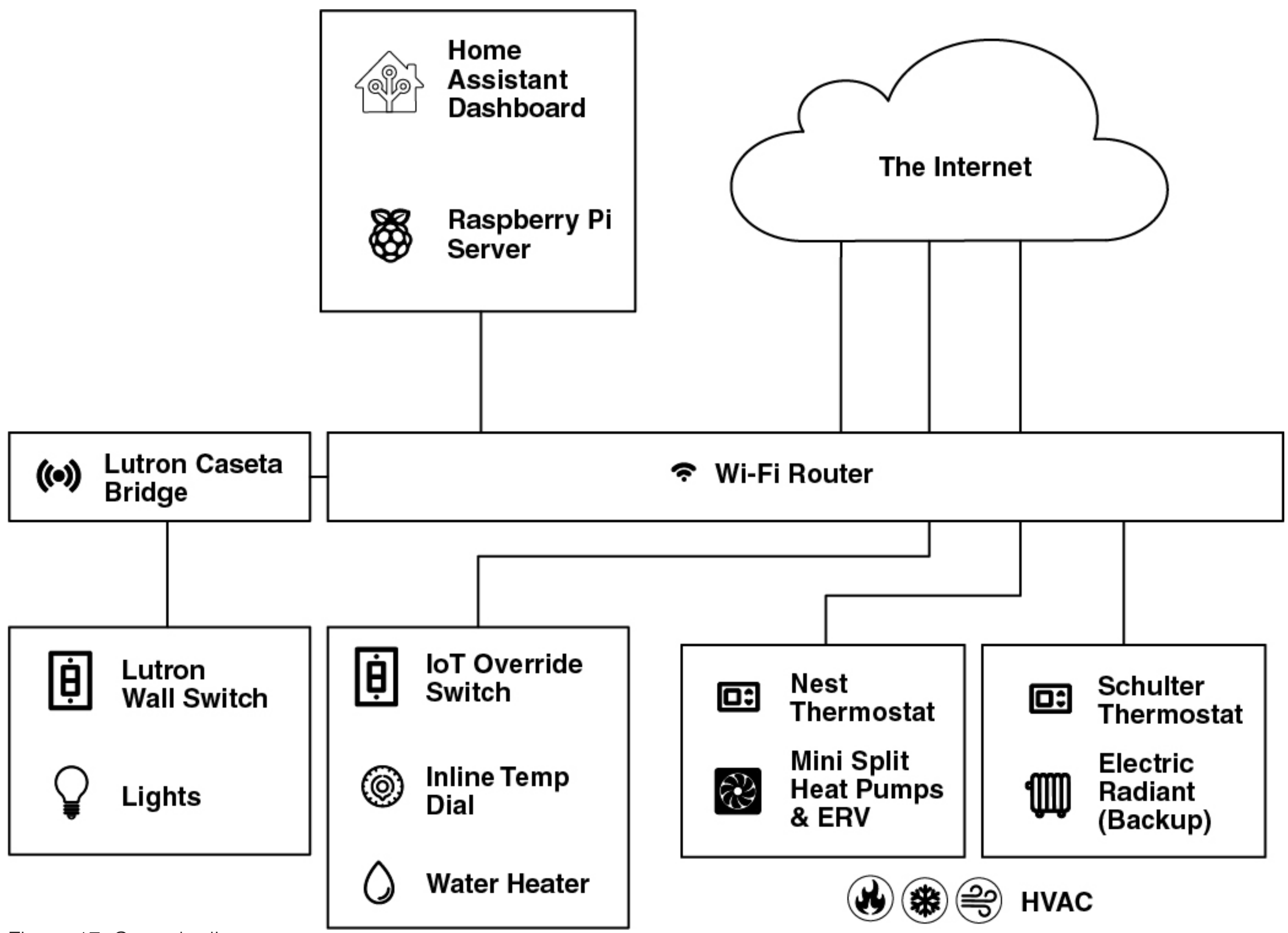

Figure 17: Controls diagram

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
2. BEopt: Building Energy optimization tool. (n.d.). Retrieved February, from https://www.nrel.gov/buildings/beopt.html
3. Modelica language. (n.d.). Retrieved February, from https://www.modelica.org/modelicalanguage
4. Vass, D. (2016, June 01). Prefab wall systems save on labor. Retrieved February, from https://www.builderonline.com/building/building-science/prefabricated-wall-panels-save-on-labor_o
5. USA New Wall Info. (n.d.). Retrieved February, from http://blog.lamidesign.com/p/usa-new-wall-info.html
6. It's time to Incentivize RESIDENTIAL heat pumps. (2020, July 22). Retrieved February, from https://rmi.org/its-time-to-incentivize-residential-heat-pumps/