

Affordable, All-Electric Cold-Climate Homes: A Look Inside the Winning 2020/2021 Solar Decathlon Build Challenge House

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ABSTRACT

Can builders construct energy efficient, resilient, and affordable all-electric houses in the coldest climates? For a long time, builders have relied on methane gas for heating homes in cold climates, believing that all-electric houses were impractical, unaffordable, or impossible. But the times are changing! The winning 2020/2021 CU Boulder Solar Decathlon Build Challenge team set out to show that with careful construction (and assisted by improvements in cold-climate air-source heat pumps) it is not only possible, but practical and affordable to design and build all-electric, net-zero energy homes in the coldest climates. This paper and associated poster gives readers a look inside the most recent winning Solar Decathlon home: the SPARC House by CU Boulder. Standing for Sustainability, Performance, Attainability, Resilience, and Community, the SPARC House is currently occupied as a year-round full-time residence in Fraser, Colorado, one of the coldest towns in the U.S. This paper describes the construction techniques used to build this home in half the time and at 80% of the cost of surrounding homes, and it provides actual data on how the home is performing. The SPARC House shows how America's next generation of architects, engineers, and builders are solving some of America's toughest building challenges.

Introduction

Through competing in the U.S. Department of Energy Solar Decathlon® 2020/2021 Build Challenge (U.S. DOE 2022), the University of Colorado Boulder Solar Decathlon team (CU Boulder) aimed to simultaneously demonstrate the feasibility of building a net-zero energy, all-electric home in one of the coldest towns in America and address the housing attainability crisis and construction challenges in mountain towns across the country.

The inspiration to compete in the Solar Decathlon came from then-sophomore engineering students Gabriella Abello and Hannah Blake (see Picture 1). In 2017, they took a trip to the Solar Decathlon Build Challenge which was hosted in Denver. There, they saw a real-life display of some of the most innovative new homes ever created—all designed and built by college students. They marveled at the incredible lineup of full-size homes which seemed so far into the future in terms of energy efficiency, and design and sustainability, yet which were all made with technology and materials available at the time. Kristen Taddonio and Joe Smyth, residents of Fraser, Colorado were also in Denver that day at the showcase. They ended up inside the same house as Abello and Blake, who were asking current students in the competition about how to get involved. These competing students were looking to sell their home so they wouldn't have to ship it back to their campus—and something clicked for Taddonio and Smyth. Having recently bought land in Fraser with the dream of building their own sustainable home someday, Kristen gave her card to Abello and said, “call us,” if they entered the next competition and needed partners to invest. Less than two years later, Taddonio's phone rang. Abello was serious on her promise to deliver, and Taddonio and Smyth agreed to sponsor the 2020 competition team.



Picture 1. Gabriella Abello and Hannah Blake, SPARC House team leads

With a committed sponsor, the student team's next step was to learn about these future homeowner's needs, and about the climate and culture of Fraser. Fraser has an annual mean temperature of 35.8 °F (2.1 °C), making it one of the coldest incorporated towns in the lower 48 states when measured by average annual temperature (NOAA 2022). The homeowners used a performance-based procurement method by providing a list of “must haves” such as a smaller, energy efficient, highly insulated, low-maintenance home properly oriented on their lot to maximize active and passive solar. They budgeted \$325,000 for construction. They also provided a list of optional “nice to have” features that they would be willing to trade off to hit their budget: a garage or carport, windows with views, an extra bedroom and bathroom or rental space, and outdoor space such as a deck or patio (Scheib, Pless, and Torcellini 2014).

Fraser is close to a ski resort in the neighboring town of Winter Park, and like many smaller mountain towns, Fraser has faced soaring housing prices in recent years (Hartford 2019). Most new development in mountain towns targets affluent vacation-home buyers, contributing to housing insecurity within local communities. Housing prices were further exacerbated by the COVID-19 pandemic and historic fires of 2020 that burned down over 400 homes in the county, increasing competition for already-scarce construction resources. Housing costs in the northern Rockies can be more than twice those elsewhere in Colorado, and up to 3.5 times the national average (see Figure 1). These prices push out locals and can make it almost impossible for seasonal workers to afford rent.

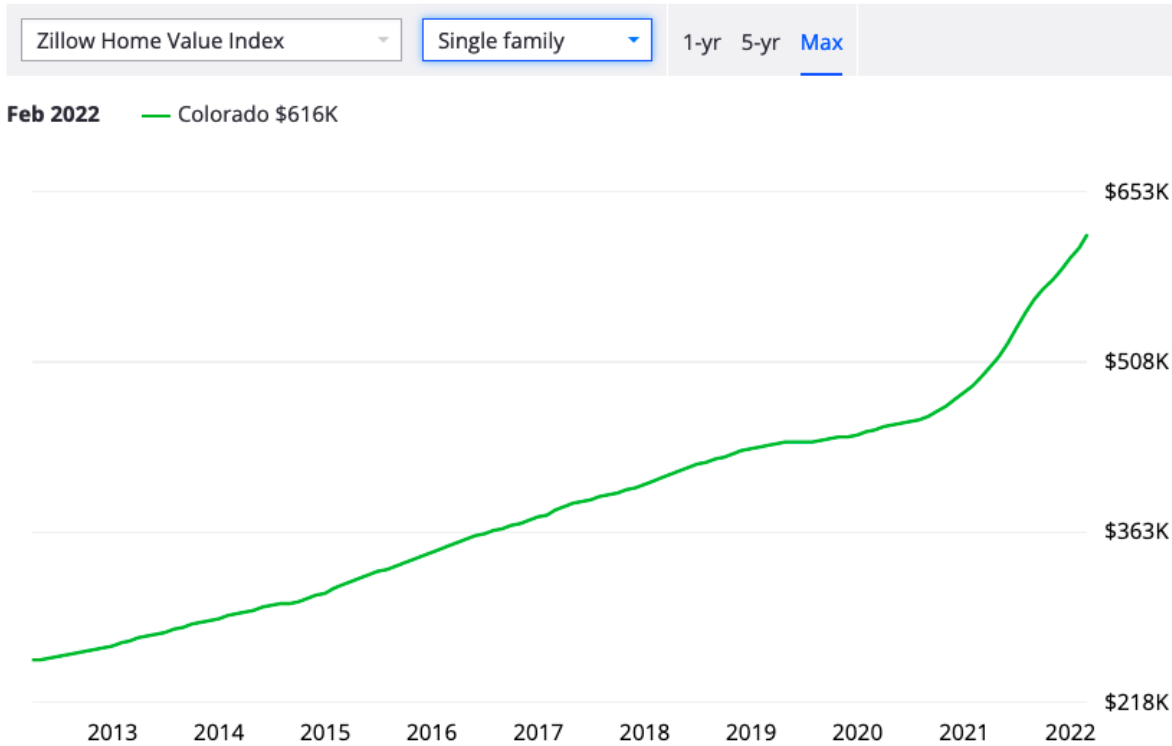


Figure 1. Median Colorado Single Family Home prices. Source: Zillow

The SPARC House

The CU Boulder Solar Decathlon team confronted these housing issues head-on by designing the SPARC House, which stands for sustainability, performance, attainability, resilience, and community. The house demonstrated fast and affordable construction methods with panelized modular prefabrication (see Picture 2); integrated systems that are designed to reduce energy and minimize maintenance suitable for the harsh climate; and included a rentable “guest suite” that could be used to supplement homeowner income and provide local workforce housing. The 1,186 sq ft SPARC House consists of three 14 x 28 ft modules connected as shown in Figure 2 with the following space layout: the first floor (kitchen, living, dining, and half bath), the second floor (owner bedroom, full bathroom, and office), and attached guest suite (second bedroom, three-quarter bathroom, kitchenette, and utility room).



Picture 2. The SPARC House panels were pre-fabricated at Simple Homes in Denver and transported via truck in sections for modular assembly in Fraser

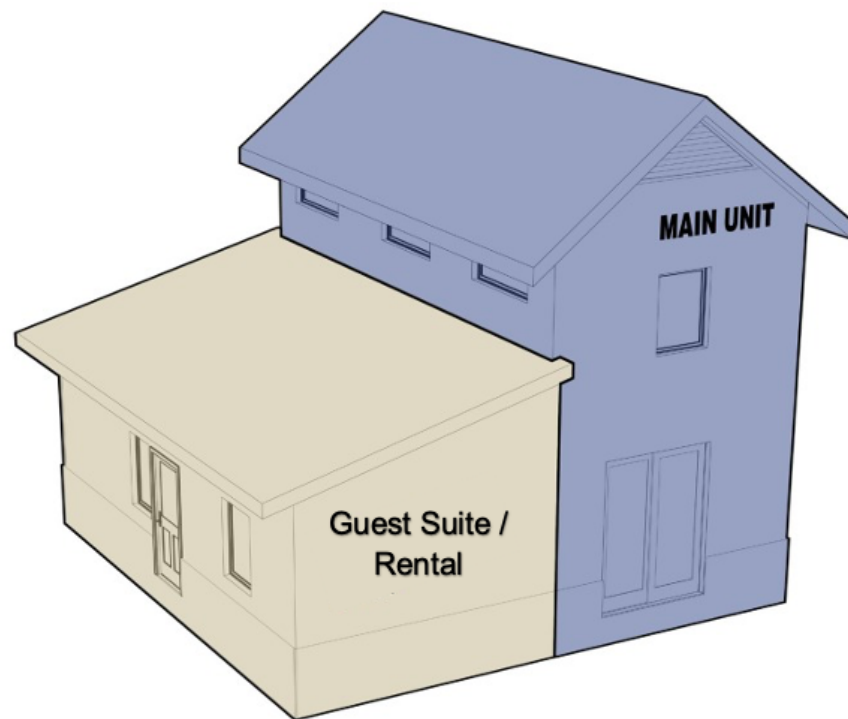


Figure 2. The three 14 x 28 foot sections, when assembled, create a “main unit” and a rentable guest suite

Design for High Efficiency

High energy performance is critical to meeting both the Solar Decathlon competition guidelines and achieving the goal of attainable living, which includes low operating costs for homeowners. Both passive and active design strategies were integrated into the SPARC House in order to optimize energy performance. The SPARC House implements the following passive design principles:

- South facing orientation for solar gain and exposure
- Highly insulated building envelope
- High performance windows (Alpen quad-pane, argon filled)
- Low infiltration building envelope

To maximize energy performance, the SPARC House was pre-fabricated with thick walls (2x10 framing) filled with natural wool insulation. This reduces reliance on foam insulation, which often contains high global-warming potential blowing agents. A continuous layer (no gaps at corners or between stories) of R-8 Rockwool insulation was also applied to the exterior of the house on top of the Solitex Mento 1000 house wrap and below the wood siding. The wall section was modeled after USA New “Best” Wall described by architect Greg La Vardera (La Vardera 2011). The total thermal resistance for the insulation is R-42 walls and R-59 roofs, which exceed the total assembly applicable code minimum of R-20+5 continuous and R-49, respectively. The windows and glazed doors have full frame U-factors ranging between 0.11 and 0.16. The siding is beetle-kill pine stained with pine tar, one of the earliest and most sustainable wood preservatives for cold climates. The dark exterior helps retain heat in colder months, and creates a microclimate that helps improve the efficiency of the three Mitsubishi mini-split air-source heat pumps that heat and cool the home, two of which are shown in Picture 3. Overhangs help deflect harsh sun entering at higher angles during the summer to prevent overheating indoors. The continuous layer of Intello Plus air barrier system helps manage moisture and control airflow throughout the home. Because the home is tightly sealed (less than 1.9 air changes per hour, with a blower-door test showed CFM50=385), a RenewAire energy recovery ventilator helps provide fresh air to the home while minimizing energy loss. ENERGY STAR Most Efficient™ Beko appliances used in the home include two counter-depth refrigerator-freezers, a dishwasher, and a stacked washer-dryer, of which the dryer is an energy efficient heat pump model. Other appliances include a Beko induction range, a microwave installed over the kitchen cooktop with a vent that exhausts fumes outside, and a 50 gallon electric tank water heater. The latter was selected due to space constraints (the utility closet lacks appropriate air circulation space for a heat pump model) and because energy modeling suggested that additional heat pump water heater energy savings may not be substantial due to the interior location and cold climate (i.e., a heat pump water heater would cool the space that would then need to be reheated by the space heating system). All interior and exterior lighting uses LEDs. The home is also equipped with a 220 V exterior outlet suitable for level 2 electric vehicle charging. The homeowners charge their plug-in hybrid vehicle (a Kia Niro PHEV with an 8.9 kWh battery and 26 mile electric range), which covers all their local driving needs.



Picture 3. Cold-climate heat pumps heated the house during the first year without backup heat

Cold-Climate Heat Pumps: Impressive Performance

The options considered to meet the space heating load of the home were radiant flooring and ground-source heat pump, and air-source ductless mini-split heat pump systems. Ground-source heat pumps were considered for their efficiency and use of passive technology to heat the home. This option promised high efficiencies even in the cold Fraser climate (ASHRAE zone 7). However, ground-source options were ruled out quickly due to complications with installation and transportation (originally, the home was supposed to be constructed on CU Boulder's campus and transported to Fraser after completion of the competition, but the plan changed to on-site construction after the onset of the COVID-19 pandemic). Additionally, the cost of installing a ground-source system did not meet the attainability goal while installation of a ductless mini-split option did, and it presented an opportunity to publicly showcase the viability of heat pump performance in a cold climate (Petersen, Gartman, and Corvidae 2019).

In addition to the three Mitsubishi cold-climate mini split heat pumps, the home has a back-up electric resistance heating system that consists of two wall-mounted radiant heaters (Berko brand) in the bedrooms, as well as two kick-space heaters, one installed in the guest suite and one in the kitchen. This back-up heating system is significantly scaled down from what the heating consultant contracted by CU Boulder originally recommended, which was designed for a worst-case scenario (heating the home to 72°F on a day with sustained temperatures of -53°F, the

record low set over 50 years ago). Such a system would have required a 400 A service panel so it was deemed impractical and unnecessary by local building experts. Indeed, climate change has resulted in warming trends in Fraser, Colorado that have exceeded the national average, and it is less likely that Fraser will see the record lows set last century over the coming decades. Scaling down the back-up heating system allowed the home to be constructed with a 200 A service panel. The home's heating system has been operating over a full calendar year, and the back-up heating system has never turned on, even on days when the temperature reached lows of -17.6°F. It is notable that although the cold-climate heat pumps are rated to operate to -14°F, they continued to operate below that temperature.

The homeowners measure temperatures at the house using an outdoor weather station from Netatmo. Figure 3 shows temperatures recorded every 30 minutes at the house during the winter, from December 21, 2021 through March 20, 2022. Overnight temperatures dropped below 14°F (-10°C) during most nights, and below -4°F (-20°C) during 20 nights. During the day, high temperatures remained below freezing on most days, exceeding 32°F (0°C) on 38 days. During a few days, daytime highs remained below 14°F (-10°C). The lowest temperature recorded was -17.6°F (-27.6°C), and the highest temperature recorded was 47.4°F (8.6°C). The average (mean) temperature was 16.6°F (-8.5°C).

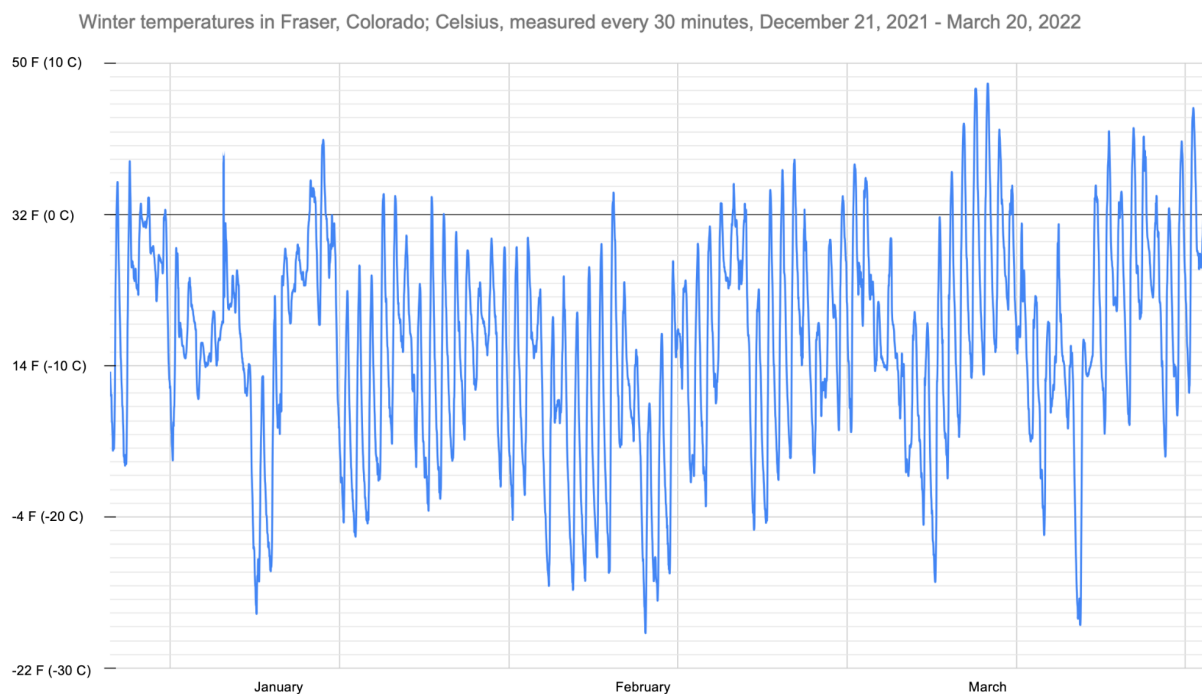


Figure 3. Winter temperatures recorded at the house

Load Shaping & Demand-Response Capability

The SPARC House's high-performance envelope and cold climate heat pumps were the primary design decisions that led to impressive annual and seasonal energy performance. Daily and hourly time scales also matter when it comes to the house's ability to reduce strain on the local power grid and maximize use of onsite solar photovoltaic (PV) generation. The model-

predicted peak demand of 9.7 kW is largely determined by the water heater, heat pumps, and EV charging if multiple of these loads are used at the same time during a period of no electricity production by PV.

To manage the daily peak load, the hot water heater was equipped with a SkyCentrics external relay module, and the heat pumps were connected to Nest thermostats, both devices enabling the homeowners to schedule preheating. The SkyCentrics module allows scheduled heating, so the water heater operates at full power during the middle of the day when solar power provides more power than the house needs, and the water heater operates at lower power/temperature during the evening and overnight. In addition to maximizing the use of onsite solar generation, this scheduling reduces energy consumption during the peak demand period (5pm – 10pm), when wholesale power costs for the local utility spike. Similarly, the Nest thermostats are programmed to increase temperatures slightly during the middle of the day; the tight building envelope and insulation help the house retain that heat. Additionally, the whole house electricity monitoring system enables the homeowners to look at production and charge the EV only when PV is being sold to the grid, when possible. The hot water control module also enables a range of control functions such as 30% demand response reduction if a water heater demand response program is developed by the utility or a demand response aggregator in the future, using the CTA-2045 open communication standard (Dayem 2018).

Solar Array & Battery Considerations

The 7.6 kW solar PV array consists of 24 panels, 8 on an upper 9:12 roof pitch and 16 on a lower 3:12 roof pitch as shown in Picture 4. Both arrays face southeast, which was an early design decision to maximize daily production within the site constraints of an off-axis lot, and tall trees and occasional afternoon storm clouds to the southwest. The panels are connected through panel-specific optimizers and a SolarEdge inverter (microinverters were also considered but it was determined that the selected system would offer similar performance).

An additional design consideration was a 14 kWh battery that would have enabled 72 hours of off grid operation for critical loads (refrigerator, heat pumps, and one lighting and appliance circuit) along with additional load shaping and demand response capability. The decision was made to exclude the battery purchase by the homeowners due to product availability limitations that included: no Tesla battery installations available in Fraser at the time of construction (Tesla batteries would have been available had the home been constructed in Boulder); and no other systems that were small enough in physical size to fit in the available floor area were rated for Fraser's elevation of 8,573 ft. The homeowners plan to purchase an electric vehicle with two-way charging capability in the future which will provide even longer back-up power for the home given the much larger battery size.



Picture 4. The 7.6 kW solar array generated 9.4 MWh during the first full year of operation

Modeled Energy Performance

In the early design phase of the SPARC House, energy modeling was performed using BEopt, the National Renewable Energy Laboratory's residential building simulation and optimization program. The CU Boulder team's energy analysis for the mechanical systems of the house looked at three main systems: space heating, water heating, and ventilation. To analyze these systems, the CU Boulder team compared the performance of different subsystems in relation to their effect on overall energy efficiency of the house, and compliance with Solar Decathlon competition guidelines and set points. The original energy model estimated that the house's energy systems would consume, on average, 7,538 kWh per year, not including EV charging. See Figure 4 for the modeled energy end use breakout.

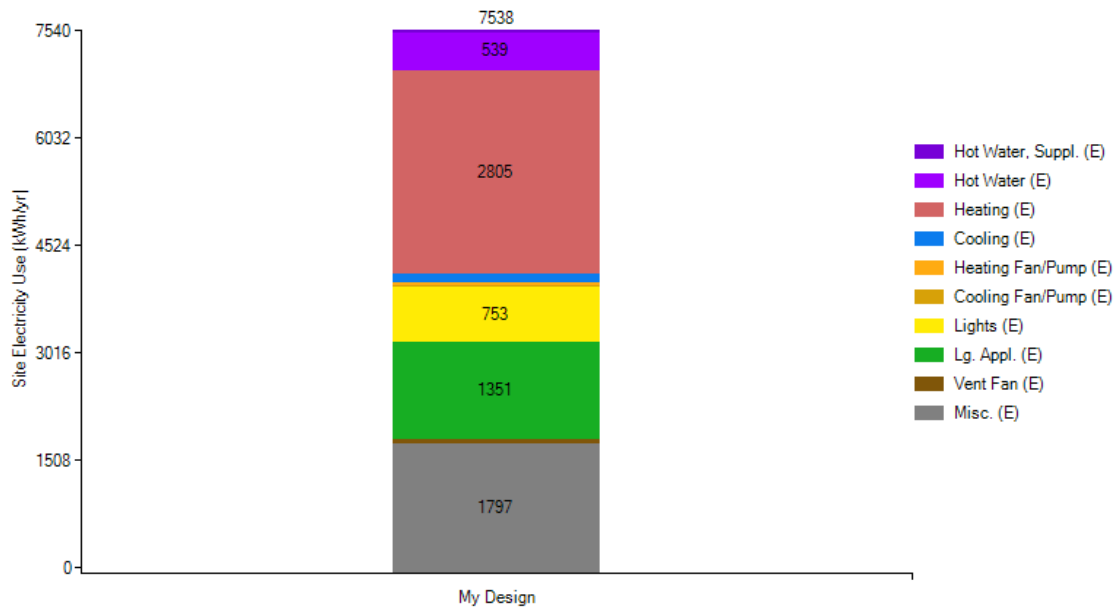


Figure 4. Modeled energy consumption

Actual Energy Performance: Net-Zero Achieved

The homeowners and CU Boulder monitored energy use after construction was complete. From April 1, 2021 until March 31, 2022, solar generation exceeded energy consumption during a full calendar year as shown in Figure 5. Specifically, the home's solar PV array produced 9,484 kWh, and the home used 8,620 kWh (see Table 1).

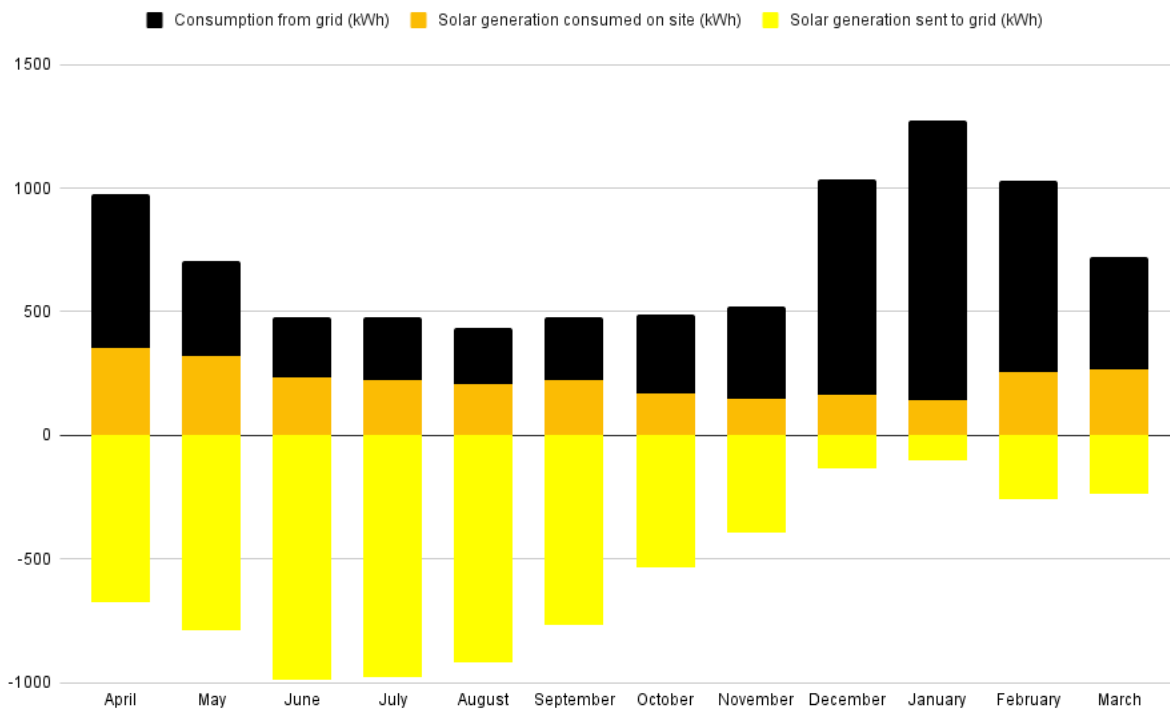


Figure 5. Actual energy performance, April 2021-March 2022

This energy consumption is inclusive of EV charging (estimated 900 kWh over 12 months). The homeowners used their electric utility's net meter analysis to determine how much energy the house consumed from the grid each month, how much solar energy the house sent to the grid each month, and the net of those two figures. They used the SolarEdge inverter app, which monitors energy generation from the solar array, to determine the total solar energy generated each month. They calculated how much solar energy the house consumed each month by subtracting the amount of solar sent to the grid from the total solar generation. Then, they calculated the total amount of energy the house consumed each month by adding that figure to the amount of grid energy consumed.

The house sent more energy to the grid than it consumed from the grid for eight months: April, May, June, July, August, September, October, and November. The house consumed more energy from the grid than it sent to the grid during four months: December, January, February, and March.

Over the full year, the solar array generated 9.8 MWh, of which 2.8 MWh was consumed on site, and 7.0 MWh was sent to the grid. The house consumed 6.1 MWh from the grid and consumed 8.9 MWh in total (including the solar consumed on site). Overall, the house sent 906 kWh more to the grid than it consumed during the year.

Table 1. Actual energy performance in kWh, SPARC House

Month	Total solar generation	Solar generation sent to grid	Solar generation consumed on site	Energy consumption from grid	Net metering	Energy consumption from grid and solar
April	1026	673	353	621	-52	974
May	1111	787	324	380	-407	704
June	1221	987	234	243	-745	477
July	1205	981	224	254	-726	478
August	1127	919	208	228	-691	436
September	989	767	222	255	-512	477
October	699	532	167	321	-211	488
November	540	394	146	378	-15	524
December	300	136	164	871	735	1035
January	248	103	145	1132	1028	1277
February	516	259	257	771	512	1028
March	878	486	392	664	178	1056
Totals	9860	7024	2836	6118	-906	8954

Construction Cost

Originally, the estimated cost to complete this home was \$321,000, exclusive of the price of land. Actual costs came in close to the estimated cost, at approximately \$330,000. With land, the total cost to build was approximately \$400,000. While \$400,000 may seem considerable for an 1,176 square foot home, it represents savings of approximately 30% below market rate for a comparable home built in the area in terms of price per square foot during the first year of occupancy (Movoto 2022), and which averaged \$450-500 per square foot at time of completion according to other sources. Prices for construction and land have increased in the intervening months.

Scoring and Reception by Judges

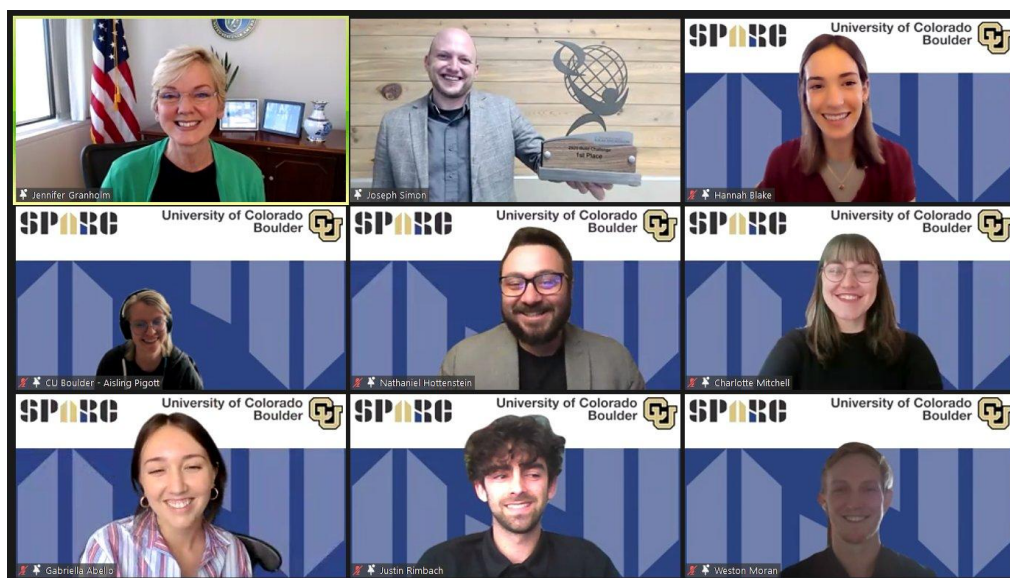
The 2020/2021 Solar Decathlon Build Challenge competition ended with a showcase and awards ceremony nearly three years after the SPARC House student team leads and homeowners first met in Denver. This time, however, the showcase and ceremony were held virtually due to the COVID-19 pandemic. The virtual experience enabled the nine teams who continued their build through the pandemic to share their innovations with each other, the media, and the public. The awards ceremony culminated in a first place overall award for the CU Boulder team and the SPARC House (see Picture 5).

The Solar Decathlon Build Challenge comprises ten contests, some of which are scored based on physical measurements of house performance and others that are scored by a jury of energy and construction industry experts. The SPARC House was the only project to place in the top three of each contest: It was awarded first place in the architecture (juried), market potential (juried), and innovation (juried) contests; second place in the energy (measured), engineering (juried), operations (measured), and financial feasibility and affordability (juried) contests; and third place in the comfort and environmental quality (measured) and presentation (juried)

contest. The high scores in every category resulted in first place overall for CU Boulder (see Figure 6).

Comments from the jury and Department of Energy Secretary Granholm highlighted the key approaches that, when combined, set the SPARC House apart as the winning project. The team's interpretation of these comments are outlined below.

- The house design is responsive to the climate, culture, and housing market of the build location, Fraser, Colorado.
- The project was sponsored by a real homeowner who will live in the house, showing feasibility of the all-electric SPARC House concepts over time, and will be able to share outcomes with a local community. The house is financially feasible and marketable for people in this community.
- The project tested a novel approach to construction, which included prefabricated panels constructed in Simple Homes' Colorado warehouse including framing, insulation, and house wraps, resulting in a house that was set in place in two days (dried-in within two months with homeowner and student labor) and demonstrating the first two-story house in Solar Decathlon history. The quick assembly time is important in a location like Fraser that has a short construction season.
- The project showed appropriate use of cold climate heat pumps, a technology with past limited applicability in a climate as cold as Fraser but one that has seen innovation (e.g., inverter-based variable speed compressors for variable capacity; use of compressor waste heat to heat inside) that now enables durable operation in even the coldest climates.
- The scope of design performance focused on operational energy and occupant comfort but also took a wider view. The SPARC House considered durability and environmental impact of materials, ultimately using mostly wood and natural materials where possible and very little concrete, foam, or blowing agents, to explore what one iteration of a resilient home might look like.



Picture 5. CU Boulder student team accepting first place honor and remarks from the U.S. Secretary of Energy Jennifer Granholm for the SPARC House in the 2020/2021 Solar Decathlon Build Challenge

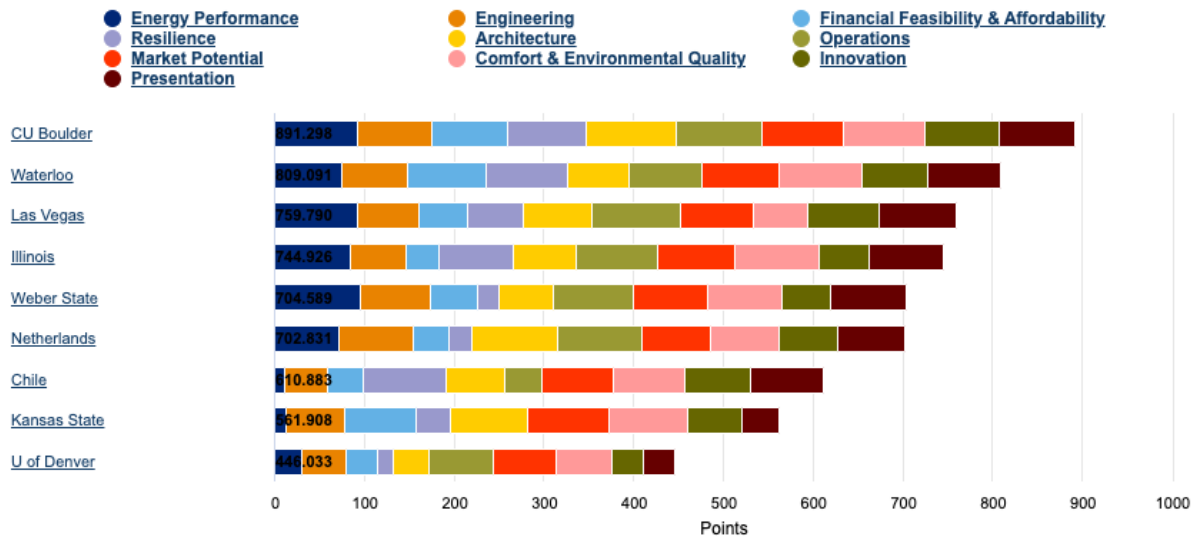


Figure 6. Collegiate team rankings for the ten Solar Decathlon contest that comprise the Solar Decathlon Build Challenge competition

Conclusion

Can builders construct energy efficient, resilient, and affordable all-electric houses in the coldest climates? The SPARC House demonstrates this is possible in theory and in practice. The house, designed by students, constructed with a novel, panelized method, and occupied by typical, albeit energy conscious Fraser residents shows the possibility through both modeled and measured results. The house was modeled in BEopt and it is operating so efficiently, as predicted by the model, that it exports excess energy to the grid on an annual basis including the use of an electric vehicle. The house is predicted to be a carbon sink when considering its wood structure, siding, and interior trim consisting largely of beetle-kill (blue stain) pine, claiming -19,154 kg CO₂ equivalent global warming potential according to a student analysis using the Athena Impact Estimator for Buildings (heat pump R-410A refrigerant, cement for the foundation, and energy use for the rockwool insulation were significant embodied emissions sources that could be reduced in future construction through utilization of heat pumps with lower global warming potential refrigerants, reduced-carbon cement, and/or alternative exterior insulation). The panelized design and build process is largely responsible for the minimal construction waste and use of planned natural materials, making the material use and quantity predictions very close to reality. Importantly, the house can be afforded by homeowners who allocate 30% of a \$65,000 annual household income toward a sustainable home according to a student-developed proforma that includes \$8,800 annual income from the guest suite, a minimal \$400 in annual utility expenses (primarily “fixed” energy charges like the \$29 per month service availability fee, which is high but common for cooperative utilities in Colorado), and lower annual maintenance costs. The annual energy costs have proven to be on par with or lower than these estimates in its first year of operation. Given that the house is newly built, no maintenance expenses have been incurred to date.

The SPARC House shows that builders can build sustainable, all-electric homes at or below typical construction costs, in even the coldest climates and shortest build seasons, and these homes are marketable and affordable for homeowners and renters.

This demonstration of what is possible but outside of the box is the cornerstone of the Solar Decathlon competition. For the CU Boulder team, it was equally important to create a comfortable and livable home for a specific future homeowner. Both occupants report that the home is quieter and more comfortable than any home they have lived in previously, and that the heat pumps provide a cozy, comfortable heat and warm the space quickly. More broadly, the community of Fraser and all similar cold-climate towns have a working example of a buildable, highly efficient, resilient, and affordable all-electric home.

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