Engineering

U.S Department of Energy

Solar Decathlon 2023

Build Competition

University of Colorado Boulder Team

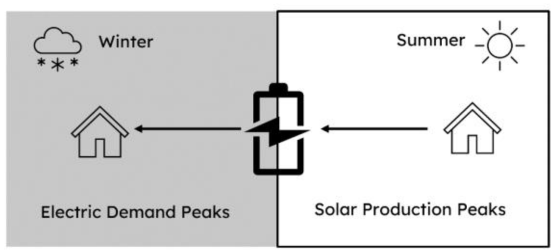
03/28/2023

Background

As the effects of climate change over the last two decades have become more prevalent in everyday life, people have become increasingly aware of the impact their everyday actions and consumption patterns have. Additionally, global insecurity, extreme weather events, and unforeseen challenges like global pandemics are on the rise. In many ways it seems the world is at an inflection point and that the changes we make today will have tremendous effect on the future. With the ever-growing demand for energy, and the immediate threat of climate change, solutions of all forms are needed—and faster.

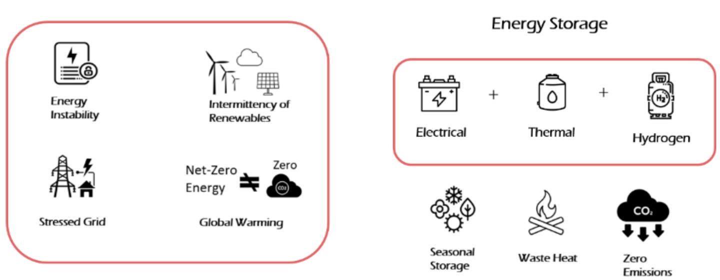
In the US, two-thirds (65%) of Americans believe the federal government is doing too little to reduce the effects of climate change. This rather Bi-Partisan view is not new and has been increasing over the last decade. The traditional strategy is to electrify everything and to shift our energy generation to renewables. Although in many ways this is extremely logical, it isn't without its challenges, some of which intensify in heating dominated climates. Furthermore, the consensus points towards Net-Zero Energy as a solution for decarbonizing our built environment; however, this will require both storing vast amounts of energy short term and long term and changing the energy economy. One potential solution to this challenge is Green Hydrogen—Hydrogen made solely through renewable energy.

Typical NZE- The Grid as A Battery



In Cold Climates, traditional Net-Zero Energy utilizes the grid as an infinite battery in which often surplus energy is supplied in the Summer and in the Winter, energy is reversed and pulled from the grid. With the shift towards electrification, the need for energy storage has become essential. Furthermore, as we electrify our buildings, additional challenges rise—such as the coincidental peaks of high energy appliances such as HVAC Systems, Dryers, Ranges and Water Heating. This requires both a better understanding of how energy is used and when, as well as better control and management of our energy uses within our buildings. Although battery technology has made tremendous advancements, some of the challenges associated with mining rare earth metals, the amount of water required, and issues with recycling, degradation, and thermal runaway have become predominant.

The Problem: The Question:



Both the inherent challenge of changing people's perception on energy and how we can achieve a decarbonized economy play a role. The primary problems addressed revolve around Energy Instability, the Intermittency of Renewables, an Electric Grid in need of infrastructure and maintenance, and the fact that Net-Zero Energy isn't zero impact. The goal and question to answer is how a combination of Short Term, Seasonal, and Thermal Energy Storage can interact with the Grid to be Energy Independent.

Design

The Canopy focused on an integrated and holistic approach to the architectural and engineering systems within the home centered around energy efficiency, occupant comfort, and energy storage.

Passive

Often passive design refers to Passive Solar, meaning an integrated approach to maximizing solar gain in the winter and limiting it in the summer. Working with the pre-established architectural guidelines for the Ponderosa Community, we had limited control over the building orientation, exterior architectural features, overall building footprint, and massing of the structure. Instead, we were able to innovate with the constraints we were given to come up with a practical, affordable, resilient, and high-performance building envelope. With a goal of eliminating operational carbon in the home, we aimed to provide a low embodied solution that could act as a model for the Ponderosa Community development.

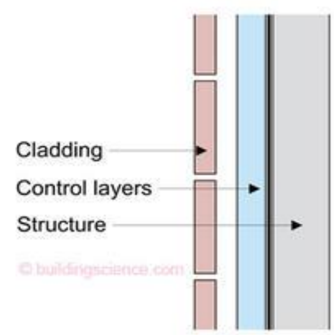
The CU Boulder team performed an engineering study detailed further in the Embodied Impact category which centered around:

1. Cost
2. Construction Duration
3. Air Quality Impact
4. Operational Performance
5. Embodied Carbon

Envelope

The purpose of the building envelope is to act as an environmental separator—keeping the outside out and the inside in. Much like our clothing shields us from the elements when we go outside, the envelope of our building must have the ability to control rain, air, vapor and heat. It is the primary defense to the elements, and the most important factor to achieving a high performance and energy efficient building. Working with Habitat For Humanity, much of their construction is reliant on volunteer labor. As such we wanted a replicable design that appreciated traditional building and construction practices while still embracing innovative and creative solutions.

We started with "The Perfect Wall" concept popularized by Joe Lstiburek of the Building Science Corporation. "In concept the perfect wall has the rainwater control layer, the air control layer, the vapor control layer and thermal control layer on the exterior of the structure. The claddings' function is principally to act as an ultra-violet screen."

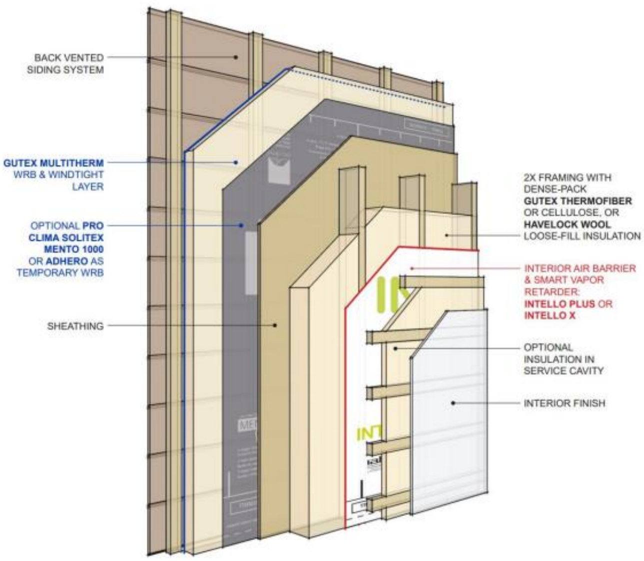


Adapting this basic idea of control layers, we worked with Industry partners 475 Building Supply to develop a high performance and vapor open assembly that balances constructability, affordability, occupant health, and embodied carbon.

As depicted below [from left to right], the layers of the wall assembly start with the **exterior siding** fastened to the vertical battens which make up the **rainscreen**. The siding acts as the primary defense against the outside and moisture, while the rain screen allows for convection within the cavity to dry out any moisture that does get in.

Exterior wood fiber insulation (Gutex Multitherm) wraps our walls in a blanket of **exterior continuous insulation**. Traditional construction incorporates insulation solely within the framing and structure of the building. Although efficient, the purpose of insulation is to prevent and reduce the heat flux through the envelope. By insulating the exterior of the framing, much like putting a jacket on our bodies we reduce temperatures within the wall cavities approaching the dewpoint temperature—leading to condensation.

An exterior **Weather Resistant Barrier** (Pro Clima Solitex Mento 1000) is fastened to our **exterior sheathing**. This serves as a vapor-open waterproof membrane and the secondary air barrier.



The home's structural system consists of **2x6 dimensional framing with dense pack cellulose insulation** to match our design philosophy and goals of constructability, organic materials, and low embodied carbon. The **primary air barrier** is installed on the inside of the stud walls and roof. This acts as the primary air control as well as the netting for the dense pack cellulose. The barrier is the Pro Clima Intello Plus which is an airtight membrane with smart vapor technology. During the winter, the perm rating decreases which helps to prevent vapor movement into the insulation. During the summer, the perm rating increases to promote drying of the insulation to the interior.

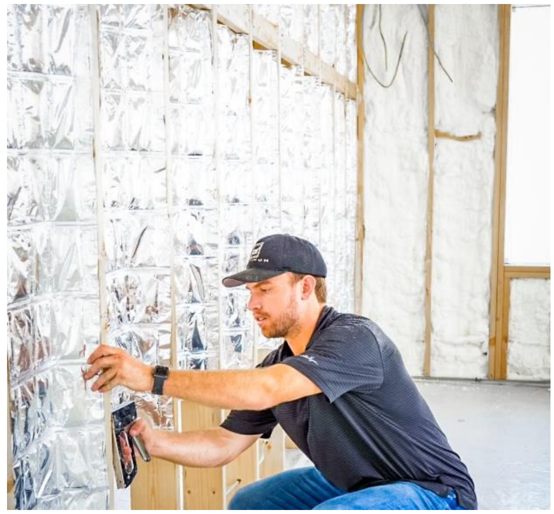
To minimize penetrating the air barrier and to help reduce air leakage, an **interior service cavity** made through horizontal battens behind the drywall, allows for the electrical and plumbing to be contained and run throughout the house controlling the number of penetrations that need to be air sealed. This cavity also allows for an ideal location for latent thermal storage using **PCM (Phase Change Material)**.

Phase Change Material

A phase change material (PCM) is a substance that exploits the change in latent heat through its phase change process. The most common PCM is water with a freezing point of 32F at atmospheric pressure. For example, take a glass full of water and ice sitting out on a hot day. The temperature of the water will remain at 32F until all the ice has melted even though the sun is heating up the water-ice mixture. As the ice melts, it changes phase and absorbs energy from the surroundings to break the molecules free from solid to a liquid state. Once liquid, the sun will sensibly heat up the water until it reaches ambient conditions. The absorption of heat while the ice melts is the latent heat of fusion which is the driving principle around PCM for thermal storage.

Working with industry partners QE Platinum, we will incorporate around 800 SF of PCM strategically within the East, South, and West walls. It will be placed on the interior side of the envelope behind the drywall to help effectively cycle the PCM.

QE Platinum has developed an organic salt hydrate PCM incorporated into aluminum sheets. These sheets are multipurposed, separating the PCM within the sheet to form a thin layer and acting as a radiant barrier and air control layer. It is lightweight, easy to install on within traditional framing cavities, and requires no specialty machinery or equipment. It is non-corrosive, non-toxic, and self-healing in case the PCM is punctured and exposed to air. Furthermore, it is not only non-flammable but a fire retardant.



The PCM both helps to shift peak energy use by enabling passive heat gain as well as provide energy storage through active heating and cooling of our heat pump. Traditional insulation is measured in terms of thermal resistance or R-Value. Instead, PCM doesn't just slow down heat flux through the wall assembly but intercepts and stores that energy. For an energy independent home this is essential to prevent peak electrical loads from the heat pump, as well as to shift the heating and cooling demand to more advantageous times to balance the energy use within the home more evenly.

Active Systems

One of the most important aspects of occupant comfort within a space is thermal comfort. Whether too hot, too cold, too humid, or too dry, the condition of indoor space requires constant balancing to meet the changing indoor and outdoor conditions. In Boulder CO, the climate is dominated by heating degree days for most of the year and has huge diurnal temperature swings in the shoulder seasons of Spring and Fall. As such, an efficient, all electric and easy solution is necessary.

Heating & Cooling

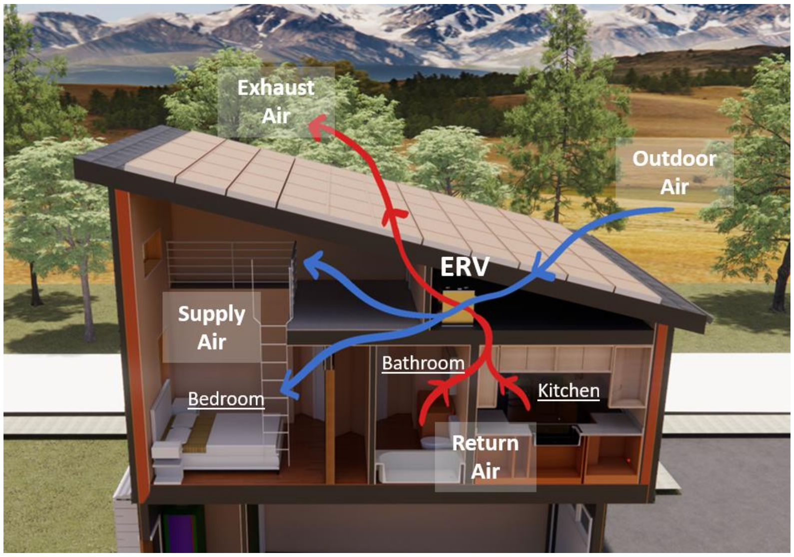
According to the 2020 RECS produced by the EIA (Energy Information Agency), in the Mountain North Region which Boulder lies, 74% of homes use natural gas for heating. Not only does this hinder the transition to decarbonizing our buildings, but it also allows the potential for toxic gases within the living space. As such, the heating and cooling system for the home consists of a highly efficient ducted Mitsubishi Hyper Heat Pump. Although we explored innovative systems such as a building integrated transpired solar collector, solar absorption cooling, and hydronic systems—the efficiency, easy, familiarity, and maintenance of the Mitsubishi Heat Pump was ultimately the driving factor. Due to the relatively compact interior space and high-performance envelope, the heating and cooling loads for the building are below 1 Ton. The heat pump's variable speed inverter compressor allows the system to vary the load to quickly ramp up and down to prevent overheating in the Summer and to overcome large outdoor temperature swings without large peaks. The heat pump will be used with our home energy control system to optimize both the performance of the heat pump as well as charge our PCM thermal storage within the walls.

Ventilation

The saying "Build Tight, Ventilate Right" although used often, stands the test of time for high performance homes. Reducing infiltration in the building not only helps to reduce the heating and cooling loads of the space, but also promotes better indoor air quality by preventing outdoor air pollutants. With an airtight indoor space, there is less dust blown through the cracks when wind blows on the envelope as well as less bugs and insects. Although an airtight envelope improves indoor air quality and comfort, there needs to be a dedicated ventilation system engineered within the home. Not only to prevent the accumulation of CO_2 and other VOCs, but also to help mitigate moisture and humidity within the space.

Balanced & Demand Response Ventilation

Constant and balanced ventilation will be provided through a Renew Aire EV Premium M ERV (Enthalpy Recovery Ventilator). The ERV will continuously extract stale air from the kitchen, bathroom, and bedrooms while heat exchanging with fresh outdoor supply air. The ERV is relatively oversized for the space based on ASHRAE 62.2 Standards, however this provides us with dual benefits. First, the oversized unit provides a larger surface area for heat exchange and ultimately better efficiency. Second, it allows us to control and respond to indoor air quality issues by ramping up or down. An occupancy sensor in the bathroom coupled with an additional "boost" button, allows the ERV to increase ventilation when the bathroom or shower is being used. In the kitchen, a boost button will allow the homeowner to increase ventilation when cooking. We wanted the ventilation system to be flexible and be able to adapt to whatever is happening within the envelope. Utilizing dual CO_2 sensors within the space allows the ERV to increase ventilation when the CO_2 concentration rises above 1000 PPM. This is especially useful when many people occupy the indoor space which could lead to a spike in CO_2. Furthermore, with the increase in wildfires in recent years, we wanted the system to be able to withstand any indoor air challenges that occur both inside and outside the envelope.

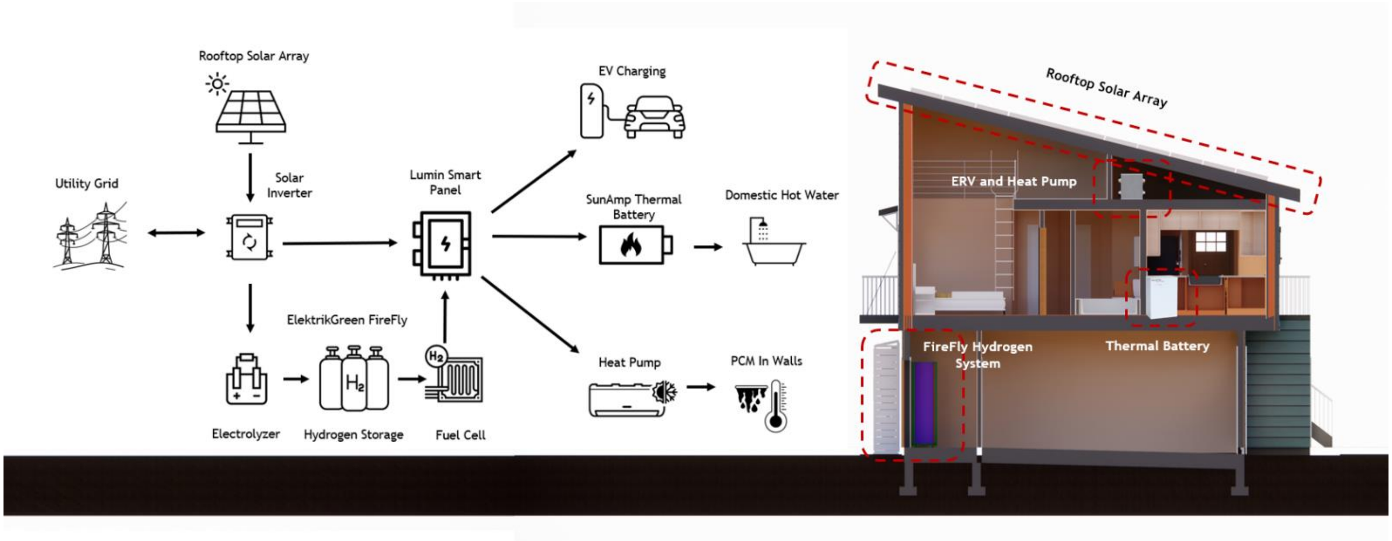


Energy System

The energy system within the home is focused on maximizing On-Site Solar Utilization through diversified energy storage. We believe that the best place to store energy is where it is produced. Solar Energy can be used in a variety of ways:

- To directly power the home
- To net-metered back to the grid
- To power our electrolyzer to produce hydrogen
- To melt PCM within our thermal battery
- To run our heat pump to charge PCM within the walls
- To charge an electric vehicle (future bi-directional charging ready)

The total energy storage capacity consists of 55 kWh of electrical storage through hydrogen, 10.5 kWh of thermal storage with our thermal battery, and 14 kWh of thermal storage with the Phase Change Material in our walls.



Solar System

A 7.2 kW rooftop solar array acts as the powerhouse of the home. The panels are rack mounted with careful consideration to prevent puncturing the air barriers during installation. A Solar Edge Grid-Tied Inverter converts DC to AC current to be used within the electrical distribution and energy system.

Hydrogen Background

Hydrogen is the most abundant element in the universe, 14 times lighter than air with the highest energy density on Earth. Although abundant it is not found by itself anywhere in nature requiring a source of hydrogen and energy to extract it. Solar Hydrogen Energy systems mimic those found in nature such as plant photosynthesis in which solar energy converts water and CO2 into sugars then stored for later use. Hydrogen is an energy carrier or secondary energy source like electricity meaning that it requires a primary energy input. Hydrogen is also a versatile energy carrier as it can be used for a variety of uses and processes.

Hydrogen for energy is not a new idea, which dates back to the 19th century with the first internal combustion engine powered by the element. Furthermore, Hydrogen in the Solar Decathlon isn't new either with the 2005 New York Institute of Technology implementing a system in their Green Machine.

With our energy needs supplied by fossil fuels Hydrogen took a back seat to the Industrial Revolution. However, with a push to decarbonize our world, The Hydrogen Economy has had tremendous acceleration. Working to shift some of the energy processes that are difficult to electrify towards clean Hydrogen. In addition, stimulating economic growth and energy exports that electricity cannot provide such as shipping energy across the ocean.

There are many ways to produce hydrogen, with most of the hydrogen currently produced through steam reformation of natural gas which releases CO2 into the atmosphere. Green Hydrogen is a form of hydrogen produced solely by renewable energy. Green Hydrogen maximizes the contribution of renewables by balancing the existing mismatch between electric demand and renewable supply. It allows power that is generated to be stored and then utilized in different forms. It allows for seasonal energy storage without degradation and the process can be completely recyclable without the need for rare earth metals.

Hydrogen System

Through a partnership with ElektrikGreen, the Canopy will feature the first grid-connected green hydrogen energy system in Colorado. The FireFly system is plug-and-play, meaning the home can be operated seamlessly with or without the system. However, through the FireFly system we are able to strive to be energy independent by storing long term (more than three days) hydrogen storage. This is especially helpful in the Winter when energy demand is high and solar production is low.

The main components of the system include a 3kW AEM Electrolyzer, a 10 kW PEM Fuel Cell, a 15kW Grid-Forming Inverter, and Hydrogen Storage Tanks. During the day when the sun is shining, excess solar electricity can be used to run the electrolyzer. The electrolyzer splits a small amount of water into hydrogen (H2) and oxygen (O2). The hydrogen is safely outside until it is needed, while the oxygen is vented harmlessly to the atmosphere. Due to the low compression of the hydrogen storage, it can be stored for use as daily, weekly, or seasonal energy storage. The 55 kWh of storage can easily be upgraded for future flexibility.

When there is an energy demand in the home that cannot be met by solar power, a fuel cell combines oxygen in the air with hydrogen to produce electricity to power the home. This process only releases water vapor and heat. This “waste-heat” has the potential to be recaptured to be used for hot water heating which is needed year-round.

The Hydrogen System has the ability to work seamlessly when the grid goes down by providing it’s own 60 Hz frequency so that the solar production can still be used to power the home. With the discharge capacity of 10kW and peak capacity of 15kW, most energy demand scenarios will be covered.

Community Power

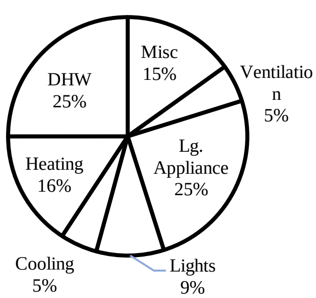
Since often power outages aren’t fixed to one home, being able to provide carbon free power to the community can help to reduce discomfort during an outage. A 20 Amp Power Inlet plug will be provided on the North side of the home which in the event of a power outage can be used as a temporary power station for the community.

EV Charging

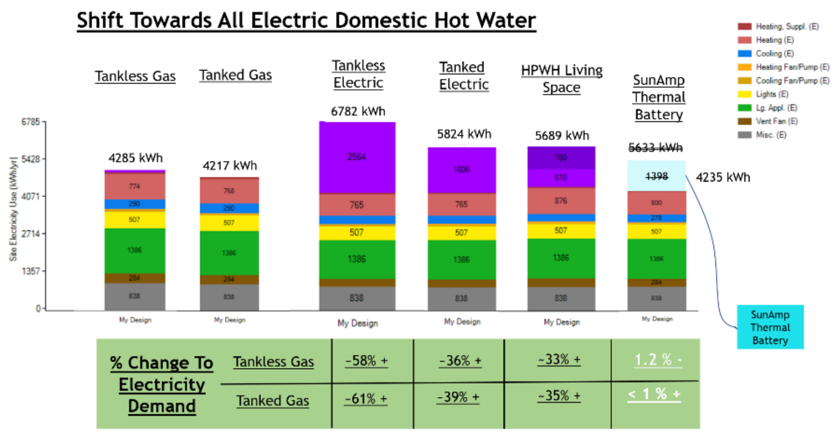
With the adoption of electric vehicles, the opportunity to use the battery in your vehicle through bi-directional charging is gaining interest. The two car garage beneath the carriage style home will be open to both the homeowner or to someone with a single story home elsewhere in the community without a garage. As such, future goals could incorporate using the EV charger as a community charging location.

Domestic Hot Water

With a high-performance envelope and a highly efficient heat pump, the share of energy that typically goes to heating and cooling is greatly reduced and rather DHW (Domestic Hot Water) and Large Appliances encompass a greater portion as shown in the figure.

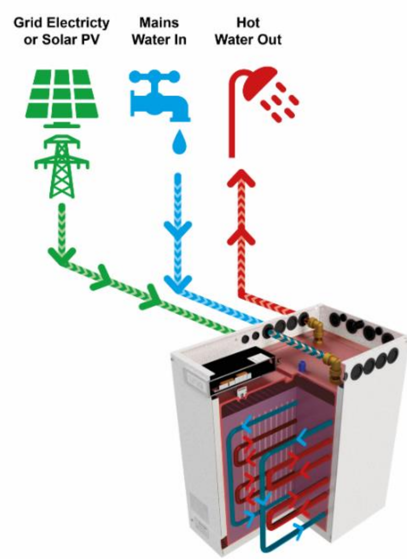


The shift to decarbonize Domestic Hot Water is especially drastic in Cold Climates due to the large lift temperature required in the winter. Tankless electric resistance water heaters have both a high energy consumption as well as high electrical peak demands. These large peaks make typical battery storage challenging to compensate for. Although HPWHs (Heat Pump Water Heaters) have made great strides in their COP (coefficient of performance) in recent years, they aren't without their challenges. When placed within the living space, they steal heat from the indoor conditioned air. When placed outside the envelope, backup electric resistance heating is required in the winter and more energy loss occurs due to the longer piping runs. The CU Boulder team analyzed the energy use of various hot water systems using BeOpt and the Building America Protocol. As shown in the figure, shifting from gas heated systems to electric drastically increased the electrical demand required by the home.

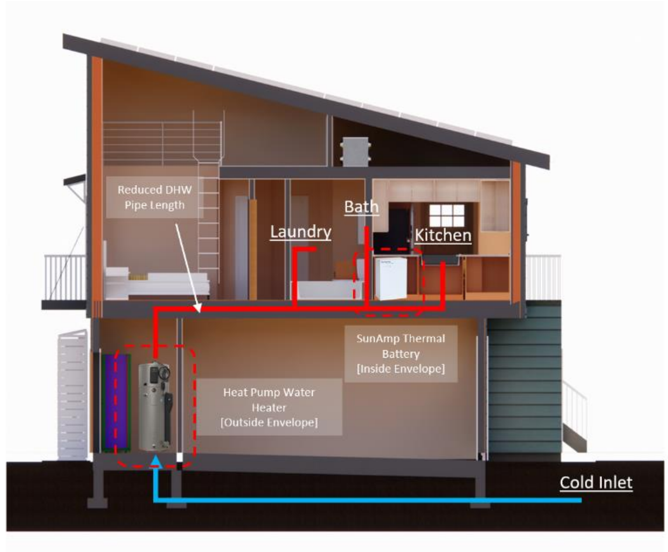


Thermal Storage (Thermal Battery)

Thermal storage can be classified as thermal mass of any kind that can store heat such as concrete, brick, or water. Typically, passive solar and thermal storage go hand in hand by charging the thermal storage with the sun to then be released at night. This idea isn't new and the first house in the US with an active solar heating system was built in 1939 on the MIT campus. Since the beginning days of rooftop solar, there have been people looking for a way to maximize their renewable investment and use as much energy on-site. Before utility scale net-metering, a common practice was to use a solar charge controller tied to either the water heater or a buffer tank to absorb excess energy in heat. These so-called Thermal Batteries were some of the early forms of energy storage in homes which have since been improved and refined. Recently, PCM (Phase Change Material) Thermal or Heat Batteries have gained market share for the ability to store any thermal energy from industrial level heat to medical level cooling and everything in between. The SunAmp Heat Battery is a vacuum insulated box filled with PCM which capitalizes on the incredible energy released during phase change. It uses an embedded electric resistance element which melts the PCM changing its phase. When there is a hot water demand, cold city tap water is fed through an embedded heat exchanger which transfers the stored energy from the PCM to the water taking advantage of the latent heat of fusion. As the PCM turns from liquid to solid it discharges its energy to the water, heating it. It is non-toxic, non-flammable, and stores 10.5kWh of Hot Water Heating Capacity.



The incredible benefits of thermal batteries come from their relatively low-cost and embodied carbon from natural materials such as salts or paraffins. They can act as a sponge for excess solar or as a demand response device to help mitigate the ever-changing impact on the utility grid. Due to the low heat loss of



the system the energy can be stored for days without fully losing its heat. In addition, it greatly reduces the space otherwise required for a water tank and can be placed closer to where the water is used, reducing heat loss. It both reduces the need for a large, pressurized tank while also providing the ability for hot water on demand like a tankless water heater which reduces both wasted energy and water. Finally, since water isn't stored, the risk of legionella is mitigated and the excess energy to heat water above 130°F is reduced.

Lastly, thermal storage can take advantage of waste heat. In the case of a Hydrogen Energy system, one of the primary disadvantages is efficiency. Both the electrolysis of water to produce hydrogen and combining hydrogen with air in a fuel cell suffer from loss of energy in the form of heat. Although rather undesirable when it comes to passenger vehicles, heat is needed year-round for water heating in buildings and homes. When a hydrogen energy system is coupled with thermal storage the efficiency of the system can reach 90%, whilst still benefiting from the advantages over batteries for its' long-term storage, no degradation, long life cycle, and recyclability. Although due to time constraints this was not implemented in the design, it will be explored more in the future.

Smart Panel Board

Using Lumin's Smart Electrical Panel Board, 12 circuits can be individually monitored and controlled. The Lumin panel is an additional panel to an ordinary main distribution panel and allows automated energy management by prioritizing specific circuits and loads through the app. In the case of a grid outage, the system will automatically shed loads to prevent from discharging all the home's energy storage. The Lumin System will be integrated into our larger Home Management System using Home Assistant.

Thermal Storage Charging

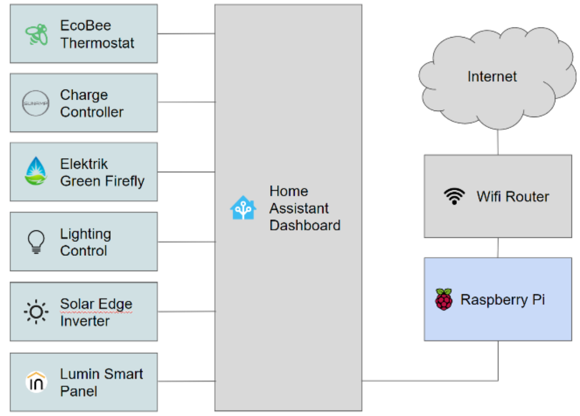
The SunAmp thermal battery is charged through integration of the Lumin Panel and Home Assistant. A model predictive control code will be incorporated into Home Assistant with a time horizon of 24 hours to control the oversized thermal storage charging based off available solar energy.

A strategy to shift peak heating demand incorporates charging the QE Platinum Phase Change Material in our walls during the day by overheating the home with our heat pump to store the excess energy in our walls. Rather than the heat going to heat the air in the room, heat will be absorbed by the PCM changing phase from solid to liquid. It was determined that 6 hours of the 75% Heating load would be used to size the amount of PCM within the walls. This equates to around 40kBtu or 14kWh of storage.

Energy Management System

Using Home Assistant, an open-source home automation software, a central control center to integrate smart home devices and energy management will be implemented. This creates a local server that can tie in various smart home devices and helps to reduce security risk. The system incorporates an overall energy dashboard to enable the homeowner to get a better understanding of how energy is being used within the home.

The energy dashboard will incorporate the hydrogen storage capacity from Elektrik Green, the Thermal Battery Capacity from SunAmp, the solar production from Solar Edge and the home energy usage from Lumin. An Ecobee Thermostat will communicate with Home Assistant and provide the opportunity to run automations or set up schedules. Furthermore, the system will be flexible to allow the addition of smart home devices in the future as well as lighting control.



Performance

Energy modeling was performed using NREL's BeOpt (Building Optimization Tool) to acquire the Site Electricity Usage. A baseline was determined using Habitat For Humanity's original design for the home which meet Boulder's stringent energy standards. Analysis into the Energy System was performed using the outputted yearly electrical data from BeOpt in Python. The control of the hydrogen and thermal storage was modeled through an model predictive control optimization which minimized the time of use cost from the grid.

Site Electricity Use (kWh/yr)

	Base Case H4H	CU Team	% Change
Ventilation Fan (kWh)	38	261	585%
Cooling Fan/Pump (kWh)	111	18	-84%
Heating Fan/Pump (kWh)	188	111	-41%
Heating, Backup (kWh)	249	0	-100%
Cooling (kWh)	360	211	-41%
Lights (kWh)	498	299	-40%
Hot Water (kWh)	648	668	3%
Misc. (kWh)	1155	868	-25%
Lg. Appl. (kWh)	1243	1108	-11%
Heating (kWh)	1717	730	-58%
Yearly Total (kWh)	6207	4273	-31%
EUI (kWh/SF/Yr) =	8.28	5.70	-31%
EUI (kBtu/SF/Yr) =	28.24	19.44	-31%

2023 Estimated Emissions [EIA Colorado Electricity Profile]

Home Size	750	SF	% Reduction
CO2 Emitted [Average Home]	5,027	*kgCO2*	0%
CO2 Emitted [Design, No Solar]	3,523	*kgCO2*	30%
CO2 Emitted [H2 System]	151	*kgCO2*	97%

20 Year CO2 Emissions [Fixed 2022 EIA Colorado Electricity Profile]

Home Size	750	SF
CO2 Emitted [Average Home]	100.55	*Metric Tons*
CO2 Emitted [Design, No Solar]	70.47	*Metric Tons*
CO2 Emitted [H2 System]	3.02	*Metric Tons*