U.S. DEPARTMENT OF ENERGY
SOLAR DECATHLON

ENGINEERING

UC DAVIS

Engineering Jury Narrative

Our H_2Ouse. Our Water Use.

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Our Climate

California has experienced the state's hottest drought years on record within these past 10 years. As a result, many of the state's unsustainable water and energy use practices within urban and rural areas have been brought to light, and calls for increased water and energy efficiency have been initiated by the state government, such as the 2014 Sustainable Groundwater Management Act (SGMA) and 2030 Climate Commitment. Based on an analysis of the social, political, economic, and environmental factors involved in the most recent California drought, it was determined that the state can increase its water and energy resilience by fostering a robust, conjunctive management of resources. Such a system aims to increase the general knowledge and sharing of collective as well as individual resource consumption data.

During the latest period of drought, Californians reduced their potable water usage by 25% and contributed 43% of all U.S. small scale solar output in 2016. It is not surprising that these two statistics have a positive relationship. California's water sector accounts for nearly 10% of the state's greenhouse gas emissions, and within that sector residential use accounts for 42% of the energy used. In addition, all of California's main methods of energy production heavily rely on water, including fracking, and thermoelectric and hydroelectric power production. Therefore, energy conservation leads to water conservation, and vice versa. This interconnectedness of water and energy is thoroughly engrained in the architecture of Our H_2Ouse, whose structure, function, and aesthetic are all aimed at reducing water and energy use in cost effective manners.

Our House Envelope

Methods of energy and water saving were implemented from the project outset. Simply by designing smaller, more efficient structures, the building would have inherent water and energy savings. Therefore, the building envelope of the home was designed to be compact, and better insulated than standard framing methods. These goals were fulfilled through the use of traditional 6.5" and 8.5"—floor and roof, respectively—structurally insulated panels (SIPs) composed of oriented strand board (OSB) and extruded polystyrene (XPS) for the floor and roof, respectively; along with a panelized bamboo-based wall system. The respective R-values of the floor and roof are R-42 and R-56. The BamCore® Wall System is similar to SIPs in that they are both structural and panelized, but the big difference is that BamCore® walls do not arrive pre-insulated. The manufacturers only provide the exterior- and interior-facing panels, and the insulation is chosen and installed by the builders. This allows the builders to choose a more environmentally friendly insulation that can be chosen specifically for the conditions present at the building site. For Our H_2Ouse, loose fill Thermafiber mineral wool was chosen for the wall insulation. Thermafiber spins their mineral wool from alternative recycled materials like rock and furnace slag byproduct from the steel industry, saving valuable natural resources. The 1' deep walls allow for 9.5" of insulation, resulting in R-40 walls. The high insulative properties of the floor, walls, and roof become extremely advantageous when designing the home's heating and cooling system. BamCore® was also selected for the carbon savings it incurs through its production and use phases. Modeled in the U.S.-weighted average climate zone over the course of 70 years, a BamCore®

home of 2,262 ft^2 would save 125 metric tons of CO_2 emissions compared to homes with traditional 2’x6’ stick framing, and 22 metric tons CO_2 emissions compared to a home with SIP walls . Additionally, with the incredibly fast growth rates of this invasive species, bamboo harvests are far more productive compared to Douglas fir, yielding ten times the material and thus sequestering higher levels of CO_2 per unit of land.

Beyond the basic materials used to construct the home, the thermally insulative properties of Our H_2Ouse's building envelope are augmented with the use of the latest in aerosol-based sealing technologies. Aeroseal, invented by UC Davis' very own Mark Modera (Director of the Western Cooling Efficiency Center) is used in Our H_2Ouse to not just plug holes in HVAC ducting, but in the entire home itself. A significant component of a building's energy demand can be attributed to air leakage through small cracks and gaps in junctions between walls, window and door frames, outlet boxes, etc.17. Currently used solely to seal HVAC ductwork, Aeroseal is a proven sealing technology with great potential to significantly reduce whole-house uncontrolled air intrusion. Preliminary tests showed Aeroseal able to seal 30% of envelope leaks, with use of greater blower-door pressures expected to achieve up to 50% sealing efficacy. Once refined in the residential market, this technology may then be applied to the commercial sector where its impact upon the state's energy grid could be far greater in scale.

We have also innovated in our solution to south side shading on windows. The standard solution for south side shading of passive houses often consists of static roof or window overhangs. Our H_2Ouse employs two dynamic strategies to overcome the unresponsiveness usually associated with this shading strategy. The first and most noticeable feature is the south deck shade structure, which features shade cloth screens that are adjustable in the north-south and east-west direction. Less noticeable, but far more innovative, is the solar-intuitive, thermochromic window coating that is installed on the inner glazing of all the home's south facing windows. This coating requires no electricity, Internet connection or any other special materials or equipment to switch between its tinted and non-tinted states, and can determine whether to allow or block solar heat gain simply based off temperature differentials. The combination of these two features allows Our H_2Ouse to employ a very responsive, adaptable and user-friendly south shading strategy.

Our HVAC System

Components

Our H2Ouse features a unique HVAC system, which consists of a Warmboard® radiant hydronic floor, a PHNIX Hero Series H8 air-to-water heat pump, a heat recovery ventilator (HRV), and an integrated humidifier. Furthermore, Our H2Ouse promotes efficiency by using a single PHNIX Hero Series H8 DC Inverter A/W HP for both space heating and domestic water heating. The heat pump will operate the radiant hydronic system during the day and the domestic hot water tank at night, although the system allows for hot water heating during the day if needed. The HRV system will provide ventilation to the house, keeping the air quality intact. The humidifier is connected to ventilation ducting, which utilizes the ERV fan to disperse the provided moisture.

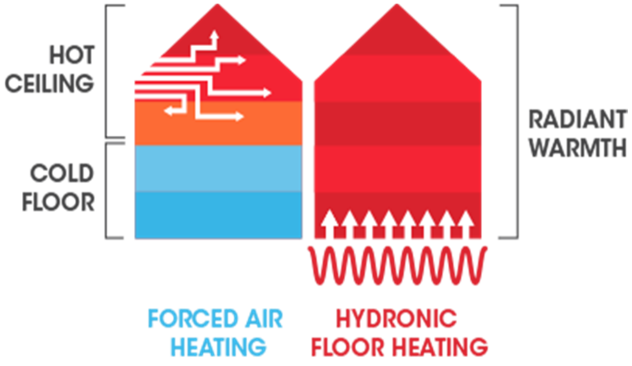


Figure 1. Forced Air vs Hydronic Floor Heating[1]

Heating and Cooling

The largest energy load for a typical residential house is the energy used to heat and cool the house. Just like how the team focused on how to reduce water use, the team also looked at how to reduce energy use. The main way Our H2Ouse does this is by improving the building envelope in strategic ways, which were covered above. The tight building envelope and high R-values help reduce thermal losses from indoors to outdoors, effectively reducing the energy input into the home's heating and cooling system. The remaining thermal loads are handled by a hydronic radiant floor system that is charged by a heat pump. The heat pump is reversible so that it can handle heating and cooling loads. The team chose a radiant system over a traditional forced air system because of its improved comfort and efficiency. Heated air from a forced air system is difficult to distribute evenly. Heat rises, which means much of the air coming out of the vent heats air nearest the ceiling and away from residents; in a radiant floor system, the heated floor is in direct contact with residents, which allows them to experience optimal indoor comfort temperatures (Fig 1). Another benefit of radiant is the inherent lack of air flow, which inhibits the distribution of allergens within the indoor space. Forced air systems intensify the allergen spread, which results in poor air quality. Surprisingly, even with these benefits, radiant systems are still quite rare. They are expensive to install which increases the payback period from savings. However, Our H2Ouse's smaller square footage mitigated increased price, and its tight building envelope reinforced the energy savings so the team felt that the radiant system was a good investment in the long-term.

Figure 2.Warmboard-R Panel Assembly[2]

The radiant flooring we chose was from Warmboard®, a manufacturer that specializes in "dry" installed systems. A dry installed system differs from more the more common "wet" installed system, which involves radiant tubing being embedded into a slab of concrete, gypsum, or similar material. The slab increases thermal mass of the home, which can be a positive addition if the goal is to store thermal energy. However, in a heating and cooling scenario where the goal is to transfer thermal energy rather than store it, a wet installation hinders reaction time of the system; it would take more time for the heat to move from the radiant tubing, through the slab, and finally to the finished floor than without a slab. A dry installed system like Warmboard®'s forgoes the slab and instead embeds radiant tubing in channels etched out in a high-grade OSB subfloor. Warmboard® goes a step further and lays a layer of aluminum on top of the OSB (Fig 2). The OSB has considerably less thermal mass than a concrete slab, which allows heat from the radiant floor to reach the finished floor surface quickly (Fig b). Aluminum, a conductive material, helps spread heat throughout the floor's surface area more evenly and efficiently (Fig c).

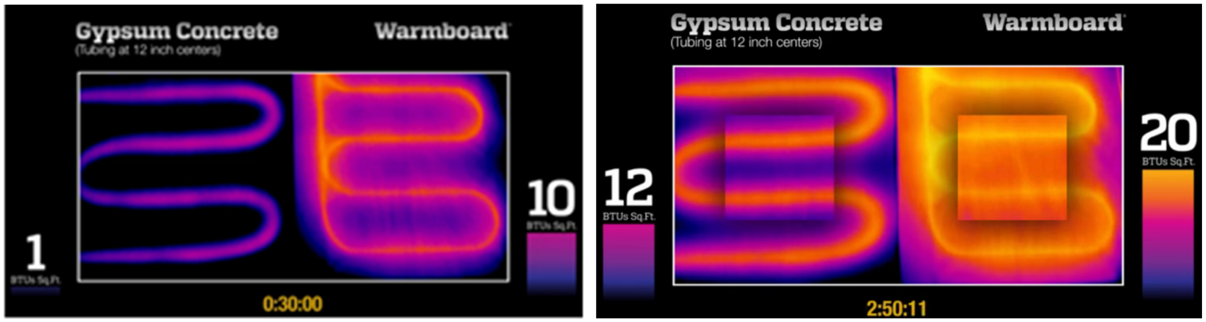


Figure 3. Gypsum Concrete vs. Warmboard[3]

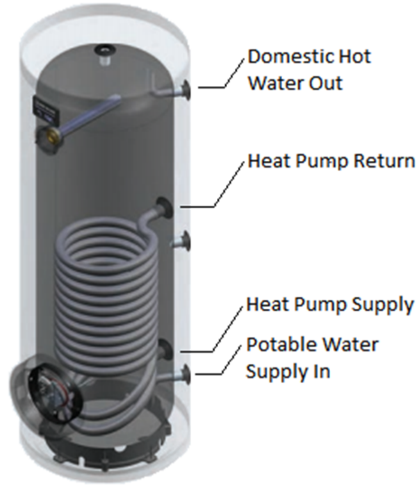


Figure 4. Weil-McLain Aqua Plus Indirect Hot Water Tank[4]

In order to decrease material usage and costs and to create an efficient system, a unique way of hooking up the heat pump was conceived. The heat pump first connects to a 3-way valve, with one arm of the valve connecting to the radiant floor system, like mentioned above. The other arm connects to an indirect hot water tank. The indirect hot water tank exchanges heat through an internal coil between a closed loop of hot water–generally from a boiler, but in this case, a heat pump—and potable water from the city supply. This allows the team to forgo a separate hot water heater, which would require its own heat source—either another heat pump or an electric heating element.

Ventilation

Because the home's heating and cooling system is not air-based, there is minimal air movement in the house, which means stagnant air and decreased inhabitant comfort. As a result, a ventilation system was included to circulate air and remove pollutants from our tight building envelope. Increased ventilation, however, creates larger demands on the heating and cooling system, as well as overly lowering humidity in dry climates such as Denver and Davis. The team created several models for humidity in the house during competition hours and found that the house humidity would often be too low using a natural ventilation system or HRV. In order to counteract this problem the team chose to use a Fantech SHR 1504 heat recovery ventilator (HRV) as the primary source of ventilation as well as invest in an actual humidifier for use in the dry climates of Denver and Davis. The HRV is intended to provide ventilation and humidity control and consists of two air paths. The first path draws in outdoor air from a supply register located near the crawlspace and diffuses it indoors through the hallway ceiling. The second air path draws air from the living space floor and exhausts it out through a return register at the crawlspace. It pulls outdoor air indoors and expels indoor air outside while a self-contained heat exchanger simultaneously transfers heat between the outgoing and incoming air streams. The heat exchanger helps with the heating and cooling efficiency by effectively "pre-conditioning" the incoming air stream using the outgoing airstream. This outgoing airstream draws air from the living and kitchen areas and exhausts it outside through the mechanical room wall while the incoming airstream draws air from the outside through the mechanical room wall (a separate vent from the one mentioned above) and supplies it into the house in the hallway. The indoor vents are deliberately placed far apart to separate the incoming fresh air and outgoing stale air as much as possible to avoid exhausting the new air immediately after it comes into the house.

This system of air transfer, however, does mean that humidity levels in the house can be uncomfortably low in the cold months of the year, especially in the dry conditions found in Denver and Davis. To mitigate the humidity concerns, the team had to consider humidification systems. Unfortunately, most whole-house humidifiers are designed to be used with a full forced-air heating and cooling system, which Our H2Ouse doesn't have. What Our H2Ouse does have is an HRV, which runs air, as discussed earlier. The original thought was to simply use a duct-compatible humidifier with the HRV system, but most of these whole-house humidifiers connect directly to the duct and cause the air in the duct to pass into the humidifier where the extra water is added. The Fantech SHR 1504 uses 6" round duct, which did not have the flat surface area needed to mount the humidifier. This would be a good for a whole-house forced-air system that already has the larger rectangular ducts, but not for Our H2Ouse's case. The team's solution was to use a Honeywell Electrode Humidifier HM700A. This Honeywell humidifier, instead forcing air to move through the humidifier to capture moisture, adds extra water in the form of steam through a small port in the duct system. This means that the humidifier can work with the much smaller duct sizes that are used for HRV systems and thus, can be used for the house.

Our Monitoring, Controls & Feedback Systems

Water and Energy Monitoring and Controls

The controls and monitoring team developed an innovative arduino-based water monitoring plan, involving +/-10% accuracy sensors mounted on every hot and cold water line cross-checked by a robust and +/-1.5% mainline sensor, allowing this cost-effective system to be quite accurate, while also allowing discernment of which water line is drawing from the mainline at any moment. Energy monitoring within Our H_2Ouse is performed by an eGauge system that allows for energy draw sensing on every circuit of the home. The combination of these two systems mean Our H_2Ouse provides comprehensive energy and water data collection and analysis, with easy retrieval of long term historic records and data trend reporting.

The control features within the home allow occupants easy regulation of indoor temperature as well diverse water conservation options. Using additional arduino-based open source software and hardware, the home's heat pump and 5-zone radiant system communicates with corresponding zone-specific humidity and temperature sensors to inform occupants of indoor temperature distributions throughout the home. Occupants can then set and schedule per-zone temperature preferences through the home's tablet-based heads up display (HUD). Lighting controls are limited to motion sensor activated and recessed, circadian LED strip night lighting. Controls relating to water conservation include a thermostatic shower shutoff valve that halts water flow once a warm temperature is reached, and resumes flow only once occupants step into the shower and trigger it to open again. The bathroom also features a faucet that dispenses water only when triggered by motion, similar to the models commonly found in public restrooms, as well as high efficiency dual flush (0.5 gal/0.95 gal) toilet. Lastly, both the dishwasher and clothes washer feature manual and/or automatic water level adjustment based off load size.

Information Feedback Systems

Our H_2Ouse features unique occupant-level and community-level devices that show real time water and energy consumption, to overcome user indifference and establish a salient reference point for appropriate and adequate resource use. Sequential illumination of individual LEDs, which correspond to incremental units of water, allow for visible water meter instant feedback near the kitchen/bathroom sink, and shower. These devices transform unconscious use and associated wastage into thought-provoking conservation, resulting from increased engagement and leading to individual behavioral changes - changes that the Blue Mustangs are confident will permeate beyond the walls of Our H_2Ouse and can influence conservation on a much grander scale.

To further expand upon the influence of Our H2Ouse, a community-level feedback device was created to educate, inspire, and facilitate awareness of water resource responsibility. Aggregated occupant water use, in relation to gallons saved when comparing to the average occupant water use, is shown via an unconventional and dynamic water feature. This feature, placed prominently at the front of the house, directly relates to the home's total water consumption compared to an average household’s total water consumption. The ambient, eco-feedback display mimics ecological processes, such as the filling and draining of reservoirs with a limited water supply, providing homeowners a more physical and relatable depiction of water conservation. The occupants are rewarded with this dynamic water feature as they save increasing amounts of water, compared to the average. This rewards positive behavioral changes and motivates occupants with a friendly neighborhood challenge, increasing neighborhood accountability and inter-household accountability, as it turns household occupants into a conservation team. This system could be upscaled, with water features for individual houses as well as a hub for a neighborhood-level water feature which aggregates all the water-saving data, allowing neighborhoods to team up and challenge other neighborhoods to this conservation game. Our H2Ouse not only engages its occupants in water conservation, but the community as a whole.

The interior of Our H2Ouse features a single device that at first appears similar to many of the tablet-based HUDs that many teams utilize for control purposes. However, the user interface (UI) of Our H2Ouse's system is unique in that it emphasizes clear and customizable information feedback formats. As such, the device features usage breakdowns, prospective economic costs that the occupants can expect based off their current water and energy usage, as well as a comparison to usage goals. The flexibility of this UI allows for settings on the device, such as how many occupants are living within the home, goals for water use, and format of displayed data to be changed by the occupant. Another unique feature of the device, and in our humble opinion one of the most exciting differentiators of Our H2Ouse, is how we have assimilated the device into the architecture of the building. The tablet itself is integrated into the home by placing it behind different pieces of two-way mirrored glass throughout the home. In this format, occupants can be greeted by information summaries while looking at themselves in the bathroom vanity mirror as they brush their teeth, shave, etc., or in a more public format located in the home's main living room. The tablet is easily removable and can be carried-to and placed-in any other alternate areas of the home depending on occupant preference. These adjustability features address the uncertainty that surrounds feedback devices, in terms of the most effective modes of information delivery and the best locations for maximum, sustained impact. This flexibility is a key innovation of the UI, as the development of effective feedback is still very much in flux. By allowing occupants the ability to alter the location and format with where and how they are displayed information, the hope is that they themselves can custom create a platform that they find most helpful and beneficial. To enhance this process, the device tracks its own effectiveness by allowing homeowners to log when placement and formatting changes were made in relation to changes experienced in water and energy use.

Our Solar System

Our H2Ouse features a solar system focused around providing occupants with grid independence and dynamic energy management based off home demand as well as grid activity. At the heart of this system is 9.7 kW solar array built from SunPower X22-360 panels and a Sunverge Integration System that features 7.7 kWh of battery storage, an AC-coupled inverter, and cloud-based energy management. Solar thermal collection was not chosen for inclusion in the design as excess power produced from this system cannot be stored in batteries or sold back to the state-wide energy grid. Array sizing was based on thorough analysis of predicted demands both at the competition in Denver, as well for simulated demands from two different housing scenarios in Davis involving the average California family household and 4 college student renters. Demand scheduling also involved close coordination with students designing the homes HVAC systems, with intermittent coordination occurring with design teams to determine any specialized power needs for active and/or dynamic architectural features.

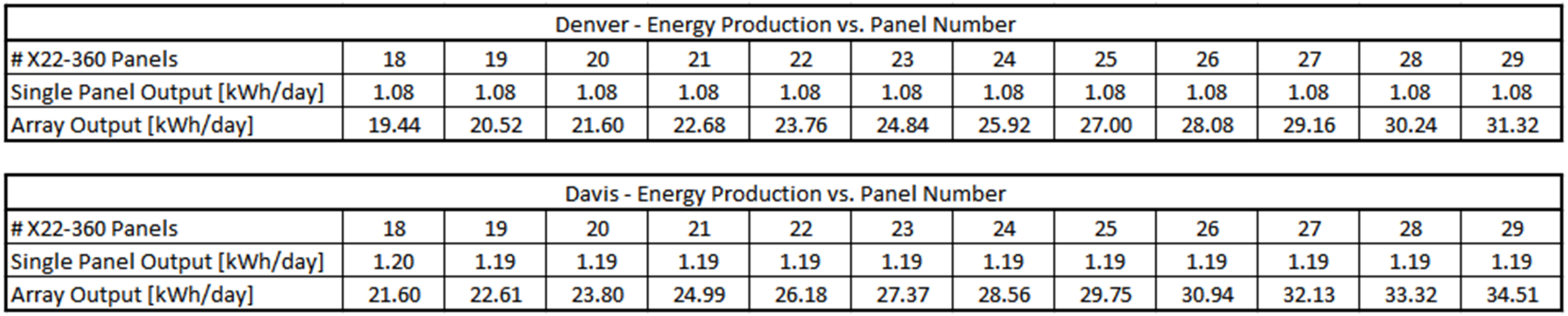
The Sunverge Integration System possesses significant lifetime performance benefits that are either more efficient than or absent from leading industry competitor models. First is the ability of the battery system to weather some of the greater total number of more rapid charge/discharge cycles , which in the case of a power outage allows for the turning on of backup power quickly enough to prevent the shutdown of electrical devices and appliances. Second, is the unit's "Virtual Power Plant" feature, which allows for the virtual and physical connection of multiple units to meet energy demands from entire communities and neighborhoods – a feature that is in direct alignment with the overarching goal of Our H_2Ouse to promote the development community-level renewable energy (and water) management. Last but not least is the system's 24/7 energy management system, which in addition to making energy storage and distribution decisions based on grid activity and dynamic pricing schemes, also allows home owners high levels of information access and control related to peak scheduling/shifting and bill optimization. This system easily networks with other smart home systems, and as such has its user interface included in the home's HUD along with the eGauge and water monitoring information feedback.

Our Energy Model

Our Energy Production

A thorough energy analysis was conducted to determine the number of panels needed for daily energy consumption. Based on the irradiation and panel surface area, the energy production of a full array as a function of the number of panels in the array was found (Table 1). The energy production of the array was compared to the energy demands in different scenarios, which then gave us the number of panels needed.

Table 1: Denver and Davis Energy Production vs Panel Number

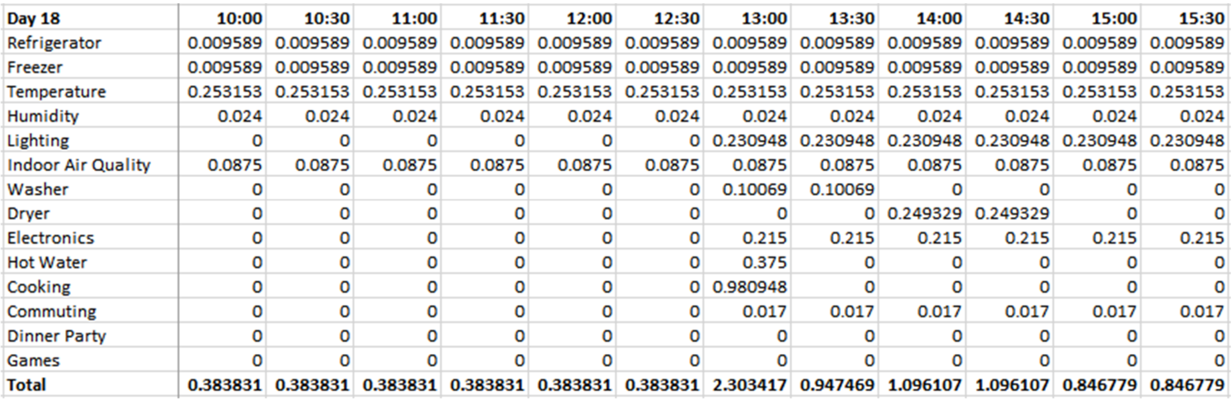


Denver - Energy Production vs. Panel Number												
# X22-360 Panels	18	19	20	21	22	23	24	25	26	27	28	29
Single Panel Output [kWh/day]	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08
Array Output [kWh/day]	19.44	20.52	21.60	22.68	23.76	24.84	25.92	27.00	28.08	29.16	30.24	31.32

Davis - Energy Production vs. Panel Number												
# X22-360 Panels	18	19	20	21	22	23	24	25	26	27	28	29
Single Panel Output [kWh/day]	1.20	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19
Array Output [kWh/day]	21.60	22.61	23.80	24.99	26.18	27.37	28.56	29.75	30.94	32.13	33.32	34.51

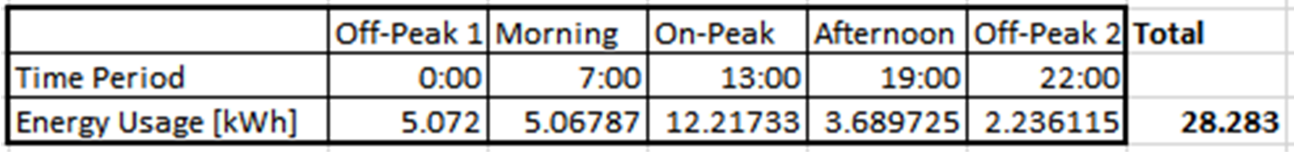
There were two scenarios taken into consideration when deciding the required number of PV panels: competition energy demands in Denver, CO, and house lifetime energy demands in Davis, CA. In Denver, the competition sub-contests determine the minimum amount of energy required per day, in addition to the general demand for tours. The competition schedule was imported into Microsoft Excel and energy usage values were added for every 30 minutes when there were sub-contests happening (Table 2). This was done for each day of the competition, and the worst day was Day 18 with an estimated 29 kWh of energy usage (Table 3). Based on this number, the home's PV array would need at least 27 panels to provide adequate electricity for all competition days in Denver.

Table 2. Model of Energy Usage in Denver, Day 18, Sample



Day 18	10:00	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00	15:30
Refrigerator	0.009589	0.009589	0.009589	0.009589	0.009589	0.009589	0.009589	0.009589	0.009589	0.009589	0.009589	0.009589
Freezer	0.009589	0.009589	0.009589	0.009589	0.009589	0.009589	0.009589	0.009589	0.009589	0.009589	0.009589	0.009589
Temperature	0.253153	0.253153	0.253153	0.253153	0.253153	0.253153	0.253153	0.253153	0.253153	0.253153	0.253153	0.253153
Humidity	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024
Lighting	0	0	0	0	0	0	0.230948	0.230948	0.230948	0.230948	0.230948	0.230948
Indoor Air Quality	0.0875	0.0875	0.0875	0.0875	0.0875	0.0875	0.0875	0.0875	0.0875	0.0875	0.0875	0.0875
Washer	0	0	0	0	0	0	0.10069	0.10069	0	0	0	0
Dryer	0	0	0	0	0	0	0	0	0.249329	0.249329	0	0
Electronics	0	0	0	0	0	0	0.215	0.215	0.215	0.215	0.215	0.215
Hot Water	0	0	0	0	0	0	0.375	0	0	0	0	0
Cooking	0	0	0	0	0	0	0.980948	0	0	0	0	0
Commuting	0	0	0	0	0	0	0.017	0.017	0.017	0.017	0.017	0.017
Dinner Party	0	0	0	0	0	0	0	0	0	0	0	0
Games	0	0	0	0	0	0	0	0	0	0	0	0
Total	**0.383831**	**0.383831**	**0.383831**	**0.383831**	**0.383831**	**0.383831**	**2.303417**	**0.947469**	**1.096107**	**1.096107**	**0.846779**	**0.846779**

Table 3. Summary of Energy Usage in Denver, Day 18

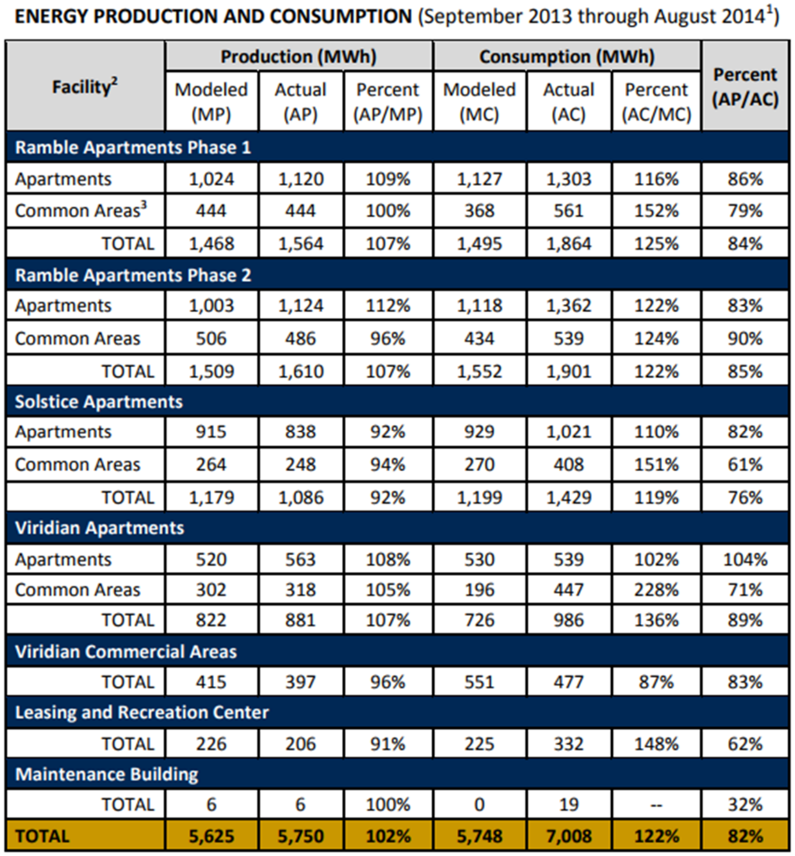


	Off-Peak 1	Morning	On-Peak	Afternoon	Off-Peak 2	**Total**
Time Period	0:00	7:00	13:00	19:00	22:00	
Energy Usage [kWh]	5.072	5.06787	12.21733	3.689725	2.236115	**28.283**

In Davis, the state of California's average electricity consumption per household was used to determine the home's long-term daily energy production. According to the U.S. Energy Information Administration, this value is about 7,000 kWh per California household per year[5]. Divided by 12 months per year and 30 days per month, the average energy use is 19.5 kWh per California household per day. However, the intent of the home also played into the decision-making process; although marketed as a single-family home, we plan Our H_2Ouse for UC Davis student housing. Student lifestyles and consumption habits differ from that of families (more electronic devices to charge and more laundry to do, to name a few differences). Davis' infamous zero-net energy housing community, West Village, did not consider these lifestyle difference and ultimately fell short of zero-net energy after construction and occupancy. The ratio between actual and modeled consumption for residential apartment areas ranged from 102% to 122% (Table 4)

In order to account for energy consumption in Our H_2Ouse, a lifestyle multiplier equal to West Village's worst case scenario (122%) was incorporated into the average energy use per California household per day. This meant the design energy consumption for Davis was 23.8 kWh, equivalent to the production of at least 21 panels.

Table 4. Energy Production and Consumption (Sep 2013 through Aug 2014)[6]



ENERGY PRODUCTION AND CONSUMPTION (September 2013 through August 2014[1])

Facility[2]	Production (MWh)			Consumption (MWh)			Percent (AP/AC)
	Modeled (MP)	Actual (AP)	Percent (AP/MP)	Modeled (MC)	Actual (AC)	Percent (AC/MC)	
Ramble Apartments Phase 1							
Apartments	1,024	1,120	109%	1,127	1,303	116%	86%
Common Areas[3]	444	444	100%	368	561	152%	79%
TOTAL	1,468	1,564	107%	1,495	1,864	125%	84%
Ramble Apartments Phase 2							
Apartments	1,003	1,124	112%	1,118	1,362	122%	83%
Common Areas	506	486	96%	434	539	124%	90%
TOTAL	1,509	1,610	107%	1,552	1,901	122%	85%
Solstice Apartments							
Apartments	915	838	92%	929	1,021	110%	82%
Common Areas	264	248	94%	270	408	151%	61%
TOTAL	1,179	1,086	92%	1,199	1,429	119%	76%
Viridian Apartments							
Apartments	520	563	108%	530	539	102%	104%
Common Areas	302	318	105%	196	447	228%	71%
TOTAL	822	881	107%	726	986	136%	89%
Viridian Commercial Areas							
TOTAL	415	397	96%	551	477	87%	83%
Leasing and Recreation Center							
TOTAL	226	206	91%	225	332	148%	62%
Maintenance Building							
TOTAL	6	6	100%	0	19	--	32%
TOTAL	**5,625**	**5,750**	**102%**	**5,748**	**7,008**	**122%**	**82%**

Since Denver needed at least 27 panels to meet the worst case competition scenario and Davis only needed 21, the team decided to go with 27 panels. Some discrepancies inherent in energy usage and consumption is accounted for between the fluctuations of weather, solar panel production, and user lifestyles. During other days of the competition when energy use is less than the worst case 29 kWh scenario, as well as the home's lifetime in Davis, the extra electricity produced will go into battery storage. This energy could then be used during night and off-peak times when the sun is down.

Many options were explored quantitatively to find the best possible solution for panel type, battery storage feasibility, and certain solar packages offered by our sponsor, SunPower. The calculations for these options are shown in Table 4 below. One Sunverge system (option 7 in Table 5 below), which includes battery storage, was determined to be the most optimal system with a willing sponsor.

Table 5. Energy Production and Storage Scenarios

Possible Systems	Off-Peak 1	Morning Peak	On-Peak	Afternoon Peak	Off-Peak 2	Total
1. Panel/Grid Only						
Energy Prod.* [kWh]	6.9	144.28	82.09	0	0	233.28
Energy Usage [kWh]	46.04	38.36	27.72	30.32	14.68	157.11
Value [$]	-1.96	5.3	10.87	-4.55	-0.73	8.93
2. Panel to Battery						
Prod. w/Batt* [kWh]	6.9	29.88	82.09	0	0	118.88
Usage w/Batt [kWh]	46.75	34.52	0	0	0	81.28
Value w/Batt [$]	-1.99	-0.56	16.42	0	0	13.87
3. Grid to Battery						
Energy Prod* [kWh]	6.9	144.28	82.09	0	0	233.28
Usage w/Batt [kWh]	181.32	0	0	0	14.68	195.99
Value w/Batt [$]	-8.72	7.21	16.42	0	-0.73	14.18
4. Panel to Honda						
Energy Prod* [kWh]	0	29.88	82.09	0	0	111.98
Energy Usage [kWh]	23.55	38.36	0	0	0	61.91
Value w/Honda [$]	-1.18	-1.02	16.42	0	0	14.22
5. Grid to Honda						
Energy Prod* [kWh]	0	144.28	82.09	0	0	226.38
Energy Usage [kWh]	155.64	0	0	0	14.68	170.31
Value w/Honda [$]	-7.78	7.21	16.42	0	-0.73	15.12
6. SunnyBoy						
Energy Prod* [kWh]	0	144.28	214.37	0	0	358.66
Energy Usage [kWh]	302.04	38.36	0	30.32	14.68	385.39
Value [$]	-15.1	5.3	42.87	-4.55	-0.73	27.79
7. Sunverge 1						
Energy Prod^ [kWh]	6.9	169.02	156.17	0	0	332.0872549
Addit. Prod~ [kWh]	0	56.55	30.45	0	0	87
Total Prod [kWh]	6.9	225.57	186.62	0	0	419.0872549
Energy Usage [kWh]	142.04	38.36	27.72	30.32	14.68	253.1125119
Value [$]	-6.76	9.36	31.78	-4.55	-0.73	29.1
8. Sunverge 2						
Energy Prod" [kWh]	6.9	139.13	139.16	0	0	285.1951552
Addit. Prod+ [kWh]	0	68.9	37.1	0	0	106
Total Prod [kWh]	6.9	208.03	176.26	0	0	391.1951552
Energy Usage [kWh]	142.04	38.36	27.72	30.32	14.68	253.1125119
Value [$]	-6.76	8.48	29.71	-4.55	-0.73	26.15

Our Heating and Cooling Loads

Energy modeling was performed using BEopt, a graphical user interface for the EnergyPlus calculation engine (Fig 5). The home is modeled in the program by indicating the dimensions and purpose (living area, garage, etc.) of the space. Characteristics of the home, including building envelope R-values, window to wall ratios, heating and cooling set points, and other parameters were inputted into BEopt (Fig 6). The weather file for the competition site and permanent location of the home—Denver and Davis—were imported from EnergyPlus to allow for two scenarios for one modeled building. With all these inputs, BEopt was able to run an analysis of Our H_2Ouse and provide thermal loads in Davis and Denver. Note that solely September and October data is relevant for the competition so graphs for those months only are provided for Denver (Fig 7). Our H_2Ouse will find its long-term home in Davis so data for all months are provided for Davis (Fig 8). The worst case scenario was used, resulting in 18,000 Btu/hr or 1.5 tons of heating and/or cooling capacity required. However, these are based on heating and cooling loads only and does not consider Our H_2Ouse's unique two-for-one heat pump used for both home conditioning and DHW heating. As a result, a 2.5 ton heat pump was chosen; 2.5 tons is equivalent to 30,000 Btu/hr, which could heat 50 gallons of supply water to adequate DHW temperature. The home's water tank has a 53.1 gallon capacity, allowing the heat pump to heat a full tank worth of water if needed in an extreme Davis scenario. With the heating and cooling capacity set, the team picked the PHNIX H8 heat pump due to its high coefficient of performance and optimized heat exchangers.

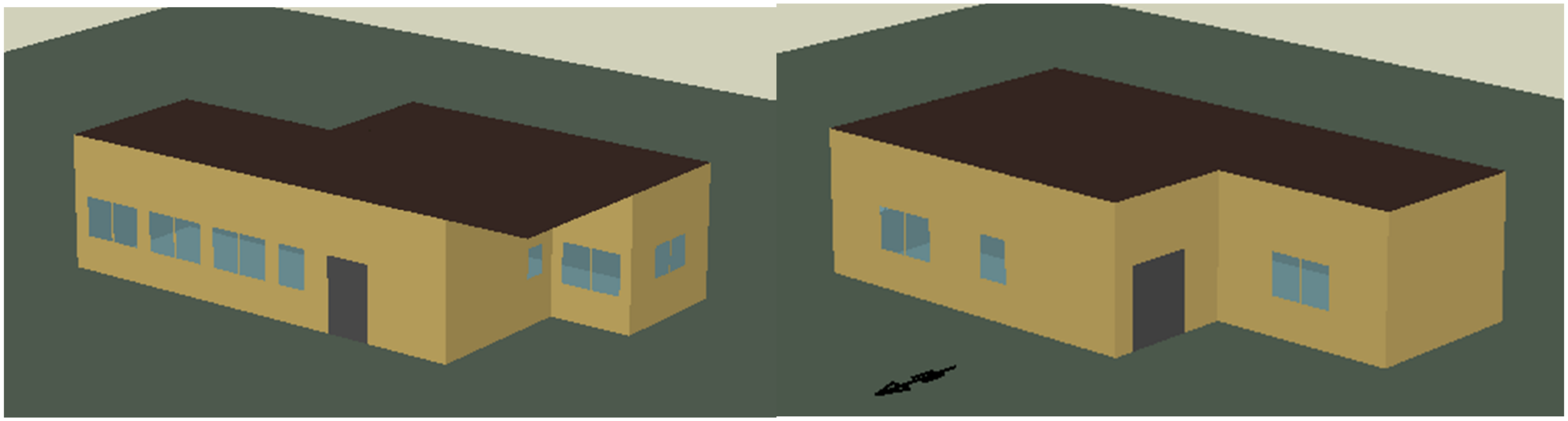
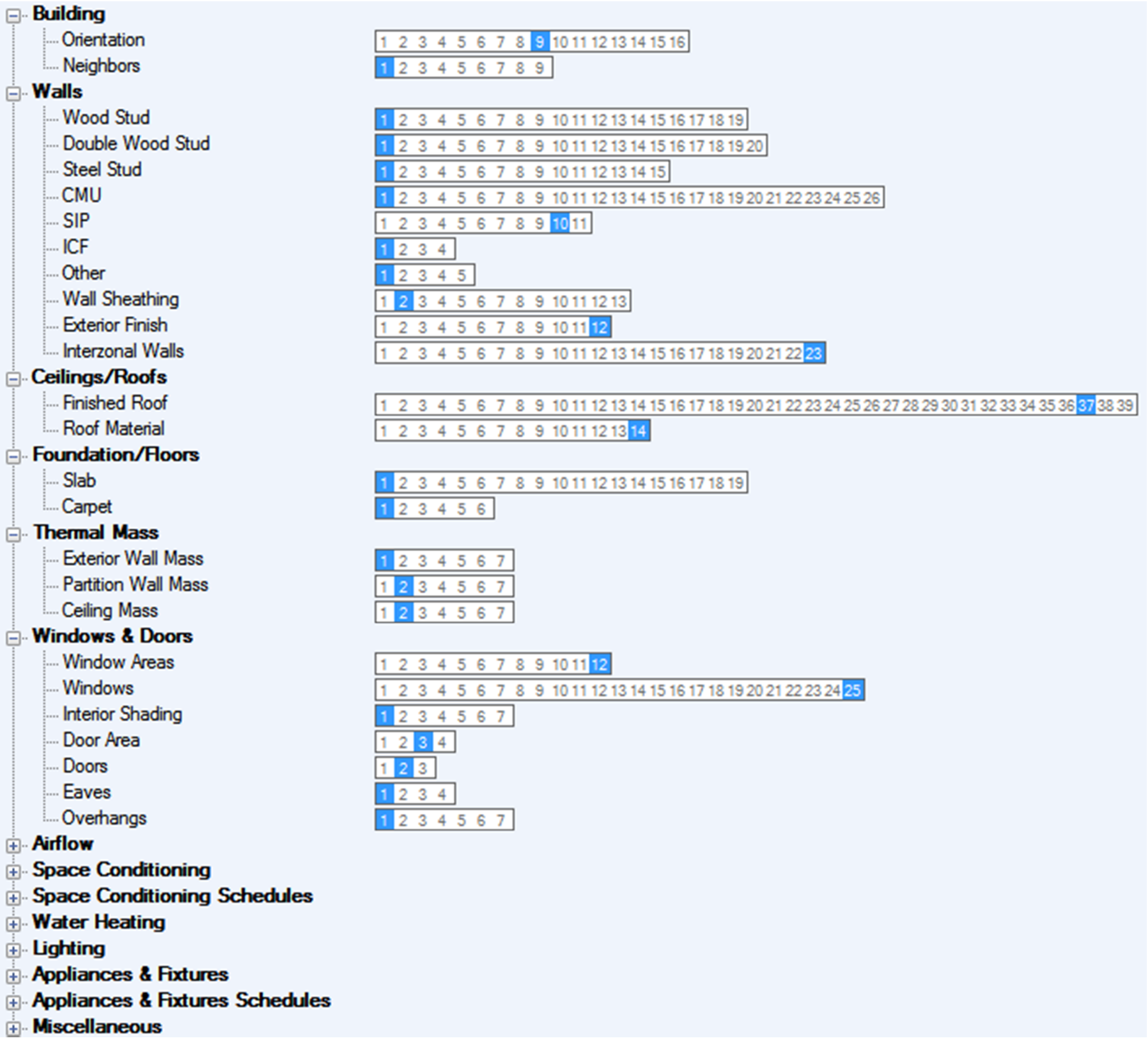


Figure 5. Visual Model Output from BEopt



- **Building**
  - Orientation: 1 2 3 4 5 6 7 8 **9** 10 11 12 13 14 15 16
  - Neighbors: **1** 2 3 4 5 6 7 8 9
- **Walls**
  - Wood Stud: **1** 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
  - Double Wood Stud: **1** 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
  - Steel Stud: **1** 2 3 4 5 6 7 8 9 10 11 12 13 14 15
  - CMU: **1** 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
  - SIP: 1 2 3 4 5 6 7 8 9 **10** 11
  - ICF: **1** 2 3 4
  - Other: **1** 2 3 4 5
  - Wall Sheathing: 1 **2** 3 4 5 6 7 8 9 10 11 12 13
  - Exterior Finish: 1 2 3 4 5 6 7 8 9 10 11 **12**
  - Interzonal Walls: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 **23**
- **Ceilings/Roofs**
  - Finished Roof: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 **37** 38 39
  - Roof Material: 1 2 3 4 5 6 7 8 9 10 11 12 13 **14**
- **Foundation/Floors**
  - Slab: **1** 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
  - Carpet: **1** 2 3 4 5 6
- **Thermal Mass**
  - Exterior Wall Mass: **1** 2 3 4 5 6 7
  - Partition Wall Mass: 1 **2** 3 4 5 6 7
  - Ceiling Mass: 1 **2** 3 4 5 6 7
- **Windows & Doors**
  - Window Areas: 1 2 3 4 5 6 7 8 9 10 11 **12**
  - Windows: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 **25**
  - Interior Shading: **1** 2 3 4 5 6 7
  - Door Area: 1 2 **3** 4
  - Doors: 1 **2** 3
  - Eaves: **1** 2 3 4
  - Overhangs: **1** 2 3 4 5 6 7
- **Airflow**
- **Space Conditioning**
- **Space Conditioning Schedules**
- **Water Heating**
- **Lighting**
- **Appliances & Fixtures**
- **Appliances & Fixtures Schedules**
- **Miscellaneous**

Figure 6. Modeling Options in BEopt

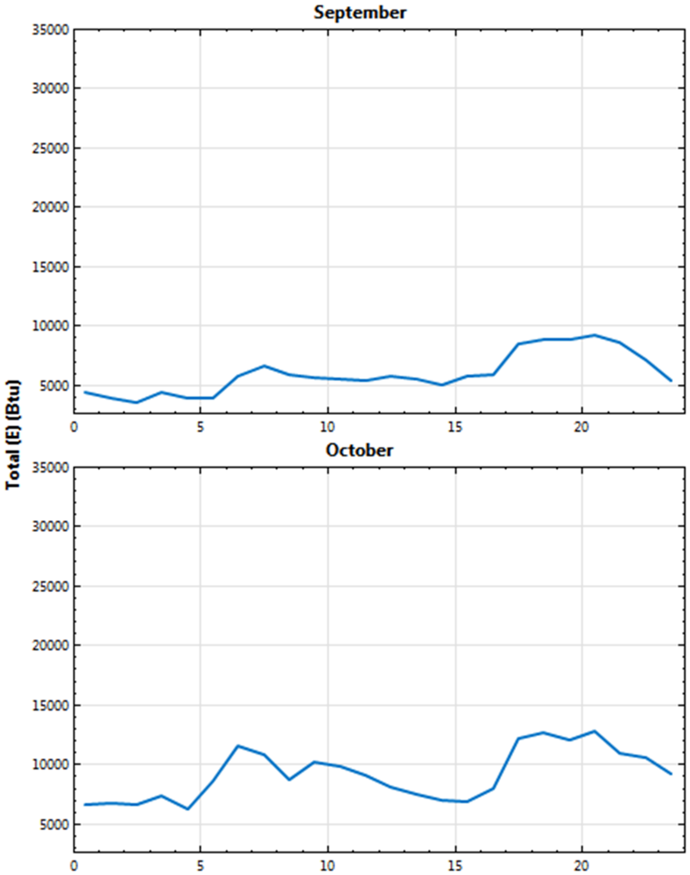


Figure 7. Denver Heating and Cooling Loads for September and October

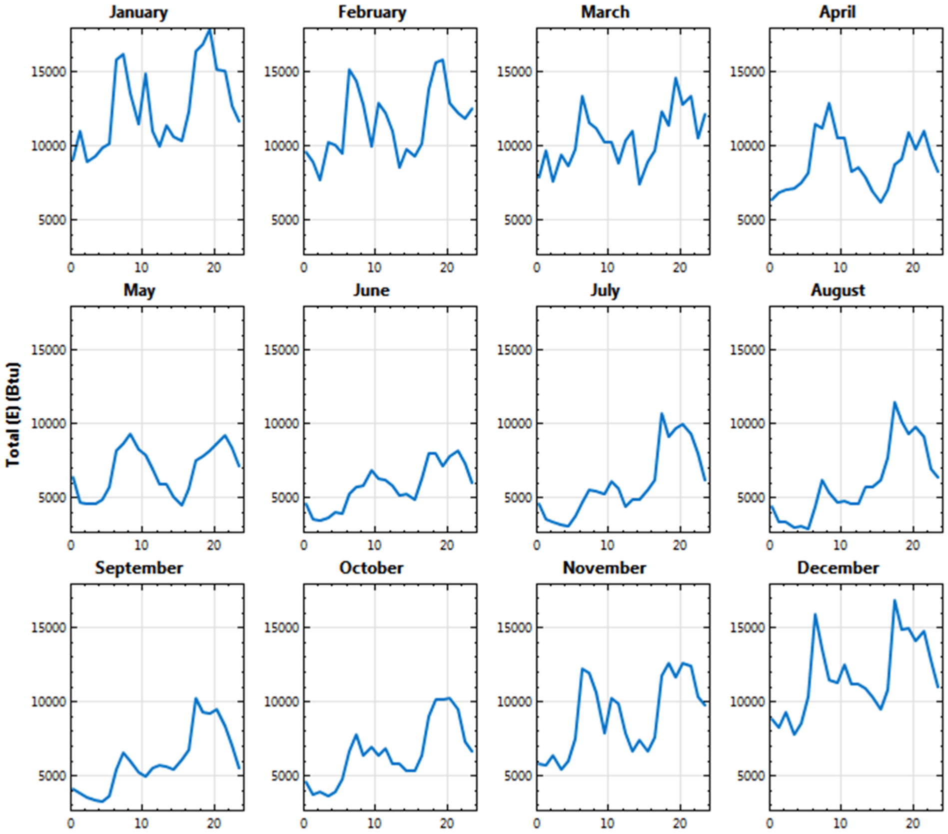


Figure 8. Davis Heating and Cooling Loads Year Round

Our Humidity

Given how dry both Denver and Davis are, the team knew that humidity would be an important aspect to consider in terms of inhabitant health and comfort. In Denver, the team calculated humidity during tour hours with the doors open as well as during normal hours based on the CFM produced by the home's ventilation system and different number of people in the house producing humidity at a time. Firstly, to calculate the humidity during tour hours, the team calculated the airflow through the house which was based on wind speed in Denver as well as air exchange caused by temperature differences between inside and outside the house. While both methods of estimation gave similar final values, the data based on temperature difference gave a more consistent value so those numbers were used to model the airflow during tour hours. Using this information the team calculated the vapor density in the house after tours and found the relative humidity, which was around 32% on average (Table 6).

Table 6. Air Flow Calculations, Sample; and Relative Humidity Results

Time (min)	Average Temperature Outside (k)	Temperature Inside (k)	Air flow (%/min)	Inputted water vapor (g)	Actual Water Vapor
1	287.45	295.1933186	0.064227147	1739.89856	1714.667018
2	287.45	295.06789	0.063704775	1729.667018	1705.292487
3	287.45	294.9544961	0.06322881	1720.292487	1696.692808
4	287.45	294.8518974	0.062795048	1711.692808	1688.795046
5	287.45	294.7589962	0.062399684	1703.795046	1681.534267
6	287.45	294.6748181	0.062039267	1696.534267	1674.85252
7	287.45	294.5984962	0.061710669	1689.85252	1668.697947
8	287.45	294.529258	0.061411047	1683.697947	1663.024044
9	287.45	294.4664134	0.061137821	1678.024044	1657.789012
10	287.45	294.4093449	0.060888647	1672.789012	1652.955205

Equilibrium Humidity	Vapor Density in house (g/m^3)	Relative Humidity in house after tours
1581.175024	6.211404086	32.08%

Using the average relative humidity as a starting point, the team calculated values of indoor humidity during non-tour hours when humidity would be measured. The team calculated the humidity levels based on the amount of extra humidity produced by the number of people in the house as well as the external humidity at the time, with various CFM values based on the different options for HRVs and ERVs. All of this data showed that there would be a much larger problem with the house getting too dry rather than too humid leading to the conclusion that a humidification system would be needed along with the ventilation system.

Table 7. Denver Humidity Calculations, Sample

Day	Hour	Outside Temperature (F)	Outside Temperature (K)	Outdoor Humidity	Saturated Vapor Pressure	Saturated Vapor Density	Actual Vapor Density Outside	Actual Vapor Density Inside	Indoor humidity	Within parameters
5-Oct	6:53 PM	60.1	288.76	20%	1768.18	13.27	2.65	5.71	29.47%	0.44716864
	7:53 PM	57.9	287.54	23%	1634.38	12.32	2.83	5.44	28.10%	0.310234825
	8:53 PM	57	287.04	25%	1582.26	11.94	2.99	5.34	27.60%	0.25982755
	9:53 PM	55.9	286.43	29%	1520.55	11.5	3.34	5.42	28.02%	0.301924269
	10:53 PM	55	285.93	28%	1471.64	11.15	3.12	5.39	27.83%	0.283088106
	11:53 PM	54	285.37	31%	1418.93	10.77	3.34	4.57	23.59%	0
6-Oct	12:53 AM	53.1	284.87	30%	1372.91	10.44	3.13	3.99	20.63%	0
	1:53 AM	48	282.04	36%	1136.11	8.73	3.14	3.65	18.87%	0
	2:53 AM	46	280.93	42%	1053.57	8.13	3.41	3.56	18.37%	0
	3:53 AM	46.9	281.43	52%	1090.03	8.39	4.36	3.88	20.04%	0
	4:53 AM	46.9	281.43	52%	1090.03	8.39	4.36	4.07	21.04%	0
	5:53 AM	44.1	279.87	73%	980.1	7.59	5.54	4.66	24.07%	0
	6:53 AM	42.1	278.76	85%	907.69	7.06	6	5.46	28.21%	0.320593091
	7:53 AM	42.1	278.76	85%	907.69	7.06	6	5.94	30.69%	0.568576928
	8:53 AM	42.1	278.76	85%	907.69	7.06	6	6.23	32.17%	0.71727898
	9:53 AM	43	279.26	86%	939.67	7.29	6.27	6.51	33.63%	0.862912711
	7:53 PM	39.9	277.54	93%	833.53	6.51	6.05	6.45	33.30%	0.829796607
	8:53 PM	39.9	277.54	93%	833.53	6.51	6.05	6.55	33.85%	0.885267588
	9:53 PM	37	275.93	93%	743.98	5.84	5.43	6.37	32.91%	0.790609961

Similar calculations were done in Davis although in this case, there was less information about the number of people in the house. The increased variability constrained the team in taking an overall estimate of how much water would be produced in the house every twenty minutes. It was found that in Davis while using an HRV, there would be problems with the house getting too dry in the colder months, similar to Denver, finalizing the decision to include a humidifier within the HVAC system.

Table 8. Davis Humidity Calculations, Sample

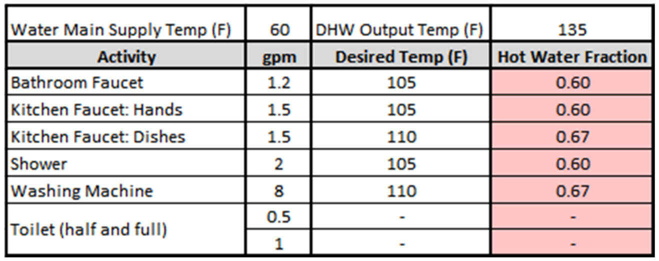
Time	Outside	Outside Temperature (K)	Outdoor Humidity	Saturated Vapor Pressure	Saturated Vapor Density	Vapor Density Outside (g/m^3)	Vapor Density Inside	Indoor humidity	Within parameters
12:15 AM	57.2	287.15	63%	1593.719044	12.02568767	7.576183233	7.576183233	38.91%	1
12:35 AM	57.2	287.15	67%	1593.719044	12.02568767	8.05721074	7.716190772	39.63%	1
12:55 AM	57.2	287.15	67%	1593.719044	12.02568767	8.05721074	7.837514032	40.25%	1
1:15 AM	57.2	287.15	67%	1593.719044	12.02568767	8.05721074	7.942646464	40.79%	1
1:35 AM	57.2	287.15	67%	1593.719044	12.02568767	8.05721074	8.033748768	41.26%	1
1:55 AM	55.4	286.15	72%	1493.205738	11.30662214	8.140767939	8.123844163	41.72%	1
2:15 AM	55.4	286.15	72%	1493.205738	11.30662214	8.140767939	8.201916151	42.13%	1
2:35 AM	55.4	286.15	72%	1493.205738	11.30662214	8.140767939	8.26956928	42.47%	1
2:55 AM	55.4	286.15	72%	1493.205738	11.30662214	8.140767939	8.328193966	42.77%	1
3:15 AM	55.4	286.15	72%	1493.205738	11.30662214	8.140767939	8.378995073	43.04%	1
3:35 AM	55.4	286.15	72%	1493.205738	11.30662214	8.140767939	8.423016673	43.26%	1
3:55 AM	55.4	286.15	72%	1493.205738	11.30662214	8.140767939	8.461163504	43.46%	1
4:15 AM	55.4	286.15	72%	1493.205738	11.30662214	8.140767939	8.494219566	43.63%	1
4:35 AM	55.4	286.15	72%	1493.205738	11.30662214	8.140767939	8.522864231	43.77%	1
4:55 AM	55.4	286.15	72%	1493.205738	11.30662214	8.140767939	8.54768621	43.90%	1
5:15 AM	55.4	286.15	72%	1493.205738	11.30662214	8.140767939	8.569195648	44.01%	1
5:35 AM	55.4	286.15	77%	1493.205738	11.30662214	8.706099046	8.663279151	44.50%	1
5:55 AM	53.6	285.15	82%	1398.307925	10.62518308	8.712650123	8.745681281	44.92%	1
6:15 AM	55.4	286.15	77%	1493.205738	11.30662214	8.706099046	8.816212431	45.28%	1

Our Hot Water Heating

A byproduct of having one heat pump for both the hot water tank and radiant floor is that the heat pump can only thermally charge one or the other at any given time. The concern is that the heat pump is preoccupied with heating or cooling the radiant floor at the same time there is also a potable hot water draw. If this continues for an extended period of time, there could be so much hot water used that the heat pump will be needed to heat new supply water in the hot water tank. To mitigate this problem, the team did a hot water use analysis and an energy balance to see how much time the heat pump is preoccupied with the radiant floor; these calculations are done to ultimately pick a correctly sized hot water tank. The water tank would need to be big enough to meet hot water demands until the heat pump meets the indoor temperature setpoint and can divert its attention to the hot water tank, but not to big that it is oversized for the home and its residents.

Similar to the energy production analysis, the water use scenarios in Denver and Davis have to be considered. Hot water usage was based on the amount of hot water needed to mix with cold supply water to get a comfortable outlet temperature at the fixture or appliance. Most of the time, this temperature is 105°F or110°F [7]. To achieve those temperatures, a certain amount of 135°F hot water from the hot water tank will need to mix with cold supply water before reaching the fixture or appliance. The 135°F hot water fraction for those temperatures are 0.60 and 0.67 of the draw, respectively (Table 9).

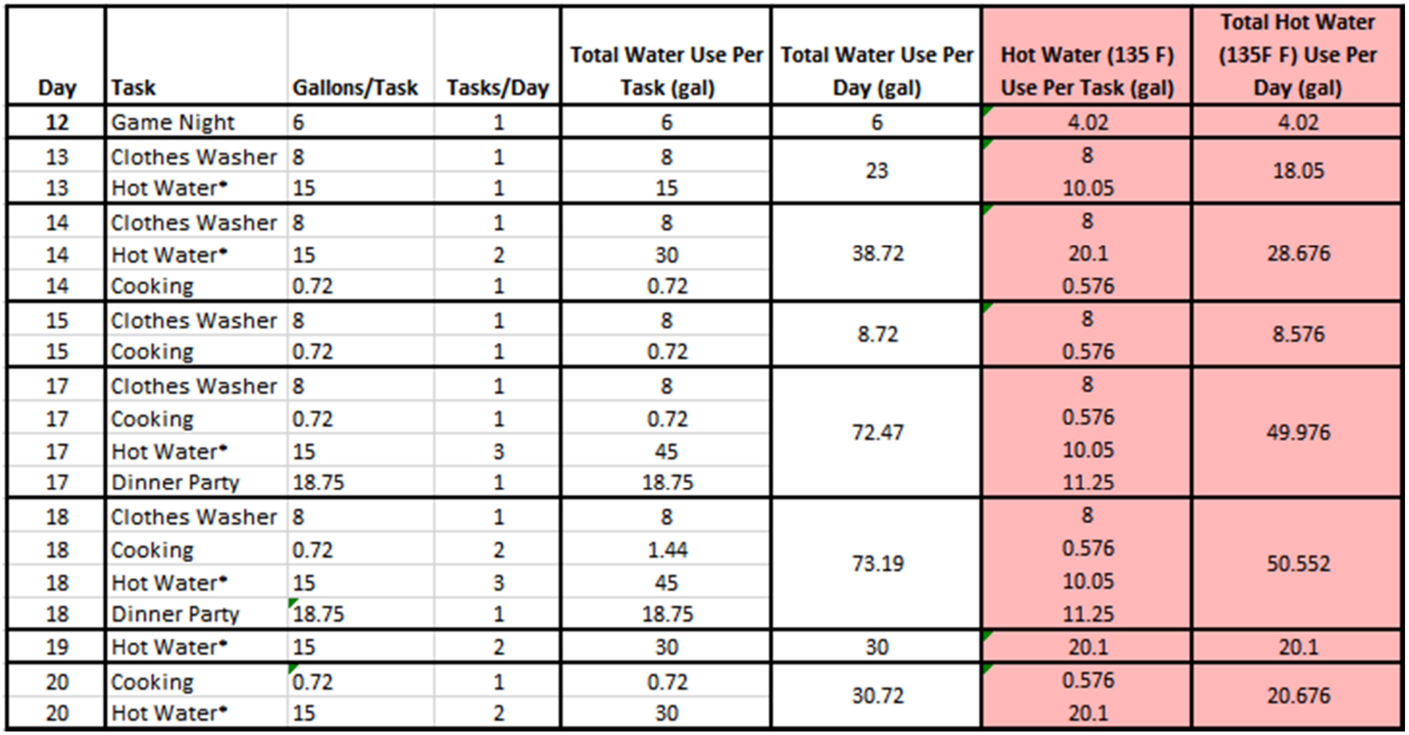
Table 9. Hot Water Mixture Fractions of Domestic Water Activities



Water Main Supply Temp (F)	60	DHW Output Temp (F)	135
Activity	**gpm**	**Desired Temp (F)**	**Hot Water Fraction**
Bathroom Faucet	1.2	105	0.60
Kitchen Faucet: Hands	1.5	105	0.60
Kitchen Faucet: Dishes	1.5	110	0.67
Shower	2	105	0.60
Washing Machine	8	110	0.67
Toilet (half and full)	0.5	-	-
	1	-	-

In Denver, the hot water usage is based on all the hot water tasks during the competition. Hot water usage for the hot water, clothes washer, and cooking tasks are calculated as described above. Hot water usage for game nights and dinner parties were estimated based on the number of people attending and how many times they would wash their hands. After getting the hot water use per task, the total hot water use per competition day was found. The results are displayed in Table 9. Competition day 18 has the most severe water draw with about 50 gallons. Since all the tasks on that day have the same time window for completion during which indoor temperature is being monitored, the water tank would have to be at least 50 gallons to accommodate that water draw during that short time period. This is to account for the worst case scenario that the radiant floor needs to be on the entire time to meet the temperature setpoints and would not be able to attend to the water heater. Because there is an impound period without any water draws at night, the heat pump will be able to heat domestic hot water in the hot water tank, leaving a tank full of hot water ready for the next day.

Table 10. Denver Hot Water Usage during Competition



Day	Task	Gallons/Task	Tasks/Day	Total Water Use Per Task (gal)	Total Water Use Per Day (gal)	Hot Water (135 F) Use Per Task (gal)	Total Hot Water (135F F) Use Per Day (gal)
12	Game Night	6	1	6	6	4.02	4.02
13	Clothes Washer	8	1	8	23	8	18.05
13	Hot Water*	15	1	15		10.05	
14	Clothes Washer	8	1	8	38.72	8	28.676
14	Hot Water*	15	2	30		20.1	
14	Cooking	0.72	1	0.72		0.576	
15	Clothes Washer	8	1	8	8.72	8	8.576
15	Cooking	0.72	1	0.72		0.576	
17	Clothes Washer	8	1	8	72.47	8	49.976
17	Cooking	0.72	1	0.72		0.576	
17	Hot Water*	15	3	45		10.05	
17	Dinner Party	18.75	1	18.75		11.25	
18	Clothes Washer	8	1	8	73.19	8	50.552
18	Cooking	0.72	2	1.44		0.576	
18	Hot Water*	15	3	45		10.05	
18	Dinner Party	18.75	1	18.75		11.25	
19	Hot Water*	15	2	30	30	20.1	20.1
20	Cooking	0.72	1	0.72	30.72	0.576	20.676
20	Hot Water*	15	2	30		20.1	

Unlike Denver, the schedule and amount of water draws in Davis is not set and will be variable depending on resident lifestyles. To resolve this, instead of calculating the amount of hot water used, the team calculated the amount of time per hour the heat pump would be preoccupied with the radiant floor. The goal of this was to determine the leftover time in that hour could be dedicated to the hot water tank. Based on that time, the team could see the amount of hot water that could be produced and compare that to a hourly worst case scenario. In this case, the hourly worst case scenario was two back-to-back 30-minute showers, which was about 72 gallons of hot water. The first shower would simply draw from the hot water tank, but the second shower would require the heat pump to run at the same time. It would take the heat pump about 35 minutes to heat up 36 gallons of water.

Another major difference between the Denver and Davis scenarios is that in Denver, the system will very likely be in heating mode. When in heating mode, the heat pump need only change its output setpoint, a diverting valve will switch between radiant floor and hot water tank, and the water will be directed in the right course. In Davis, cooling mode has to be considered which adds another layer of complexity to the calculations. The heat pump itself would have to switch modes from cooling the radiant floor to heating the hot water tank. All the thermal mass in the heat pump will be cold and the process of switching will result in dynamic losses that have to be overcome before heating the hot water tank. As a result, only late-spring to early-fall months were analyzed for Davis. Based on the thermal mass of the heat pump, it would take the heat pump about 2 minutes to switch back and forth heating and cooling modes. In total, the heat pump would need 37 minutes to overcome dynamic losses and heat up water, leaving about 23 minutes to cool the radiant system.

The time the heat pump was on for the radiant was calculated through an energy balance on the home (Table 11). Outdoor temperatures and wind speed from weather data files were imported. Based on the occupancy—four students during the academic year and two students during the summer—and solar heat gain, an exit wind temperature from windows was determined. An assumption was made that above 80°F, windows would be closed, and no wind would be allowed to cool the home. From exit wind temperatures, a heat transfer analysis was performed to determine the house temperature for every hour (Table 12). The home's exterior walls were modeled as a semi-infinite solid with constant energy flux as the boundary conditions. The initial temperature condition was that the home and outdoor temperatures were at equilibrium. Heat gain from sun and residents were displaced by heat loss from natural wind ventilation—when applicable. The final net heat gain or loss was used to determine a temperature difference and this was added to the previous hour's house temperature. Depending on whether or not this new indoor temperature was within comfortable temperature setpoints—assumed same as competition setpoints—the heat pump would input its own heat gain or loss. Finally, the amount of time per hour it took for the heat pump to make up the temperature difference between setpoint and modeled temperature were calculated. For many days of the year, the heat pump would need to run less than 23 minutes. The only exceptions were extremely hot days in the middle of the summer, but the team decided it would be okay; according to the Cold Climate Housing Research Center, less hot water is used during the summer than in the winter[8]. Also note that the two 30-minute shower scenario was a worst case scenario; most often, the heat pump will have more leeway in terms of time.

Table 11. Energy Balance on House Based on Wind Speeds, Sample

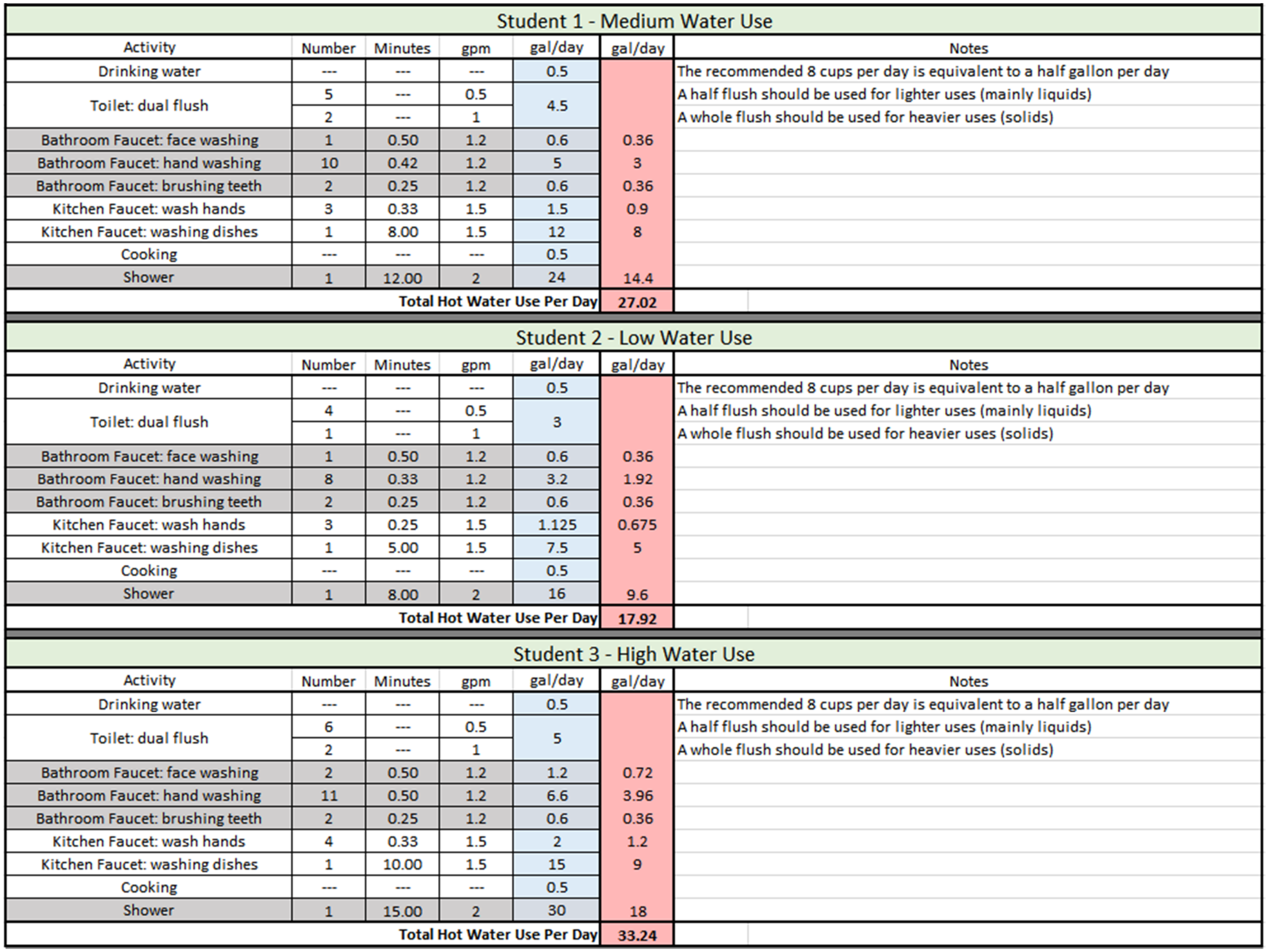
Month	Day	Hour	T_amb (C)	T_amb (F)	Mass Flow Rate (kg/s)	Window Solar Gain (W)	Window Solar Gain (btu/hr)	People Solar Gain (W)	Total Solar Gain (W)	T_amb (C)	T_exit (C)	T_amb (F)	T_exit (F)
9	8	0	21.6	70.9	5.41	0	0	200	200	21.6	21.8	70.9	71.2
9	8	1	20.9	69.5	5.37	0	0	200	200	20.9	21.1	69.5	69.9
9	8	2	20.2	68.3	5.38	0	0	200	200	20.2	20.4	68.3	68.7
9	8	3	19.6	67.2	5.50	0	0	200	200	19.6	19.8	67.2	67.6
9	8	4	19.0	66.2	5.68	0	0	200	200	19.0	19.2	66.2	66.5
9	8	5	18.5	65.3	5.95	0	0	200	200	18.5	18.7	65.3	65.6
9	8	6	20.4	68.7	6.24	50	170	200	250	20.4	20.6	68.7	69.0
9	8	7	24.4	75.9	6.09	690	2353	200	890	24.4	25.1	75.9	77.2
9	8	8	28.4	83.2	5.77	1595	5441	200	1795	28.4	28.4	83.2	83.2
9	8	9	32.5	90.6	5.38	1816	6196	200	2016	32.5	32.5	90.6	90.6
9	8	10	36.3	97.4	4.39	2835	9673	200	3035	36.3	36.3	97.4	97.4
9	8	11	38.5	101.3	3.31	2534	8647	200	2734	38.5	38.5	101.3	101.3
9	8	12	39.7	103.4	4.35	3142	10722	200	3342	39.7	39.7	103.4	103.4

Table 12. Heat Pump Usage Model, Sample

Month	Day	Hour	q''_wind (W/m^2)	q''_window solar gain (W/m^2)	q''_people (W/m^2)	q''_ natural (W/m^2)	delta T (C)	T_house (C)	T_amb (C)	T_house (F)	T_amb (F)	q''_heat pump (W/m^2)	time (s)	time (min)
9	8	0	2.93	0.0	1.2	-1.8	-0.3	21.6	21.6	70.9	70.9	0	0	0
9	8	1	2.95	0.0	1.2	-1.8	-0.3	20.9	20.9	69.5	69.5	0	0	0
9	8	2	2.95	0.0	1.2	-1.8	-0.3	20.2	20.2	68.3	68.3	0	0	0
9	8	3	2.88	0.0	1.2	-1.7	-0.3	19.6	19.6	67.2	67.2	0	0	0
9	8	4	2.79	0.0	1.2	-1.6	-0.3	19.0	19.0	66.2	66.2	0	0	0
9	8	5	2.66	0.0	1.2	-1.5	-0.3	18.5	18.5	65.3	65.3	0	0	0
9	8	6	3.17	0.3	1.2	-1.7	-0.3	20.4	20.4	68.7	68.7	0	0	0
9	8	7	11.57	4.1	1.2	-6.3	-1.2	24.4	24.4	75.9	75.9	0	0	0
9	8	8	0.00	9.4	1.2	10.6	2.0	26.4	28.4	79.6	83.2	105	190	3
9	8	9	0.00	10.7	1.2	11.9	2.3	25.6	32.5	78.1	90.6	105	466	8
9	8	10	0.00	16.7	1.2	17.9	3.4	25.6	36.3	78.1	97.4	105	851	14
9	8	11	0.00	14.9	1.2	16.1	3.1	25.6	38.5	78.1	101.3	105	937	16
9	8	12	0.00	18.5	1.2	19.7	3.8	25.6	39.7	78.1	103.4	105	1161	19

As a secondary check on water usage calculations, the typical water uses of a four-student and single family household were examined. The typical water use of a single student was found empirically by having team members record their day-to-day water activities at home. From this data, student water usage patterns were categorized as medium, low, and high water use (Table 13). The column in blue indicates total water use and the column in red indicates 135°F hot water use calculated from the hot water fractions. Water use from when guests are over are also considered as they may use the bathroom, wash their hands, etc (Table 14). Different cases were compiled based on these numbers (Table 14). The worst case scenario was if all four students—two medium, one low, and one high water use—as well as three guests, were all at home with two loads of laundry that day. The water usage for this scenario was 118 gallons per day. This equates to about three different hours of two back-to-back showers. Many days do not have three hours of more than 23 minutes of required radiant cooling. The case for a single family was extremely similar, with the worst case being 116 gallon per day (Table 16, 17). Ultimately, these series of calculations proved that the 53.1 gallon capacity indirect water tank would be suitable for all the modeled scenarios: Denver and Davis, student housing and family home.

Table 13. Davis Student Hot Water Use Classification



Student 1 - Medium Water Use

Activity	Number	Minutes	gpm	gal/day	gal/day	Notes
Drinking water	---	---	---	0.5		The recommended 8 cups per day is equivalent to a half gallon per day
Toilet: dual flush	5	---	0.5	4.5		A half flush should be used for lighter uses (mainly liquids)
	2	---	1			A whole flush should be used for heavier uses (solids)
Bathroom Faucet: face washing	1	0.50	1.2	0.6	0.36	
Bathroom Faucet: hand washing	10	0.42	1.2	5	3	
Bathroom Faucet: brushing teeth	2	0.25	1.2	0.6	0.36	
Kitchen Faucet: wash hands	3	0.33	1.5	1.5	0.9	
Kitchen Faucet: washing dishes	1	8.00	1.5	12	8	
Cooking	---	---	---	0.5		
Shower	1	12.00	2	24	14.4	
				Total Hot Water Use Per Day	**27.02**	

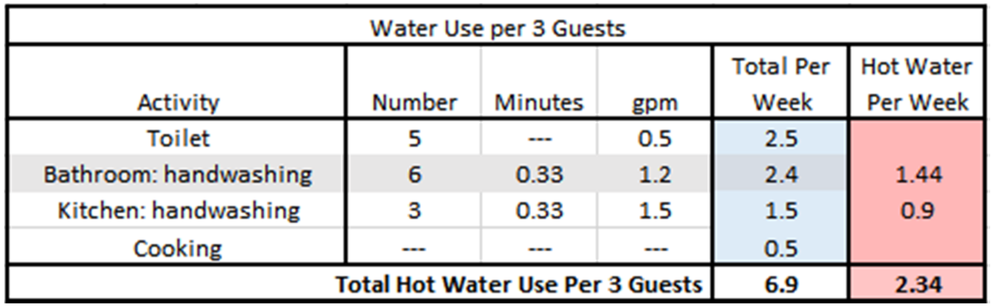
Student 2 - Low Water Use

Activity	Number	Minutes	gpm	gal/day	gal/day	Notes
Drinking water	---	---	---	0.5		The recommended 8 cups per day is equivalent to a half gallon per day
Toilet: dual flush	4	---	0.5	3		A half flush should be used for lighter uses (mainly liquids)
	1	---	1			A whole flush should be used for heavier uses (solids)
Bathroom Faucet: face washing	1	0.50	1.2	0.6	0.36	
Bathroom Faucet: hand washing	8	0.33	1.2	3.2	1.92	
Bathroom Faucet: brushing teeth	2	0.25	1.2	0.6	0.36	
Kitchen Faucet: wash hands	3	0.25	1.5	1.125	0.675	
Kitchen Faucet: washing dishes	1	5.00	1.5	7.5	5	
Cooking	---	---	---	0.5		
Shower	1	8.00	2	16	9.6	
				Total Hot Water Use Per Day	**17.92**	

Student 3 - High Water Use

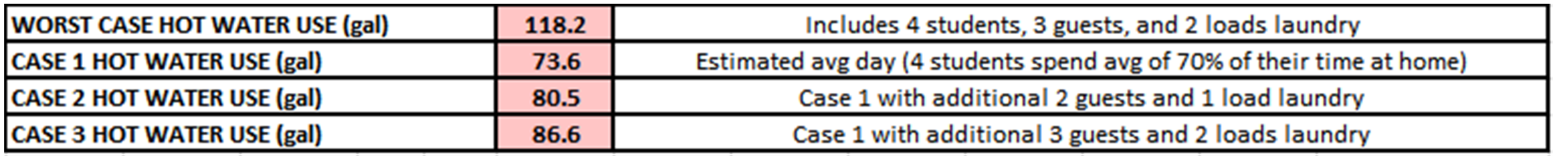
Activity	Number	Minutes	gpm	gal/day	gal/day	Notes
Drinking water	---	---	---	0.5		The recommended 8 cups per day is equivalent to a half gallon per day
Toilet: dual flush	6	---	0.5	5		A half flush should be used for lighter uses (mainly liquids)
	2	---	1			A whole flush should be used for heavier uses (solids)
Bathroom Faucet: face washing	2	0.50	1.2	1.2	0.72	
Bathroom Faucet: hand washing	11	0.50	1.2	6.6	3.96	
Bathroom Faucet: brushing teeth	2	0.25	1.2	0.6	0.36	
Kitchen Faucet: wash hands	4	0.33	1.5	2	1.2	
Kitchen Faucet: washing dishes	1	10.00	1.5	15	9	
Cooking	---	---	---	0.5		
Shower	1	15.00	2	30	18	
				Total Hot Water Use Per Day	**33.24**	

Table 14. Davis Guest Hot Water Use



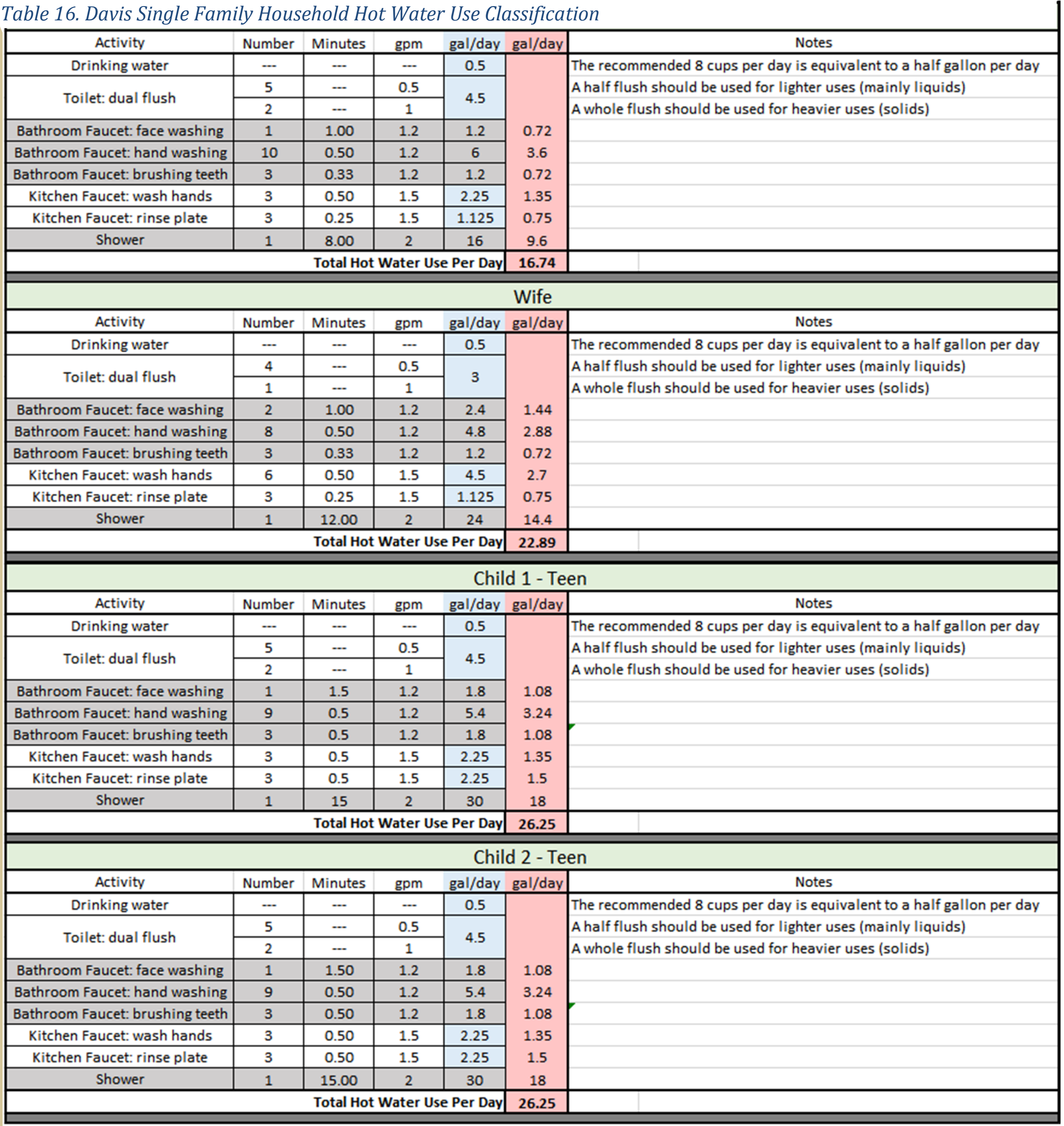
Water Use per 3 Guests					
Activity	Number	Minutes	gpm	Total Per Week	Hot Water Per Week
Toilet	5	---	0.5	2.5	
Bathroom: handwashing	6	0.33	1.2	2.4	1.44
Kitchen: handwashing	3	0.33	1.5	1.5	0.9
Cooking	---	---	---	0.5	
Total Hot Water Use Per 3 Guests				**6.9**	**2.34**

Table 15. Davis Student Hot Water Use Summary



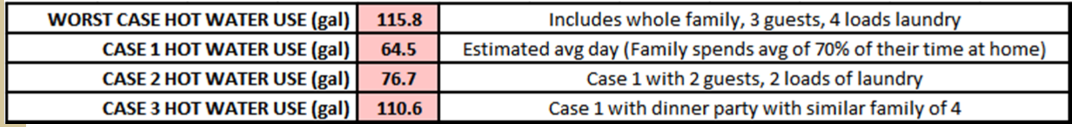
WORST CASE HOT WATER USE (gal)	**118.2**	Includes 4 students, 3 guests, and 2 loads laundry
CASE 1 HOT WATER USE (gal)	**73.6**	Estimated avg day (4 students spend avg of 70% of their time at home)
CASE 2 HOT WATER USE (gal)	**80.5**	Case 1 with additional 2 guests and 1 load laundry
CASE 3 HOT WATER USE (gal)	**86.6**	Case 1 with additional 3 guests and 2 loads laundry

Table 16. Davis Single Family Household Hot Water Use Classification



Activity	Number	Minutes	gpm	gal/day	gal/day	Notes
Drinking water	---	---	---	0.5		The recommended 8 cups per day is equivalent to a half gallon per day
Toilet: dual flush	5	---	0.5	4.5		A half flush should be used for lighter uses (mainly liquids)
	2	---	1			A whole flush should be used for heavier uses (solids)
Bathroom Faucet: face washing	1	1.00	1.2	1.2	0.72	
Bathroom Faucet: hand washing	10	0.50	1.2	6	3.6	
Bathroom Faucet: brushing teeth	3	0.33	1.2	1.2	0.72	
Kitchen Faucet: wash hands	3	0.50	1.5	2.25	1.35	
Kitchen Faucet: rinse plate	3	0.25	1.5	1.125	0.75	
Shower	1	8.00	2	16	9.6	
				Total Hot Water Use Per Day	**16.74**	
Wife						
Activity	Number	Minutes	gpm	gal/day	gal/day	Notes
Drinking water	---	---	---	0.5		The recommended 8 cups per day is equivalent to a half gallon per day
Toilet: dual flush	4	---	0.5	3		A half flush should be used for lighter uses (mainly liquids)
	1	---	1			A whole flush should be used for heavier uses (solids)
Bathroom Faucet: face washing	2	1.00	1.2	2.4	1.44	
Bathroom Faucet: hand washing	8	0.50	1.2	4.8	2.88	
Bathroom Faucet: brushing teeth	3	0.33	1.2	1.2	0.72	
Kitchen Faucet: wash hands	6	0.50	1.5	4.5	2.7	
Kitchen Faucet: rinse plate	3	0.25	1.5	1.125	0.75	
Shower	1	12.00	2	24	14.4	
				Total Hot Water Use Per Day	**22.89**	
Child 1 - Teen						
Activity	Number	Minutes	gpm	gal/day	gal/day	Notes
Drinking water	---	---	---	0.5		The recommended 8 cups per day is equivalent to a half gallon per day
Toilet: dual flush	5	---	0.5	4.5		A half flush should be used for lighter uses (mainly liquids)
	2	---	1			A whole flush should be used for heavier uses (solids)
Bathroom Faucet: face washing	1	1.5	1.2	1.8	1.08	
Bathroom Faucet: hand washing	9	0.5	1.2	5.4	3.24	
Bathroom Faucet: brushing teeth	3	0.5	1.2	1.8	1.08	
Kitchen Faucet: wash hands	3	0.5	1.5	2.25	1.35	
Kitchen Faucet: rinse plate	3	0.5	1.5	2.25	1.5	
Shower	1	15	2	30	18	
				Total Hot Water Use Per Day	**26.25**	
Child 2 - Teen						
Activity	Number	Minutes	gpm	gal/day	gal/day	Notes
Drinking water	---	---	---	0.5		The recommended 8 cups per day is equivalent to a half gallon per day
Toilet: dual flush	5	---	0.5	4.5		A half flush should be used for lighter uses (mainly liquids)
	2	---	1			A whole flush should be used for heavier uses (solids)
Bathroom Faucet: face washing	1	1.50	1.2	1.8	1.08	
Bathroom Faucet: hand washing	9	0.50	1.2	5.4	3.24	
Bathroom Faucet: brushing teeth	3	0.50	1.2	1.8	1.08	
Kitchen Faucet: wash hands	3	0.50	1.5	2.25	1.35	
Kitchen Faucet: rinse plate	3	0.50	1.5	2.25	1.5	
Shower	1	15.00	2	30	18	
				Total Hot Water Use Per Day	**26.25**	

Table 17. Davis Single Family Household Hot Water Use Summary



WORST CASE HOT WATER USE (gal)	**115.8**	Includes whole family, 3 guests, 4 loads laundry
CASE 1 HOT WATER USE (gal)	**64.5**	Estimated avg day (Family spends avg of 70% of their time at home)
CASE 2 HOT WATER USE (gal)	**76.7**	Case 1 with 2 guests, 2 loads of laundry
CASE 3 HOT WATER USE (gal)	**110.6**	Case 1 with dinner party with similar family of 4

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