ENERGY AND WATER PERFORMANCE OF AN OFF-GRID TINY HOUSE IN CALIFORNIA

Alana Bowen Siegner,[1] Brett Webster,[2] Ian Bolliger,[3] Daniel M. Kammen[4]

ABSTRACT

The impetus for buildings to decarbonize and move towards radical energy and water efficiency is increasingly strong and identified as a priority within the green building sector. The tiny house movement offers an opportunity to both address the challenges of affordable housing and contribute to residential building decarbonization. Tiny houses de-emphasize mass consumption and excessive belongings and have potential to address equity issues such as gentrification by providing living spaces to low-income residents in desirable housing locations. This paper analyzes the Tiny House in My Backyard (THIMBY) project, investigating building sustainability concepts through the design-build-occupy process in a three-year-old structure. THIMBY demonstrates energy and water efficiency technologies inside an award-winning small living space (18.5 m^2). THIMBY was designed to reduce energy and water use by 87 and 82% compared to California residential averages. In practice, it has reduced site energy by 88% and has emitted 96% fewer carbon emissions than a 2100 square foot California Energy Commission 2016 Title 24 minimally compliant home. We discuss the differences between design and performance of energy and water systems, which we find offer important lessons for the further expansion of the tiny house movement and other alternative and micro green housing types. We find that optimizing such houses through integration of energy and water saving technologies, home energy management systems, and strong communication between modelers, builders and occupants will be essential to achieving dramatic energy (87%), water (82%), and carbon (96%) savings.

KEYWORDS

tiny house movement; residential building decarbonization; energy and water savings

1. INTRODUCTION

Residential buildings are responsible for 21.8% of U.S. energy consumption and 8% of water use (U.S. Department of Energy 2016; National Association of Home Builders 2017). In order to meet pressing climate goals, residential energy use must be rapidly decarbonized. Homes

1. Alana Siegner, Ph.D., University of California, Berkeley Energy and Resources Group, Climate Farm School Director at Terra.do. laney@terra.do

2. Brett Webster, M.P.P, University of California, Berkeley; Manager at RMI Carbon Free Buildings

3. Ian Bolliger, Ph.D., University of California, Berkeley Energy and Resources Group, VP, Aladdin Sustainability Lab at BlackRock

4. Daniel M. Kammen, Class of 1935 Distinguished Professor of Energy at the University of California, Berkeley, founding director of the Renewable and Appropriate Energy Laboratory (RAEL)

must be more resilient to climate impacts (e.g. extreme weather events, power outages, flooding, drought, etc.) as well as water efficient and electrified, and construction must shift towards materials with lower environmental impact (Wei et al 2013; Sheikh and Callaway 2019). Coinciding with escalating climate concerns, soaring home prices and housing stock shortages are key drivers of inequality and gentrification in places like California's San Francisco Bay Area (Buhayar and Cannon 2019). These trends combine to necessitate a shift in the business-as-usual approach to residential planning and construction (IPCC 2018; UNEP 2018). In response, the green home building industry is growing rapidly, with the potential to deliver significant energy and water savings (USGBC 2014; Statista 2018). Exemplifying this effort, Leadership in Energy and Environmental Design (LEED) certified residences report savings of 20–30 percent in home energy and water use (USGBC). Homes completed by the ZEBRAlliance (a public-private partnership with Oak Ridge National Laboratory) with a ground-source integrated heat pump used 55–60 percent less energy than homes with similar appliances (ORNL 2010). While impressive, these efforts have seen relatively low uptake (less than 1% of the total U.S. housing stock is LEED certified; USGBC). The 90% or greater reduction in greenhouse gas emissions called for by mid-century (IPCC 2018) requires a more aggressive, innovative, and zero-carbon approach to housing. Furthermore, current green building trends do not always incorporate affordability considerations, and "green homes" are predominantly available to the wealthy in the residential market.

The tiny house movement, focused on residences with areas of under 20 m^2 (compared to the 243 m^2 US average for single-family detached homes; Statista 2018), has potential to generate radical reductions in residential energy and water use. In addition, tiny homes offer affordable alternatives to land- and water-intensive rural and suburban sprawl development. Despite this potential to simultaneously address significant climate and equity challenges, current research on design and performance of affordable, low-carbon tiny houses remain limited. This paper addresses the gap in the literature by presenting a case study of a tiny house design-build-occupy project, reporting on the design decisions, energy modeling, and performance over the first three years of occupancy.

Off-grid-enabled homes represent a positive response to both energy generation trends and climate change impacts. As the use of renewable and distributed energy increases at the utility level in the US, homes can function as loci of added generation and storage, interacting usefully with emerging smart, decarbonized energy systems. In cases where the grid mix is increasingly renewable, the extra power and storage capabilities can be used to support and provide ancillary services to the grid (e.g. Pradhan et al. 2013). The rapid evolution and declining costs of energy storage technologies means that individual residences can now play a larger role in meeting local supply via power sales to the utility (Wilson 2017). Furthermore, recent wildfires and widespread power outages in California, Australia and elsewhere underscore the advantage of self-sufficient, battery-enabled single-family and mini-grid energy solutions as a form of disaster preparedness and climate resilience. We designed a tiny home that demonstrates some of the emerging technologies integrated into off-grid residences.

We investigate the real-world performance of an 18.5 m^2 off-grid tiny house design-build-occupy project in California and consider opportunities for scaling or applying technologies and systems to other green home projects. This project explores tensions between its two orthogonal goals of residential affordability and sustainability; our team chose to prioritize sustainability above all else, and the resulting affordability of the project is discussed in our results and analysis.

We provide one of the first quantitative assessments of the gap between design projections and realized energy and carbon savings in a tiny house context.

We also report water system performance and assess the savings achieved through a composting toilet and onsite greywater filtration. Although such water systems are not currently legalized in many places including California, it is an important research task to evaluate the water saving benefits as part of a pathway towards policy change. Legalizing these systems under "best practice" circumstances will require data collection and appropriate regulation to ensure public health and safety. Residential water savings and efficiency measures are increasingly important in drought-plagued Western states such as California, where municipal water use reductions were recently mandated statewide by Governor Brown in an emergency measure during the drought years of 2014–2015 and became part of statewide water conservation policy in 2018 (AB 1668 and SB 606). On average, California residences consume 170 gallons per day (California Department of Water Resources 2014) with demonstrated reductions possible through behavior and technology changes made in recent years (e.g. low flush toilets, rainwater collection for toilet flushing, shorter showers). If radical water consumption reductions are to be realized, it will require thinking outside the box and innovating on waterless toilet and greywater recycling installations such as those presented in this case study.

THIMBY Project Overview

The Tiny House in My Backyard (THIMBY) project, a tiny house on wheels, was designed and built for the Sacramento Municipal Utility District's Tiny House Competition, the first such contest in California. THIMBY was built on a two-axle trailer and designed to be able to function off-grid, via solar photovoltaic (PV) generation, lithium-ion battery storage and domestic water tanks mounted underneath the trailer. The house has an optional grid tie-in point, allowing it to remain powered during colder, rainy winter months without the use of a fossil-fuel generator, enabling flexibility in potential siting locations. THIMBY represents a frontier for energy and water efficient residential construction. Designed for 2-person occupancy, 2,000 kWh annual energy consumption and 30 gallons per day water consumption, THIMBY leverages its small footprint to achieve radical energy and water efficiency.[5]

Following the competition, the house has been occupied by two people for the past three years. In the first years of occupancy, the house has demonstrated significant energy and water savings compared to California residential averages. THIMBY's efficient, all-electric appliances model the future residential technologies necessary to meet California's aggressive climate targets for emissions reductions and are in alignment with the recommendations of the Deep Decarbonization Project (Wei et al. 2013; California Energy Commission 2011; California Energy Commission 2018).

The following sections present the design and construction of THIMBY's building systems; our approach to evaluating the performance of its energy and water systems; the results of this evaluation using data from the first three years of occupancy; and a discussion of the implications for small-footprint, sustainable, and affordable residential buildings. This includes consideration of siting/permitting for tiny houses in residential communities, policy interventions needed, and discussion of other synergistic trends in the green building and distributed energy

5. THIMBY was designed with a set of specific residential behaviors and attitudes in mind that make perfect comparison to conventional California residences impractical: residents of THIIMBY do not have a clothes washer/dryer or dishwasher in the home, and do not have a full-size refrigerator, but rather a smaller under-counter unit.

FIGURE 1. THIMBY Energy System Components.

industries (e.g. community microgrids, home energy management systems). We conclude with recommendations for continued research into off-grid-capable, energy-efficient residences and suggestions of ways in which municipal building and zoning codes could be updated to scale advanced energy and water efficient residences.

2. DESIGN/BUILD PROCESS

2.1 Building Envelope Design

The building envelope was designed to balance sustainability and affordability goals. Tiny homes have high surface area-to-volume ratios relative to larger homes, leading to faster temperature change for a given thermal gradient; thus, high-performing insulation was necessary to minimize winter space heating load. Recycled denim insulation fills the wall cavities, carbon-negative[6] cork insulation panels sit between the framing and the exterior siding, and a weather-tight liquid-applied material seals window openings consistent with the overall house rainscreen (R-guard product line). Phase-change material (Bio-PCM from Phase Change Energy Solutions, M-51) lies in the ceiling cavity alongside insulation to provide passive temperature regulation. These construction materials were chosen according to the static energy model (described in section 2.3.1 below) to maximize building performance while minimizing the envelope's embodied carbon.[7] Specific materials chosen to minimize embodied carbon included: 1) wood framed

6. As cork is harvested from the outer bark of the cork tree once every 9 years while the tree continues to grow, and requires relatively little processing to be made into insulation panels, it is considered a carbon-negative material. See further explanation here: http://www.thermacork.com/what

7. In some cases, detailed performance evaluations and life cycle analyses (LCAs) were not yet available for particular innovative materials. Some choices were made on best available information. For example, a full LCA was not available for the cork-based insulation or Magnesium Oxide shower paneling; as very new materials on the market, they were chosen due to promising low-carbon material input

FIGURE 2. THIMBY electrical schematic.

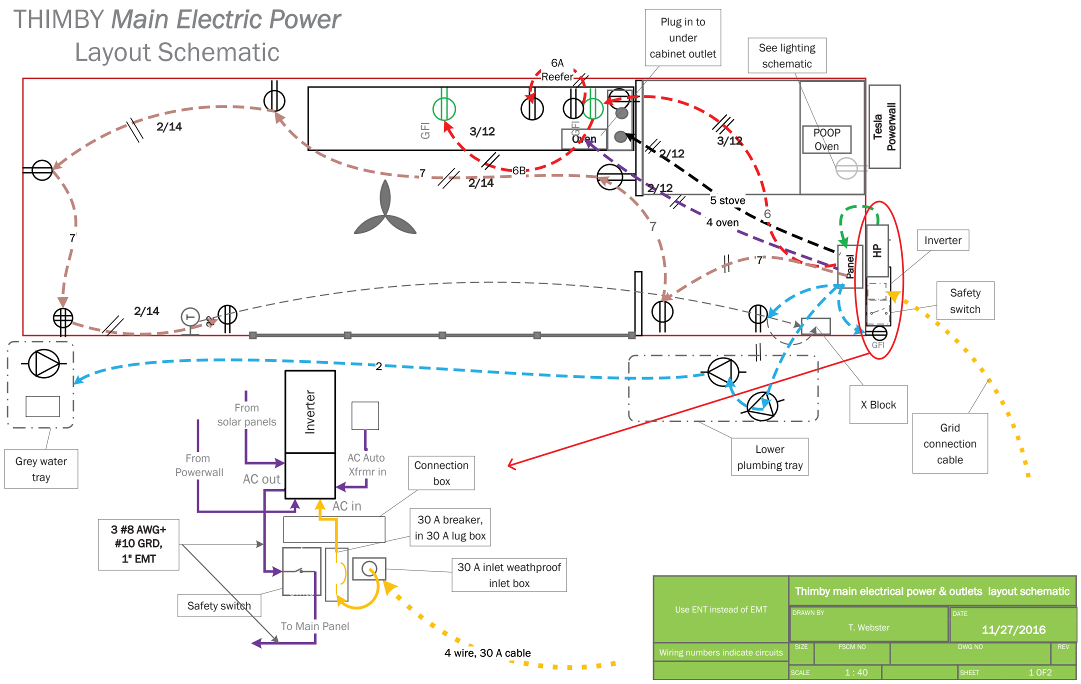


Figure Credit: Tom Webster (THIMBY team member and UC Berkeley Research Specialist, Center for the Built Environment)

structure and windows, 2) repurposed interior and exterior wall cladding from salvage yard, 3) Magnesium Oxide (MgO) panels for bathroom wall covering, 4) Thermacork continuous exterior insulation, 5) Metacryllics roof coating, and 5) use of recycled denim batts for interior insulation. An embodied carbon calculator was developed for the THIMBY project by the Bay Area Environmentally Aware Consulting Network (BEACN) to compare the carbon footprint of candidate materials for each of the construction components (electrical, plumbing, interior, exterior, and structure); it is available at http://beacn.github.io/.

2.2 Energy and Water Systems Design

2.2.1 Energy

The energy system includes a 2.2 kW solar array, 6.4 kWh lithium-ion battery, inverter, energy recovery ventilator (ERV) and a CO_2 air-to-water heat pump. Figure 1 illustrates the system components physically installed on the house and Figure 2 is a schematic of the electric power system.

Heating and domestic hot water are provided by the single air-to-water heat pump and 42-gallon hot water storage tank. A hydronic radiant floor loop provides space heating and is sized to meet the design condition heating load (See Figure 3). Hot water tubing runs underneath the finish floor through grooves in aluminum-faced subfloor panels that help with

data, but waste/recycling data was not yet available.

heat distribution. While orientation of the house is flexible due to its wheeled foundation, it is designed to ideally face south, allowing for passive solar gains via glass doors on the south facade.

Cooling is mostly passive and consists of four primary design strategies: 1) 6.5 m^2 of phase-change material in the ceiling is set to change phase at 77F, effectively functioning as additional thermal mass on hot days; 2) an efficient (6 watt) ceiling fan provides air movement, which has been shown to have a significant cooling effect on occupants (Arens et al. 2013); 3) adjustable shading over the south-facing windows helps prevent unwanted solar heat gain; and 4) operable windows allow for natural ventilation and nighttime flushing in summer months.

Ventilation is provided by an ERV, which exchanges heat between incoming fresh air and outgoing indoor air to minimize ventilation heating load in the winter. When outdoor temperatures are comfortable, the operable windows can provide natural ventilation and nighttime ventilative cooling (in summer) in lieu of the ERV.

FIGURE 3. THIMBY Warmboard Radiant Floor Layout.

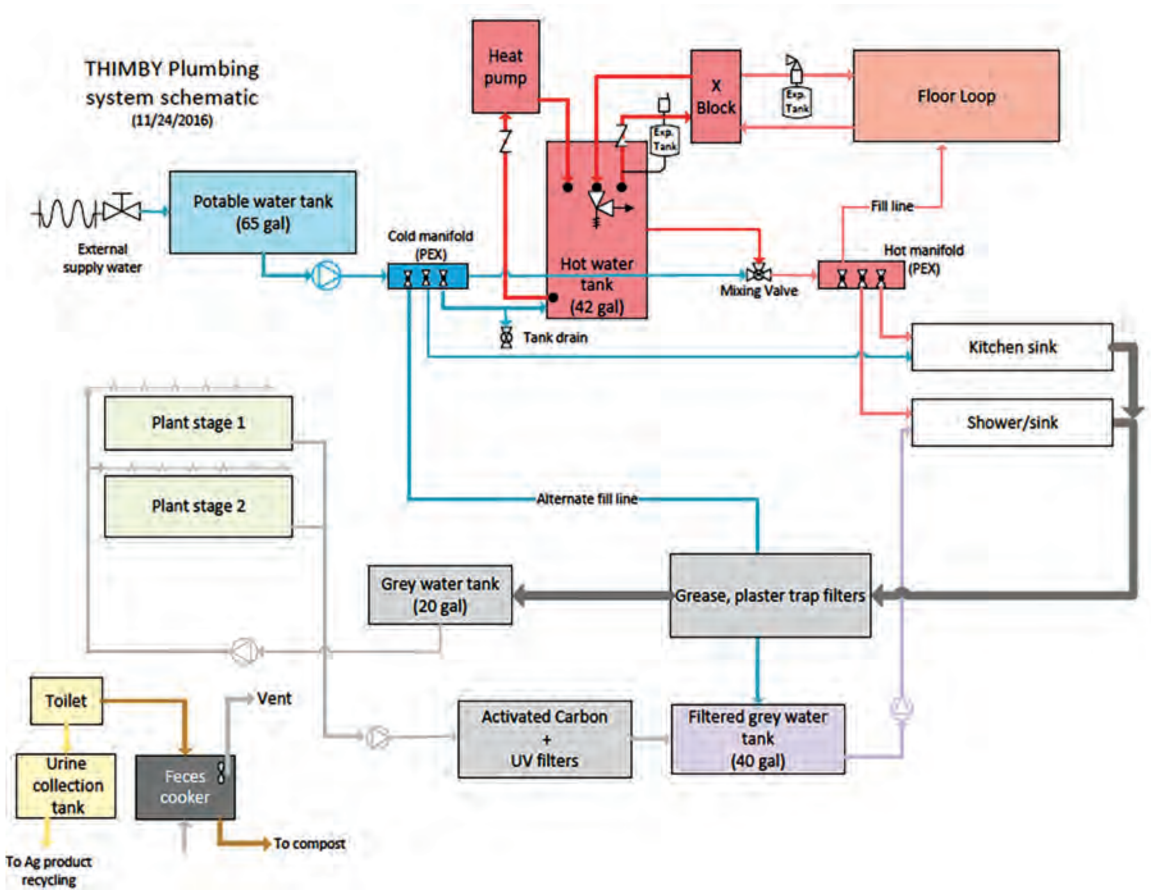
FIGURE 4. Water filtration and catchment system.

2.2.2 Water

The water system design includes a greywater filtration loop that recycles sink and shower water back to irrigation and non-potable reuse, a rainwater catchment tank, a urine recovery system, and a waterless heat-composting toilet (illustrated in physical layout in Figure 4 and as a flow diagram in Figure 5).

THIMBY builds on common water-saving by eliminating high-use appliances, recycling greywater, capturing rainwater, and replacing the largest sector of residential municipal water use (outdoor watering) with an innovative home greywater- and rainwater-fed irrigation system. Total water use is primarily a function of shower frequency and duration and is modeled at 113 liters per day (30 gallons). THIMBY's design eliminates the largest indoor uses of water (toilet flushing, clothes washing) and assumes very efficient hand-dish washing behavior from users. The house separates all water and waste streams and treats each according to reuse needs. Urine is diverted and delivered to a university lab that performs ammonia and nitrogen recovery for agricultural fertilizer (see Tarpeh, Udert & Nelson 2017). Solid waste is separated and treated in a composting toilet with a heating unit to kill pathogens.

FIGURE 5. THIMBY plumbing schematic.



2.3 Energy Modeling and Technology Selection

2.3.1 Static model

The first model developed for THIMBY was a static heat-balance model. We used this model to simultaneously design the envelope (minimum performance to be achieved) and the energy systems needed for a worst-case winter scenario. The model included the wall assembly (with modelled heat bridges and windows properties), estimated infiltration (0.15/h ACH), and ventilation using an energy recovery ventilation system (additional 0.15/h). We designed a high-performance envelope especially considering limited width of the trailer. U-values were set at 0.23 W/m^{2}K for the walls, 0.15 W/m^{2}K for the roof and 0.12 W/m^{2}K for the floor (R-values of 25, 23, and 47 respectively). For our modelled winter design day, we assumed internal gains of ~10 W/m^2 (assuming 1 occupant, low electrical devices usage, lighting, hot water tank losses), no passive solar gains (assuming no incoming solar insolation) and outdoor temperature of 5.6°C (42°F, taken as a low Winter average in Berkeley). To maintain a minimum indoor temperature of 16°C (60.8°F) for 60 consecutive hours, we would need a total energy of 11 kWh. This simplified analysis indicated the need to maximize both our solar and energy storage systems while taking into account physical limitations in size and weight inherent to a mobile tiny house project. We examined the Pareto front of PV size and storage capacity combinations that could allow the house to operate year-round without grid connection in the Bay Area under ideal usage.

Energy use is highly seasonal in design-phase models due to the operation of the space heating system in winter, which represents over 30 percent of load when in use due to the increased demand on the heat pump water heater. The static model was not used to model a summer scenario, as we assumed that passive cooling, thermal storage through PCM, and an overhead fan were adequate for the building's intended climate zone. Windows were designed with adjustable external shading devices to allow passive solar heat gains in the winter and block unwanted solar heat gains in the summer.

In a grid-connected system, PV systems are often sized to be zero net energy (ZNE) over the course of a year, effectively using the grid as a very large "battery" that can provide energy during all of the hours for which there is no PV generation. In the off-grid case, the PV and storage must be sized to meet the "worst-case" condition where energy demand is high and production is low for several days in a row. This design approach results in a low utilization factor of the energy produced over the course of the year. The majority of the time, the tiny house energy system is producing a much larger amount of energy than is needed to serve loads within the house, making THIMBY an ideal candidate to be connected to a microgrid or regular grid infrastructure.

2.3.2 Energy systems selection

Table 1 lists the technical equipment used for THIMBY's energy systems, chosen based on the static modeling process. The solar array was designed to take advantage of all available roof area (Eight 285-Watt panels) and has an adjustable racking system to allow optimal generation across seasons. THIMBY employs off-the-shelf battery storage through a 6.4 kWh-capacity Li-ion battery (Tesla Powerwall). The 159-litre (42-gallon) hot water tank, coupled to a heat pump water heater, provides an additional ~5 kWh of thermal storage. Hot water tanks represent significant additional energy storage potential available in most residential buildings (i.e. those without tankless systems), yet the "low quality" energy stored in hot water typically serves only Domestic Hot Water (DHW) uses. In THIMBY, a hydronic radiant floor provides space heating. This transitions the end use with the largest annual load from electric to thermal, as energy for space heating is stored thermally in the hot water tank.

The use of a heat pump water heater coupled to PV generation was a more cost-effective, energy-efficient, and low-emissions alternative to electric on-demand plus solar thermal space and water heating systems also considered for this project (Northwest Energy Efficiency Alliance 2015, SMUD 2012, Raghavan et al. 2017). In the off-grid tiny house case with limited rooftop area, if some rooftop area is allocated to solar thermal, it detracts from the ability of PV to serve as an effective electric backup (e.g. via powering electric water heater). The heat pump we chose uses a low-Global Warming Potential (GWP) refrigerant (CO_2) and provides a high Coefficient of Performance of 3.5; it is promoted as part of California's Deep Decarbonization Pathway (Raghavan et al 2017; Sheikh 2017).

2.3.3 Dynamic model—EnergyPlus

A dynamic model was used during the design phase to corroborate heating load results from the heat-balance calculations described above. An EnergyPlus model of the house was created using the same envelope parameters at the stud, cavity, and fenestration conditions as in the static model. Dynamic energy modeling in EnergyPlus improves accuracy of energy use calculations

TABLE 1. List of technical equipment.

Equipment	Technical properties	Integration[(a)]	Cost
PV (8 panels) Sunmodule Plus SW 285-300 MONO (5-Busbar)	2.2 kW peak	On the roof, South oriented 37° inclined compared to horizontal plane (adjustable) Total surface of 13.4 m^2 (1.68 m^2/panel)	$2,356
Lithium-ion battery storage Tesla Powerwall (version 1)	6.4 kWh-capacity	Outside (East side)	$3,300
Inverter SolarEdge Single Phase StorEdge Inverter (SE7600A-USS)	DC-coupled architecture stores PV power directly to battery; for both off-grid and grid-tied applications. 7600 VA rated AC power output	Outside (East side)	$3,060
CO_2 heat pump air/water Sanden SanCO_2	Coefficient of Performance = 3.5	Outside (East wall shelf)	$2,000
Hot water tank Stainless Steel Storage tank (GAUS-160QTA)	159 litres (42 gal) (assuming hot water temperature ranging between 38° to 65°C, this represents 5 kWh-capacity)	Inside (near the East facade) 1.80 m high, 0. 57 m diameter	$1,600
ERV Panasonic WhisperComfort Spot ERV (FV-04VE1)	Consumes 23 W @ 40 CFM, 1479 RPM	In ceiling, with supply vent on South wall and exhaust vent on East wall at heat pump intake 0.53 × 0.43 m grille size with 2 × 0.1 m ducts	$466
Ceiling fan Aeratron AE2	6 W at high speed	Inside center of the main room 1.09 m. diameter	$369
Phase change material Phase change solutions Q25C-M51	1 kWh / phase transition	Ceiling of the main room (inner side) Total surface of 6.50 m^2	$472
Radiant floor Warmboard Inc. Warmboard-R panels	1.3 cm tubing with .06 cm 1060 aluminum conductive surface	Floor of the main room Total surface of 5.9 m^2	$450
Taco X-pump block for radiant floor	All-in-One Heat Exchanger, Dual-sided Circulators and Mixing Control Package	In the mechanical equipment wall above the hot water tank	$1,259

[(a)] Assuming a North/South orientation of the house with the trailer tongue directed towards East for some end uses, allowing for improved technology selection and sizing; however, many of the newer technologies used in THIMBY are not well represented in the off-the-shelf model.

An Oakland, CA weather (.TMY) file was imported and annual simulations were run at sub-hourly intervals to model ideal heating loads throughout a typical meteorological year. Ideal loads were used as the HVAC model instead of specific HVAC equipment because the aim was to verify the heating load calculations accounting for internal and solar gains. Lighting, water heating, plug loads, occupancy, and cooking were input into the model according to the same schedules and power consumption assumptions in the static model.

3. BUILDING PERFORMANCE MONITORING

3.1 Resource Use: Energy, Carbon and Water

To continuously monitor system performance, we installed in THIMBY a low-cost, off-the-shelf sensor network. The information produced by this network facilitates a dual research-operational objective: promoting empirical performance research and allowing residents to better adjust behaviors to meet energy savings or comfort objectives. THIMBY's data is made transparent to the occupant through multiple online monitoring platforms. PV generation data coming from the home's smart inverter is available on the SolarEdge monitoring portal, and circuit-level load data derived from current transformer units is available via the Solar Analytics dashboard.

Monthly energy consumption and generation data were collected through the SolarEdge platform and are stored online to compare monthly or annual generation over time.[8] These data are compared to a minimally compliant mixed-fuel (gas and electric) Title 24[9] 2016 home and the average California home according to the 2009 Residential Energy Consumption Survey (RECS).

We present results on carbon performance during the operational phase only, in terms of carbon savings compared to operating other residential buildings. While efforts were made to consider the lowest embodied carbon materials in building design (see above), a full LCA was not the aim of this analysis. We calculated annual emissions by multiplying hourly electricity imports from the grid by hourly marginal emissions factors for the California Independent System Operator (CAISO) NP15 region where the house has been located throughout the three years of occupancy. Hourly marginal emissions factors were pulled from the WattTime database which creates an annual carbon profile for each balancing authority by averaging hourly data from the previous three years. Emissions 'credits' from electricity exports were not considered, as the house is not currently permitted or enabled to feed in excess generation to the grid. Hourly emissions over the three years of data were summed and divided by three to get an average emissions per year. The total annual emissions were then divided by square footage and number of occupants to produce two normalized results. These results were then compared to two modelled cases: a Title 24 2016 home, and a minimally compliant mixed-fuel Title 24 2019 home with the required capacity of onsite solar PV. Hourly energy use profiles were generated

8. Due to the fact that THIMBY has moved several times in the past two years, its generation data is not directly comparable over time and is interrupted at several time intervals. Nevertheless, online monitoring is an important methodological tool for those monitoring off-grid home energy performance to understand during which months consumption will be most constrained (or back-up grid connection will be necessary).

9. Title 24 refers to the Building Energy Efficiency standards for California's energy code for newly constructed and existing buildings. Revised standards are published every three years.

for the comparison cases using the California Building Energy Code Compliance (CBECC-Res) software. In both comparison cases, no onsite laundry facilities were modeled to account for the fact that THIMBY does not have onsite laundry. Electricity consumption was multiplied by the same hourly annual emissions factors as in the THIMBY case. For the 2019 Title 24 case, where solar PV is required, the emissions 'credit' of solar exports was calculated by multiplying the exported kWh by the marginal grid emissions factor on an hourly basis. Natural gas consumption was multiplied by an emissions factor of 53.07 kgCO2/mmbtu (EIA 2016). A site to source natural gas leakage rate of 2.3% was assumed and these non-combustion emissions were assumed to have a 100-year global warming potential of 30 (Alvarez et al. 2018; EPA 2020). THIMBY carbon performance was not compared to the 2009 RECS average California home because hourly emissions profiles were not available in the RECS dataset.

A simple water flow meter was installed at the hose connection inlet to measure daily water use during the first seven months of occupancy. Water quality testing was performed to evaluate the efficacy of the greywater filtration system, and adjustments were made to system components based on test results.

3.2 Evaluating Occupant Experience

The first users of the THIMBY project were two of the modelers and builders themselves, alleviating any communication problem between modelers, builders, and occupants occurring in some innovative green home projects. This was possible because the house was constructed for a competition and not for sale and may not be realistic in other building industry projects. Experimental university projects can thus provide valuable contributions to the design-build-occupy literature. The occupants first lived in the house at the location where construction took place, through university approval for "living lab" research and data collection. They first had to move the house in March 2018, and then again in October 2018, due to university research approval expiring and being out of compliance with town zoning policy respectively. Each move entailed some disruption to regular occupancy (as systems had to be shut down for transport and set up in a new location), for a period of approximately two months in February-March 2018, and approximately two weeks in October 2018.

We employ methods of participant-observation and key informant communications for gathering and presenting relevant data on house maintenance, siting locations, and other logistical considerations surrounding occupant experience.

4. RESULTS

* 817 kWh/yr predicted for space and water heating, 1113.4 kWh/yr for plug loads, lighting, cooking (induction) and refrigeration[10]

**Savings calculated from actual performance data

10. The actual energy usage does not perfectly align with EnergyPlus modeling by end use. The EnergyPlus model provides lighting totals as 17.4 kWh/year and plug loads as 1096 kWh/yr, including all wall outlets, refrigerator and cooking appliances, for a total of 113.4 kWh/yr for all these end uses. THIMBY lighting is combined on the same circuit as the ERV, so the data is not able to be disaggregated for direct comparison with the dynamic model. A further note on the model vs. actual performance comparison is that we did not calibrate our energy models to the exact weather data from the first year of occupancy. Our goal with EnergyPlus modeling was practical: to inform construction and materials selection, not to enable direct comparison with actual consumption nor to refine the E+ model with calibrated performance data. This comparison table is provided here for context and transparency rather than for implications on the energy modeling process.

TABLE 2. Tiny House Design vs. Performance metrics.

Metric	Units	Initial Design (static calculation)	Initial Design (dynamic calculation)	Performance (3 year average)	California Residential Average	% Savings**
Total Site Energy Consumption	kWh/year	2442	1979.9*	1,343	18,171 kWh/yr	93
Energy Use Intensity (EUI)	kWh/sq. ft.	14.4	11.6	8.3	15.8	48
Water Efficiency	gal/person/day	30	*N/A*	31	170	82

Compared to California residential averages, the design phase models predict that THIMBY would reduce total site energy use by 87 percent and indoor water use by 82 percent (EIA 2009; DeOreo et al 2011). Performance results are broken down by energy, carbon and water below.

4.1 Energy Performance

The energy system consumed an estimated 1407 kWh/year during the first year of operation, and 1,343 kWh annually averaged over the three years of occupancy, compared to design-phase predictions of 2442 kWh initially, using the static model described in section 2.3.1 above, and 1979 kWh/year predicted by the dynamic model summarized in 2.3.3.

The tiny house has moved locations and micro-climate zones within the Bay Area twice in three years. In the most recent two sites, space constraints and local tree cover prevented the optimal orientation of the house, such that solar generation is lower than predicted, especially in the sensitive winter months. This required use of grid imports in the most recent site, where the house has been located since October 2018. The annual energy consumption for the past three years of occupancy is presented in Figure 7 below, compared to a 2016 CEC Title 24 compliant home (CEC 2016) and an average California home. There have been interruptions to occupancy and use for 1–2 months in each of the past three years, and overall annual energy consumption has fluctuated between 1,159 and 1,464 kWh/year.

The grid imports relative to self-consumption from solar panels and battery are summarized for a "typical year" in Figure 6 (note: grid imports would be reduced if the tiny house was sited optimally, with south-facing orientation and no shading from nearby trees).

In aggregate, the tiny house has produced 2.88 MWh of energy over its lifetime (from October 2016 through November 2019), generating energy in the range of 77 kWh/month (winter) to 135 kWh/month (fall) and providing environmental benefits of 2031 kg of CO_2 emissions savings (compared to generating 2.88 MWh with a fossil fuel energy system, calculated using the emissions factor for the US: 689.56 g CO_2/kWh).[11]

11. From SolarEdge Technical Note November 2016 https://www.solaredge.com/sites/default/files/monitoring_platform_environmental_benefits_calculation.pdf

FIGURE 6. Monthly Energy Consumption by Source.

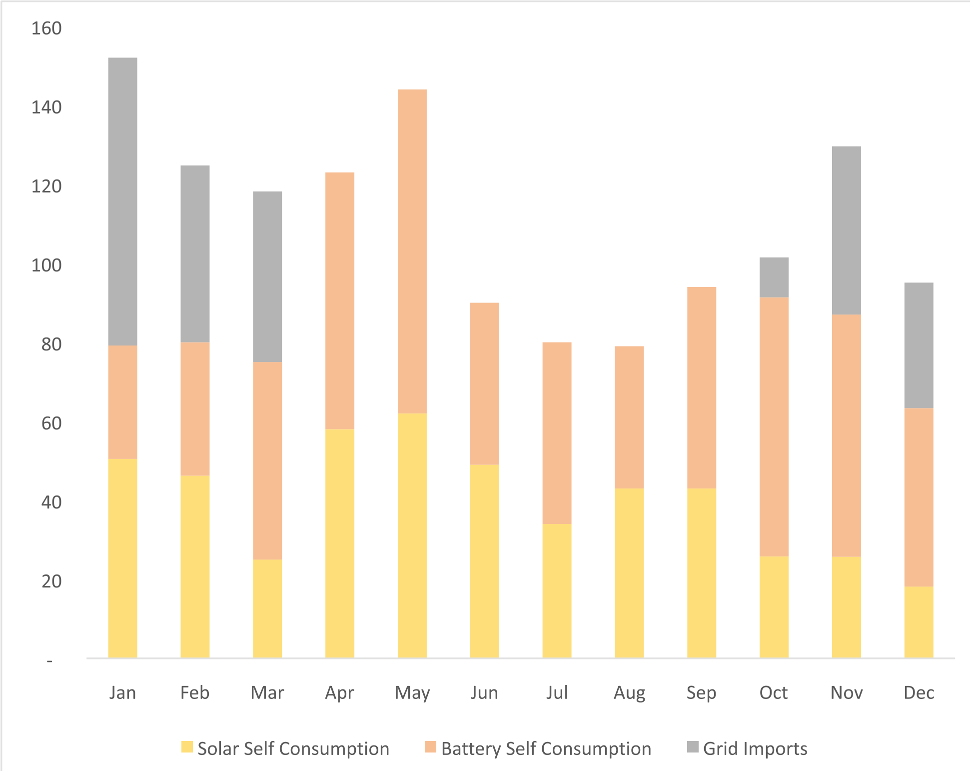


FIGURE 7. Annual Site Energy Use Comparison.

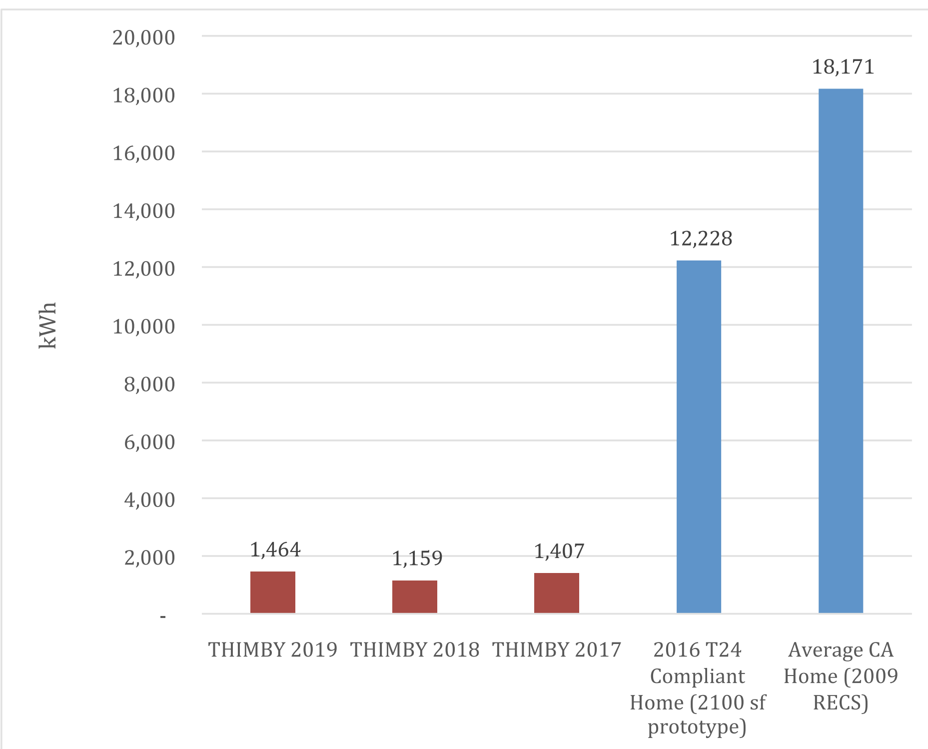


FIGURE 8. Annual Greenhouse Gas Emissions.

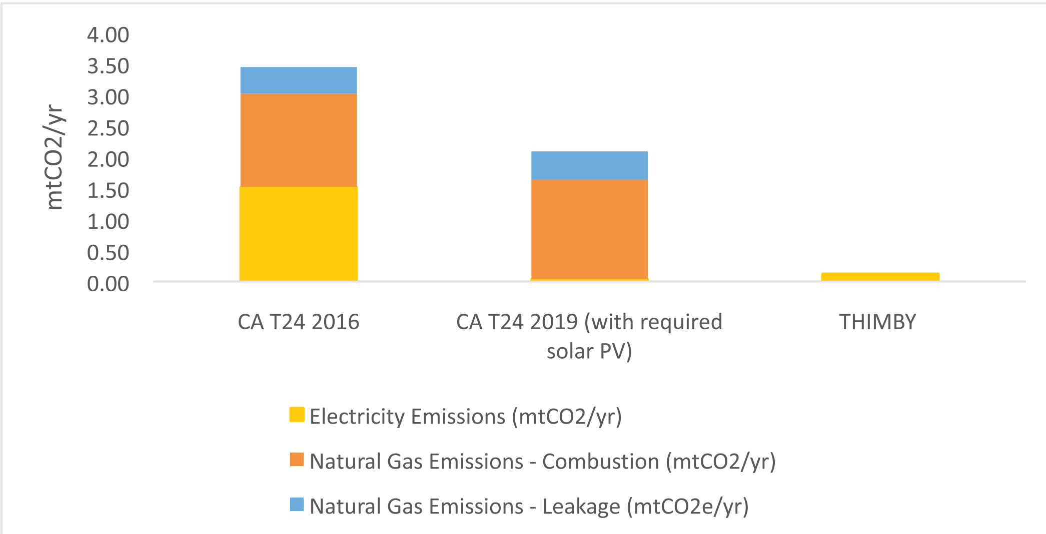
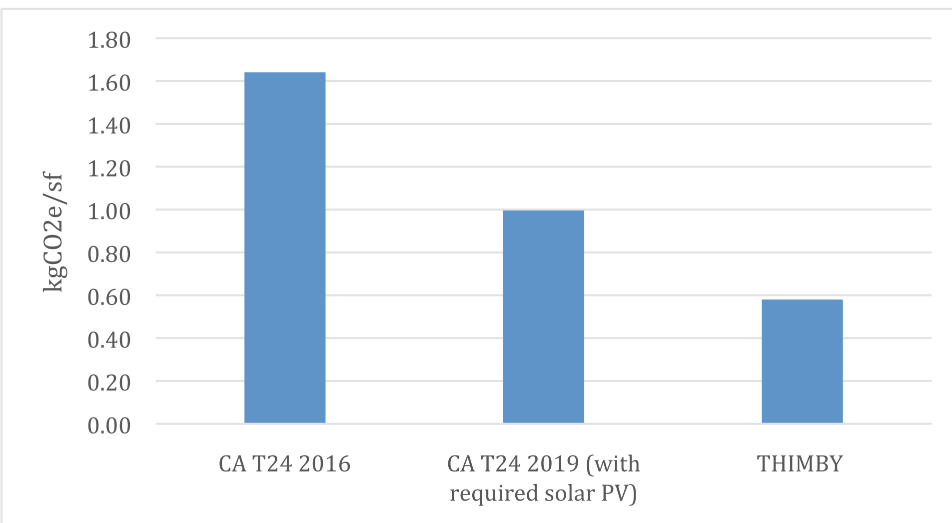


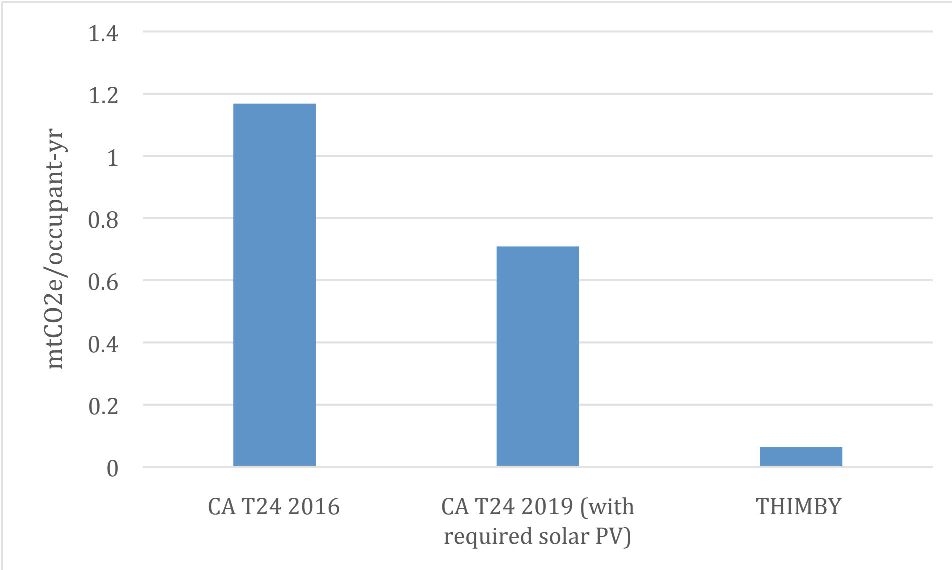
FIGURE 9. Annual Emissions per Square Foot.



4.2 Carbon Performance

THIMBY emits 96% fewer carbon emissions than a 2100 square foot 2016 Title 24 minimally compliant home, and 94% fewer emissions than a minimally compliant 2019 home with the required solar PV panels (see Figure 8 below). Normalized by square footage, THIMBY emits 65% fewer emissions per square foot than a 2016 T24 compliant home and 42% fewer emissions than a 2019 T24 compliant home with required solar PV (see Figure 9). Normalized by number of occupants, THIMBY emits 95% fewer emissions per occupant than the T24 2016 case, and 91% fewer emissions than the T24 2019 case (see Figure 10).

FIGURE 10. Annual emissions per occupant.

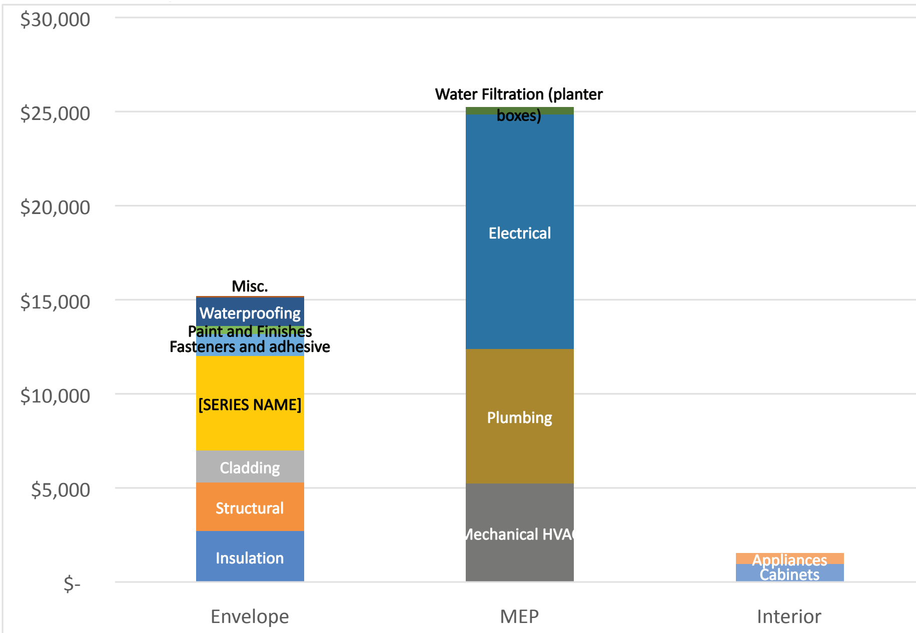


4.3 Water Usage

Water usage, measured with a simple water flow meter, closely tracked design estimates. Because many high-water use domestic appliances are not present, it is less complicated to forecast water use. The primary "innovation" of the THIMBY water system occurred in the design phase incorporating a greywater recycling system. Testing performance was a question of both ensuring consistent functioning and measuring water quality as well as quantity, rather than only measuring the amount of water consumed. Our results show that design estimates did overestimate shower water use, which is found to be closer to 6 gallons/shower on average rather than 8. Estimates for dishwashing, drinking, teeth brushing and hand washing (relatively small water uses) were fairly accurate.

Diverting wastewater from a municipal treatment plant represents energy as well as water savings from avoided wastewater treatment energy consumption (approximately .3W/gallon). THIMBY is designed to treat wastewater onsite, thus eliminating energy use required to treat wastewater mechanically at treatment plants—estimated at 73 kWh/MG (PGE 2006). The public water supply constitutes a small but growing share of U.S. electricity consumption (6.1 percent; Congressional Research Study 2017). Efforts to substitute less energy-intensive treatment and water supply options are increasingly being incorporated into green building certifications (via gravity fed rainwater catchment, ecological treatment, capturing stormwater runoff in rain gardens, laundry-to-landscape design, etc.). Onsite greywater treatment reduces the load burden on treatment plants, where load capacities are strained by population increases in fast-growing urban centers such as the San Francisco Bay Area. From a life cycle perspective, it is important to consider the embedded energy of materials selected for home greywater systems, as they are processing much lower volumes of water and are thus a higher potential value of carbon per gallon of water treated (unless repurposed materials are used). It is worth recognizing that due to economies of scale, not all applications of home greywater treatment might be environmentally beneficial. However, using home systems according to local codes and in conjunction with other functions such as landscape irrigation can produce synergies

FIGURE 11. Cost of Materials by Category.



between wastewater processing reduction (cost and energy savings) and water savings (due to avoided municipal water use for outdoor watering).

Water quality monitoring occurred at regular intervals in the first six months of use, primarily testing for bacterial presence in the filtered greywater to ensure the safety of reuse. No E. Coli presence was found, the main parameter of concern for health reasons. Other testing parameters included ammonia, Total N, turbidity, and BOD. Results varied due to the variation in constituents present in the greywater and residence time in holding tanks but did not exceed thresholds of concern.

The greywater system can be dismantled to regularly flush or replace materials and can be used to irrigate onsite trees and landscape features directly rather than recirculating (as a permanent irrigation feature or while further retrofits are being made to parts of the loop). The THIMBY greywater filtration system is not yet performing as designed, due to suspended and dissolved solids (TDS/TSS) passing through the planter box filtration system and causing turbidity levels above 1 NTU, which then prevents the UV light from providing disinfection. This system is being retrofit with new materials along the lines of a traditional slow-sand roughing filter to improve filtration quality. In the meantime, functionality is limited but sufficient to allow some filtration of greywater before applying for irrigation purposes to non-edible plants, which are thriving in their current growing conditions.

While self-treatment of greywater back to in-home use is not currently permitted in most city building codes, California is moving towards increasing the approved uses of greywater. Metrics on safe home greywater treatment systems require further development, and as a result of this project a home greywater treatment "box" is being prototyped at an independent green building company.

4.4 Cost Analysis

The graph (Figure 11) above represents the cost breakdown of materials for the envelope, mechanical, electrical and plumbing systems (MEP), and interior. The total cost in materials was $42,000. For a complete breakdown of material costs, see Appendix A—Bill of Materials.

5. DISCUSSION

5.1 Challenges in Measuring Annual Site Energy Consumption

A dominant experience overlapping with the initial time period for evaluating THIMBY performance has been the need to constantly seek out acceptable siting locations for such an innovative, off-grid tiny house. After receiving permission to live in the house as "test residents" for a period of one year at the campus research facility, the house residents needed to find a new location. A location was found through personal contacts, and neighbors expressed consent for the tiny house to locate in a driveway in their neighborhood. However, the town did not have zoning policies in place to allow for tiny houses to be used as "primary residences," so ordered the removal and relocation of the house six months later. The tiny house moved again to a more rural location in Northern California, where zoning ordinances were less strict and spacing between properties was greater. The aftermath of the 2017 wildfires in this area, which left many local residents seeking alternative means of housing during the rebuilding process, created a legal and social environment of leniency towards alternative housing arrangements. In light of climate change and related impacts such as a prolonged wildfire season in California, it is especially timely to consider revisions and updates to town and county zoning codes to create the structures, conditions, and processes necessary for alternative and mobile dwelling units (especially those self-powered by clean energy) to integrate more easily into California communities. This policy relevant finding will be discussed further in the conclusion section below.

Interruptions to use aside, the variation in seasonal energy consumption was less than expected. Due to a relatively low space heating load (a function of both tight envelope and mild climate zone), monthly energy use did not vary as significantly as expected.

At the current site, the house is plugged into the grid to facilitate continuous energy supply, as the siting location does not allow for optimal orientation (south-facing) for THIMBY solar panels. The generation has been lower in the current site due to various factors including orientation, periods of intense smoke during the 2018, 2019, and 2020 fire seasons, and a particularly rainy winter in 2018–2019 (precipitation recorded as 200% of normal). Since the house is plugged into the grid (with the inverter programmed to "maximize self-consumption"), occupants are naturally less concerned with minimizing energy consumption on cold and rainy days, and therefore energy consumption during the winter months is slightly higher than it might otherwise be (but not significant in the context of dramatically lower energy consumption compared to other residential cases shown in the Results section above). Siting, orientation, zoning, and occupant behavior are constant logistical variables to consider in any tiny house living situation and are of particular importance for the off-grid case where grid connection or backup generation must be considered.

5.2 Contextualizing Energy, Carbon, and Water Performance

Given the variety of technology idiosyncrasies, occupancy disruptions, and learning curves at play during the first years of test-residency, continued long-term study of energy performance in a consistent site is an important next step for future off-grid-capable tiny house projects. Reasons for discrepancies between design and performance are specific to the innovative technologies and appliances within the house, their interactions as a system, and unexpected maintenance required during the first three years. In the first year of occupancy, the inverter did not function properly in off-grid mode for several time intervals, leading to several short periods of load testing and atypical usage while the problems were being corrected. Additionally, the induction cooktop consumes relatively little energy for tasks like boiling water when compared to a gas stove yet draws over 100 Watts when plugged in but not in use, negating major energy savings unless the user cuts power to that circuit or unplugs the stove when not in use. As users who were also designers, builders, and monitors of energy usage through a real time data portal, we were able to observe this phantom load relatively quickly and correct behavior to unplug the stove when not in use. However, this sort of unanticipated appliance behavior caused our initial static model projection for cooking to be lower than actual consumption for the first year. In the third year, the heat pump malfunctioned and required several weeks of occupant troubleshooting, reading error codes and corresponding with the system manufacturers, and waiting for replacement parts to arrive (there were not trained maintenance personnel available to assist with this new technology). This disrupted water heating activities as the heat pump did not run for a multi-week period.

There are many reasons why the carbon performance comparisons are not perfect comparisons. First, the THIMBY analysis was performed with measured energy consumption data, whereas the comparison cases are modeled results. Second, especially for the total carbon analysis, the modeled prototypes are an order of magnitude larger buildings than THIMBY. The 2100 square foot CBECC-Res prototype is a three-bedroom house with modeled occupancy of 2.95 people, whereas THIMBY has supported just two occupants (CEC 2019). While imperfect, the intention of the carbon performance comparison is predominantly to investigate the first-order magnitude of difference between tiny house emissions and average or prototypical homes in California. The results suggest considerable carbon savings, both in terms of total values and when normalized by square footage and occupancy. It should further be noted that these comparisons are made with buildings that comply with the two most recent building energy code cycles, thus making them among the highest performing homes in the state and the nation. The vast majority of the residential building stock in CA was built before these two code cycles and is, on average, lower performing from an energy and carbon perspective (E3 2019).

The water analysis for the tiny house did not seek to directly estimate and add on water use by the occupants at other locations for activities they could not accomplish in the tiny house, such as clothes washing. The occupants were able to wash clothes at the landlord's home or a family member's home. We simply argue that in more community-oriented or collective living arrangements, such as apartment buildings, it is logical to share appliances and achieve water use efficiency by only washing full loads, for example, minimizing use of scarce resources.

A final point for consideration in the energy, carbon, and water performance is that this project strives to demonstrate minimized environmental impact that can occur when dramatically designing homes and living experiences for sustainability. The human behavior and social norms around household energy consumption (e.g. perceiving energy as cheap and abundant) are critical elements to address in reducing carbon footprints associated with energy consumption. Many comparisons to per capita or per household averages in energy, carbon, and water are imperfectly drawn, with the larger point being to showcase dramatic changes to "business as usual" that are possible within a much smaller than average home footprint, without compromising comfort or quality of life. The two occupants of the tiny house have been happy and comfortable with their living situation for approximately 4 years, and have had minimal disruptions to essential living functions such as electricity supply, cooking, showering, and working remotely (as has been the case during the COVID-19 pandemic).

5.3 Learning from Tiny Houses: Innovative, Affordable Green Building Solutions

Tiny houses are dynamic and novel residence types given that they are often built on wheels and move locations as need. Mobility is part of the appeal of tiny homes, a growing trend in sustainable living, for reasons which include ability to relocate easily amidst climate-driven disruptions such as wildfires. While THIMBY is not as easily mobile as some tiny houses on the market, the results of this analysis demonstrate that ability to move location was essential for remaining "in use" as a residence, and possible with considerable advance planning; in order to move more easily, we would have had to reduce the weight of certain equipment and materials. Acknowledging that THIMBY has operated in three different residential locations in the past 4 years, this case study offers an important contribution of tiny house performance data in three different locations (within a 50-mile radius).

The most innovative contribution of the THIMBY project is the integration of many cutting-edge energy technologies in a small, all-electric home with no fossil fuel site or source energy consumption. The electrification of all residential end uses served by on-site renewable electricity is a promising avenue for decarbonizing the residential building sector. All-electric home construction is now mandated for new construction in Berkeley beginning January 2020, a first of its kind ordinance in the United States (Delforge 2019). Thus, the results of this analysis are relevant to those in the green building industry, particularly to building energy researchers studying the performance of electrified homes and the technologies they contain. The dramatic reduction in energy demand through the combination of a small footprint and high-performing building envelope enable 100% renewable on-site energy production to meet demand during most times of year. THIMBY energy consumption represents an 88 percent energy savings over a 2016 California Title 24 compliant home and a 92 percent savings compared to an average California home, noteworthy results for green building researchers and practitioners.

From an affordability standpoint, our results state that the materials cost of the house was $42,000. We did not track labor hours from those working on the project, as this involved dozens of individuals from both the core project team and volunteer "work parties;" the labor was largely contributed on a volunteer basis by unskilled individuals, guided by 2 project Construction Managers. We conducted a simple construction cost calculation using an online tool to estimate the cost of building a simple 18.5 square meter home, and found that estimate to be $42,000. At a total of $84,000, we conclude that THIMBY is affordable to those living below the median household income for the region ($112,449 in 2019 dollars), although land access remains a consideration. Furthermore, the technology used is becoming more affordable in most cases, and there is opportunity to optimize the manufacturing process of similar homes as the structure is simple and conducive to a pre-fabricated approach.

This case contributes to understanding of practical maintenance concerns surrounding new energy technologies and systems such as CO_2 air-to-water heat pumps. Early adopter challenges faced in the THIMBY project include difficulty finding trained maintenance support for some energy technologies (including the heat pump, which the users have had to self-maintain and troubleshoot through trial and error), systems integration, and imperfect applications of technology to small footprint off-grid living. Trained maintenance personnel should ideally be widely available to support market adoption of new technologies like the CO_2 heat pump. Additionally, designing a house in order to operate entirely off-grid raises questions and concerns over resource efficiency, as solar panels will greatly over-generate during sunny hours (producing significantly more energy than can be stored in the battery), and battery life is not sufficient to last through several cloudy days, making back-up energy sources necessary (additional batteries or diesel generator) during the winter months. The house did not make it through either of the first two winter seasons without losing power and requiring a backup generator to restart the house or needing to plug in to an onsite grid connection.

The off-grid challenges experienced by a single residence can be ameliorated by community-scale energy systems or microgrids, offering increased resilience and load flexibility. Off-grid communities or microgrids are better able to balance solar generation, batteries, and loads than an individual off-grid residence. California is funding renewable energy integration in community microgrids through their Advanced Energy Communities program (California Energy Commission 2018) and facing increased pressure to implement viable microgrid models as concern mounts over wildfire danger associated with centralized power lines. Scaling from a single tiny house demonstration project to an off-grid capable community of such homes would be a beneficial step for future projects and a step towards greater resilience in the face of climate impacts.

Despite the above-listed maintenance considerations and challenging winter experiences, the energy technologies and spatial layout of the house are sufficient and sustainable to such a degree that they provide a high level of occupant comfort and satisfaction to those testing out the THIMBY systems in these initial "living lab" years. This is due in part to the fact that the occupants enjoy participating in the design, integration, and improvement of low-carbon home energy systems, and are committed to the sustainability ethic of "living tiny." Throughout its first three years of occupancy, the house and its technologies have served as a valuable educational demonstration and tour facility for various groups interested in constructing tiny homes and/or integrating similar technologies into all-electric homes.

Given the educational and sustainable living benefits of these innovative, mobile houses juxtaposed with the challenges of legally siting and using off-grid systems (e.g. composting toilet, greywater filtration), there is a need for policy development to allow for their permitted existence and in order to truly unlock the potential of tiny houses to offer affordable, climate resilient, energy efficient housing. Initiating a public health evaluation and permitting process with the requisite state and local agencies for demonstration homes to serve as examples and testing grounds would be an important first step in this process. It has been estimated that local policy can help address up to 35% of all carbon footprint abatement potential statewide in California (Jones and Kammen 2013). Incorporating, incentivizing and planning for advanced energy homes such as THIMBY is a necessary development in town and county zoning codes and planning processes to advance the clean energy transition. Smaller residences with solar panels, batteries, and smart inverters can address both affordability and resilience concerns in housing markets such as the San Francisco Bay Area, offering potential to self-power in the case of future power shut-offs such as those experienced in California in Fall 2019 and 2020. Statewide incentives, demonstration projects, and updated permitting processes can expedite the construction and adoption of innovative, resilient off-grid-capable small housing solutions.

6. CONCLUSION

THIMBY's experience builds on and reinforces prior research pointing out areas of continued growth for the green building industry in order to realize dramatic energy and water savings, in line with the most recent IPCC reports and 2015 Paris Agreement goals. As THIMBY remains a work in progress, additional research, replication and policy work is needed to a) demonstrate longevity of positive energy performance metrics, b) scale up to tiny house communities, and c) facilitate legal approval and siting opportunities for mobile, off-grid-capable tiny houses. The demonstrated potential for high energy performance and associated emissions savings in the use phase of this fossil fuel free home provides significant motivation for this future work. THIMBY 1.0 has already inspired two additional university student-led tiny house design-build projects.

The strategies deployed here for design-build-occupy integration and transparent energy monitoring for occupants are transferable and can be scaled to larger green building projects. Replication of all-electric energy systems and off-grid home water systems, in parallel with safety evaluations and low-cost water quality testing, will go a long way towards advancing decarbonized residential buildings and enabling the policy changes required to support such living systems. Allowing off-grid tiny houses to exist and scale could also enhance the ability to meet California's increasingly stringent emissions reduction targets, Zero Net Energy building (ZNE) mandates, and onsite solar requirements for new buildings while addressing affordable housing challenges coexisting with climate-related threats. Responding to climate change and mid-century emissions reductions targets requires scalability of proven green building types in ways that maintain affordable housing availability and promote social sustainability. The THIMBY project, an energy- and water-efficient home, advances this objective.

ACKNOWLEDGEMENTS

This research received significant support from several members of the THIMBY project team, who contributed to the energy modeling, building design, and technology integration. These individuals include Tom Webster, Imran Sheikh, and Kenny Gottlieb.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

REFERENCES

Alvarez, R. et al. (2018). Assessment of methane emissions from the US oil and gas supply chain. *Science*. Vol. 261 Iss. 6398 pp. 186–188

Blomgren, E., Bolliger, I., Ma, K., & Schmid, M. (2016). *Home Energy Management System for Off-Grid Tiny House*. https://ecal.berkeley.edu/files/ce295/projects/S16/schmidmathias_5312024_68719679_THIMBY_Final_Report.pdf

Buhayar, N. and Cannon, C. (2019). "How California Became America's Housing Market Nightmare." Bloomberg. https://www.bloomberg.com/graphics/2019-california-housing-crisis/

Arens, E. et al. (2013). Air movement as an efficient means towards occupant comfort. Prepared by the Center for the Build Environment at the University of California, Berkeley for the State of California Air Resources Board. https://ww3.arb.ca.gov/research/apr/past/10-308.pdf

California Energy Commission 2011—Title 24 standards

California Energy Commission 2018—Title 24 standards

California Energy Commission. (2018). Funding Opportunities for the Electric Program Investment Charge (EPIC) Program. https://www.energy.ca.gov/contracts/epic.html

California Energy Commission. (2019). RESIDENTIAL ALTERNATIVE CALCULATION METHOD REFERENCE MANUAL FOR THE 2019 BUILDING ENERGY EFFICIENCY STANDARDS TITLE

24, PART 6, AND ASSOCIATED ADMINISTRATIVE REGULATIONS IN PART 1. https://ww2.energy.ca .gov/2019publications/CEC-400-2019-005/CEC-400-2019-005-CMF.pdf

Delforge, P. (2019). Berkeley Passes Nation's First All-Electric Building Ordinance. Accessed November 26, 2019. https://www.nrdc.org/experts/pierre-delforge/berkeley-passes-nations-1st-all-electric-building-ordinance

DeOreo, W. B. et al. (2011). California Single Family Water Use Efficiency Study. Prepared for California Department of Water Resources. Retrieved from http://www.irwd.com/images/pdf/save-water/CaSingleFamilyWaterUseEfficiencyStudyJune2011.pdf

E3. (2019). Residential Building Electrification in California Consumer economics, greenhouse gases and grid impacts. Accessed 2 February 2020. https://www.ethree.com/wp-content/uploads/2019/04/E3_Residential_Building_Electrification_in_California_April_2019.pdf

Energy Information Administration (EIA). (2016). Carbon Dioxide Emissions Coefficients. Accessed 2 February 2020. https://www.eia.gov/environment/emissions/co2_vol_mass.php

Environmental Protection Agency (EPA). (2020). Understanding Global Warming Potentials. Accessed 2 February 2020. https://www.epa.gov/ghgemissions/understanding-global-warming-potentials#Learn%20why

IPCC (2018). Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)].

Jones, C. and Kammen, D.M. (2013). Spatial Distribution of U.S. Household Carbon Footprints Reveals Suburbanization Undermines Greenhouse Gas Benefits of Urban Population Density. *Environ. Sci. Technol., 48*(2), pp. 895–902. DOI: 10.1021/es4034364.

Lakshmi, M.V.S., Sai Babu, C., Prasad, S. (2012). Design of off-grid homes with Renewable energy sources. IET Conference Proceedings, pp. 297–303, DOI: 10.1049/cp.2012.2229. IET Digital Library, http://digital-library.theiet.org/content/conferences/10.1049/cp.2012.2229

Northwest Energy Efficiency Alliance. (2015). Heat Pump Water Heaters for Demand Response and Energy Storage. Accessed 10 November 2018. https://neea.org/resources/heat-pump-water-heaters-for-demand-response-and-energy-storage

Oak Ridge National Laboratories (2010). New Oak Ridge Homes are Laboratories for Energy Efficiency. Accessed 29 May 2018 from https://www.ornl.gov/news/new-oak-ridge-homes-are-laboratories-energy-efficiency

O'Shaughnessy, E., Cutler, D., Ardani, K., & Margolis, R. (2018). Solar plus: Optimization of distributed solar PV through battery storage and dispatchable load in residential buildings. *Applied Energy, 213*, 11–21. https://doi.org/10.1016/j.apenergy.2017.12.118

Pradhan, S. R., Bhuyan, P. P., Sahoo, S. K., Prasad, G. S., (2013). Design of Standalone Hybrid Biomass & PV System of an Off-Grid House in a Remote Area. *Int. Journal of Engineering Research and Applications*. Accessed 10 November 2018. https://pdfs.semanticscholar.org/12c2/648c1f8a9f051f4bc21e2c80f55bb76fdaea.pdf

Raghavan, S., Wei, M., and Kammen, D.M. (2017). Scenarios to decarbonize residential water heating in California. *Energy Policy, 109*, 441–451. https://doi.org/10.1016/j.enpol.2017.07.002

Sheikh, I. (2017). *Decarbonizing residential space and water heating: The case for electrification*. ACEEE Summer Study Proceedings.

Sheikh, I. & Callaway, D. (2019). Decarbonizing Space and Water Heating in Temperate Climates: The Case for Electrification. *Atmosphere* 10(8), 435 https://doi.org/10.3390/atmos10080435

Statista (2018). Green Buildings in the US—Statistics and Facts. https://www.statista.com/topics/1169/green-buildings-in-the-us/

Tarpeh, W., Udert, K. M., & Nelson, K. (2017). Comparing Ion Exchange Absorbents for Nitrogen Recovery from Source-Separated Urine. *Environmental Science & Technology, 51*(4), 2372–2381. DOI: 10.1021/acs.est.6b05816

UNEP (2018). The Emissions Gap Report 2018. United Nations Environment Programme, Nairobi.

U.S. Energy Information Administration (2009). Residential Energy Consumption Survey: Household Energy Use in California. Retrieved from EIA database.

U.S. Energy Information Administration (2015). California Electricity Profile 2015.

U.S. Green Building Council (2014, March). LEED in Motion: Residential. Retrieved from USGBC database.

Wei, M. et al. (2013). Deep carbon reductions in California require electrification and integration across economic sectors. *Environmental Resource Letters, 8*(1). doi:10.1088/1748-9326/8/1/014038

Wilson, Mark. 2017. "Lazard's Levelized Cost of Storage Analysis—Version 3.0," 49. https://www.lazard.com/media/451087/lazards-levelized-cost-of-storage-version-50-vf.pdf

APPENDICES

Appendix A. Complete Bill of Materials

https://docs.google.com/spreadsheets/d/1AF9Cslyg8SSqNS0bg6XypAoJ33lhDbD9e1frtfkyivU/edit?usp=sharing