BUILDING ENERGY MODELING AND TECHNO-ECONOMIC FEASIBILITY ANALYSIS OF ZERO NET ENERGY TINY HOMES IN COASTAL HUMBOLDT COUNTY, CALIFORNIA

By

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ABSTRACT

BUILDING ENERGY MODELING AND TECHNO-ECONOMIC FEASIBILITY ANALYSIS OF ZERO NET ENERGY TINY HOMES IN COASTAL HUMBOLDT COUNTY, CALIFORNIA

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This thesis conducts a techno-economic feasibility analysis of tiny homes. Scenarios generated using a mathematical and physical model of energy use of zero-net energy tiny homes in coastal Humboldt County are compared with conventional energy systems powered by fossil-fuels for lifecycle economic cost, energy efficiency, greenhouse gas emissions, and energy use. A residence of 2,425 ft.^{2} (near the regional average) is simulated to offer a broader standard of comparison. A tiny home village model with outlying bedrooms and a central building for cooking, laundry and shower facilities is compared to a standalone tiny home model. A community services building is modeled to estimate energy use and annualized energy costs for the tiny home village.

Under the assumptions of the analysis, zero-net energy (ZNE) tiny homes are found to be recommendable on economic grounds over fossil-fuel models. Building energy optimization is found to reduce the lifecycle cost of modeled tiny homes while lowering energy use. In many cases considered, annualized energy use is lowered in excess of 30%, and lifecycle cost is reduced from 8-14%. Modeled zero net energy tiny homes use approximately 85% less energy than a modeled home closer to the regional average square footage, and energy use per occupant of modeled zero net energy tiny homes is 50% lower than the per capita energy use for California reported by the Energy Information Administration. Under the assumptions of the analysis, fully functional, zero-net energy tiny homes are economically favorable to a tiny house village with a central community building unless the cost of tiny homes is kept very low.

ACKNOWLEDGEMENTS

I offer my heartfelt gratitude to my entire family, who have always been supportive of my education. I extend sincere gratitude to my thesis committee, Peter Alstone, Charles Chamberlin, and Arne Jacobson, and Graduate Coordinator Margaret Lang, without whom my thesis work would not have been possible. A special thanks and acknowledgement must also be given to professor Lonny Grafman, who taught Development Technology with professors Alstone and Jacobson in Spring 2017, for his insights and his passion for tiny homes. I express gratitude to Steven Shoemaker, Pramod Singh, and all my colleagues who participated in the Spring 2017 semester Development Technology course. My colleagues Jimento Aikhuele, Michael Avcollie, Keivan Branson, Derek Ichien, Gaurav Kumar, Jake Rada, and Mahayla Slackerelli all contributed greatly to the tiny house project. It has been an honor and a wonderful experience to work with all my professors and colleagues in the Environmental Systems Graduate Program at Humboldt State. Any virtues of my thesis belong to my professors and colleagues. The faults are mine.

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INTRODUCTION

Tiny homes are smaller residential structures of varying configurations and design. They lack a formal, precise definition, but most commentators characterize them as occupying less than 400 square feet of interior floor space (NFPA, 2017; Mingoya, 2015). They may be built on conventional building foundations, be designed for mobility, or be placed on wheels[1]. While once an obscure niche concept, tiny homes have recently risen in prominence and popularity for reasons ranging from environmental ethics to cultural ethos, social ethics, or financial capability (Pera, 2016). Figure 1 shows an image of a tiny house in Sonoma County, California.

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[1] There is no exact agreement on a precise definition. Some organizations maintain that tiny homes are always on wheels (NOAH, 2018). Other organizations include tiny homes on a foundation (County of Placer, 2018a).

Figure 1: A tiny house in Sonoma County, California.
(Image Source: Ben Chun, 2017, Creative Commons)

This thesis quantifies the environmental impacts of tiny home designs in terms of greenhouse gas emissions and the economics and extent of their energy use under different configurations using building energy modeling techniques. The economic analysis considers the lifecycle cost and annualized energy costs of modeled tiny homes.

Additionally, this thesis seeks to fill a gap in existing literature by offering a critical analysis of current residential building codes in California and coastal Humboldt County in relation to tiny homes. The analysis includes the practical safety, infrastructural, and lifecycle cost considerations crucial to considering tiny homes as a short or long-term residential option. The implications of building codes in Humboldt County and California for their design, economic feasibility, and net energy use are also considered. To this end, the feasibility analysis considers tiny home designs compatible with two primary use cases: a tiny home village intended for low-income or houseless individuals, and an individual tiny home that more closely resembles a typical residence, but scaled down in size.

Energy models considered for the village use case include raised foundation tiny homes (“tiny homes on wheels”), tiny homes on a standard foundation, and tiny homes powered by solar panels, but not connected to the grid (off-grid solar). The individual tiny home is modeled as a slab-on-grade foundation, but is modeled as a tiny home on wheels as a sensitivity analysis. The approach used to analyze tiny home models will be explained in the methods section.

Figure 2 shows features for a fully functional, code-compliant, slab-on-grade tiny home. These features include a fire sprinkler, smoke alarm, 30-inch minimum leeway for kitchen walkways, and a secondary means of egress at least 32 inches wide required by NFPA 5000, Section 22.2.1.2 (NFPA, 2017). The figure also shows approximately scaled energy efficiency options for grid-tied tiny homes, such as an energy-star-rated miniature refrigerator and a mini-split heat pump.

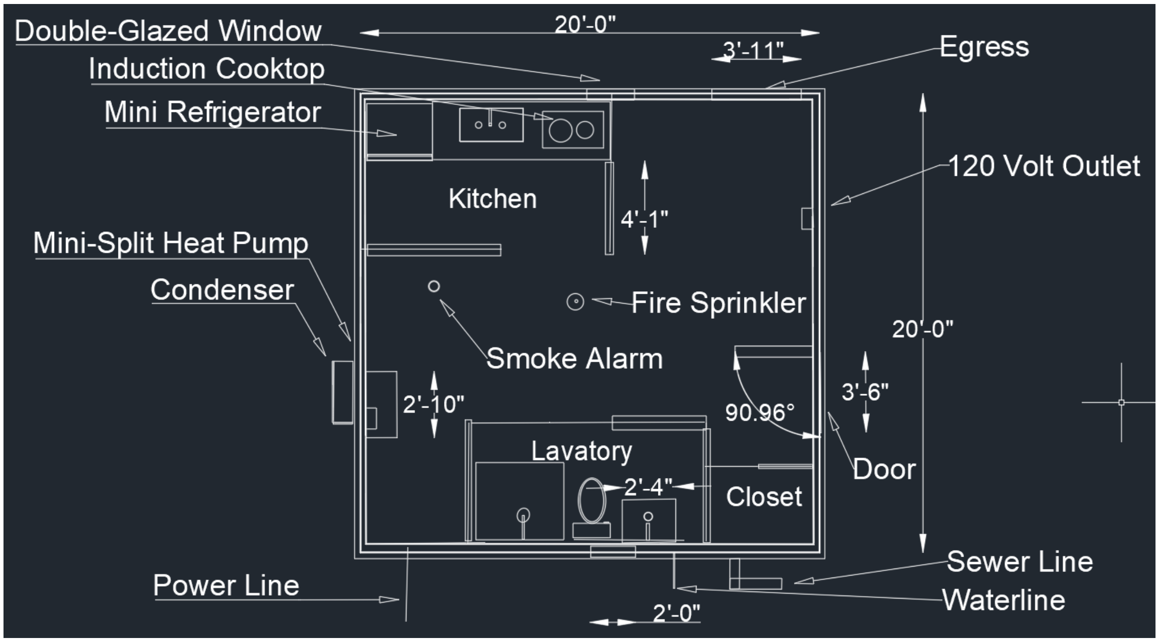

Figure 2: Hypothetical schematic for a 400-square foot house using a grid-connected, slab-on-grade design. Walls and electrical outlets not to scale.

Among other uses, the construction of tiny homes as an alternative to conventional housing has recently received popular attention as a potential pathway to house houseless community members. In Humboldt County, California, multiple organizations have expressed interest in construction of a tiny house village for houseless community members, most notably Affordable Homeless Housing Alternatives, or AHHA (KHSU, 2018). In June 2018, AHHA submitted a proposal for a tiny home village to the City of Arcata. This proposal is based on an analysis conducted by a development technology course in the Environmental Systems Graduate Program. A previous proposal for a village was submitted by AHHA in 2016 to Humboldt County for the use of Measure Z funds (AHHA, 2016). Humboldt County has an estimated 1,300 houseless community members (Humboldt Housing and Homeless Coalition, 2015).

As a part of the Environmental Systems development technology graduate course, my colleagues and I met with houseless community members in conjunction with AHHA in Eureka, California in 2017 on three separate occasions. Organized into three teams, we discussed the life conditions and needs of houseless community members, their energy use and needs, and their perspective on the creation of a tiny home village.

We heard of the dangers, struggles and challenges of living without a permanent residence in Eureka, where a temporary houseless camp located in a marsh (known as the Palco Marsh) was disbanded by local authorities. Since the disbanding of the houseless encampment, Humboldt County has received national attention due to a continuing housing crisis (New York Times, 2018). Houseless community members interviewed by teams of graduate students, as well as local non-profit organizations, support the idea of the establishment of a tiny home village to ameliorate the housing crisis in Humboldt County (KHSU, 2018). For this reason, tiny home village configurations and models appropriate for the benefit of the houseless community are modeled in the analysis, and monthly bills are estimated to discern the financial feasibility.

In the next section, a literature review discusses the social and environmental import of tiny homes, building science and building energy modeling methods in relation to tiny homes, contemporary greenhouse gas emissions techniques, principles of lifecycle cost analysis, and building codes and policy in relation to tiny homes.

Next, the methodology section begins by describing the assumptions of the analysis, including the approach used in a heat conduction study used for the scoping of building energy modeling methods. The remainder of the methodology section details the optimization and design methods for the models considered and parameter inputs used, and explains the methods for the greenhouse gas emissions, lifecycle and annualized energy costs, and annualized energy use analysis.

Analyses described in the methodology section are presented in the results chapter, including the heat conduction study findings, and results for building energy optimization, building energy model designs, annualized energy use, utility bills, lifecycle cost, and greenhouse gas emissions.

The discussion section reflects on the ideal uses and characteristics of BEopt as a building energy modeling tool for tiny homes, and contextualizes building energy model results with analyses of per capita energy use data. The discussion also examines indoor environmental metrics of modeled tiny homes. The discussion section ends with recommendations for a tiny home village use case to house houseless individuals.

The thesis concludes with a brief synthesis and overview of the qualitative characteristics of the methods and results presented, and offers remarks for future research in the building energy modeling of tiny homes.

LITERATURE REVIEW

For all the popular interest and potential uses of tiny homes, contemporary analyses of energy use of tiny homes as well as their lifecycle costs, efficiency, and optimal design are lacking in the academic literature. I review the existing academic and industry literature pertaining to tiny homes, and outline their recent social history. I also critically examine their potential to fulfill a useful function in residential society and coastal Humboldt County. I then review standard methods in techno-economic feasibility analysis to offer sufficient background information for understanding the techno-economic feasibility of tiny homes.

A techno-economic feasibility analysis of tiny homes involves conventional building science, policy-integrated microeconomic analysis, greenhouse gas emissions analysis, and consideration of local, regional, and state building codes. The method of estimating net annual energy use involves contemporary building energy simulation techniques. The energy analysis serves as the basis for estimating life cycle energy costs, annual greenhouse gas emissions, and monthly utility bills. Consequently, this review covers the history and state of the art of computational building energy modeling (BEM) techniques, the principles of building science, the methods of lifecycle economics, and the building code policy that forms the foundation for the techno-economic analysis of tiny homes in coastal Humboldt County, California.[2]

Social and Environmental Import of Tiny Homes

The interest in the use of tiny homes to ameliorate houselessness reflects a broader national trend. Public awareness of tiny homes recently emerged in areas such as Portland, Oregon and Madison, Wisconsin, as a means of providing shelter and basic needs for houseless people (Mingoya, 2015). Tiny home villages constructed in Madison and Portland have been followed by proposed or constructed tiny home villages in municipalities throughout the United States (Mingoya, 2015).

However, tiny homes also appear to have captured the American public's imagination. A popular interest has emerged, complete with television shows, websites, magazines, blogs, third-party structural certification, jamborees, at least one association, and other institutions and materials (Louche, 2016; Mitchell, 2016; Pera, 2016).[3]

Multiple potential benefits or uses of tiny homes have been noted in both popular and academic sources. In her thesis, Amelia Mutter identifies tiny homes as a potential means to address world resource overconsumption, noting that the average size of a single-family home has doubled since 1950 (2013). Catherine Mingoya identifies the

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[2] While there exists a vast amount of literature and popular media pertaining to tiny homes, academic literature in this area is very limited. Henceforth, some sources in the literature review are of popular or commercial rather than academic, research, or regulatory origin. These sources are noted accordingly in the text and references section.

[3] See also the American Tiny House Association website (americantinyhouseassociation.org). An internet search on July 28, 2018, yielded a multitude of web pages and blogs related to tiny houses.

potential for tiny homes to offer increased stability for houseless people exposed to the chronic instabilities of temporary housing (2015). In Lake County, California, the popular press noted an upsurge of interest in tiny homes due to the destruction of over 1,500 homes from fires, many of which have not been rebuilt or replaced (Jordan, 2017).

While tiny homes are often associated with environmental ethics, Pera notes that most occupants of tiny homes are motivated more by financial freedom and lifestyle (2016). Nonetheless, their smaller size offers the possibility for lower net energy use and reductions in the associated environmental impacts of residential buildings, such as greenhouse gas emissions. This is significant because the residential sector constitutes roughly 20 percent of annual energy use in the United States (Energy Information Administration, 2018d).

However, affordability for people who may otherwise face housing insecurity is a potentially significant use case for tiny homes beyond the houseless community. In 2016, it was estimated that 22% of Humboldt County residents exceed a housing affordability threshold, defined as 30% or more of pretax household income (Mckinsey, 2016). Across California, it was estimated that nearly half of households exceed this threshold (Mckinsey, 2016). In this context, tiny homes also represent a potential pathway to home ownership and stable, individualized housing without the financial barriers of larger, more expensive homes.

Building Science and Tiny Home Design

The building science section of the literature review provides an overview of water and wastewater system configuration in tiny homes, zero-net energy design, building energy analysis and modeling, the modeling of domestic hot water systems, and mechanical system components in tiny homes. In this analysis, building science constitutes the physical and mathematical basis through which the energy use of buildings is determined, the qualitative and indoor environmental characteristics of buildings may be discerned, and upon which economic and greenhouse gas emissions analyses may be built.

Tiny home design and configuration of water and wastewater systems

Tiny homes are known for the flexibility of their configurations. Mingoya notes that some tiny homes are built on prefabricated trailer beds or raised, mobile platforms, sometimes to avoid building code violations (2015).[4] One common difference between tiny homes and conventional buildings is water and sewer infrastructure. Mingoya (2015) notes that market-rate tiny homes are often equipped with a bathroom, but that tiny homes are rarely connected to a sewer system due to the cost and reduction in mobility. Water is often brought in through a hose or storage tank and can be released

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[4] In California, any structure that is not built on conventional foundations is not considered a permanent residence and falls under the purview of the Department of Motor Vehicles (D. Moxon, personal communication; Mingoya, 2015, page 16.).

into a municipality's storm system (Mingoya, 2015).[5] Sewer waste is handled through compost toilets or waste collection tanks. Alternatively, occupants may establish agreements to use the facilities of a nearby conventional home. Tiny home communities for houseless or low-income individuals tend to rely on centralized bathrooms (Mingoya, 2015).[6]

Some commercial sources note the use of rainwater catchment systems in tandem with tiny homes. Another website for a tiny home builder notes that gravity fed showers are used, as well as water tanks pressurized with water pumps, and that indoor plumbing in tiny homes resembles those used in RV parks (Waldman, 2018).[7]

Because in most jurisdictions, tiny homes on wheels are regulated as RV's, their plumbing systems fall under NFPA standard 1192. NFPA 1192 does not specifically address rainwater catchment systems. The 1192 standard has provisions for potable gravity water storage systems, including a top vent to assist draining or filling (NFPA, 2018a). All components of any system installed would have to conform to NFPA standards for pipes, fittings, components, and air, waste, and water management (NFPA, 2018a).

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[5] Greywater discharge is regulated by Chapter 15 of the California plumbing code; unless applicable municipal or county regulations state otherwise, it is allowed without a permit under certain conditions (greywateraction.org, 2018).

[6] Mingoya was writing with respect to tiny home villages in Portland, Oregon, and Madison, Wisconsin. Differences in climate, geography, and policy must be considered, as appropriate, in applying her discussion of tiny house village characteristics and relevant policies to coastal Humboldt County.

[7] Rainwater catchment systems are a compelling possibility for tiny home applications; however, their technical feasibility lies beyond the analytical scope. For further information, see the following online sources:
https://www.rainwatermanagement.com/tiny-house-rainwater/
https://www.tinyhomebuilders.com/blog/off-the-grid-rainwater-collection/

Tiny homes and zero-net energy design

One promising possibility for tiny homes is zero-net energy design. Multiple definitions of “net zero” are used by government institutions, differentiated either by type (energy, water, or waste), or by scope (Department of Energy, 2017; California Public Utilities Commission, 2018a). The Department of Energy and other institutions define a zero-net energy building as one that produces as much renewable energy as it consumes annually on a source-energy basis. Source energy serves as a better indicator of the environmental impact of a building than site energy. Therefore, it constitutes a common metric to compare the energy use of models with multiple fuel types (Deru, M., and Torcellini, P., 2007; Dept. of Energy, 2006). This is true because it often takes approximately three times the energy at a remote source (such as from a natural gas turbine power plant) to produce a quantity of usable energy at a site (Dept. of Energy, 2017).[8,9] Greenhouse gas emissions analysis must still account for the emissions factors of the various energy types. For the purposes of this study, the source energy definition of zero-net energy is used, meaning that I assume a specific ratio of source energy to site energy for different energy types.

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[8] BEopt version 2.8.0.0, the simulation software used to model energy use in the following analysis, uses a default electricity source-site ratio of 3.150. This is the same source-to-site ratio (when interpreted to the same number of significant figures) listed by the Department of Energy (NREL BEopt Development Team, 2018; Dept. of Energy, 2017). However, because this ratio is identical for grid-tied, on-site PV electricity and imported electricity, it does not affect the annual greenhouse gas emissions reported by BEopt for zero-net energy buildings (NREL BEopt Development Team, 2018).

[9] However, this does not imply that a zero-net energy home must produce three times the energy as is actually used, but only that, for instance, 1 kilowatt hour generated on-site displaces 3 (or the relevant conversion factor) kilowatt hours of source energy.

Energy use can be reduced either through building envelope and mechanical efficiency measures, renewable energy generation, or both. To give an example of an efficiency measure, a more efficient building envelope may be able to maintain a set point temperature of 72°F using less energy, but leaving aside qualitative differences, the energy service experienced by the user is the same. The energy use of a building also depends on site characteristics such as climate, orientation to the sun, and the character of the surrounding terrain (Leckie, et al., 1981).

In cases where tiny homes are built on prefabricated trailer beds or raised, mobile platforms, the principles of building energy efficiency, site characteristics, and building codes intersect, because the choice of building foundations and geometry inevitably influences the building envelope efficiency (NREL BEopt Development Team, 2018). Furthermore, site characteristics such as the water table and soil composition influence the viability of different building types (Leckie, et al., 1981).[10] Finally, the codes and standards for the tiny homes on wheels and tiny homes built on a foundation are very different, as structures built on wheels in California are not considered a permanent legal residence (D. Moxon, personal communication, 2018). The differences between applicable codes are reviewed further in the building codes and policy section.

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[10] This has important implications for coastal Humboldt County, and the use of tiny homes for houseless people. Coastal Humboldt County gets large volumes of precipitation. Additionally, previous encampments for houseless community members in Humboldt County were located near marshy areas with high water tables, making flooding and moisture an acute and constant issue (Singh, et al., 2017).

Building energy analysis and modeling

Building energy modeling (BEM)[11] is defined as the use of physics-based computer programs to analyze and determine building energy use (Dept. of Energy, 2018). One of the primary goals of BEM is to inform strategies to maximize building energy efficiency, defined here as the ratio of useful energy produced (e.g., heating, cooling, etc.) to net energy expended in a system (e.g., energy from a solar panel, wind turbine, or electricity grid) (Dept. of Energy, 2018). Engineers and building designers have used BEM techniques in various forms since the 1960's (Judkoff, et al., 2008). Building energy modeling programs use weather data combined with physical and energetic properties of HVAC systems, building envelopes, renewable energy systems, and other building systems to analyze a structure's energy use (Department of Energy, 2018; Department of Energy, 2015). Over decades, numerous simulation programs evolved, such as DOE-2, BLAST, and their successor program, EnergyPlus (Judkoff, et al., 2008; Dept. of Energy, 2016). These programs are engineering and design tools which can be used to properly size HVAC equipment, optimize energy performance, or conduct lifecycle cost analysis (Department of Energy, 2016). DOE2 was developed in response to the 1970's energy crisis in the United States and the substantial fraction of total energy use in the United States used by buildings (Department of Energy, 2016).[12]

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[11] Building energy modeling is also referred to as building energy analysis simulation (Judkoff, et al., 2008).

[12] The Energy Information Administration reports that 39% of total energy consumption in the US is attributed to residential and commercial buildings (2018).

Contemporary simulation techniques often involve both a simulation engine (e.g., EnergyPlus, DOE2, or BLAST) and a separate interface (e.g., BEopt, eQuest, or OpenStudio) (Department of Energy, 2016; NREL BEopt Development Team, 2018). Interfaces help users define the assumptions and inputs concerning the set point temperature, energy use frequency, and general building parameters.

The feasibility analysis in this thesis uses the Building Energy Optimization Tool (BEopt) designed by the National Renewable Energy Laboratory. BEopt conducts economic analysis, both in terms of the first-cost of materials and equipment, and the recurring energy costs based on utility rates, financing, renewable energy incentives, and other metrics (Christensen, et al., 2005; NREL BEopt Development Team, 2018).[13] BEopt was designed for the optimization of zero-net energy (ZNE) buildings (Christensen, et al., 2005).

In basic language, BEopt determines the global minimum least cost of the pre-defined search space options considered, with the goal of cost-effective zero-net source energy buildings (Christensen, et al., 2005).[14] It accomplishes this by simulating the energy use of modeled buildings through a simulation engine, EnergyPlus.[15] BEopt analyzes different building characteristics, such as HVAC types and efficiencies, building

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[13] While EnergyPlus version 8-7-0 includes basic cost calculation facilities, EnergyPlus is not intended to be a lifecycle cost analysis tool in isolation (Department of Energy, 2016).

[14] This generalization offers clarity and analytical relevance at the expense of the vast complexities of building energy modeling. BEopt performs a number of particular tasks, in a vast array of contexts, including building energy surveys, comparison of simulation engine performance, and modeling specific building mechanical components and configurations (NREL, 2018).

[15] Different versions of BEopt can use different simulation engines, but for this study, BEopt is used with EnergyPlus Version 8.8.

envelope insulation types and properties, and other characteristics by sending multiple designs to the simulation engine (Department of Energy, 2015).

BEopt uses a sequential search optimization algorithm to identify potential discrete options between a reference model and the end-path, which can be adjusted to zero-net energy, minimum cost, or the feasibility of solar panels (NREL BEopt Development Team, 2018). Sequential search algorithms are a general class of optimization algorithms that iteratively evaluate different solutions by using a systematic set of procedures (Haith, Douglas, 1982). BEopt's sequential search functions by iteratively choosing the steepest-slope option (slope being defined in terms of energy savings and cost) until a global optimum is reached in the discrete search space (Horowitz, et al., 2008). While sequential search algorithms can be used with continuous functions, BEopt is designed using discrete options, because most frequently, construction or retrofit project choices are discrete (Christensen, 2005a).[16] Once the sequential search algorithm identifies all the efficient options along the search paths, economic calculations for energy use and lifecycle cost are displayed in the user interface (NREL BEopt Development Team, 2018).[17]

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[16] While linear or non-linear functions may be used in other aspects of the simulation process (i.e., when the simulation engine sizes an HVAC system, or when an input file is created that covers a wall assembly with a chosen insulation type with price in dollars per square foot), the optimization routine itself is entirely discrete (Christensen, 2014; Horowitz, et al., 2008).

[17] Due to the dynamic and complex nature of building energy modeling, multiple design optimization methods are possible (NREL BEopt Development Team, 2018). A general schematic for the structure of programs involved and framework of the BEopt version used for this analysis can be found in the methods section.

Building energy model software can be evaluated for accuracy through the model validation process (Booten, et al., 2012). In essence, building energy model results are compared to energy data collected from an existing building to verify accuracy, and the internal algorithms and calculations of the program are improved over time. While model validation techniques applied to building energy use simulations lie beyond the scope of this study, they are important for understanding and interpreting the results. Accuracy can vary substantially based upon the context of the simulation, varying anywhere from under 5% to 100% error or more (National Renewable Energy Laboratory, 2010).

However, this is not to suggest that BEM techniques are less accurate than manual industry-standard methods; many of the most common ASHRAE cooling load calculation methods were developed based on building energy simulation results (Thoms, Rao, and Wong, 2017). For instance, building energy simulation programs such as CBECC-RES and EnergyPro are used to verify compliance with Title 24 building energy standards in California (California Energy Commission, 2018).

Building energy models can also be adjusted for accuracy before they are used through model calibration, where a model or program is adjusted to better reflect the data (Kim, et al. 2017). Calibration functions by reducing error from model inputs, which persist in the model outputs (Robertson, Polly, and Colis, 2013). Calibration is a form of data-driven or inverse approach modeling that is only applicable to built structures (ASHRAE, 2017). NREL uses calibration studies to improve the accuracy of retrofit simulations by reducing error in the model inputs (Robertson, Polly, and Colis, 2013). In the instance of a new design or building that is not pre-existing, empirical data specific to the modeled building would not be available (Robertson, Polly, and Colis, 2013).

Similarly, many of the details of mathematical computations involved in EnergyPlus simulation lie beyond the purview of this study. The models use established formulas in the building energy modeling field, such as finite difference approximation methods (Dept. of Energy, 2015).

EnergyPlus simulates building energy use and solar PV generation, and BEopt optimizes the building energy efficiency configuration. Other techniques are used to optimize the mix of renewable energy and energy storage technologies. The National Renewable Energy Laboratory uses a program called REopt in conjunction with EnergyPlus and BEopt to optimize the net present value of the renewable energy and dispatchable load mix (O'Shaughnessy, et al., 2018). Recently, NREL has published a web tool offering limited functionality; however, the complete software package is not open source (NREL, 2019).[18]

Off-grid solar designs and applications represent an emergent area of building energy modeling. As noted in the economics section, PV and battery prices have declined and are expected to continue to decline. Neither NREL's BEopt nor the System Advisor Model (SAM) model off-grid solar designs (NREL BEopt Development Team, 2018). Potentially useful information for off-grid solar applications can still be gleaned from these programs, as both hourly PV array output and the interaction of an hourly

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[18] See "Reopt: Renewable Energy Integration and Optimization" at https://reopt.nrel.gov/tool.

electricity load profile with a PV array and battery bank can be modeled, albeit with the assumption of grid-sourced electricity interaction (NREL BEopt Development Team, 2018).

The sole application of building energy models to tiny homes found in the academic literature, Rettenwender, et al. report results from EnergyPlus for constructed tiny homes at the Tiny House Design Lab (2018). This study used EnergyPlus to size an HVAC system and also to determine the thermal conditions inside a constructed tiny home for weather extremes without an HVAC system. The tiny home was modeled using the weather data files of three metropolitan areas: San Francisco, California, Seattle, Washington, and Vancouver, Canada. The modeled tiny home maintained a comfortable indoor temperature in the San Francisco, California climate, but required indoor heating in more extreme climates. However, this study only reports conclusions for a single tiny home, and should not be interpreted as applicable to tiny homes other than the specific model studied.

Modeling and analysis of domestic hot water systems

Water heating is the second-largest contributor to residential energy use after space heating (Shapiro and Puttagunta, 2016). Correspondingly, the compatibility of tiny homes with increasingly efficient heat pump water heaters is significant to their potential use to reduce residential energy consumption.

The primary measure of energy efficiency for gas or electric resistance domestic hot water heaters is the uniform energy factor, defined as the ratio of useful energy delivered to the water to energy expended in the system (BEopt development team, 2018). The uniform energy factor is differentiated between the rated and installed energy factors. The rated uniform energy factor (previously referred to as simply the energy factor) is a metric printed in specifications by the water heater manufacturer. The terms refer to differing procedures, as the Department of Energy improved the testing procedure to more accurately reflect water heater efficiency (Department of Energy, 2015c). The standardized testing procedure is defined by the Department of Energy.

The installed energy factor reflects the real performance of the water heater in use. The installed energy factor is generally lower than the rated value due to derating and degradation (BEopt development team, 2018). The efficiency of heat pump water heaters is described by the coefficient of performance, defined as the ratio of useful energy (or energy moved by the heat pump) to expended energy (Borgnakke and Sonntag, 2009). The energy factor and conversion efficiency of water heaters is tested by methods established by the Department of Energy in the Code of Federal Regulations Part 430 (BEopt Development Team, 2018).

Because the energy factor describes a conversion of one type or medium of energy to another (i.e., electrical energy to heat energy, or combustion energy to heat energy), the greatest possible energy factor attainable is 1. The coefficient of performance, however, can achieve values greater than 1 because the COP reflects the use of energy to move, rather than convert, heat energy (Borgnakke and Sonntag, 2009;

Sparn, Hudon, and Christensen, 2009). Heat pump water heaters can consequently attain higher levels of energy efficiency than electric resistance or gas water heaters. Figure 3 below shows the relation between measured coefficient of performance and tank water temperature for multiple heat pump water heaters. Data for Unit C differ because the tested HPWH was not able to achieve continuous operation at temperatures below 20° C due to its design configuration (Sparn B., Hudon, K., and Christensen, D., 2014).

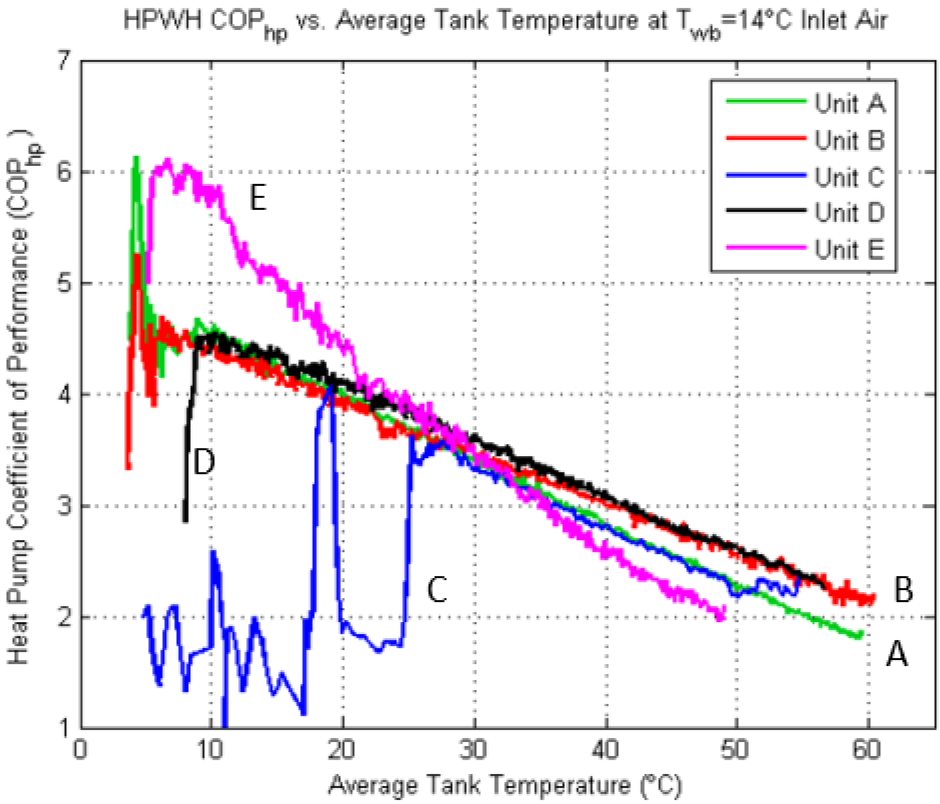


Figure 3: Heat Pump Water Heater data showing the average temperature and coefficient of performance. (Image Source: Sparn, Hudon, and Christensen, 2014.)

Table 1 shows the test parameters and coefficients of performance corresponding to the data shown in Figure 3. The figure and table data all originate from a study of heat pump water efficiency study in the Northeast. Since heat pump technology offers the most possibility for increases in energy efficiency and conversion from fossil fuel use, studies of the real performance of air-sourced heat pumps are important to understanding the likely energy use of these systems in practice.

Table 1: Comparison of System COP from Draw Profile Tests
(Data Source: Sparn, B., Hudon, K., and Christensen, D.,2014)

HPWH Mfr.	COP_{Sys}	COP_{Sys}	Test Parameters
	High Use (Morning)	Low Use (Evening)	Inlet Water Temperature (°C/°F)
Unit A	3.55	3.42	14/58
Unit B	1.21	1.81	Tank Set Point (°C/°F)
Unit C	1.44	2.61	57/135
Unit D	3.85	5.37	Flow Rate Range (Liters/Min.)
Unit E	1.68	2.77	1.9-11.4

Air source heat pump water heaters operate at higher efficiencies with warmer ambient air temperatures and lower efficiencies with colder ones (Sparn B., Hudon, K., and Christensen, D., 2014). In a recent study of heat pump water heaters in the Northeast, Shapiro and Puttagunta (2016) found that even in colder climates heat pump water heaters can achieve a measured coefficient of performance as high as 2.6. Heat pump water heater efficiency also decreases with increasing use, because the average temperature of water in the tank decreases (Shapiro and Puttagunta, 2016).

As with building envelopes, energy use in domestic hot water systems can be modeled using one-dimensional, finite difference formulas that solve coupled mass and energy balance equations (Burch and Erickson, 2004). Other important parameters include the tank type, tank volume, recovery efficiency, the location, assumed lifetime, set point temperature, and fuel conversion efficiency (BEopt development team, 2018; Burch and Erickson, 2004). In the techno-economic analysis given in later sections, domestic hot water systems are primarily analyzed in a central community or services facility for a houseless village use case, or in the instance of slab-on-grade foundation tiny home design as a sensitivity using a low-volume water heater tank.

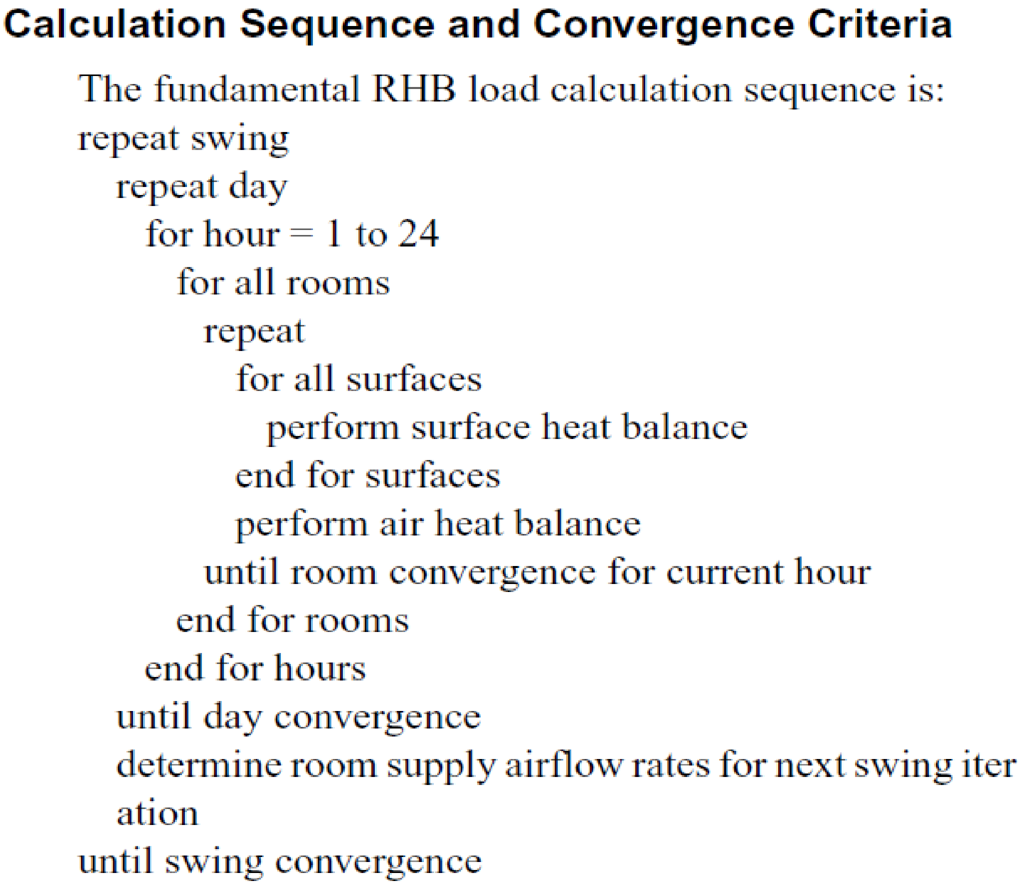
The energy factor or coefficient of performance influences the economics of domestic hot water systems. The only previous study of the techno-economic feasibility of tiny homes in Humboldt County estimates recurring energy costs of heating water for a central services facility at $2,781 annually to serve approximately 18 people, or approximately $0.02 per gallon (Singh et al., 2017). This only includes recurring energy costs and does not include amortized costs. No studies of the techno-economic feasibility or annualized energy costs of low-volume water heaters for slab-on-grade tiny homes is found in the literature.

Building envelope, HVAC, and mechanical systems

Energy efficiency measures such as building envelope insulation are commonly considered to be among the most feasible methods to reduce greenhouse gas emissions (Mckinsey and Company, 2018). This fact, in combination with a goal of achieving affordable tiny homes in a mild coastal climate, lends significance to energy efficiency measures in designing building envelopes and heating, ventilation, and air conditioning (HVAC) systems for tiny homes.

However, building energy design also involves moisture control, indoor air quality, and removal of contaminants from the interior space (Mcquiston, 2005). A heat balance of a tiny home with one occupant in Humboldt County's coastal climate suggests that in many instances a heat source would be necessary to prevent moisture accumulation in the interior space and wall assembly, particularly during the cooler winter months (Alstone, Lecture, 2017). This concern adds to the need to provide heating for tiny home occupants.

Design methods for residential HVAC systems are provided by the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) or the Air Conditioning Contractors of America (ACCA). ACCA Manual J is regarded as an industry standard calculation method, and differs only in details from methods published in the 1989-2001 editions of ASHRAE Fundamentals; other methods developed by ASHRAE include the residential heat balance method and the residential load factor method (Barnaby et al., 2005). Computational capacity advances have rendered 24-hour simulation methods more common, although the residential load factor method can be implemented using standard spreadsheet capabilities (Barnaby et al., 2005). Barnaby, et al. (2005) provide the pseudocode for the residential heat balance (RHB) method developed by ASHRAE, shown in Figure 4.



Calculation Sequence and Convergence Criteria

The fundamental RHB load calculation sequence is:

```
repeat swing
   repeat day
      for hour = 1 to 24
         for all rooms
           repeat
              for all surfaces
                 perform surface heat balance
              end for surfaces
              perform air heat balance
           until room convergence for current hour
         end for rooms
      end for hours
   until day convergence
   determine room supply airflow rates for next swing iter
   ation
until swing convergence
```

Figure 4: Algorithm for the residential heat balance method developed by ASHRAE (Image Source: Barnaby, et. al, 2005)

The term “swing” refers to temperature swing, which is defined as temperature deviations above a cooling set point or below a heating set point, and is used to iteratively estimate a heating or cooling load (Barnaby et al., 2005). The algorithm iteratively performs a heat balance on surfaces and then on the ambient air for each hour.

Greenhouse Gas Emissions

Multiple methods exist to estimate annual greenhouse gas emissions from building energy use. Average greenhouse gas emissions accounting, or a greenhouse gas emissions inventory, is the most widely instituted method (LaRiviere, J., et al., 2016). In this method, standard carbon emissions factors are used for each energy source type, and multiplied by the number of energy units for each energy source over a given time interval (California Climate Action Registry, 2009).[19] Recently, some researchers have developed marginal emissions accounting, whereby the effect of adding renewable energy or efficiency measures onto an energy grid is calculated based upon advanced algorithms or real-time data streams (LaRiviere, J., et al., 2016). In marginal emissions accounting, the time-dependent composition of grid-sourced electricity is used to determine the emissions offset by using renewable energy sources, often for organizational greenhouse gas emissions accounting and optimizing the greenhouse gas reduction benefits of renewable energy investments (LaRiviere, J., et al., 2016). However, this method requires complex, real-time analysis of the energy grid (LaRiviere, J., et al., 2016).

The BEopt tool employs average emissions (NREL BEopt Development Team, 2018). Standard default emissions factors are taken from ANSI/ASHRAE standard 105-2014, expressed in units of mass per unit of energy (e.g., lbs CO_{2e}/kWh, lbs CO_{2e}/therm,

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[19] This is typically the case, although equivalent carbon dioxide may require the use of a global warming potential multiplier, as in the case of methane and other high-potency greenhouse gases (CCAR, 2009).

etc.). However, carbon emissions factors vary significantly based on geographical region, and users can input customized emissions factors and source-site ratios (EIA, 2018; NREL BEopt Development Team, 2018).

While California has instituted a cap and trade program, the avoided costs of greenhouse gas emissions are not included in the economic analysis in this study. This is because the market rates of greenhouse gas emissions have been found to not reflect the full social and environmental cost of emissions (Stanford, 2019). Additionally, the end user such as a tiny home resident typically is not compensated for avoided greenhouse gas emissions, although grid-connected tiny homes may receive the bi-annual California climate credit (California Public Utilities Commission, 2019b).

Life Cycle Economics and Tiny Homes

As with other subjects pertaining to tiny homes, few academic articles address the life cycle costs of tiny homes. However, multiple methods exist for the economic analysis of buildings and building energy use, and most of these are applicable to tiny homes as well. These methods include the net present value (or present worth), cost/benefit ratio, internal rate of return, simple and discounted payback period, and levelized cost of energy (or conserved energy). The following discussion outlines common life cycle cost estimation methods used in the energy field, and enumerates their comparative uses and assumptions in relation to tiny homes. Recent research and economic analysis from building energy analysis and modeling are also presented.

The economic analysis of building energy use presents complex challenges, particularly in relation to energy efficiency and distributed renewable energy. Inevitably, a number of ultimately subjective judgments are introduced, either directly in the analysis or by the economic circumstances and mechanisms upon which the analysis is based. In any given economic analysis of building energy use, these potentially include (Hackett, 2006; Hackett, 2016):

- The time value of money
- The integration of policy-based incentives or design constraints
- Inflation
- Interest rates
- Utility or fuel cost escalation rates
- The economic pricing of environmental impacts
- Social, qualitative, and other considerations or externalities
- Upfront costs of equipment, infrastructure, or labor

The extent to which some or all these considerations enter into an economic analysis of tiny homes varies considerably by the jurisdiction, source of funding, use case, design, and overall economic context.

The form or significance that these assumptions may take depends on the type of economic analysis undertaken. For instance, Meier notes that one advantage of calculating the levelized cost of conservation in terms of a unit of currency per unit of energy (e.g., $/kWh) is that it circumvents assumptions about the future cost of energy (1983). On the other hand, any attempt to compare the economic benefits of PV with grid-sourced electricity over the life cycle of a PV array will inevitably be based on assumptions about both the life cycle solar electricity production, the future cost of grid-sourced electricity, and the underlying rate structures, which tend to change substantially over time.

One of the most common metrics for life cycle cost analysis is net present value (NPV). The net present value is defined in Equation 1 as follows (Hackett, 2016):

$$\mathrm{NPV} = \sum_{j=0}^{n} \frac{Net\ Benefits_j}{(1+r)^j} \qquad (1)$$

where:
Net Benefits_j = Net benefit j years from the present
r = the annual discount or interest rate used (fraction/year)
j = years from the present
n = end of the project life (years from the present)

Hackett notes that the practice of discounting tends to subvert projects with large up-front costs and benefits yielded far into the future (2006). However, it is widely considered to be the best metric to determine economic feasibility (Hackett, 2016).

A common metric related to the net present value is the levelized cost of electricity (LCOE), defined as the discounted lifecycle cost divided by the discounted lifecycle production of a renewable energy system (Hackett, 2016). The LCOE is widely used to gauge the economic competitiveness of energy generation technologies (EIA, 2018a; Fu, et al., 2017). For PV technologies, the LCOE often varies proportionally to the upfront capital costs when the ongoing costs are relatively low (EIA, 2018a). Numerous studies have computed the levelized cost of PV electricity (Fu, et al., 2017). The National Renewable Energy Laboratory reports an LCOE range for residential PV electricity in the United States from \$0.08 - \$0.11 /kWh with the federal Investment Tax Credit (ITC) in 2017.[20] The LCOE range increases to \$0.13 - \$0.17 /kWh without the 30% federal ITC included in the US residential PV market (Fu., et al., 2017).

Due to the considerable assumptions and uncertainties intrinsic to policy-integrated micro-economic analysis, sensitivity analysis is widely used in tandem with the LCOE, NPV, and other metrics. In a sensitivity analysis, a parameter is varied, while holding other parameters constant, to observe the effect of an assumption on the outcome (O'Shaughnessy, et al., 2017). Sensitivity analyses may reflect various levels of extent and sophistication; some may alter only a few parameters as a general gauge of sensitivity or to check specific alternate outcomes while others systematically and exhaustively explore a much wider range of parameters. More recent techniques model input parameters with probability distributions and construct cost estimate distributions through a random sampling simulation (Monte Carlo) method (Fingerman, et al., 2018). In the absence of a substantive literature on sensitivity analysis of tiny home economic assumptions, there would appear to be reasonable latitude to adopt a method appropriate to the precision and purpose of the analysis.

For the use case of tiny home villages, monthly utility bills, mortgage payments, and water bills are potentially an important metric for feasibility. For example, AHHA seeks to keep utility costs below \$30 per month for residents (N. Wade, personal communication, 2018). From a technical perspective, the rapidly shifting utility rates and

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[20] This range is drawn from three different states, and is not intended to reflect the full range of prices throughout the entire United States (Fu, et al., 2017).

structures renders monthly utility bill estimates susceptible to substantial uncertainty. Nonetheless, reasonable assumptions about inflation and utility escalation rates in the case of grid-sourced electricity can be informative.[21]

While PV electricity production is variable, and net metering arrangements change as with other utility billing rate structures, the annualized global horizontal irradiance upon which PV production is based tends to be predictable within a given margin of uncertainty, barring drastic changes in conditions (Habte, et al., 2017). Consequently, the levelized cost of PV electricity provides an informative economic metric. This is because most of the cost of PV panels is paid upfront,[22] reducing uncertainty regarding the life cycle cost of the PV system once a defensible estimate for the upfront cost is known.

While the annualized energy cost is an important metric, the minimization of building costs through efficient design considerations involves the intersection of economics and building science. For instance, O’Shaughnessy, et al. (2018b) found that load-shifting techniques using smart appliances designed to store heat or cooling capacity during peak solar hours are often more cost effective than battery storage technology, although this isn’t always the case. In this study, this was accomplished by altering the set point temperature of water heaters and HVAC systems, allowing them to store excess energy during peak PV production hours, thus reducing the amount of grid-sourced

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[21] This is especially true for low-income citizens and non-profit groups seeking to establish a tiny home village.

[22] A PV array may be financed through various loan arrangements, extending the cost burden over time; however, loan terms are often also known in advance.

electricity used (O’Shaughnessy, et al., 2018b). However, for homes with net metering, load-shifting is not necessary from an economic perspective. For grid-connected systems, the extent of this result is found to depend on utility billing rate structures, with systems operating under lower average net metering rates benefiting the most relative to PV without load shifting measures (O’Shaughnessy, et al., 2018). No studies on the techno-economic feasibility of solar-integrated load-shifting strategies for tiny homes is found within the academic literature, although guidebooks published online do list model specifications and approximate construction costs (Rettenwender, et al., 2018).

Historically, PV costs have substantially declined since early versions of the technology in the 1960’s and 70’s. Prices continue to fall and globally, PV prices fell 80% from 2008 to 2016. Many authors expect cost declines to continue (O’Shaughnessy, et al., 2018). Lithium ion battery costs have also declined by close to 5% annually in the last two years, a trend which is expected to continue (O’Shaughnessy, et al., 2018).

The building energy software used for this study, BEopt version 2.8.0.0, calculates the lifecycle cost for every building simulated. The calculation is based on a common lifecycle costing methodology for federal programs by the National Institute of Standards and Technology (NIST) called Handbook 135 (1995). Relevant parameters in the lifecycle cost calculation include mortgage down payments and interest, discount rates, and escalation rates. Fuel escalation rates are adjustments for the projected or assumed future cost of energy. Handbook 135 indicates that results are likely to be sensitive to recurring costs and the future cost of energy, which is a function of the escalation rate and mortgage payments (1995). For this reason, a sensitivity analysis of the fuel escalation rate and mortgage down payment and interest rate is recommendable.

Building Codes and Policy

Consistent with other subject areas pertaining specifically to tiny homes, formal academic literature on building codes and policy is comparatively sparse. Pera, in her presentation at Humboldt State University, explained that both building codes and zoning ordinances were potentially applicable to tiny homes, and that specific policies vary by jurisdiction (2016). Many jurisdictions have minimum size requirements for conventional residential houses of 1,000 – 1,500 square feet, while others may be as low as 70 square feet (Mahoney, 2018; Pera, 2016).[23] By comparing the building codes relevant to tiny homes in multiple California counties, this portion of the literature review establishes that building codes applicable to tiny homes built on standard foundations often share commonalities in many counties, because they are often based on, or variations of, California Title 24 standards.

Due to the upsurge in interest in tiny houses, many counties, commercial entities, and organizations have published information describing the building code process, even altering their building codes and policies to accommodate tiny homes (Shasta County, 2017; Pera, 2016; NFPA, 2017). The National Fire Protection Association (NFPA) notes

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[23] Building code standards vary widely, even within counties such as Humboldt. Depending on the building classification, there may be no minimum square footage requirement. Furthermore, many jurisdictions have made provisions to accommodate tiny homes, or even exempted structures in tiny home villages (Mahoney, 2018).

that tiny homes can possess characteristics of recreational vehicles, manufactured homes, modular dwellings, or site-built dwellings (NFPA, 2017). Tiny homes are typically built on wheels for the purpose of circumventing zoning restrictions, for affordability, and for ease of building, rather than for mobility, because mobile homes do not require a permit (Pera, 2016).

Multiple counties in California have published fact sheets to describe the relevant building codes for tiny homes (Shasta County Department of Resource Management, 2017; County of Placer, 2018a). In Placer County, California, a tiny home on wheels is considered a recreational vehicle that is regulated by zoning and land use. As such, they cannot be permanently occupied (County of Placer, 2018a). However, recently Placer County announced that new ordinances will be proposed for tiny homes, with the goal of increasing the total number of homes and housing types available (County of Placer, 2018b). Pre-fabricated or modular tiny houses are classed with conventional homes on a foundation. Consistent with general building codes in other areas, tiny homes on foundations in Placer County require a valid building permit and must conform to all other building and zoning requirements. Below is a list of requirements (with minor truncation) for tiny homes on foundations in Placer County, Ca., taken from the County's fact sheet (County of Placer, 2018a):

- The tiny home must have at least one habitable room that is at least 150 square feet in gross floor area.[24]
- The building must be designed to meet requirements for snow, wind, flood plain, and wildfire hazard.
- Habitable rooms must have a minimum area of 70 square feet.
- Smoke detectors and carbon monoxide alarms are required.
- All sleeping areas must have one egress window or door directly to the building exterior.
- The structure must meet minimum plumbing, waste disposal, heating, and energy code requirements.
- Kitchens must be deemed habitable, but have no floor area minimum.
- Bathrooms have minimum clearances, but are not deemed habitable.
- Tiny homes require a residential fire sprinkler in accordance with regulations.

The Shasta County Department of Resource Management (SCDRM) published a similar fact sheet (Shasta County Department of Resource Management, 2017). Figure 5 shows a schematic for a tiny home for Shasta County. Regulations in Shasta County also distinguish between tiny homes on wheels and on foundations, and the necessity for a building permit, fire sprinklers, and other requirements (Shasta, 2017). However, their minimum square footage requirements differ: Shasta County requires a living room with a 220 square feet minimum area, citing the California Residential Code (CDC), section R304.5.[25]

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[24] The term "habitable space" has a precise definition in the California building code. It is defined as "space in a building for living, sleeping, eating, or cooking" (CEC, 2016). These spaces have specific requirements for ventilation and other building characteristics, some of which are based on ASHRAE standards (CEC, 2016).

[25] This minimum does not include the required separate closet, or an additional 100 square feet for every occupant beyond the first two.

The County of Humboldt (and also the City of Arcata) list the following wide range and large number of California Title 24 requirements for all buildings requiring a permit (County of Humboldt, 2018):

- 2016 California Administrative Code, Title 24, Part1 - Section 8000
- 1997 Uniform Housing Code - Section 8090
- 2016 California Referenced Standards Code, Title 24, Part 12, including Appendix - Section 8110
- 2016 California Existing Building Code - Section 8130
- 2016 California Historical Building Code, Title 24, Part 1 - Section 8150
- 2016 California Energy Code, Title 24, Part 6 - Section 8160
- 2016 California Electrical Code, Title 24, Part 3 - Section 8030
- 2016 California Building Code, Title 24, Part 2, Volumes 1 & 2 including:
    - Appendix B (Board of Appeals)
    - Appendix H (Signs)
    - Appendix I (Patio Covers)
    - Appendix J (Grading) - Section 8000
- 2016 California Mechanical Code, Title 24, Part 4 - Section 8040
- 2016 California Plumbing Code, Title 24, Part 5 - Section 8050
- 2016 California Residential Code, Title 24, Part 2.5

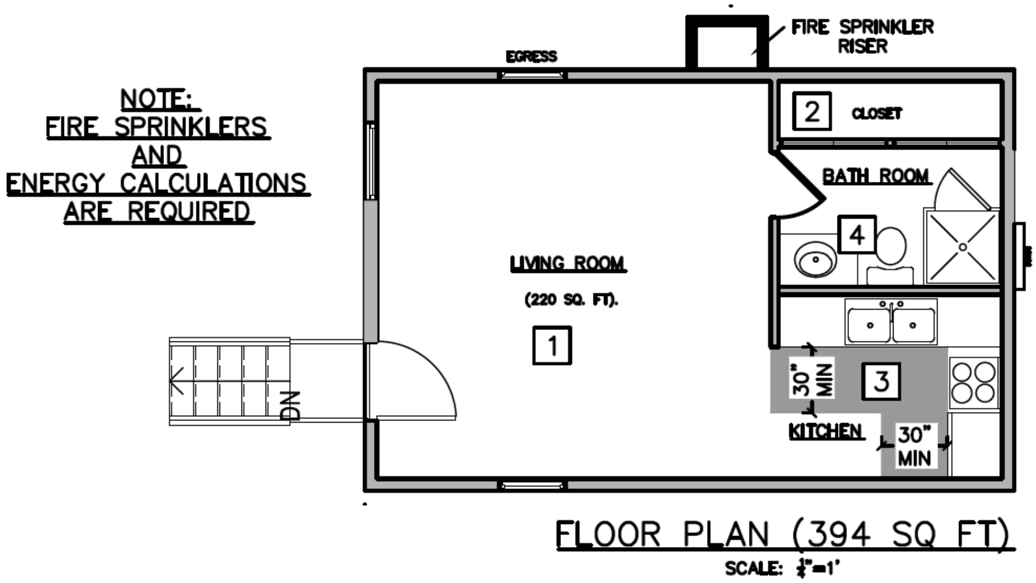

Figure 5: Example tiny home layout for Shasta County, California
(Image Source: Shasta County Department of Resource Management, 2017)

Because residential homes with foundations in Humboldt County Fall under California Title 24, Part 2.5, the minimum square footage for residential dwelling in Humboldt County generally is now one habitable room of 70 square feet (California Department of Housing and Community Development, 2016). However, this is for the County of Humboldt in general, and does not preclude the possibility that municipalities may have different building codes. One of the reasons stated for amending the previous minimum square footage from 220 square feet to 70 square feet was to accommodate tiny homes, and the lack of scientific support for the previous minimum (California Department of Housing and Community Development, 2016).

In Humboldt County, the requirements for tiny houses vary by jurisdiction, (whether it is considered within a municipality, or unincorporated Humboldt County) and whether the property in question is eligible for an alternative owner builder (AOB) permit.[26] Alternative owner builder permits pertain to property that is not eligible for water or sewer service from a service district. Typically, these rely on well water and a septic tank or similar system. These permits tend to have more flexibility in terms of building code requirements than buildings within a municipality and do not require structural inspections. For instance, in coastal Shelter Cove, the minimum square footage requirement is 400 square feet, whereas an AOB permitted structure would have no minimum square footage requirement. AOB requirements typically only pertain to 1-2 tiny homes built for use by the property owner, and would not pertain to an entire tiny home village. This is because the zoning regulations limit the number of structures built on a property, and whether the structures are intended for private or public use (D. Moxon, personal communication, 2018).

Any tiny home built on foundations in coastal Humboldt County would have to conform to all standard building code requirements, including water and sewer code standards. A tiny home village intended for temporary public use would be classified under different zoning requirements, such as a campground.

Tiny homes built on a travel trailer would be classified as an RV and not as a permanent residence. They are technically not legal permanent residences in California. Consequently, a tiny home village concept based on tiny homes built on a flatbed trailer would most likely require zoning for an RV park. This would imply that a tiny home

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[26] The following discussion is based on a telephone conversation with the County of Humboldt's building department, August 3rd, 2018 (D. Moxon, personal communication, 2018).

village under this framework would be intended for temporary, rather than permanent, habitation.

A building official with the City of Davis, California notes that any tiny home falling under the Title 24 residential building code would have to conform to requirements for the following building elements (Mahoney, 2018):

- light
- ventilation
- heating
- minimum room size—70 square feet of gross floor area
- ceiling height—7 feet 6 inches, with several exceptions
- sanitation, toilet, bath, and shower spaces
- emergency escape and rescue openings
- means of egress
- smoke alarms and carbon monoxide alarms

However, there exists precedent for exemption of tiny home villages intended for temporary housing for houseless community members. The City of Eugene, Oregon's building official inspected tiny homes in Opportunity Village for safety and exempted them from official building code restrictions (Mahoney, 2018).

Consequently, with respect to building codes, a number of potential configurations and use cases emerge. For most areas of Humboldt County, tiny homes conforming to the building code requirements of the jurisdiction, intended for personal use and limited to one or two homes per parcel are allowed; structures in unincorporated Humboldt County with an AOB permit have more flexibility with respect to building codes. Otherwise, this case typically requires conformance to California residential building code standards, or the particular standards of the jurisdiction. For tiny home villages, tiny homes on wheels would require land zoned as an RV park and could not be intended for permanent residence, barring a building code exemption from the relevant jurisdiction. Other tiny home village configurations would likely require special exemption from the County or jurisdiction in which it is established; hence, collaboration with the relevant local building and zoning agencies in the establishment of a tiny home village would be recommendable.

Applicable building codes can influence the feasible configurations and construction of tiny homes. Tiny homes built off-site without knowing the ultimate use location might contradict the building codes in the jurisdiction where they are ultimately used (Mahoney, 2018). This would also be true of any tiny homes considered to be manufactured homes (NFPA, 2017a). On the other hand, the municipality of Eugene's building official inspected tiny homes for safety and exempted them from the city's building codes (Mahoney, 2018).

However, safety criteria independent of building code standards have been developed for tiny homes. In an effort to establish consistent safety and building standards, organizations such as the National Organization of Alternative Housing (NOAH) offer certification of tiny homes on wheels (Pera, 2016; Mahoney, 2018; National Organization of Alternative Housing, 2018). NOAH is a trade association for tiny home builders and manufacturers. Below are the NOAH safety standards, taken from their website (National Organization of Alternative Housing, 2018):

Definition: A tiny house on wheels (THOW), for the purposes of these Guidelines, is:

1. A structure that has at least 70 square feet and no more than 400 square feet of first floor interior living space. Lofts are not included in this square footage calculation.
2. Is mounted on a movable foundation.
3. Includes basic functional areas that support normal daily routines (such as cooking, sleeping, and toiletry)

Standard and codes for the construction of a Tiny House on Wheels.

1. Meets the following National Codes and Standards:
    1. NFPA 1192
    2. ANSI 119.5
    3. NFPA 70 (National Electric Code)
2. The home must be capable of withstanding a minimum of 140 mile per hour winds, 50 pound per square foot snow load, and 6.5 seismic earthquake (zone 4)
3. The home must be equipped with moisture barriers, vapor barriers, fans and vents to adequately control moisture in the home.
4. The trailer must be engineered to support the weight of the home and contents. (locate axels to balance and track the home during towing. Rule of thumb 60/40 ratio, with 60% toward the tongue)
5. The home must have a minimum insulation of R13 in walls and floor; and a minimum insulation of R-19 in the ceiling.
6. All Windows and Skylights must be double pane.
7. All entry doors must be equipped with weather stripping to prevent air infiltration.
8. All sleeping areas (including lofts large enough for a bed) must have a primary and a properly labeled secondary means of egress.

The indicated codes for tiny homes on wheels, NFPA 1192 and NFPA 70, are standard residential regulatory codes for recreational vehicles and electricity, respectively (NFPA, 2017b; NFPA, 2018). While NFPA 1192 fills a manageable 64 pages, NFPA 70 is a general electrical code that spans over 800 pages (NFPA, 2017b; NFPA, 2018). Standard practice would require a licensed professional would be required to construct a tiny home consistent with electrical building codes. The same holds true of NFPA 5000, a voluntary building and construction safety code that applies to tiny homes on slab-on-grade foundations (NFPA, 2018b).

Synthesis

To synthesize, both academic studies and regulatory structures lag behind the public enthusiasm for tiny homes, but many regulatory bodies and jurisdictions are adjusting to accommodate their use. Applicable zoning laws and building codes change considerably, depending upon whether tiny homes are built on wheels, and vary considerably by jurisdiction. Tiny home villages for houseless community members exist in multiple cities in the United States, and precedent exists for the idea of using tiny homes to reduce resource consumption, offer a lower-cost residential option, or provide inexpensive housing after fires.

Building energy modeling methods and lifecycle cost analysis are standard methods applicable to residential housing, although few publicly available academic studies have used these methods to analyze the techno-economic feasibility of tiny homes or tiny home villages. Contemporary methods and literature in building energy modeling, lifecycle cost analysis, and greenhouse gas emissions accounting were reviewed to discern their use in the energy analysis of tiny homes.

The next section introduces the methodology for the building energy modeling and techno-economic feasibility of tiny homes. The study is composed of sections that include the optimization and design of building energy models, and the economic lifecycle cost, energy use, and greenhouse gas emissions analysis.

METHODS

In order to model grid-connected tiny homes and a community services building, the analysis uses the Building Energy Optimization Tool (BEopt) version 2.8.0.0, produced by the National Renewable Energy Laboratory. This building simulation software reports the annual energy use, greenhouse gas emissions, and lifecycle and annualized energy economic costs. It also enables a sensitivity and comparative analysis of different building designs. The BEopt modeling tool is specifically designed for building design optimization and comparative analysis, and can model smaller structures with customized design inputs (NREL BEopt Development Team, 2018).

Electricity production for an off-grid solar tiny home is modeled using Homer, version 2.68. Homer is microgrid optimization software that calculates the feasibility based on user inputs. Instead of simulating a building load profile, Homer functions by accepting a load profile and corresponding global horizontal irradiance (GHI) data. The zero-net energy tiny home load profile from Beopt is used for this purpose, in addition to a solar PV array sized for the use case.

BeOpt is an interface with the building simulation engine, Energyplus. Once the user specifies the building characteristics and geometry, BEopt creates a set of files that generates an input file, which is sent to the simulation engine. The simulation engine then simulates the building over a one-year interval and sends the results back to BEopt. Using BEopt can also be a convenient research method for generating simulation engine input files for further modification, such as in the modeling of phase change materials (Tabares-Velasco, Christensen, Bianchi, and Booten, 2012).

While Energyplus contains a facility for lifecycle cost and economic calculations, the economic calculations reported by BEopt are not calculated by the simulation engine. This can be verified by examining the input file generated by Energyplus.[27] Utility bill calculations were handled in the simulation engine in previous versions of BEopt, but are handled directly by BEopt to improve flexibility and computational efficiency (Christensen, et al., 2014). In practice, this gives the user more flexibility in utility rate structure inputs through the BEopt GUI.[28]

In the present analysis, BEopt is essentially used in two stages for tiny home models considered. The first stage consists of a lifecycle cost optimization. This stage identifies designs that are more energy efficient and have a lower lifecycle cost under the assumptions of the analysis. The discount rates and assumptions related to mortgage payments were set to zero for most optimizations to observe the lifecycle cost of tiny home models using the simple present value calculation. Different discount rate and mortgage assumptions may lead to different optimization economic results. Consequently, discount rates and a mortgage rate sensitivity analysis were included in the design phase to observe variation in the results due to these parameters.

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[27] A screenshot showing the empty lifecycle cost parameter fields in the Energyplus input file is included in Appendix A.

[28] An image of BEopt’s detailed utility rate calculation screen is shown in Appendix B.

In the second stage (indicated for consistency as the design phase), a single design is chosen based upon the optimization results to conduct the lifecycle cost, energy use, and greenhouse gas emissions analysis for the model considered. Discount rates and mortgage payments were altered during the design phase to observe the sensitivity of lifecycle cost to these parameters. The design results for lifecycle cost, energy use, and greenhouse gas emissions are the result of this overall process.

The community services building was modeled in the design stage only. This is because larger buildings take more time to simulate, and so simulating higher volumes of larger buildings becomes impractical without a higher computational capacity.

Finally, a conventional home was also modeled to provide a means of comparison with the tiny home models, and to place the analysis in a broader perspective.

Assumptions and Scope

It is important to note the underlying assumptions, scope, and limitations of the techno-economic feasibility analysis of tiny home models. A clear delineation of the analytical scope can assist decision makers to make well-informed and responsible decisions.

Important characteristics of tiny home design not considered in the analysis that would benefit from a separate study include:

- Detailed analysis of electrical and plumbing codes
- Water or sewer configurations and costs
- Structural considerations and architectural design (Alstone, Lecture, 2019)
- Geographical and time-dependent variation in construction, mechanical system, and labor costs (Alstone, Lecture, 2019)

Consequently, the variation in prices described in the optimization results only describes variation due to energy configurations in the context of energy prices, configurations, and efficiency, and does not reflect an in-depth analysis of construction and labor costs (Alstone, Personal Communication, 2019). To illustrate, if one tiny home model uses more envelope insulation than another, then the extra insulation cost will be reflected in the model results, but variation from real material markets or geographical location will not. For instance, a certain wall assembly that uses R-19 insulation is assumed to be $2.65 per square foot across all models, but the amount and types of insulation used differs. These differences in building envelope structure will be reflected in the life cycle cost results. Similarly, the costs of higher efficiency mechanical systems are reflected in the lifecycle cost, based on national average price data (NREL BEopt Development Team, 2018). BEopt prices are based in RSMeans and California DEER study data (Tetra Tech, 2009). Table 2 below summarizes the components of the lifecycle cost calculations of the models considered.

Table 2: Cost Assumptions for Building Energy Models

Included	Not Included
Construction Costs	Acquisition of Land
Labor Costs	Property Taxes
8.5% Arcata Sales Tax	Engineering Costs
Recurring Energy Costs and Associated Fees	Permitting and Inspection Fees
Energy Escalation Rates	-

However, the electricity and natural gas prices and rate structures are specific to coastal Humboldt County and the use cases considered. While the lifecycle cost analysis conducted by BEopt includes the cost of more efficient insulation, mechanical systems, and appliances, the input parameters are not specific to coastal Humboldt County, and so are not going to reflect geographical variation. Costs for these parameters are national averages adjusted for a local 8.5% sales tax during the design phase. Costs do not include engineering or architectural costs associated with approval or review of plans. These costs may add significantly to the lifecycle cost of a tiny home implementation (Alstone, Lecture, 2019).

While the simulations conducted for this study included a far broader scope beyond the reported results, the most informative or significant results were chosen for brevity.

Overall, the building energy models are intended to outline in broad terms the comparative technical and economic feasibility of possible energy configurations while accurately representing the variation in energy use and energy cost, rather than arrive at a single numerical outcome.

Use Cases

For the sake of clarity in the analysis, it is useful to define terms, and to distinguish between the definitions of the terms “building energy model,” “use case,” and “model energy type.” In the analysis conducted here, a “building energy model” is a specific configuration of building geometry and characteristics that was simulated using building energy modeling software.

A use case, in contrast, is defined here as the circumstances or manner in which a building energy modeled is intended or expected to be implemented in reality, if a building is actually built or lived in.

This analysis considers two primary use cases: a tiny home village use case, and an “individual” use case. Building energy models that correspond to the tiny home village use case are intended for use in a village setting with a community services building, and may or may not have all components normally associated with a typical residence, such as laundry facilities, a full kitchen, or hot water. Any energy services not modeled in the tiny home would be located in the community services building, which would have to be sized and modeled appropriately for the number of tiny homes it serves. This use case is typically considered for projects or implementations that intend to house presently houseless individuals. The village use case tiny homes in this study are modeled with an HVAC system, mechanical ventilation, and plug loads.

An “individual” use case, in contrast, is intended to function without support from any external buildings (excepting external laundry facilities, much like an apartment) and is intended to resemble a scaled-down version of any other residence. Models that fall under this use case would contain a bathroom, shower, hot water, HVAC system, and NEC-compliant electrical system. These tiny homes might be built on a raised foundation with wheels, or built on a slab. However, all energy models for the individual use case in this study are of the slab-on-grade design.

Importantly, use cases are not mutually exclusive. It is just as technically possible to have individual, fully functional tiny homes that house houseless individuals, or individuals with a house that would prefer for financial or other reasons to live in a tiny home with a community services building. These two use cases were chosen because financial constraints were assumed to be relevant for all cases considered.

Finally, a “model energy type” refers to a specific energy type that a model or set of models might assume. For example, a set of building energy models that all use propane for heating and cooking and electricity for all other uses would be considered to have the same model energy type. This concept can be useful in considering collections of models that all have similar characteristics.

For the sake of clarity, all tiny home models presented in this study that are of the individual use case will be specifically referred to as “individual.” All other models will be of the tiny home village use case, unless noted otherwise. Table 3 below shows the energy models and corresponding use cases considered, and the analysis phases used. Detailed results for lifecycle cost, annualized energy use, or greenhouse gas emissions (or all three) correspond to the design phase.

Table 3: Use Cases and Corresponding Building Energy Models Considered.

Modeled Building(s)	Use Case	Model Energy Type	Foundation Type	Analysis Phases
Tiny Homes	Village	Zero Net Energy, All Electric	Trailer (Pier and Beam)	Optimization and Design
Tiny Homes	Village	Propane and Electricity	Trailer (Pier and Beam)	Optimization and Design
Tiny Homes	Village	Off-Grid Solar	Trailer (Pier and Beam)	Optimization and Design
Tiny Homes	Village	Zero Net Energy, All Electric	Slab on Grade	Optimization Only
Tiny Homes	Individual	Zero Net Energy, All Electric	Slab on Grade	Optimization and Design
Tiny Homes	Individual		Slab on Grade	Optimization and Design
Average-Sized House	Individual	Gas, no PV	Slab on Grade	Optimization and Design
Community Services	Village	PV Model	Slab on Grade	Design Only
Community Services	Village	Natural Gas Model	Slab on Grade	Design Only
Community Services	Village	All Electric Model	Slab on Grade	Design Only

Building Energy Models

The analysis considers three primary energy model types for the village use case of tiny homes: a propane, zero-net energy (ZNE), and off-grid solar. Both the zero-net energy and the off-grid solar models are compared to the fossil fuel or base model with respect to greenhouse gas emissions, net energy use, life cycle economic cost, and monthly utility bills. Results are presented so that it is possible to compare either net electrical energy use, or overall equivalent net energy use, by converting energy to a common unit, such as British Thermal Units (BTUs). With the exception of the off-grid model, which is modeled in Homer optimization software, the analysis uses BEopt simulation load profile results for the annual energy load profile of the modeled tiny homes. Figure 6 shows an image of a zero-net energy tiny home modeled in BEopt.

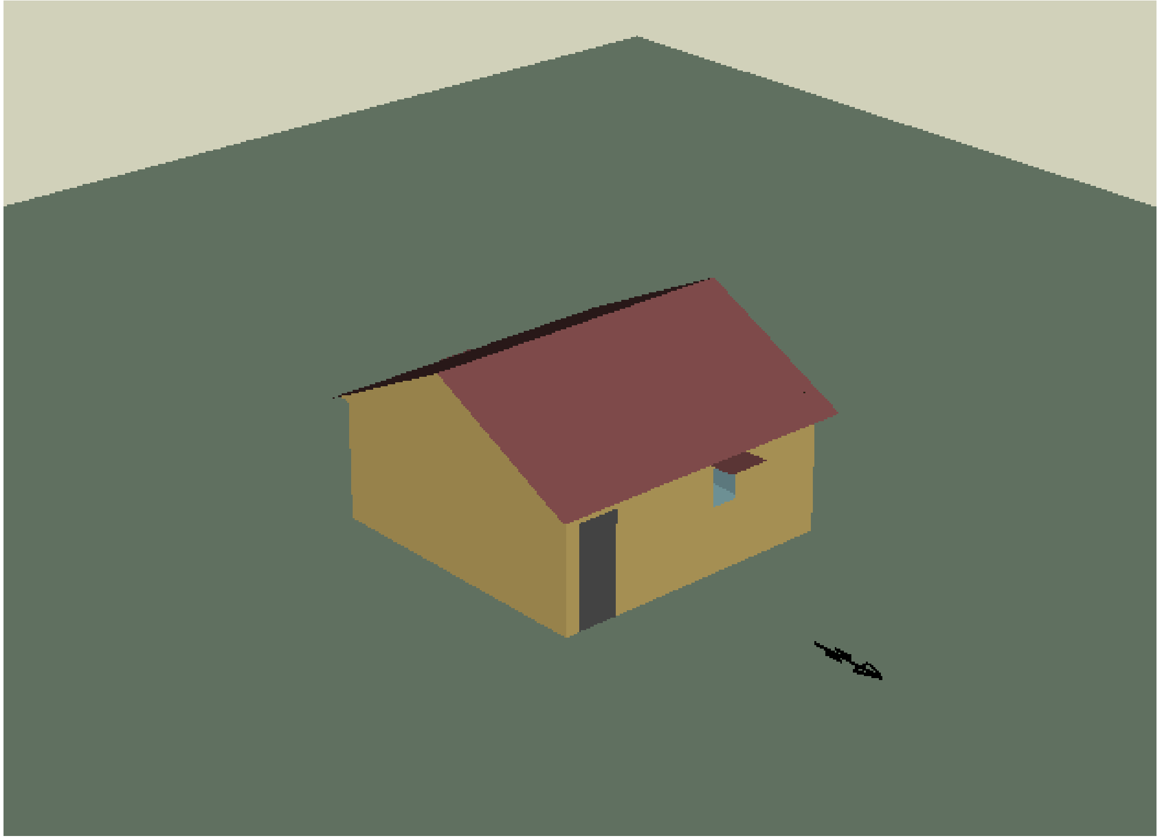

Figure 6: Image of a zero-net energy tiny home model generated by BEopt.

Because the EnergyPlus simulation engine and BEopt interface used for this study do not contain a facility specific to tiny homes, tiny homes on wheels were modeled as a “pier and beam” foundation design (Alstone, personal communication, 2018). Previous research suggests that any loss in precision due to distinctions between pier and beam design and tiny homes on wheels is small compared to alternative calculation methods that attempt a from-scratch computer program implementation (Harkness, unpublished, 2018). This is because the EnergyPlus simulation engine is the result of decades of research by the Department of Energy (Department of Energy, 2016). The heat conduction study supporting this conclusion will be presented and explained.

Access to a central services facility that provides showers, cooking, and laundry facilities is modeled to complete the village use case for tiny homes. The individual, slab-on-grade tiny home models can also be considered as a sensitivity analysis for the pier on beam models. Comparison of the two use cases can offer insight into whether a community village framework for the village use case makes more economic sense than simply designing tiny homes to provide hot water and a kitchen, and locating them near a laundromat or laundry facility.

The community services building is modeled in a manner similar to the only other known existing study of tiny home villages in Humboldt County (Singh et al., 2017). The building is designed to accommodate showers and laundry facilities. The review of Humboldt County building codes indicates that a tiny home village with a central services facility, where more than two tiny homes are contained on a single property with a central services building, would require a zoning or building code exemption from the relevant jurisdiction (Moxon, 2018). However, the model approach for the village use case includes important differences in the analytical method, the choice of mechanical infrastructure, and the underlying assumptions. These differences are enumerated in the community services section.

The individual use case is modeled using slab on grade tiny home designs for zero-net energy types. The energy consumption of an individual tiny home with a hot water heater is also compared to a modeled conventional home, because previous work on tiny homes in Humboldt County indicates that hot water comprises a significant share of the annual energy bill (Singh et al., 2017).[29]

Scoping of Modeling Methods through a Heat Conduction Study

To explore the possibility of modeling tiny homes on wheels with a specialized program, a separate study was conducted that used weather data and insulation input parameters to model heat conduction through walls (Harkness, 2019, unpublished). This study utilized a numerical algorithm implemented in the simulation engine used in this study, EnergyPlus.

The study used a one-dimensional implementation of the Crank-Nicolson method to model heat conduction through insulation materials. Equation 2 shows the heat

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[29] For typical uses on a property with fewer than 2 tiny homes, a conventional, slab-on-grade building design that complies with California Title 24 residential standards is consistent with Humboldt County building codes in many areas (Moxon, 2018). Grid-connected, slab-on-grade tiny homes were also modeled in a similar manner as conventional homes, but scaled down.

conduction equation, rendered here as a one-dimensional, second-order partial differential equation (Harkness, 2019, unpublished, as cited in Chapra and Canale, 2015).

$$\frac{\partial T}{\partial t} = \frac{k}{\rho C_p}\left(\frac{\partial^2 T}{\partial x^2}\right) \qquad (2)$$

where:

$T = temperature\ (°C)$

$\frac{\partial T}{\partial t} = First\ order\ derivative\ of\ temperature\ with\ respect\ to\ time\ \left(\frac{°C}{s}\right)$

$k = thermal\ conductivity\ (\frac{W}{m * °C})$

$\left(\frac{\partial^2 T}{\partial x^2}\right) = Second\ order\ derivative\ of\ temperature\ with\ respect\ to\ space\ (\frac{°C}{m^2})$

Equation 3 below shows the semi-implicit Crank-Nicolson algorithm used in the program to solve the heat conduction equation, taken from the 2015 EnergyPlus Engineering Reference (2015a). It was determined that while the program successfully modeled conduction heat transfer through a single wall surface under ideal conditions, other major elements of heat transfer, including convection, radiation, air film resistance, and interactive effects, were not modeled. The results of this study are located in Appendix C.

$$C_p \rho \Delta x \frac{T_i^{j+1} - T_i^j}{\Delta t} = \frac{1}{2}\left(k_w \frac{T_{i+1}^{j+1} - T_i^{j+1}}{\Delta x} + k_e \frac{T_{i-1}^{j+1} - T_i^{j+1}}{\Delta x} + k_w \frac{T_{i+1}^{j} - T_i^{j}}{\Delta x} + k_e \frac{T_{i-1}^{j} - T_i^{j}}{\Delta x}\right) \quad (3)$$

where:

$T = Node\ temperature\ (^\circ C)$

$i = node\ being\ modeled$

$i + 1 = adjacent\ node\ to\ interior\ of\ construction$

$i - 1 = adjacent\ node\ to\ exterior\ of\ construction$

$j + 1 = new\ time\ step$

$j = previous\ time\ step$

$\Delta t = calculation\ time\ step\ (seconds)$

$\Delta x = Finite\ difference\ layer\ thickness\ (meters)$

$C_p = Specific\ heat\ of\ material\ (\frac{J}{kg * {}^\circ C})$

$k_w = Thermal\ conductivity\ for\ interface\ between\ i\ node\ and\ i + 1\ node\ (\frac{W}{m * {}^\circ C})$

$k_e = Thermal\ conductivity\ for\ interface\ between\ i\ node\ and - 1\ node\ (\frac{W}{m * {}^\circ C})$

$\rho = density\ of\ the\ material\ (\frac{kg}{m^3})$

Tiny Home Energy Modeling Optimization Methods

As described in the introduction, BEopt functions as a user interface with the EnergyPlus simulation engine, which performs the energy analysis for each case. BEopt can simulate a single existing building or retrofits (design mode), multiple simulations at once (parametric mode), or use a sequential search algorithm technique to optimize the energy efficiency of a building by successively choosing among identified options to form a least-cost efficiency curve (NREL BEopt development Team, 2018).

The user enters building, weather, and economic parameters into the BEopt interface. When a simulation is performed, BEopt creates .xml files, which are processed to produce .idf files used in the simulation engine, EnergyPlus. The simulation engine results are processed by the BEopt GUI, which generates other output files, depending on how the user implements the program. Figure 6 below shows a file input and output schematic for BEopt 2.8.0.0.

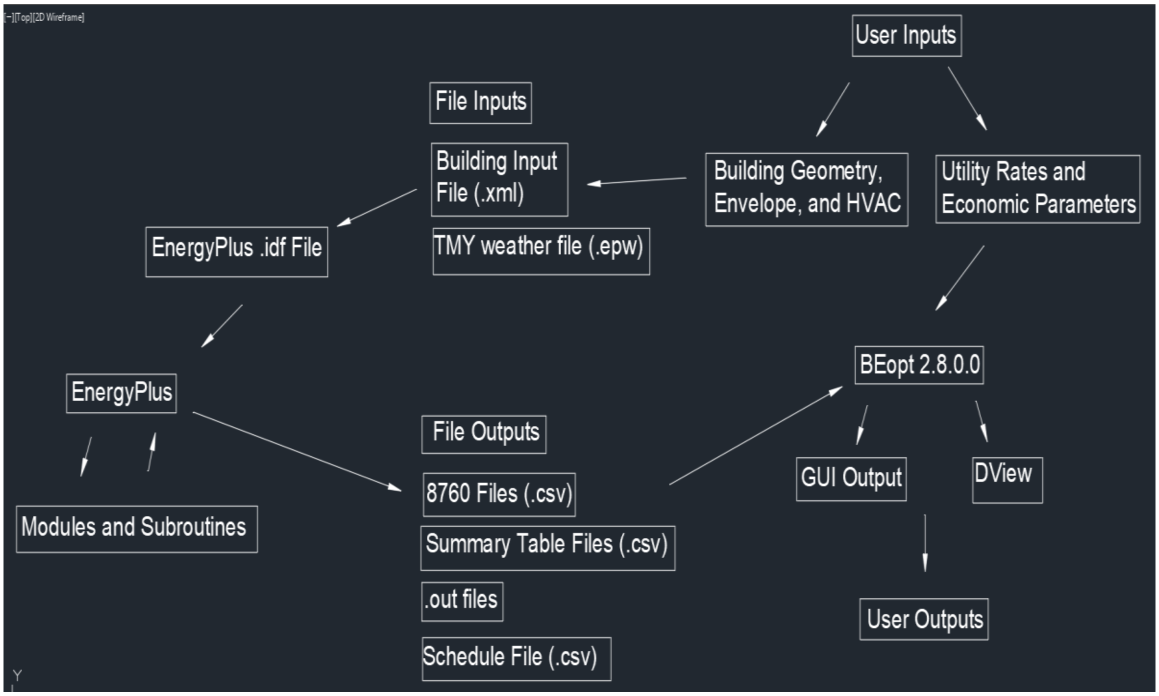

Figure 7: General Use Schematic for BEopt 2.8.0.0. Generated in AutoCAD.

Design phase models created through BEopt were identified using the sequential search technique for each case. This step was taken to identify the most energy efficient options, and to enable comparison with similar options. It also allows for design latitude in the event of constructing or implementing a tiny home, because a designer can choose among multiple options with similar energy efficiency profiles or alter parameters as appropriate to their project (Christensen, et al., 2006). The algorithm is designed to minimize the number of simulations; nonetheless, BEopt can run many hundreds or thousands of simulations, covering a wide parameter search space to identify the least-cost or highest-efficiency option (Christensen, et al., 2005a). Figure 7 below shows an optimization performed for the ZNE model of a slab-on-grade tiny home design.[30]

When interpreting optimization results, one must consider whether the parameters shown are absolute or relative to a reference case. In Figure 7, the y-axis (lifecycle cost, in dollars) is an absolute quantity, whereas the x-axis is relative to a simulation taken as a "base" model for this optimization. Most optimization graphs generated by BEopt show an optimal line, in black. The optimal line, or east cost line, in BEopt shows the lower cost boundary of each optimization, and is generated automatically by the BEopt GUI for each optimization. The least-cost building energy model lies on the lowest point of the least cost line. Contingent upon the configuration of the optimization, the least-cost curve may not always traverse the entire discrete search space chosen for the optimization, as is shown on the far left of Figure 7. BEopt is designed such that a careful choice of a reference case and discrete search options typically yields an optimization curve. The optimal line can be generated externally by connecting the least-cost options using a programming language, given the output data.[31]

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[30] The literature refers to the set of all possible building characteristics as a parameter search space (Horowitz, et al., 2008). Because this search space is discrete in nature, references to the optimization search space are also referred to in this thesis as a discrete search space (Christensen, et al., 2008).

[31] To be clear, Figure 7 actually shows tiny homes configured for the village use case, but slab on grade tiny homes were for the village use case and were not analyzed in the design phase of the analysis for the sake of brevity.

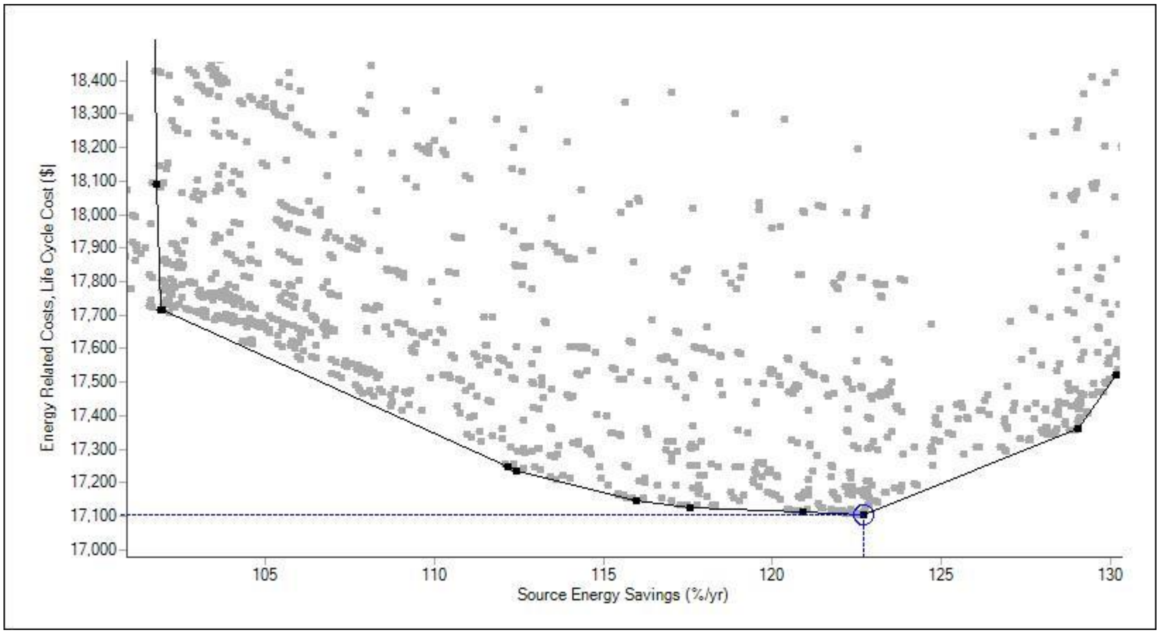
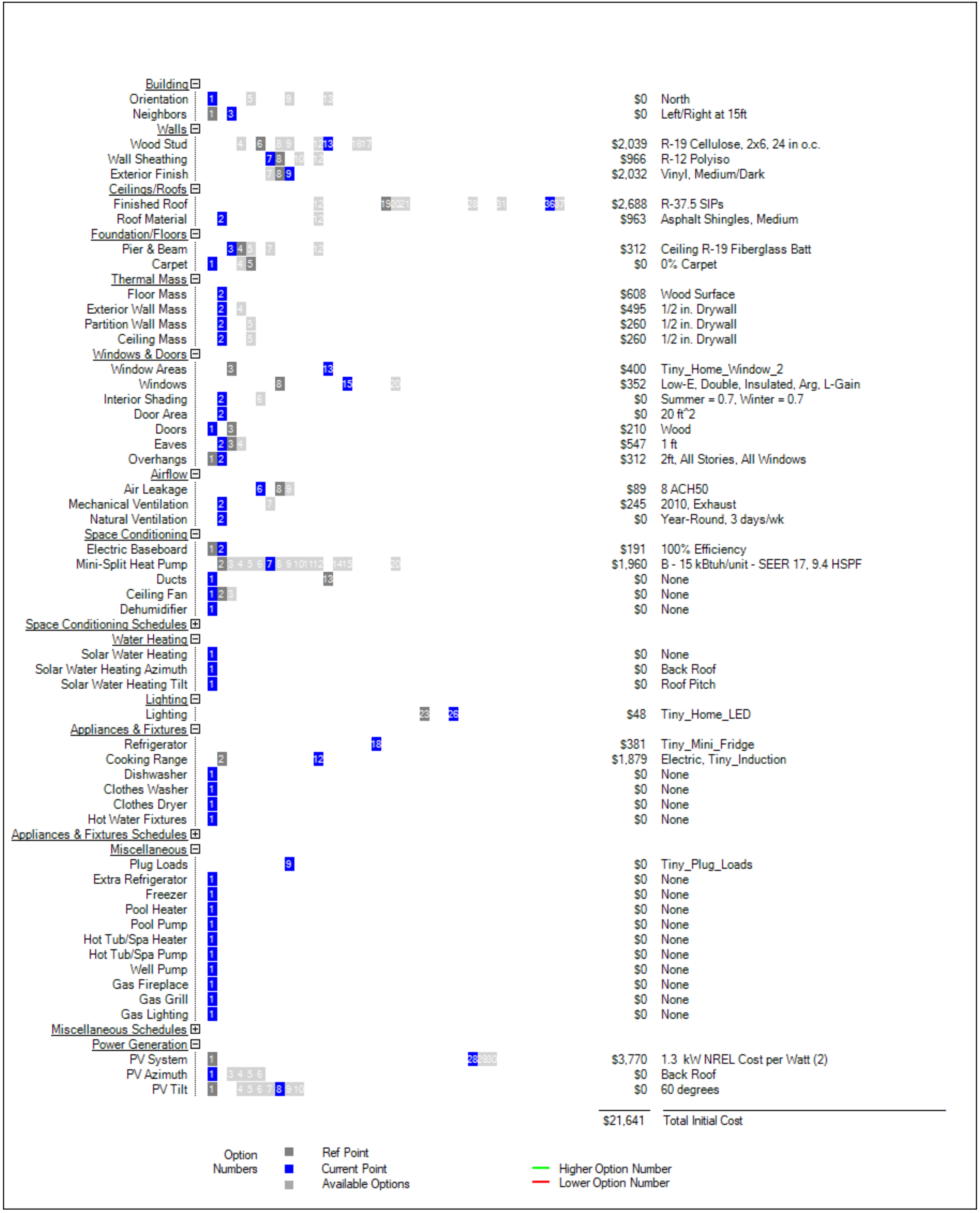


Figure 8: Optimization of a 400-square foot, zero-net energy, slab-on-grade tiny home in BEopt. Each point represents a tiny home with different insulation or mechanical system characteristics. The optimization consists of over 1,400 simulations. Origin not shown. The black line is intended to show the optimal design cost for each energy savings level (Horowitz, et al., 2008).

The Arcata typical meteorological year 2 weather file from the NREL NSRDB database (TMY2.epw file) was used for each simulation (NREL BEopt Development Team, 2018). BEopt contains default parameters for efficiencies and upfront costs of HVAC system components and common household appliances (refrigerators, washers and dryers, etc.). The default parameters were used for building envelope and mechnical systems described unless otherwise noted. This means that, for instance, if an optimization configuration lists vinyl exterior finish as a considered option, the conductivity, density, and specific heat of vinyl finish that is pre-programmed into BEopt were used for these simulations unless otherwise noted, and can be found by looking up these values in the BEopt 2.8.0.0 GUI.

Figure 8 shows chosen input parameters for a BEopt optimization. Each square beside a building feature represents a potential option that defines the discrete search space traversed by the sequential search algorithm. Essentially, this set of options defines the search space for BEopt, and the simulations run in the simulation engine are chosen from among these discrete options using the sequential search algorithm.



Building		
Orientation	$0	North
Neighbors	$0	Left/Right at 15ft
Walls		
Wood Stud	$2,039	R-19 Cellulose, 2x6, 24 in o.c.
Wall Sheathing	$966	R-12 Polyiso
Exterior Finish	$2,032	Vinyl, Medium/Dark
Ceilings/Roofs		
Finished Roof	$2,688	R-37.5 SIPs
Roof Material	$963	Asphalt Shingles, Medium
Foundation/Floors		
Pier & Beam	$312	Ceiling R-19 Fiberglass Batt
Carpet	$0	0% Carpet
Thermal Mass		
Floor Mass	$608	Wood Surface
Exterior Wall Mass	$495	1/2 in. Drywall
Partition Wall Mass	$260	1/2 in. Drywall
Ceiling Mass	$260	1/2 in. Drywall
Windows & Doors		
Window Areas	$400	Tiny_Home_Window_2
Windows	$352	Low-E, Double, Insulated, Arg, L-Gain
Interior Shading	$0	Summer = 0.7, Winter = 0.7
Door Area	$0	20 ft^2
Doors	$210	Wood
Eaves	$547	1 ft
Overhangs	$312	2ft, All Stories, All Windows
Airflow		
Air Leakage	$89	8 ACH50
Mechanical Ventilation	$245	2010, Exhaust
Natural Ventilation	$0	Year-Round, 3 days/wk
Space Conditioning		
Electric Baseboard	$191	100% Efficiency
Mini-Split Heat Pump	$1,960	B - 15 kBtuh/unit - SEER 17, 9.4 HSPF
Ducts	$0	None
Ceiling Fan	$0	None
Dehumidifier	$0	None
Space Conditioning Schedules		
Water Heating		
Solar Water Heating	$0	None
Solar Water Heating Azimuth	$0	Back Roof
Solar Water Heating Tilt	$0	Roof Pitch
Lighting		
Lighting	$48	Tiny_Home_LED
Appliances & Fixtures		
Refrigerator	$381	Tiny_Mini_Fridge
Cooking Range	$1,879	Electric, Tiny_Induction
Dishwasher	$0	None
Clothes Washer	$0	None
Clothes Dryer	$0	None
Hot Water Fixtures	$0	None
Appliances & Fixtures Schedules		
Miscellaneous		
Plug Loads	$0	Tiny_Plug_Loads
Extra Refrigerator	$0	None
Freezer	$0	None
Pool Heater	$0	None
Pool Pump	$0	None
Hot Tub/Spa Heater	$0	None
Hot Tub/Spa Pump	$0	None
Well Pump	$0	None
Gas Fireplace	$0	None
Gas Grill	$0	None
Gas Lighting	$0	None
Miscellaneous Schedules		
Power Generation		
PV System	$3,770	1.3 kW NREL Cost per Watt (2)
PV Azimuth	$0	Back Roof
PV Tilt	$0	60 degrees
	$21,641	Total Initial Cost

Figure 9: BEopt building envelope and mechanical system parameters for the ZNE pier and beam optimization, village use case. The parameter inputs generated over 800 simulations.

When this initial set of possible options is run in BEopt (technically, a parameter search space), the sequential search algorithm finds the optimal model by considering options in a series of steps, called iterations (NREL BEopt Development Team, 2018). At each iteration, the algorithm simulates models, and chooses the model with the highest ratio of cost decrease to energy savings increase (NREL BEopt Development Team, 2018). Figure 10 below shows results of an optimization, where the left bar shows the energy use of the beginning simulation, and the bar labeled "iteration 42, point 12" shows the optimized model energy use. For the sake of consistency, barplots shown in results with this notation can be interpreted in the same way: the iteration of the optimization routine, followed by the number of the energy model at that iteration.

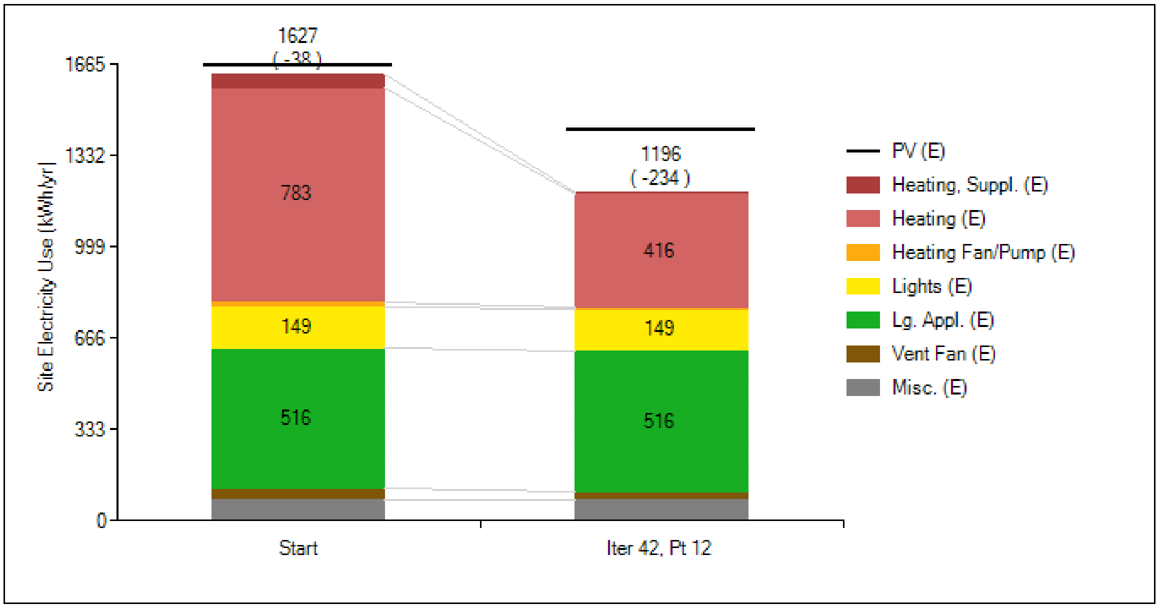


Figure 10: Beginning and ending simulations for a pier and beam, zero-net energy tiny home. The bar labeled "start" was the first simulation in the optimization, and the bar labeled "Iter 42, Pt 12" represents the cost-optimal model, which was the 12th simulation on the 42nd iteration. From top to bottom: the energy use types in each bar graph appear in the same order as the legend to the right. The lines between the bars indicate the change in energy use for each type.

Once models are identified through the sequential search optimization, the resulting parameters are used in a general lifecycle cost and greenhouse gas emissions analysis.[32] The optimized models for each energy configuration are then compared, with the conventional or fossil fuel model acting as the “base” model.

As will be described in the results section, many results from the zero-net energy optimizations are substantially net negative. This is because BEopt does not autosize PV arrays. BEopt was designed so that once the global optimum point is reached, the building design is held constant and PV capacity is increased to achieve zero-net energy

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[32] The methods for the lifecycle cost and greenhouse gas emissions analyses are given in the lifecycle cost and greenhouse gas emissions subsections of the methods section.

(NREL BEopt Development Team, 2018). Because the variation in annualized energy use is substantial, it is more efficient to simply run an optimization with a limited number of PV array sizes and resize models with a lower energy use than it does to substantially increase the size of the discrete search space. This was one of the reasons that the analysis was broken into an optimization phase and a design phase.

The models chosen for the detailed design phase analysis were chosen from among models with less energy use and lower cost under the economic assumptions of the optimization run. These choices were focused on creating detailed designs with a lower lifecycle energy use, lifecycle cost, and lifecycle greenhouse gas emissions. Images showing the optimization parameters used are included in Appendix D.

Tiny Home Building Energy Use and Geometry: Village Use Case

The literature review indicates that energy efficient building design is one of the most economically feasible methods of limiting greenhouse gas emissions, and that high-efficiency building envelopes tend to pay themselves over the course of their lifecycle (Mckinsey and Company, 2018). For this reason, zero-net energy tiny homes were first modeled in the optimization phase, where the annualized energy use and estimated lifecycle cost can be directly compared between models. Every effort was made for tiny home models to be more energy efficient than minimum California Title 24 standards, which require all newly constructed low-rise residential buildings to be zero-net energy by 2020 (California Public Utilities Commission, 2018c). The zero-net energy policy was implemented after it was found to be economically feasible, because it will lower energy use and greenhouse gas emissions (California Public Utilities Commission, 2018d). As discussed in the literature review, different energy types are compared using the concept of source energy (California Public Utilities Commission, 2018a). However, because one of the primary purposes of the analysis was to observe the performance of different energy sources, not all tiny homes were modeled with PV.

In order to facilitate comparison between use cases, tiny homes were all modeled with identical geometry. Given a tiny home implementation, these assumptions can be altered to reflect encountered conditions. Table 4 and Table 5 below list basic building geometry and characteristics for the Zero-net energy and propane design phase models. These models are the result of the initial optimization phase. All appliances not listed in Tables 4 and 5, respectively, are included under the plug loads category.

While there is no specific relative humidity target, tiny homes are all modeled with mechanical ventilation systems and heating to insure control of interior moisture and humidity. Moisture and humidity control are a major issue in coastal Humboldt County, and critical to occupant health, comfort and safety (Alstone, Lecture, 2017).

Table 4: Building Parameters and Characteristics for the Zero-net Energy and Propane Design Phase Models, Tiny Home Village Use Case

Pier and Beam Models	Propane Model	Initial Cost	ZNE Model	Initial Cost
Orientation	East	$0	North	$0
Neighbors	Left/Right at 15ft	$0	Left/Right at 15ft	$0
Wood Stud	R-21 Fiberglass Batt, 2x6, 24 in o.c.	$2,010	R-36 Closed Cell Spray Foam, 2x6, 24 in o.c.	$4,330
Wall Sheathing	R-15 XPS	$1,460	R-12 Polyiso	$970
Exterior Finish	Vinyl, Medium/Dark	$1,980	Vinyl, Medium/Dark	$2,030
Finished Roof	R-38C Fiberglass Batt, 2x10, R-24 Polyiso	$1,900	R-38C Fiberglass Batt, 2x10, R-25 XPS	$2,360
Roof Material	Asphalt Shingles, Medium	$800	Asphalt Shingles, Medium	$960
Pier & Beam	Ceiling R-19 Fiberglass Batt	$310	Ceiling R-38 Fiberglass Batt	$430
Floor Mass	Wood Surface	$610	Wood Surface	$610
Exterior Wall Mass	2 x 1/2 in. Drywall	$710	1/2 in. Drywall	$500
Partition Wall Mass	2 x 5/8 in. Drywall	$440	2 x 5/8 in. Drywall	$440
Ceiling Mass	2 x 5/8 in. Drywall	$440	2 x 5/8 in. Drywall	$440
Window Areas	10 Square Feet	$400	10 Square Feet	$400
Windows	Low-E, Triple, Insulated, Air, H-Gain	$410	Low-E, Double, Insulated, Arg, L-Gain	$350
Interior Shading	Summer = 0.5, Winter = 0.95	$0	Summer = 0.7, Winter = 0.7	$0
Door Area	20 ft^2	$0	20 ft^2	$0
Doors	Fiberglass	$280	Wood	$210
Eaves	None	$0	1 ft	$550
Overhangs	2ft, All Stories, All Windows	$310	2ft, All Stories, All Windows	$310
Total	-	$12,060	-	$14,890

Table 5 shows the infiltration rate and mechanical system characteristics used for the analyses. The air exchange rate was chosen to be lower than the standard residential rate of 7 air exchanges per hour used in NREL's Building America Housing Simulation Protocols (Wilson, Metzger, Horowitz, and Hendron, 2014).

Table 5: Mechanical, HVAC, and Load Characteristics for the ZNE and Propane Models, Tiny Home Village Use Case.

Pier and Beam Models	Propane Model	Initial Cost	ZNE Model	Initial Cost
Air Leakage	6 ACH50	$110	6 ACH50	$110
Mechanical Ventilation	2013, Exhaust	$250	2013, Exhaust	$250
Natural Ventilation	Year-Round, 3 days/wk	$0	Year-Round, 3 days/wk	$0
Furnace	Propane, 78% AFUE	$1,670	Electric Baseboard, 100% Efficiency	$190
Mini-Split Heat Pump	None	$0	A - 9 kBtuh/unit - SEER 14.5, 8.2 HSPF	$1,850
Cooling Set Point	None	$0	80 F	$0
Heating Set Point	67 F	$0	67 F	$0
Humidity Set Point	None	$0	None	$0
Lighting	LED Lighting, 150 kWh/Year	$50	LED Lighting, 150 kWh/Year	$50
Refrigerator	Compact Refrigerator, 200 kWh/Year, 2.5 Cubic Feet	$380	Compact Refrigerator, 200 kWh/Year, 2.5 Cubic Feet	$380
Cooking Range	Propane	$820	Induction Cooktop	$1,880
Plug Loads	70 kWh/Year	$0	70 kWh/Year	$0
PV System	None	$0	1.0 kW	$2,900
PV Azimuth	None	$0	South	$0
PV Tilt	None	$0	40 degrees	$0

Off-grid solar model

The load profile for the off-grid solar model was taken from the zero-net energy model for the village use case described in Tables 4 and 5 above. As a consequence, it resembles the grid-connected case in geometry, building envelope, and mechanical system characteristics. A solar array and battery storage system was then sized to meet 95% of the load profile. The combination of solar PV array and battery storage system was modeled in Homer, version 2.68.

Table 6 lists the economic assumptions and input parameters for the off-grid solar PV and battery sizing optimization conducted by Homer. Battery sizing was based on the method described by Gilbert M. Masters in *Renewable and Efficient Electric Power Systems* (2013). The battery price is based on NREL's Q1 2016 cost benchmark (Ardani, et al., 2017).

Table 6: Input Parameters Used for Homer Optimization Software.

Parameter	Value	Unit
Annual Energy load	1170	kWh
Peak Load	1.04	kW
Max Number of Days Without Sunlight	3	Days
Assumed Discharge Rate	0.97	Fraction
Maximum Depth of Discharge	0.8	Fraction
Battery Voltage	2	Volts
String Voltage	12	Volts
Number of Strings in Parallel	1	#
Installed Battery Cost (Assumed)	500	$/kWh
Solar PV Cost	$2.90	$/Watt

HVAC equipment sizing and modeling

The literature review indicates that the industry standard for the calculation of residential HVAC heating and cooling loads is contained in the Air Conditioning Contractors of America (ACCA) Manual J. BEopt's version 2.8.0.0 contains an autosize function incorporating the calculations given in the ACCA Manual J, 8th Edition (NREL BEopt Development Team, 2018). For this reason, the autosize function in BEopt is used to size HVAC systems. For instance, for the zero-net energy slab-on-grade tiny home modeled, the BEopt optimization feature might indicate that over some number of simulations, a mini-split heat pump and backup electric resistance baseboard heaters with a particular combined capacity (in BTU/hr.) would be the most cost-effective or energy-efficient heat pump size for the tiny homes considered.

Mini-split heat pump units intended for use in tiny homes or other small square-footage spaces are available on the market. Specifications for these products were included whenever possible to increase analytical realism in the results.

Appliances

Parameters for assumed appliance usage and appliance types were adjusted to be consistent with use in tiny homes. Whenever possible, aggregated product data were used to verify the analytical assumptions to lend realism and robustness to the analysis. For instance, the Energystar database was used to search for refrigerators appropriate for a tiny home (Department of Energy, 2019 a). Because a non-compact refrigerator (defined by Energystar as having greater than 7.75 cubic feet of interior volume) takes up more interior floor area and consumes more energy in the tiny homes considered, energy efficient and compact refrigerators were identified based on assumptions of energy use and unit dimensions (Department of Energy, 2019b). Figure 11 below shows a frequency distribution of annual energy use for compact refrigerators listed in the Energystar database. Since the 612 listed compact refrigerators average 245 kWh per year, with a standard deviation of approximately 41 kWh, we may defensibly assume an annual energy use of approximately 190-225 kWh for a tiny home with a compact, energy efficient refrigerator.

Whenever possible, a descriptive statistical analysis also informs the assumed dimensions for a highly-constrained floor space. For instance, the 34-inch by 30-inch floor area reserved for a compact refrigerator in Figure 9 is more than ample space for 100 percent of the compact refrigerators listed in the EnergyStar database with an interior capacity of less than 4.5 cubic feet. Designs based in data offer flexibility in the ultimate implementation. The annualized energy use tends to increase with interior volumetric capacity of the refrigerator.

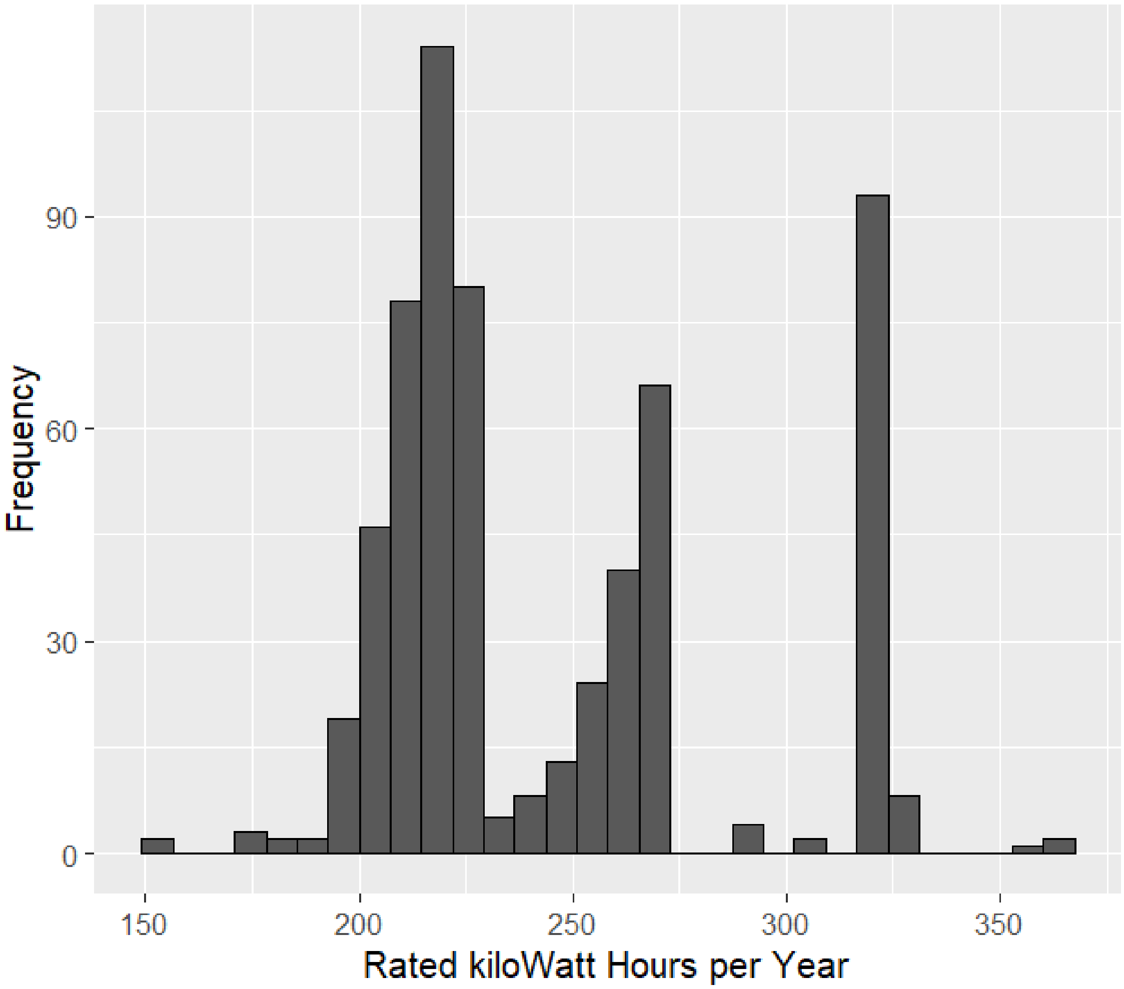

Figure 11: EnergyStar compact (< 4.5 ft.^{3} of interior capacity) refrigerators from the EnergyStar database. EnergyStar-rated compact refrigerators with interior capacity of less than 4.5 ft.3 have an average annual rated use of 245 kWh per year.

Tiny Home Building Energy Use and Geometry: Individual Use Case

The methodology for the individual use case tiny homes mirrors the village use case. However, the input parameters for the optimization and design phase models differs. Table 7 and Table 8, below, show the input parameters for the individual use case tiny home considered for the design phase. The economic parameters used are the same for the village use case, and will be listed in Table 10.

Due to the interest in tiny homes on wheels, a sensitivity analysis is conducted on the assumed foundation design, replacing the slab and slab insulation with an R-38 fiberglass batt. The annualized energy use results for this sensitivity analysis are presented in the results section.

Table 7: Input Parameters for the Zero-net Energy Tiny Home, Individual.

Category Name	Pier and Beam, ZNE, Individual Tiny Home	Initial Cost
Orientation	North	$0
Neighbors	Left/Right at 15ft	$0
Wood Stud	R-36 Closed Cell Spray Foam, 2x6, 24 in o.c.	$4,330
Wall Sheathing	OSB, R-15 XPS	$2,150
Exterior Finish	Vinyl, Medium/Dark	$2,030
Finished Roof	R-38C Fiberglass Batt, 2x10, R-25 XPS	$2,360
Roof Material	Asphalt Shingles, Medium	$960
Slab	Whole Slab R40, R10 Gap XPS	$1,960
Floor Mass	Wood Surface	$610
Exterior Wall Mass	2 x 1/2 in. Drywall	$730
Partition Wall Mass	2 x 5/8 in. Drywall	$440
Ceiling Mass	2 x 5/8 in. Drywall	$440
Window Areas	10 Square Feet	$400
Windows	Low-E, Double, Insulated, Arg, L-Gain	$350
Interior Shading	Summer = 0.5, Winter = 0.95	$0
Door Area	20 ft^2	$0
Doors	Fiberglass	$280
Eaves	1 ft	$550
Overhangs	2ft, All Stories, All Windows	$310

Table 8: Mechanical System Parameters for the Zero-Net Energy, Individual Tiny Home.

Category Name	Pier and Beam, ZNE, Individual Tiny Home	Initial Cost
Mechanical Ventilation	2013, Exhaust	$250
Natural Ventilation	Year-Round, 3 days/wk	$0
Furnace	Electric Baseboard, 100% Efficiency	$190
Mini-Split Heat Pump	A - 9 kBtuh/unit - SEER 14.5, 8.2 HSPF	$1,850
Cooling Set Point	80 F	-
Heating Set Point	67 F	-
Humidity Set Point	60% RH	-
Dehumidifier	Autosized, Standalone	$150
Water Heater	Electric Premium Efficiency	$470
Draw Profile	National Average, 33 Gallons per Day	-
Distribution	R-2, TrunkBranch, Copper	-
Lighting	LED Lighting, 150 kWh/Year	$50
Refrigerator	Compact Refrigerator, 200 kWh/Year, 2.5 Cubic Feet	$380
Cooking Range	Electric	$920
Plug Loads	70 kWh/Year	$0
PV System	2.35 kW	$6,820
PV Azimuth	Back Roof	$0
PV Tilt	Roof, Pitch	$0

Greenhouse Gas Emissions

As indicated by the literature review, the Building Energy Optimization tool uses average greenhouse gas emissions accounting. Table 9 gives the emissions factors used as input parameters into BEopt.

Sensitivity values were chosen for the electricity and natural gas emissions factors. In the case of electricity, a value of 0.50 lbs./kWh was chosen, because this number is closer to CAISO's current average emissions (California Independent System Operator, 2019a, 2019c).[33] The CAISO reports that approximately 26.21% of the total load was served by renewable energy in 2018 (California Independent System Operator, 2019b). If the emissions factor follows a downward trajectory from increasing renewable energy sources, then a lower value will reflect a more likely emissions factor projected into the future. In the case of natural gas, a higher value was chosen due to uncertainty about leakage rates in the natural gas production and distribution system.

Table 9: Greenhouse Gas Emissions Factors Used in the Design Phase Greenhouse Gas Emissions Analysis

Parameter	Value	Sensitivity	Unit	Source
Grid-Sourced Electricity	0.21	0.50	lbs. CO_2e/kWh	Redwood Coast Energy Authority (2018)
Propane	12.6	-	lbs. CO_2e /Gallon	Environmental Protection Agency (2018)
Natural Gas	11.7	15	lbs. CO_2e /Therm	Environmental Protection Agency (2018)

The greenhouse gas emissions calculation for each model is simply the average emissions factor by the total annual energy use, in corresponding units (kWh, gallons of

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[33] A simple annual ratio of total emissions to total energy from data reported by CAISO shows that the average emissions has decreased from 0.65 lbs. per kWh in 2014 to 0.51 lbs. per kWh in 2017 (California Independent System Operator, 2019a, 2019c).

propane, or therms, respectively), for each energy type in the model. These totals are then summed for the annual greenhouse gas emissions total, in metric tons per year.

Lifecycle Cost Analysis

The BEopt lifecycle cost calculation is used for the analysis, which is based on the NIST Lifecycle Costing Handbook 135 (NREL BEopt Development Team, 2018). The lifecycle cost analysis includes mortgage payments (if they are modeled), discount and inflation rates, energy escalation rates for each energy type, default assumptions about construction and labor costs, and assumptions about the residual value of the building at the end of the analysis period (NREL BEopt Development Team, 2018). The lifecycle cost is expressed by the net present value equation, in constant 2018 dollars (NIST, 1995):

$$LCC = \sum_{t=0}^{N} \frac{C_t}{(1+d)^t} \qquad (4)$$

where:

LCC = Total LCC in present-value dollars of a given alternative,
C_t = Sum of all relevant costs, including initial and future costs, less any positive cash flows, occurring in year t,
N = Number of years in the study period, and
d = Discount rate used to adjust cash flows to present value.

Table 10 below shows the economic input parameters used for the analysis. Parameters are applied to all cases uniformly, unless otherwise noted. A zero percent inflation rate was used because the lifecycle cost analysis uses constant 2018 dollars discounted to the present value, in accordance with NIST Lifecycle Handbook 135 Methodology (1995). The NIST methodology excludes inflation because it is a constant dollar analysis (NIST, 2018).

Table 10: Economic Input Parameters and Sensitivity Analysis Values for All Tiny Home Design Phase Models.

Primary Analysis		Sensitivity Analysis	
Parameter	Value	Value	Unit
Location	Arcata, California	-	-
Terrain	Suburban	-	-
Project Analysis Period	30	-	Years
Inflation	0	-	Percent/Year
Discount Rate	0.0	3,6	Percent/Year
Efficiency Material Cost Multiplier	1.0	-	-
Efficiency Labor Cost Multiplier	1.0	-	-
PV Material Cost Multiplier	1.0	-	-
Down Payment	100.0	25	Percent
Mortgage Interest Rate	-	4	Percent
Mortgage Period	-	30	Years
Incentives	No Incentive	30% Fedral ITC	-
Electricity Utility Rate	EL-6 TOU Care, EL-1 Care Basic	-	-
Propane Fuel Price	2.4	2.60	$/Gallon
Electricity Escalation Rate	0.66	1.90	Percent/Year
Propane Escalation Rate	1.14	-	Percent/Year

The lifecycle cost analysis for tiny homes was conducted both using the BEopt Graphical User Interface, and with an external, spreadsheet-based lifecycle cost analysis. Lifecycle costs found using the BEopt GUI and an external spreadsheet were compared using a percent error calculation; in most cases they were within 5% agreement. This approach was taken to lend transparency to the lifecycle cost calculation, to observe variation in economic results, and to make it easier to conduct sensitivity analysis of economic parameters. The spreadsheet calculates both the discounted and undiscounted lifecycle costs. The results for the external spreadsheet and calculations from BEopt are included in the results section.

While BEopt is overall flexible in its modeling capabilities, a few economic calculations internal to BEopt were useful to check externally. For instance, the default cost function that models water heater distribution systems assumes a structure greater than 860 ft.^{2}, as can be shown by Equation 5 from the BEopt help file (NREL BEopt Development Team, 2018):

$$L_{Pipe} = 366 + 0.1322 * (X_{FF} - 2432) + 86 * (N_{Bedrooms} - 2.85) \qquad (5)$$

Where:

$L_{Pipe} = Hot\ water\ distribution\ system\ pipe\ length\ (feet)$
$X_{FF} = Finished\ Floor\ Area\ (ft.^2)$
$N_{Bedrooms} = Number\ of\ Bedrooms$

Setting the left-hand side of Equation 4 to zero, the number of bedrooms equal to 1, and solving for the finished floor area gives 866.9 ft^2. However, this function is only used with an autosize feature used for costing purposes, and does not affect the building energy simulation parameters sent to the simulation engine (NREL BEopt Development Team, 2018).

The spreadsheet based analysis allowed a check on the precision of BEopt's reported economic results for a few other reasons. These reasons include:

- The replacement costs for mechanical equipment escalate inexplicably over the project analysis period even if 0% inflation, 0% discount rate, and 0% escalation rate is used.
- Air exchanges per hour is given a cost, even if no reference building is used to calculate savings from efficiency measures.
- PV array modeling is of limited precision, as BEopt 2.8.0.0 does not model degradation rates.

Costs for construction parameters were taken from BEopt defaults and adjusted for the Arcata, California sales tax rate of 8.5%. This approach has been adopted previously by reports prepared for the Environmental Protection Agency because BEopt's default cost parameters are based on RSMeans and California Database for Energy Efficient Resources data (Tetra Tech, 2009).

Utility rates, mortgages, and economic calculations

Monthly utility bills were modeled using BEopt's utility rate calculation facility.[34] Because the literature review and community interest indicated an emphasis on low-income use cases and financial feasibility, low-income utility rates were used for the analyses (Singh et al., 2017; Pera, 2016). The primary residential electric utility generation provider in Humboldt County is Redwood Coast Energy Authority, which provides electricity through a recently-launched Community Choice Aggregation

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[34] The electricity rates used in this study are located in Appendix E.

program (Redwood Coast Energy Authority, 2018). An investor-owned utility, Pacific Gas and Electric Company (PG&E), provides transmission and billing services.

Utility rate structures change by model energy type. The conventional fossil-fuel and all-electric models use PG&E California Alternative Rates for Energy (CARE) program rates. Electricity EL-1 and EL-6 CARE rates from July 2018 were entered manually into BEopt for the propane and zero-net energy models, respectively. Utility rates are set by the California Public Utilities Commission, and "inverted block" rate structures are often used to promote energy conservation. In these rate structures, utility customers pay a "base" rate specified by the geographical region, primary heating energy source, and season. The baseline electricity quantity is then multiplied by the number of days in the month to calculate the monthly baseline electricity amount. Humboldt County exists in PG&E baseline territory V.

For example, the EL-1 PG&E rate for July-September of 2018 allots 13.6 kWh per day for all-electric residences during the summer months in territory V. An all-electric house under this rate would then be allotted 421.6 kWh for the month of July. Energy used less than or equal to this amount is assigned the baseline rate of $0.13686/kWh. Energy use above this amount in the billing rate period but less than four times the baseline amount of 1686.4 kWh/month would be assigned the next tier rate of $0.18075/kWh, and so on. Because the high-envelope-efficiency tiny homes modeled in a mild coastal climate would rarely be expected to use over 3,000 kWh per year or 8.2 kWh/day, the baseline rate is nearly always applicable for electricity in the base cases without solar PV. In practice, the annual energy use for these cases can be estimated accurately by simply multiplying the total annual electricity use by the average electricity rate.

Net energy metering (NEM) 2.0 time-of-use rates were applied to grid-connected tiny homes with the addition of solar PV panels. Under NEM 2.0, energy is exchanged back and forth between the house and the electricity grid, depending on whether solar PV production exceeds energy use. Excess energy is given a credit and energy used from the grid is billed, based on a Time of Use rate structure. Net metering rates also change by season and usage amount similar to declining block rate structures; the complexity of the rate system increases substantially as a result.

Electricity rates are set across California by the California Public Utilities Commission. One uncertainty in economic lifecycle cost analysis arises from shifting utility rates and rate structures, especially in California. Declining block rate structures are set to be replaced by time-use-rates in 2019-2020 in California (California Public Utilities Commission, 2018b). Time of Use rates bill energy by time of the day and other factors. These rates add additional complexity to estimating annual energy bills, because the time at which energy is used and/or produced must be taken into account. Shifting rate structures add an additional source of uncertainty in a lifecycle cost analysis that extends many years into the future.

Aside from the rate structures, a lifecycle cost analysis also introduces assumptions about the future cost of electricity. Other sources of uncertainty include economic inflation rates and fuel cost escalation rates. Inflation rates are familiar to most as the inflation of the value of currency over time and affect the cost of most goods.

Fuel escalation rate methodology and analysis

The literature review indicates that life cycle cost analysis outcomes are likely to be sensitive to energy escalation rates (NIST, 1994). Therefore, a methodology was formulated to test the influence of a reasonable range of escalation rates on the final comparative life cycle cost analysis of tiny home models. For this purpose, a standard predictive (NIST) method and an empirical retrodictive (energy price data analysis) method were combined to establish a reasonable range of likely energy escalation rate parameters.

The predictive analysis uses the NIST methodology from the 2018 supplement to Handbook 135 (2018). The method is applied over a 30-year time horizon (2018-2048), which is the period assumed in the energy models. Energy escalation rates based on the NIST methodology are used for both the optimization stage analysis and the design analysis.

The NIST life cycle method indicates that the fuel escalation rate may be modeled as a linear or other function of time (1995). Discount rates and escalation rates for use in federal DOE contracts are listed in the Annual Supplement to Handbook 135 (2018). The supplement indicates that the Department of Energy often uses a standard discount rate of 3% (2018). Low-income individuals may have a very high discount rate due to valuing money in the present highly. However, because tiny home village residents aren’t assumed to cover the capital costs in the village use case, lower, project-level discount rates were applied in the analysis.

Table 11 below shows the projected energy escalation rates for the California-inclusive census region. The factors corresponding to the analysis period and energy type are used in Equation 3 to calculate the escalated energy price, excluding inflation.

Table 11: Escalation Factors (Unitless) in the NIST 2018 Supplement to Handbook 135. (Source: Table Cb-4 in Lavappa and Kneifel, 2018)

Residential Fuel Type	2018-2023	2023-2028	2028-2033	2033-2038	2038-2043	2043-2048
Electricity	0.4	1.6	1	0.5	0.5	0.4
Distillate Oil	6.9	0.9	1	0.9	0.6	0.3
LPG	1.8	1.5	1.1	0.9	0.7	0.7
Natural Gas	0.2	2.9	0.6	0.4	0.4	0.4

The 2018 NIST supplement recommends the following equation for the calculation of the escalation factor from the escalation factors listed in Table 10 (Lavappa and Kneifel, 2018):

$$p_y = p_0 \prod_{i=1}^{N} (1 + e_i)^{k_i} \qquad (3)$$

Where:

p_y = price at end of year y;
p_0 = unit price at base date;
e_i = annual compound esclation rate for period i from the table (in decimal form); and
k_i = number of years over which escalation rate e_i occurs.

Assuming an analysis period of 30 years for California beginning in 2018, the escalation factor for residential electricity in California using the NIST methodology would be:

$$(1 + 0.004\,)^5 * (1 + 0.016\,)^5 * (1 +\ 0.01)^5 * (1 +\ 0.005)^5 * (1 + 0.005\,)^5 * (1 + 0.004\,)^5 =\ 1.245$$

In 2018, the base CARE rate for electricity is $0.12706/kWh. Thus, the NIST methodology gives an estimated base declining block CARE rate price of $0.1581/kWh for California for the year 2048. Because California net metering rates are often based in Time of Use (TOU) rate schedules, Time of Use Care rates were also analyzed.

While the NIST methodology makes it possible to estimate the future cost increases of electricity in constant dollars, the BEopt GUI asks the user to input energy escalation rates as an annual percentage. To arrive at an escalation rate as an annual percentage, the Excel solver tool was used over a thirty-year analysis period to determine what constant annual energy percentage increase would result in a price of $0.17/kWh, in 2018 dollars.

The retrodictive escalation rate analyses vary by time frame, based on the availability of data.[35] Retrodictive escalation rates are used to establish useful annual percent intervals for a sensitivity analysis. Table 11 below gives a synopsis of the fuel escalation rates found with each method, the data sources, and time intervals analyzed. The average annual national inflation rate for 2000-2018 is estimated at 2.4% based upon

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[35] Code written in the R statistical computing language used to download and process energy price data is included in Appendix F.

analysis of Consumer Price Index (CPI) data for California (2019). An adjusted value of 2.2% was used for all inflation-adjusted analysis after a sensitivity analysis showed minimal difference on the analytically derived escalation rates. This was done to maintain consistency throughout the study.

Table 12 summarizes the energy escalation rates estimated for electricity, natural gas, and propane, excluding the assumed 2.2% general economic inflation rate. The purpose of deriving escalation rates from multiple sources is to establish a reasonable range of potential values for a sensitive parameter, and to include data specific to coastal Humboldt County whenever possible.

Table 12: Escalation Rates, by Energy type, Using the NIST Method and Data Analysis

Energy Type	Unit Rate	Rate Structure	Rate Name	NIST (%/Year)	Data (%/Year)	Data Source
Electricity	($/kWh)	CARE Time of Use	(EL-6)	0.66	2.26	PG&E, 2008-2018 data
Electricity	($/kWh)	CARE Declining Block	(EL-1)	0.75	1.90	PG&E, 2008-2018 data
Natural Gas	($/Therm)	CARE Residential	(GL-1)	0.83	1.61	PG&E, 2000-2019 data
Propane	($/Gallon)	National Average	None	1.14	1.14	EIA, 2000-2017 data

The escalation rate for propane fuel cost in the data column of Table 12 was estimated using data from the Energy Information Administration (2018). Figure 12 below shows national propane prices collected during the winter months of each year (October-January). A propane price of $2.43 per gallon in 2018 with an escalation rate of 1.14% per year was used for the analysis.

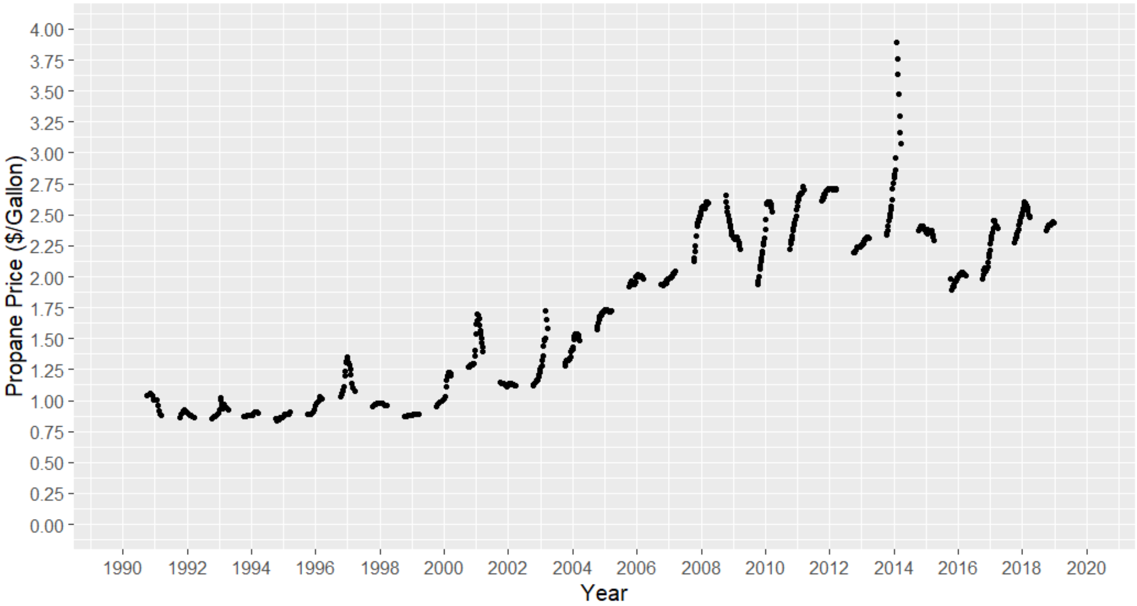

Figure 12: Historical propane fuel prices, unadjusted for inflation.
(Data Source: Energy Information Administration, 2019b)

Similarly, the electricity escalation rates given in the data column of Table 12 were estimated using historical data for EL-1 CARE program rates for the Pacific Gas and Electric Company.[36] Figure 13 below shows historical EL-1 CARE rates, by tier. Because tiny homes are assumed to use most of their electricity from the base rate, the base CARE rate was used for the escalation rate analysis.

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[36] Because utility rates are set by the California Public Utilities Commission, these rates are common to all investor-owned utilities in California.

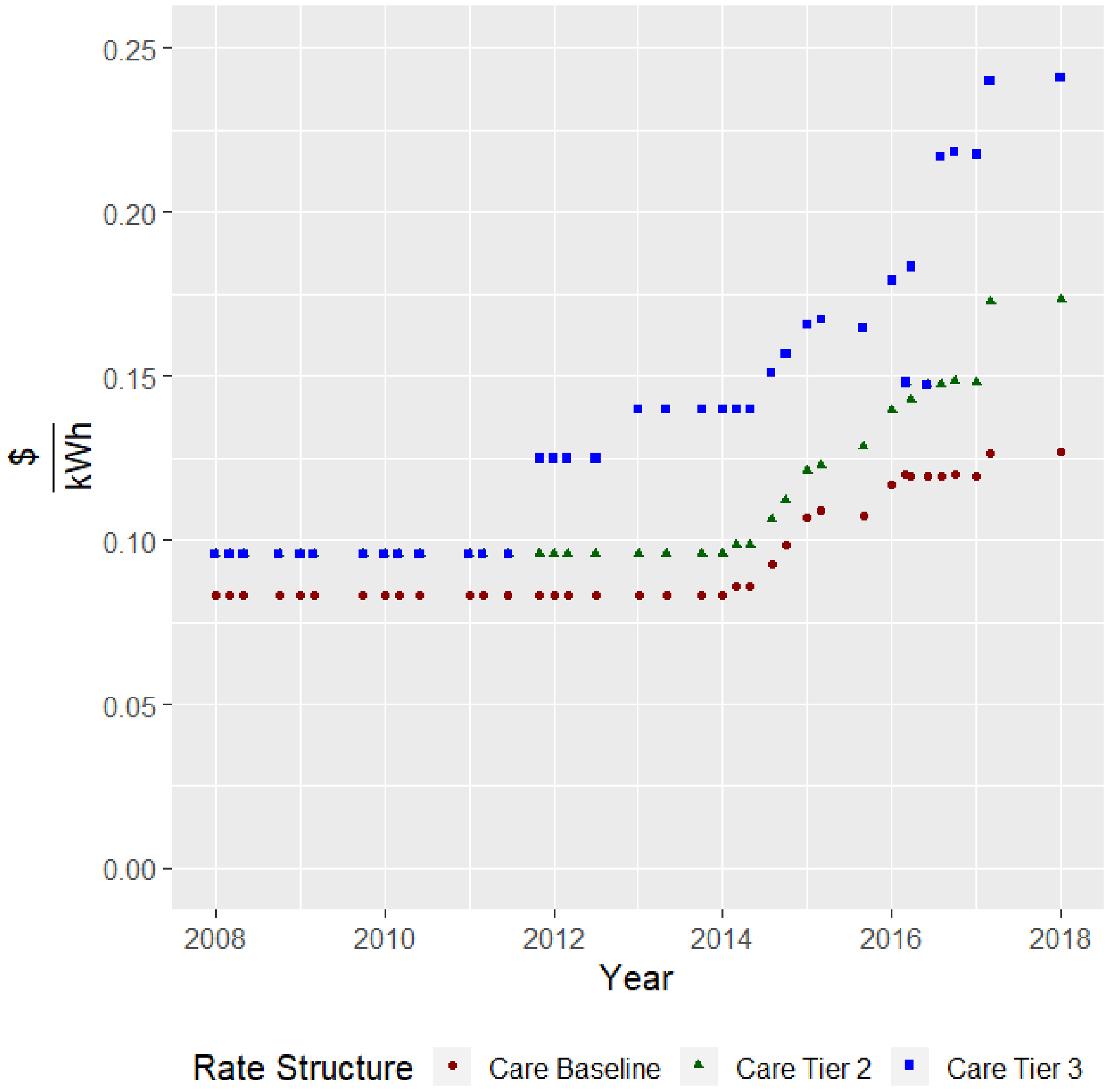

Figure 13: Historical EL-1 Care rates for Pacific Gas and Electric, by rate tier. (Data Source: Pacific Gas and Electric Company, 2019)

As noted in the literature review, residential rates in California are likely to shift to Time of Use rates. Additionally, the ZNE model uses NEM 2.0 rates, which are based in Time of Use. Because Time of Use rates vary by season, peak usage, and tier, the reported average rate for each rate period was used. The escalation rate for the Time of Use rate (using the average rate for each month) was estimated to be 0.747% per year, excluding inflation.[37] Figure 14 below shows historical average Time of Use rates reported by Pacific Gas and Electric Company for 2008-2018.

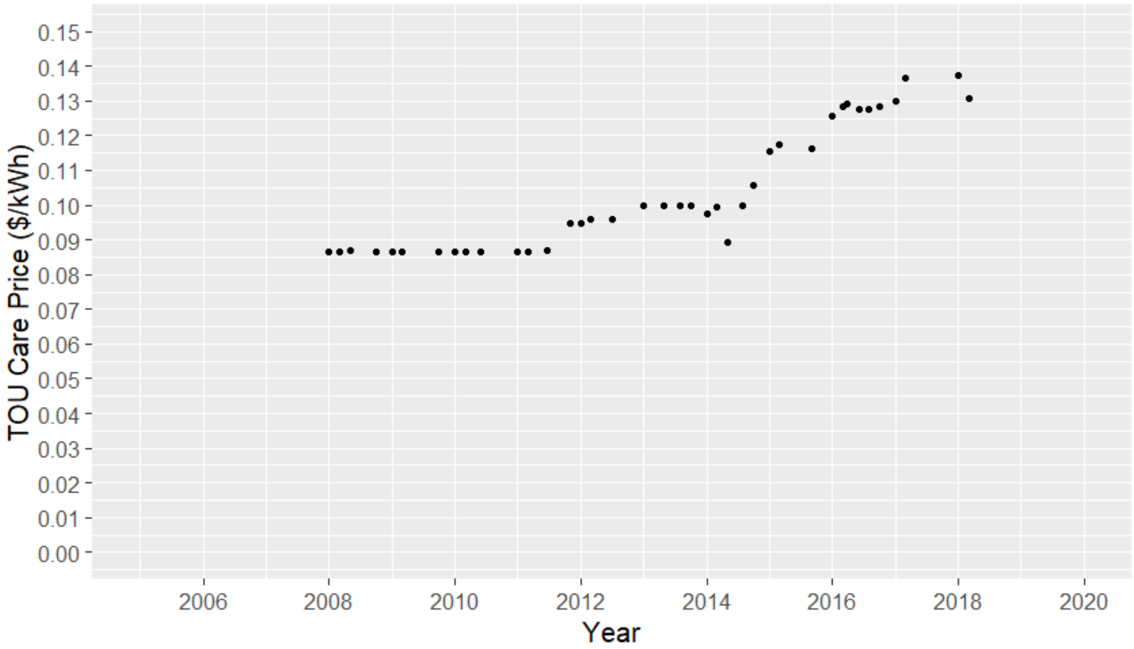

Figure 14: Historical CARE EL-6 Time of Use rates for Pacific Gas & Electric Company. (Data Source: Pacific Gas and Electric Company, 2019)

Pacific Gas and Electric natural gas rates were analyzed to determine reasonable assumptions for the community services building base model. Historical natural gas rate data from 2000-2018 are shown in Figure 15, below. The NIST methodology resulted in

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[37] The average in the Time of Use escalation rate analysis was used because the number and configuration of time periods in the rates change multiple times over the interval considered, enough so that it would not have been strictly accurate to refer to a single rate structure.

an annual energy escalation rate of 0.83%, after inflation, while data analyzed from 2000-2019 showed an average annual percentage increase of 1.614%, excluding inflation.

The data-derived escalation rates for electricity in California are higher than the NIST methodology, as might be expected because both the geographical scope and the analysis period differ. Notably, the NIST method agreed very closely with national propane data, even with different analysis intervals. Average electricity prices reported by the EIA, by state, are given in Figure 16 for 2017. The time interval over which the annual escalation rate was computed (2000-2018 for data analyses, and 2018-2048 using the NIST methodology) differs in length and time interval, so the two analyses are not directly comparable.

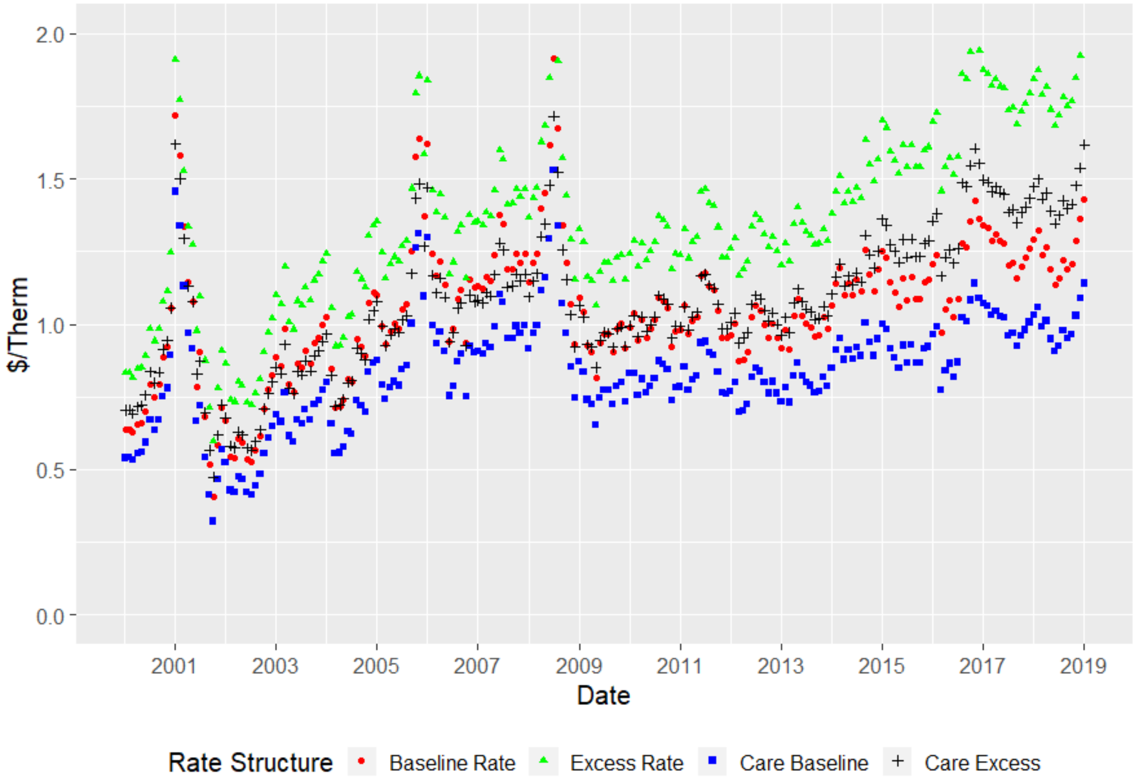

Figure 15: Residential and CARE natural gas rates, 2000-2018.
(Data Source: Pacific Gas and Electric Company, 2019)

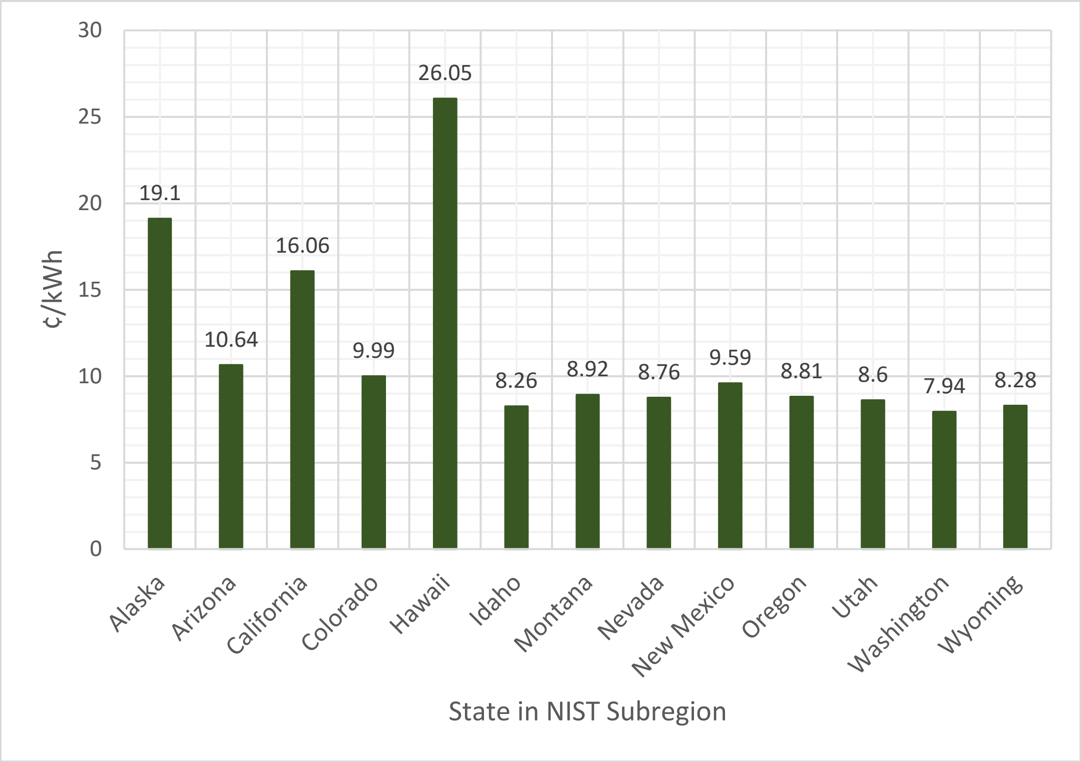

Figure 16: Average electricity prices 2017, by state.
(Data Source: Energy Information Administration, 2019a)

Furthermore, any forecast over a multi-state or national region will be subject to substantial uncertainty. For instance, the NIST estimate for Time of Use escalation results in a 0.66% annual increase, while the observed electricity escalation after inflation was found to be 2.26%. Hence, the optimized models used in the lifecycle cost analysis were subjected to annual escalation rate sensitivity analyses corresponding to the range of observed historical escalation rates.

The off-grid solar model does not require utility rate calculations, but introduces technical challenges, as well as the need to accurately estimate the up-front and ongoing costs of storage, PV, and balance of systems maintenance. In all cases involving recurring energy costs, a sensitivity analysis is conducted on the underlying rate assumptions.

Solar PV Sizing and Economics

A levelized cost of energy (LCOE) analysis of PV electricity circumvents assumptions about the future cost of electricity for the cases where off-grid PV replaces the need for a utility connection. For this reason, the levelized cost of solar energy is included in the analysis. Because BEopt does not model degradation rates over the lifecycle of the solar array, a separate economic analysis of the levelized cost of solar energy was conducted for models with a solar PV system.

The LCOE is defined as the ratio of discounted net costs to discounted energy produced (Hackett, 2016). The analysis considers discount rates of 0%, 3%, and 6%. The 3% rate was chosen because this is a standard rate used in the NIST Lifecycle Cost handbook 135 (NIST, 2018). A 0% per year discount rate was applied in the analysis because a tiny home village might be funded through grants, from organizations, or from governmental agencies in which a comparison to competing investment choices is not relevant.[38] Additionally, a 6% per year discount rate was applied to observe the variation in results. The analysis was intended to be structured to allow for easy comparison among discount rates applicable to a particular project. The analysis views the overall lifecycle cost of the scenarios considered without assuming the bearers of various costs;

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[38] The discount rate used in the net present value calculation corresponds to interest rates for this reason; it is used to compare the financial outcomes of competing investment options.

For instance, in the case of a tiny home village for houseless people, the analysis doesn’t make assumptions about what fraction of costs are born by the residents or any organization. For this reason, the discount rates considered are appropriate for a funded project and not a higher discount rate and not necessarily low-income residents.

Solar PV incentives are included in the lifecycle PV analysis, primarily the 30% federal investment tax credit (ITC) as a sensitivity analysis. While the tax credit is 30% for residential solar installations placed in service by December, 2019, it is being phased down to 26% through December, 2020, and 22% through December, 2021 (Department of Energy, 2019c). Additional solar PV incentives could apply to low-income residential cases, such as the CPUC’s Single-family Affordable Solar Housing (SASH) program (California Public Utilities Commission, 2019a).

The initial PV sizing for tiny homes and the community services building was conducted using Solar Energy International’s methodology published in the Solar Electric Handbook (Solar Energy International, 2012). After tiny home and community services building models were optimized for life cycle cost, a parametric analysis was conducted on the PV array size to align the modeled annual energy use with the annual PV output with respect to the BEopt model.

Decreasing the size of the solar array to avoid an annual sellback of electricity in BEopt frequently has the effect of lowering the lifecycle cost. This is due to the structure of net metering rates in California, whereby customers who sell more electricity to the grid than they use are credited back a fraction of the retail value of electricity, typically near $0.03/kWh in 2017-2018. Simply, under current net metering agreements, oversizing PV panels tends to render them less cost-effective.

Once the tiny home models were optimized in BEopt, the BEopt economic inputs were used in a spreadsheet-based analysis model with a 1% degradation rate to find the levelized cost of energy. Because BEopt does not model degradation rates, the spreadsheet-based sizing and economic analysis is presented with the BEopt results. The spreadsheet-based analysis uses the same Typical Meteorological Year 2 (TMY2) global horizontal irradiance data used for the simulations. Analysis of the data file gives an average global horizontal irradiance of 3.92 kWh/m^2/day. Table 13 below shows the assumed parameters used for the spreadsheet-based analysis.

Table 13: Parameters Used for Spreadsheet-Based PV Sizing Analysis

Use Case	Annual Electricity from BEopt (kWh)	Daily Average Energy (kWh)	Average Peak Sun Hours Per Day (kWh/m^2/Day)	Inverter Efficiency	General System Derate Factor
Community Services Building	16,439	45.04	3.92	0.97	0.86
ZNE Village use Case	1,172	3.21	3.92	0.97	0.86
PV standalone ZNE Tiny Home	2,972	8.14	3.92	0.97	0.86

In a constructed implementation of tiny homes, analysis based on either satellite data (LIDAR) or site-collected data (from a solar pathfinder or similar instrument) could potentially provide a site-specific method for solar PV sizing.

Community Services Building Energy Modeling

Due to the interest in the use of tiny homes for housing the houseless, a community services or village center facility building was modeled in BEopt. One reason for this choice was to complement the only known previous study of this use case in coastal Humboldt County, conducted during a Development Technology course at Humboldt State University (see Singh et al., 2017). Figure 17 below shows a BEopt-generated rendering of the modeled central community building.

Three primary sub-cases were considered: a natural gas model, an all-electric model, and a PV and electric model. The square footage of the building was chosen to be consistent with use by 6 tiny homes with approximately 18 occupants to complement or supplement the only previous known study.

As with modeled tiny homes, the building envelope elements were chosen for higher efficiency relative to minimum Title 24 efficiency standards in California. All models considered were slab-on-grade designs, and grid connection was assumed.

Figure 17: A community services facility for a tiny home village modeled in BEopt 2.8.0.0.

Due to the challenges of modeling a structure intended to provide laundry and shower facilities for multiple tiny homes, the community services building was modeled as a multifamily dwelling unit consisting of six pieces. This approach was taken to ensure that the correct magnitude of energy use for 18 people was appropriately modeled.[39] The structure was then adjusted to connect the six units together with corridors. The hot water system was modeled as a centralized unit, and the hourly output was checked with reasonable assumptions about the hot water demands of 18 people. Figure 18 below shows a rendering of the village use case of tiny homes. This figure does not show the exact window fraction and foundations used for the tiny homes modeled, because the central building and tiny homes were modeled in separate files. However, it is intended to show the general layout of the tiny home village modeled.

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[39] For R code used to check energy modeling output against thermodynamic principles of water heating, see Appendix G.

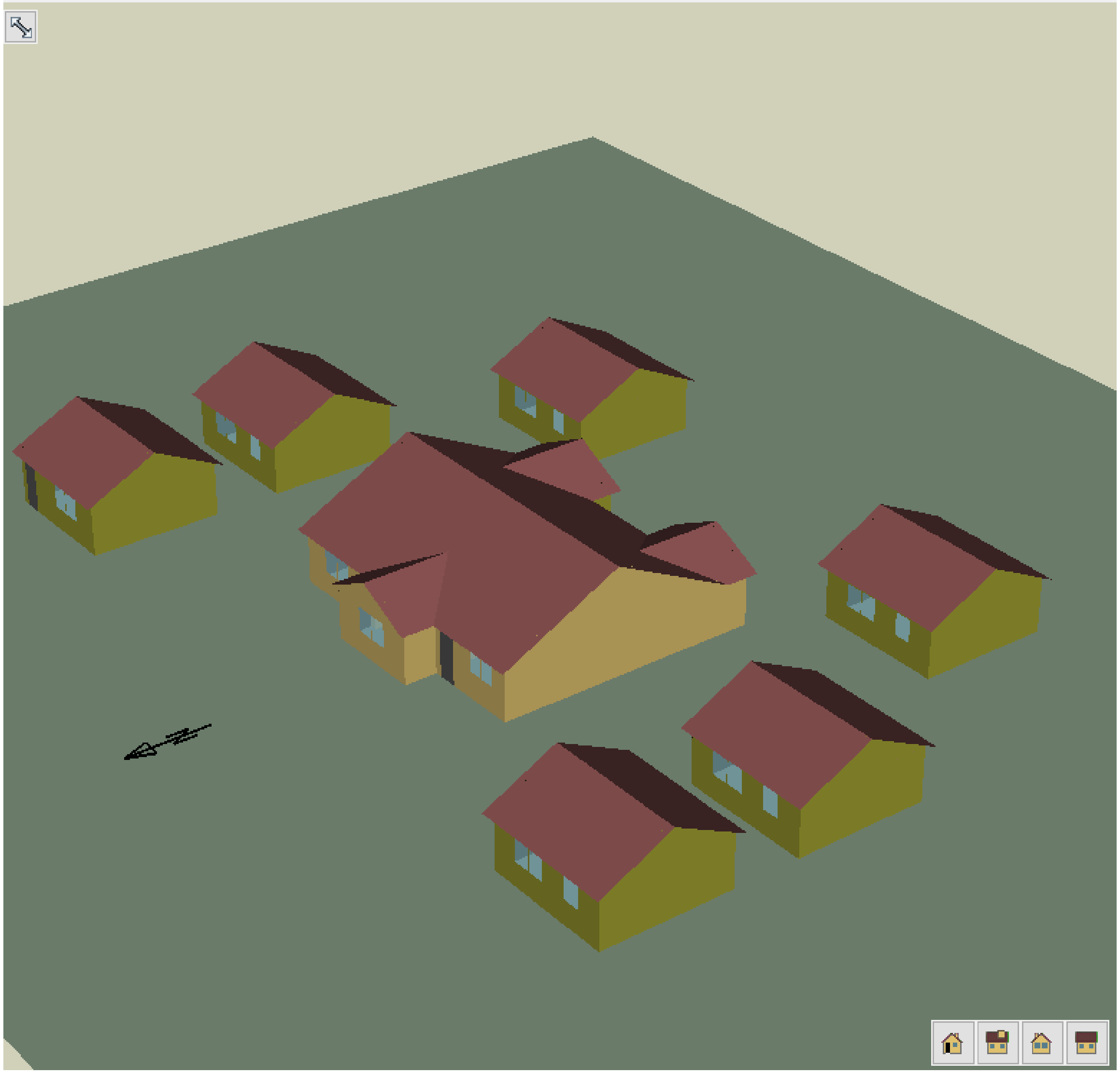

Figure 18: A rendering of the village tiny home use case. The central community building provides laundry, cooking, and showering facilities for surrounding tiny homes.

For easy comparability, the three community services building models were designed to be identical in square footage and layout, and only differ in energy type (solar PV, all electric, or natural gas). Utility rates were altered to be consistent with each energy configuration. The economic analysis was restricted to annualized utility bills, as the primary purpose of the analysis was to observe the energy use and monthly bill amounts under different configurations. Additionally, because optimization methods would have been impractical for a building of this size without additional computational power, building envelope characteristics similar to the optimized tiny home models were chosen for all models. Building envelope parameters for the community services building are listed in Table 14. Mechanical envelope parameters for the community services building are listed in Table 15.

The community services building was designed to be used in tandem with tiny homes for the tiny home village use case, where residents use the central facility for cooking, laundry, and shower facilities, and live in tiny homes near the central building.

Table 14: Building Parameters for the Community Services Building

Category Name	Community Services Building, All Models
Building Area	3502 Square Feet
Orientation	North
Neighbors	None
Wood Stud	R-21 Fiberglass Batt, 2x6, 24 in o.c.
Wall Sheathing	R-12 Polyiso
Exterior Finish	Vinyl, Medium/Dark
Finished Roof	R-38C Fiberglass Batt, 2x10, R-24 Polyiso
Roof Material	Asphalt Shingles, Medium
Slab	Whole Slab R40, R10 Gap XPS
Floor Mass	Wood Surface
Exterior Wall Mass	2 x 1/2 in. Drywall
Ceiling Mass	2 x 5/8 in. Drywall
Window Areas	F15 B15 L0 R0
Windows	Low-E, Triple, Insulated, Air, H-Gain
Interior Shading	Summer = 0.7, Winter = 0.7
Door Area	20 Square Feet
Doors	Fiberglass
Eaves	1 ft

Table 15: Mechanical Envelope Parameters for the Community Services Models.

	Solar PV and All Electric Model	Gas Model
Category Name	Current Option Name	Current Option Name
Air Leakage	7 ACH50	7 ACH50
Mechanical Ventilation	2010, Exhaust	2010, Exhaust
Natural Ventilation	Year-Round, 3 days/wk	Year-Round, 3 days/wk
Furnace	-	Gas, 78% AFUE
Air Source Heat Pump	Air Source Heat Pump SEER 17, 8.7 HSPF	-
Cooling Set Point	80 F	80 F
Heating Set Point	67 F	67 F
Humidity Set Point	60%	60%
Dehumidifier	Autosized, Standalone	Autosized, Standalone
Lighting	100% LED	100% LED
Refrigerator	Top Mounted, EF = 21.9	Top Mounted, EF = 21.9
Cooking Range	Electric	Gas
Plug Loads	4350 kWh per year	4350 kWh per year
PV System	12.8 kW	-
PV Azimuth	South Roof	-
PV Tilt	Roof, Pitch	-
Washer	EnergyStar	EnergyStar
Dryer	Electric	Gas

Figure 19 below shows a layout of the community services building. The figure was generated from EnergyPlus, the simulation engine, using the same input file used to run the simulation. However, it is important to emphasize that the analysis focuses on energy use configurations and feasibility, rather than architectural details.

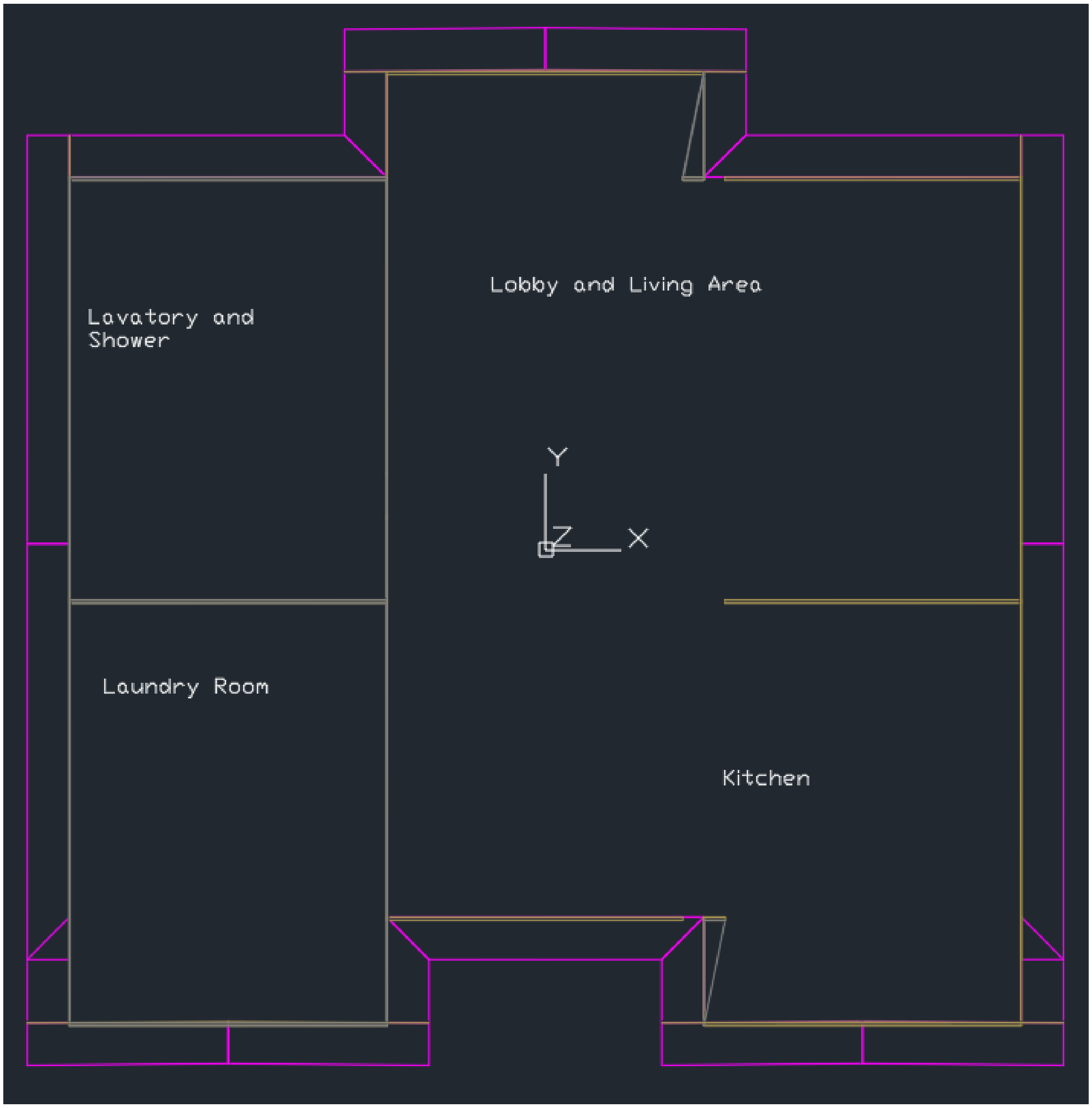

Figure 19: General floorplan for the community services building (3502 ft^2.). This image was exported to Autocad from EnergyPlus using the input file (generated by BEopt) that was used to run the simulation.

Comparison of Tiny Home Models to a Modeled Conventional Home

In order to obtain a broader perspective on the potential energy use savings of tiny homes, a conventional home was modeled in BEopt for comparison with tiny home models. The intent of this model was to illustrate how much energy a typical 3-bedroom home might use annually in coastal Humboldt County modeled in the same framework as the tiny homes and community building, and to describe the energy, cost, and greenhouse gas emissions savings potential of tiny homes in comparison to conventional housing. The conventional home model is based on a reduced energy version of the Building America 2010 benchmark simulated using a weather file for Arcata, California. These Building America benchmark are designed to serve as a reference level of energy use against which energy savings improvements are compared (Department of Energy, 2012).

The building is modeled with a 2,425 $ft.^2$ floor area, slightly larger than the average 2,386 $ft.^2$ reported by the Census Bureau for newly built homes in the West census region for 2010 (United States Census Bureau, 2010). A sensitivity analysis on the square footage of the model was chosen to be very close (1,575 square feet) to the California average household square footage of 1,583 reported by the EIA (2009).

In order to enable meaningful and direct standards of comparison, the individual use case tiny home was used, because it contains a hot water heater and most energy uses (excepting a washer and dryer) associated with a typical residence. While the appliance and other energy uses would not exactly match, the intent was to render the models directly comparable.

Publicly available per capita energy use data for California from the Energy Information Administration were analyzed to place the simulation results in a broader social perspective. A comparative discussion of the per capita energy use data with the results is located in the discussion section.

Sensitivity Analysis

One of the primary advantages of optimization modeling is that an optimization can be configured to view building envelope or mechanical systems that are sensitivity factors. For instance, a sensitivity analysis of interior wall insulation type can be accomplished using a BEopt optimization configured for this purpose. By optimizing a building energy model before more detailed analyses are conducted, variation in the results based on mechanical and building envelope parameters is observed, and specific changes can be tested for. While this is not necessarily identical or equivalent to a traditional sensitivity analysis, it serves the purpose of observing variation, which is especially useful given that building energy models contain too many parameters to conduct a sensitivity analysis on all of them, some of which may have significant interactive effects.

The sensitivity analysis considers only economic parameters, because economic parameters such as mortgages, energy escalation rates, and discount rates are not optimized in BEopt. The economic parameters considered are listed in Table 10, along with the original economic parameters, for direct comparison.

Synopsis of Methods

The methods section began by introducing the assumptions and scope of the analysis, defining the terms building energy model, energy model type, and use case, and delineating the models considered for individual tiny homes and a tiny home village supported by a central community services facility. The analysis was broken into phases: the optimization phase, which identifies models with lower energy use and a lower lifecycle cost, and a design phase, which uses the results of the optimization phase to analyze the lifecycle cost, greenhouse gas emissions, and energy use of tiny homes in more detail.

Optimizations and input parameters for the sequential search algorithm in BEopt were described. The input parameters for design phase models were given, and methods used in the greenhouse gas emissions estimation and lifecycle cost analysis were described. Finally, the sensitivity case, which considers changes in several economic parameters, was enumerated. The results section that follows gives the results of these analyses.

RESULTS

This section begins with results for the optimization simulations, which included anywhere from dozens to over 1,000 simulations of different building envelope and mechanical designs for the energy model types and use cases considered. The second and third sections present results for the annualized energy use of village and individual tiny homes. Subsequent sections show the greenhouse gas emissions, lifecycle cost, and the sizing of PV systems associated with each case.

Finally, the energy use of community services building models is presented. The results section concludes with a comparison of the tiny home modeling results with the modeling of an average-sized home and the results of a sensitivity case for village use case tiny homes.

Tiny Home Energy Modeling Optimization Results

The optimization results show a broad range of annualized energy use outcomes, depending on the insulation and mechanical system efficiencies. Figure 19 below shows the optimization results for village use case, zero-net energy tiny homes on a slab-on-grade foundation. This optimization was used to observe likely outcomes for a slab-on-grade model type, but was not included in the design phase analysis. Figure 20 shows the same data with site energy savings on the x-axis and a magnified y-axis scale.

Ideally, the beginning point in sequential search optimization lies to the side of the graph corresponding to the highest lifecycle cost and energy consumption. However, this is not always necessarily the case, depending on the choice of beginning optimization, and depending on the discrete search space chosen. The choice of initial discrete search space determines the shape of the resulting optimization results. In the following figures, black lines down the center of the search space indicate the beginning of the optimization, meaning that a significant fraction of the chosen search space was less energy efficient than the initial optimization point. However, the starting point of the optimization algorithm does not affect the validity of the resulting energy models.

There are different types of optimizations BEopt can conduct, and different types of optimal points, such as maximum energy savings relative to a reference case, or minimum cost. In Figure 20, the blue circle indicates the lowest lifecycle cost with respect to the economic parameters entered into BEopt. As described in the methods section, simulations that are net negative would have PV arrays resized for zero-net energy if they were chosen for analysis in the design phase.

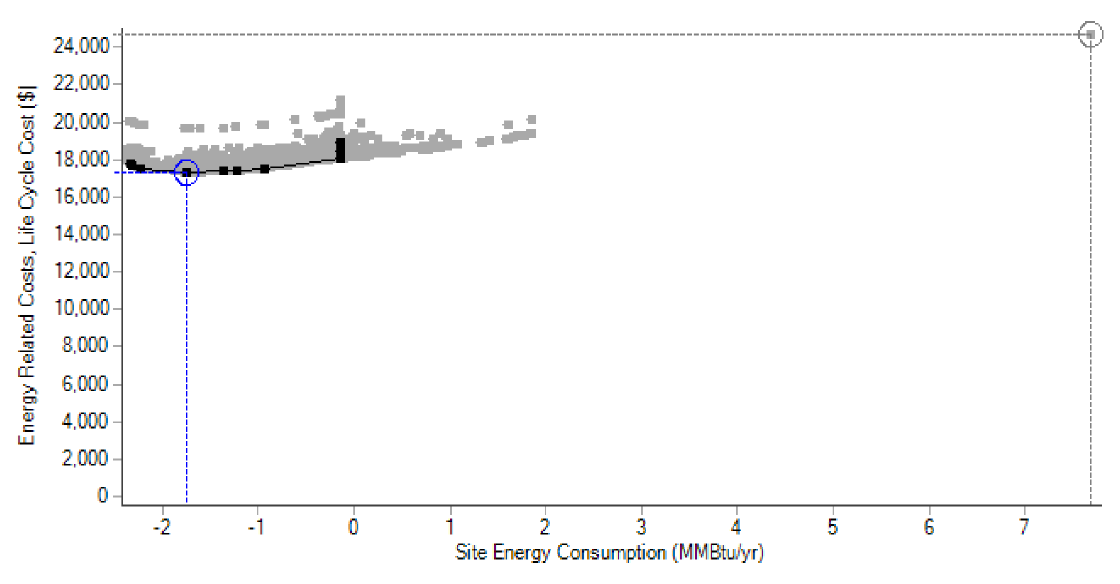

Figure 20: Zero-net energy, slab-on-grade tiny home optimization results. These results are for the tiny home village use case.

The circled point, or very bottom point on the optimization curve, shows the optimal (lowest life cycle cost) design option in these figures. However, in practice, there may exist a number of reasons to choose one of the other simulated options. Because the data are identical to Figure 20, Figure 21 omits the axis so that the discrete convex optimization curve created by BEopt's sequential search algorithm may be observed. The circled point in Figure 21 shows the least-cost option along the optimization curve under the economic assumptions.

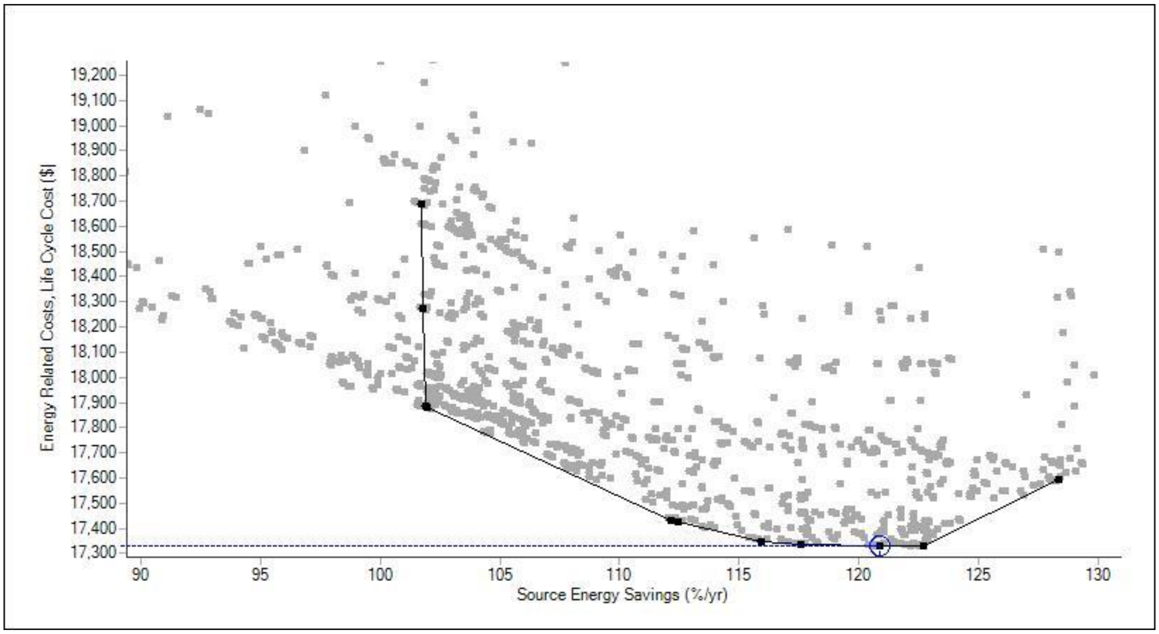

Figure 21: Optimization results for slab-on-grade tiny homes for a village use case.

Figure 22 below shows optimization results for over 1,200 pier and beam tiny homes. The origin of the y-axis scale was set to zero to avoid visually exaggerating the actual variability of the results, which is only a fraction of the total variability likely to be seen by real use cases due to construction and labor costs. The x-axis variation in the region of the simulation results shown represents an annual energy use difference of approximately 1,400 kWh per year, or 43,000 kWh over the assumed 30-year lifecycle of a modeled tiny home. The y-axis represents a difference of $3,200 in energy-related costs over the lifecycle of the building.

The graph shows that the energy use of modeled tiny homes varies far more than the lifecycle cost under the analytical assumptions. The zero-net energy design for the lifecycle cost analysis was taken from the lower left-hand region of the graph in the region of the blue circle, which contains simulated models with a lower calculated lifecycle cost and annualized energy use. The black circle shows the beginning point of the optimization. The flat line may be explained by the return of net metering rates, which compensate close to $0.03 per kWh for the rate structure used in this simulation. This means that past zero-net energy, the customer would be credited $0.03 per kiloWatt hour. In many instances, the solar array of optimized buildings could be resized to align net annual energy use with consumption, thus reducing the lifecycle cost further, because BEopt does not autosize solar arrays.

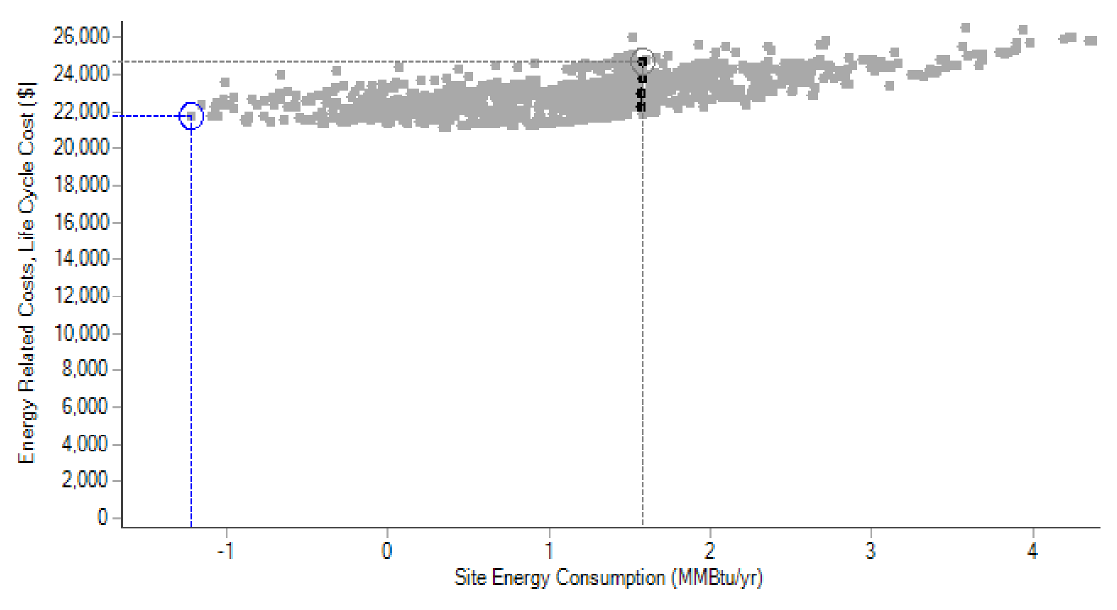

Figure 22: Optimization results for pier and beam tiny homes with PV.

The propane model optimization exhibited a more linear optimization pathway. This is likely due to the parameter search space configuration. Nonetheless, the optimization effectively reduced both the lifecycle cost and the annualized energy use. Figure 23 shows the optimization results for the propane tiny home model.

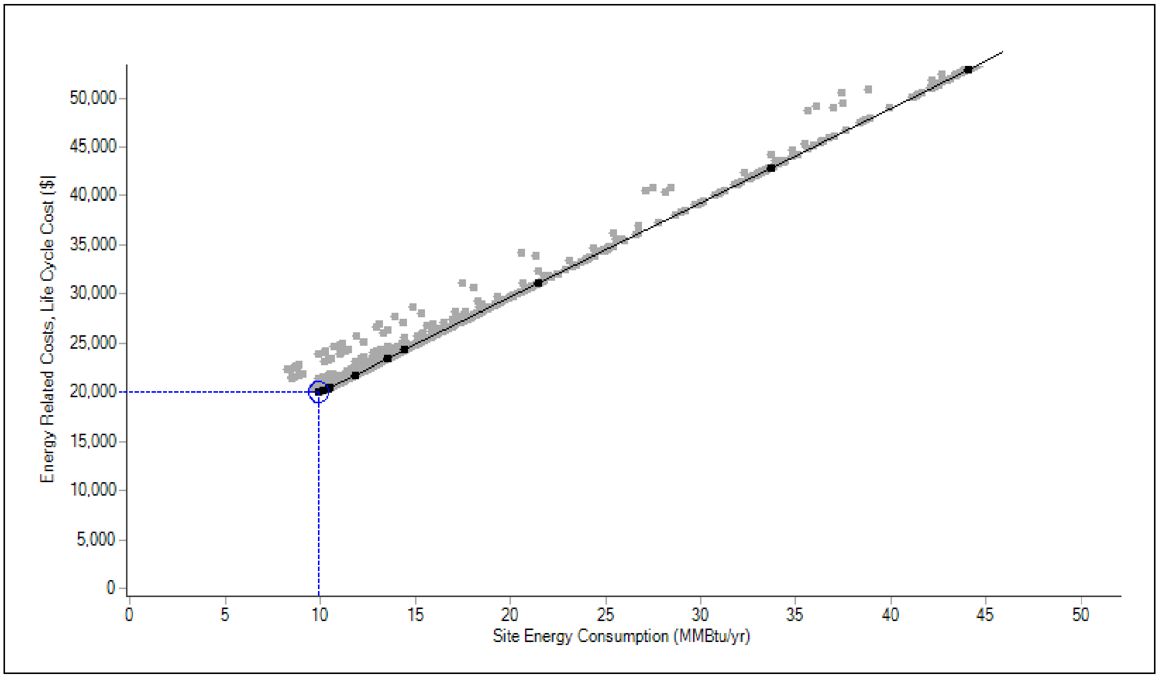

Figure 23: Optimization results for pier on beam tiny homes with propane.

The conventional home optimization is shown in Figure 24. This optimization used fewer iterations because the simulation runtime is proportional to the size of the modeled building, and the conventional home model was used to compare energy use.

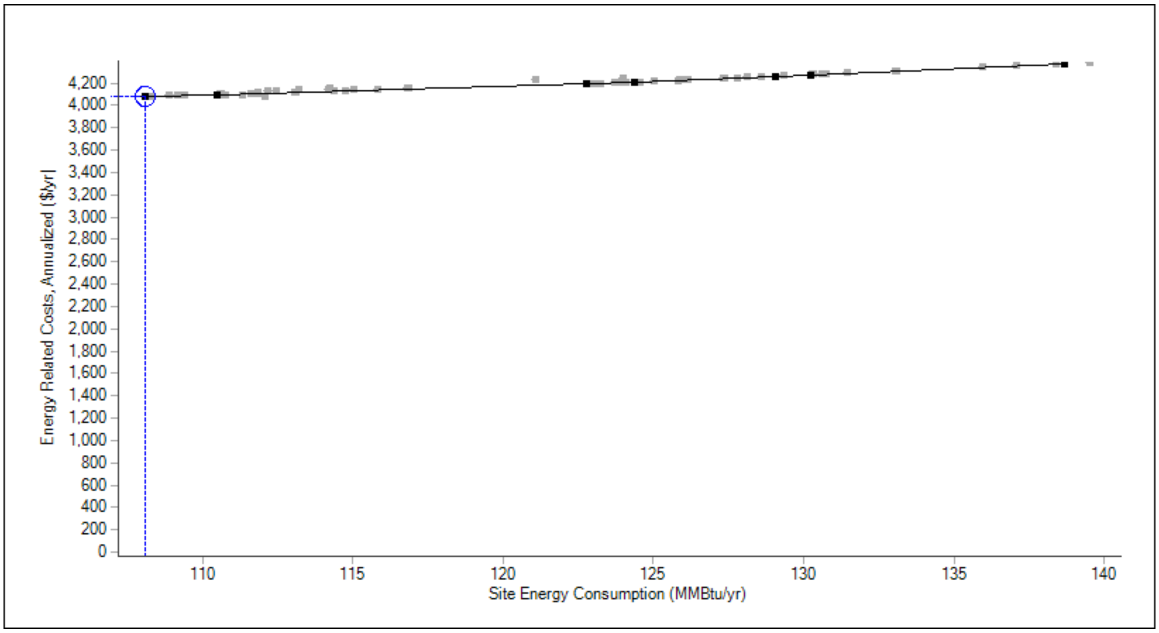

Figure 24: Optimization of a conventional home for comparison purposes with tiny homes.

Figure 25 below shows the annual site energy use for the base and optimized pier and beam zero-net energy models. On-site energy consumption was reduced by nearly 50%, and net energy was reduced from 463 kWh per year to -358 kWh per year. The figure shows that most of the annual energy savings is attributable to heat energy savings, either from building insulation, a different mechanical heating system, or both. Energy savings through properly sizing the HVAC system was a common occurrence during the optimization phase.[40]

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[40] While the HVAC system sizes simulated by Energyplus are not guaranteed to be available on the open market, a review of available products shows that air-sourced heat pumps sized for tiny homes less than 550 square feet in size exist. While many of these products have capacities above those modeled by Energyplus, the modeled costs appear to be within a reasonable range of what is available on the open market. See https://climateright.com/mini-split-4000-12000btu-diy-quick-connect-air-conditioner-heater.html

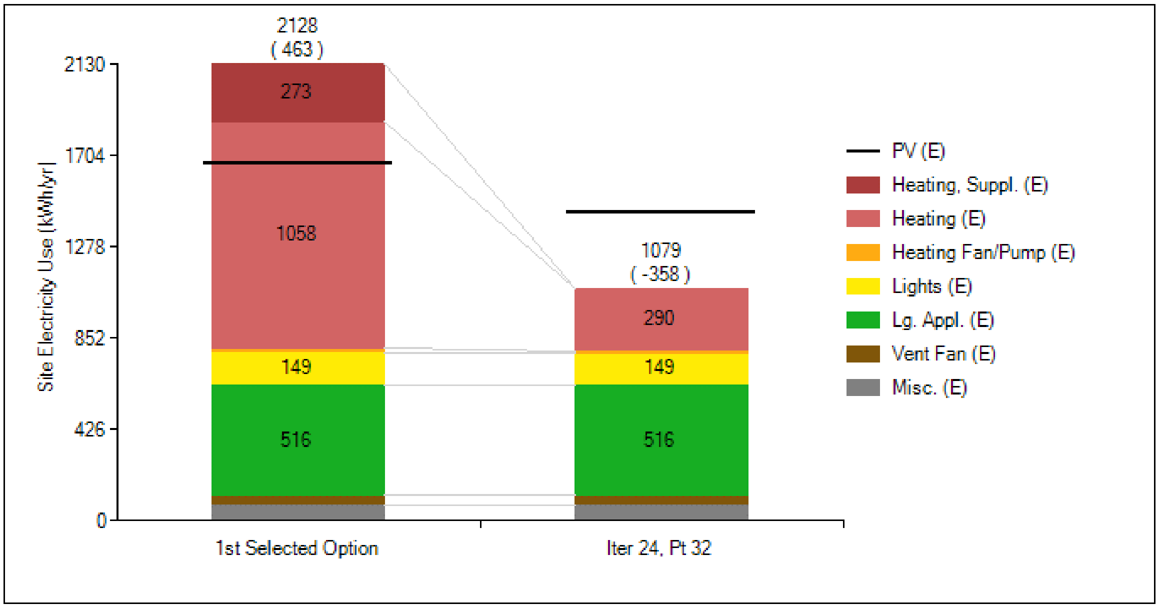

Figure 25: Before and after annual energy use totals for pier and beam tiny homes with solar PV. While the reported lifecycle cost for the optimized tiny home was lower than the first selected option, it achieved zero-net annual energy. The energy use types in each bar graph appear in the same order as the legend to the right, from top to bottom. The lines between the bars indicate the change in energy use for each type.

The optimization results for the individual tiny homes show an annual site energy consumption that was optimized from 2,559 kWh to 2,142 kWh. These tiny homes were modeled to be fully functional, with a 20-gallon water heater that uses half the national average, or approximately 15 gallons of hot water per day. The design phase hot water use was later adjusted to reflect the national average so that results were more comparable with the community use case. While the lifecycle costs reported were not adjusted for local sales tax or California-specific prices, the fully functional, ZNE, slab on grade, individual use case is similar in annual utility cost to the pier and beam that does not contain running hot water, near $100 annually. Figure 26 shows the optimization results for the individual, slab-on-grade tiny homes.

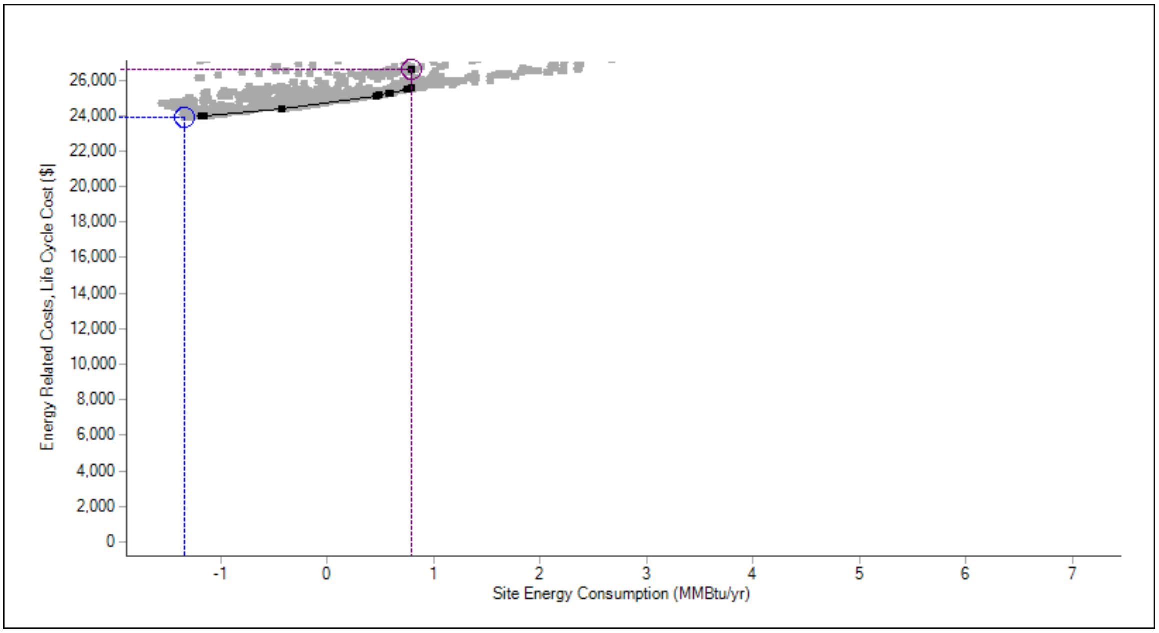

Figure 26: Optimization results for individual, slab-on-grade tiny homes (1,500 iterations).

Figure 27 shows a focused image of Figure 25. The red and blue circled points correspond to the beginning and end of the optimization, respectively. The change in annual energy consumption corresponds to a 22% reduction, from approximately 2,800 kWh to 2,170 kWh. The optimization annual site energy consumption results for these two points is shown in Figure 28. The black lines in Figure 28 show the simulated annual PV electricity production. Depending on the analytical assumptions, the optimized simulation suggests that the PV system size could be adjusted to reduce the lifecycle cost further.

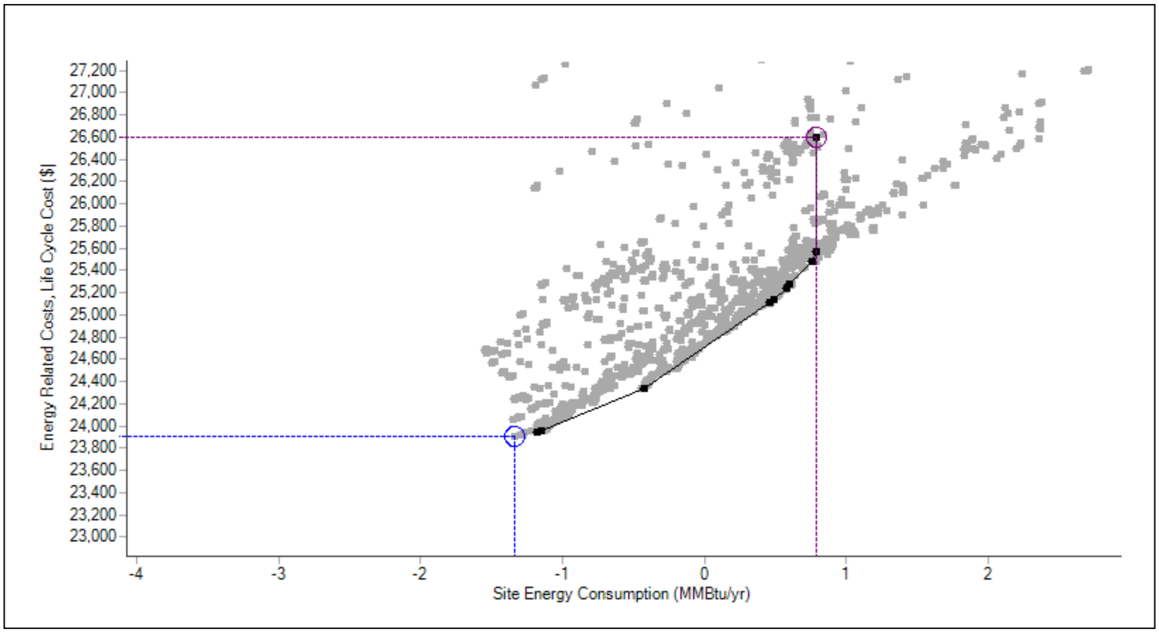

Figure 27: A focused image of Figure 24.

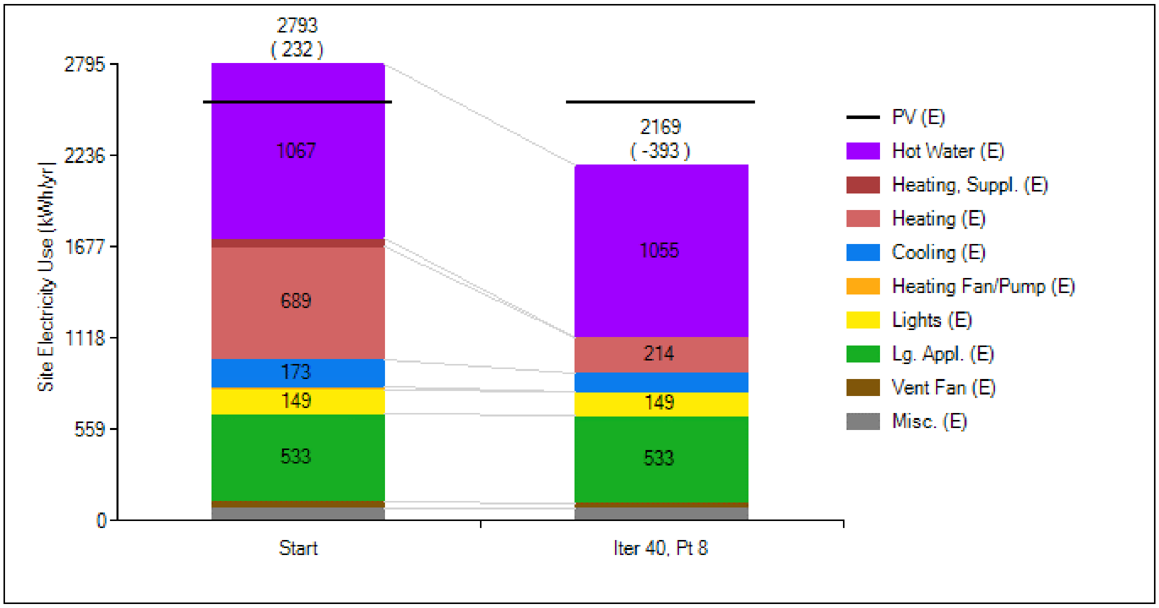

Figure 28: Annual site electricity use results for the beginning and ending simulations of the individual, slab-on-grade optimization. The energy use types in each bar graph appear in the same order as the legend to the right, from top to bottom. The lines between the bars indicate the change in energy use for each type.

Tiny Home Annualized Energy Use: Village Use Case

The zero-net energy model was found to have an annual energy use of 1,169.85 kWh, while the propane model was found to use 2,897.7 kWh equivalent of energy annually. Eighty-one percent of the propane model's energy use was from propane or 89.1 gallons of propane per year. The net annual energy use of the zero-net energy model was found to be -113.15 kWh. Figure 29 shows the simulated energy use, by energy type, for the zero-net energy model. Table 16 shows the annual energy use totals and net energy use, by use type and energy type, for the zero-net energy and propane models.

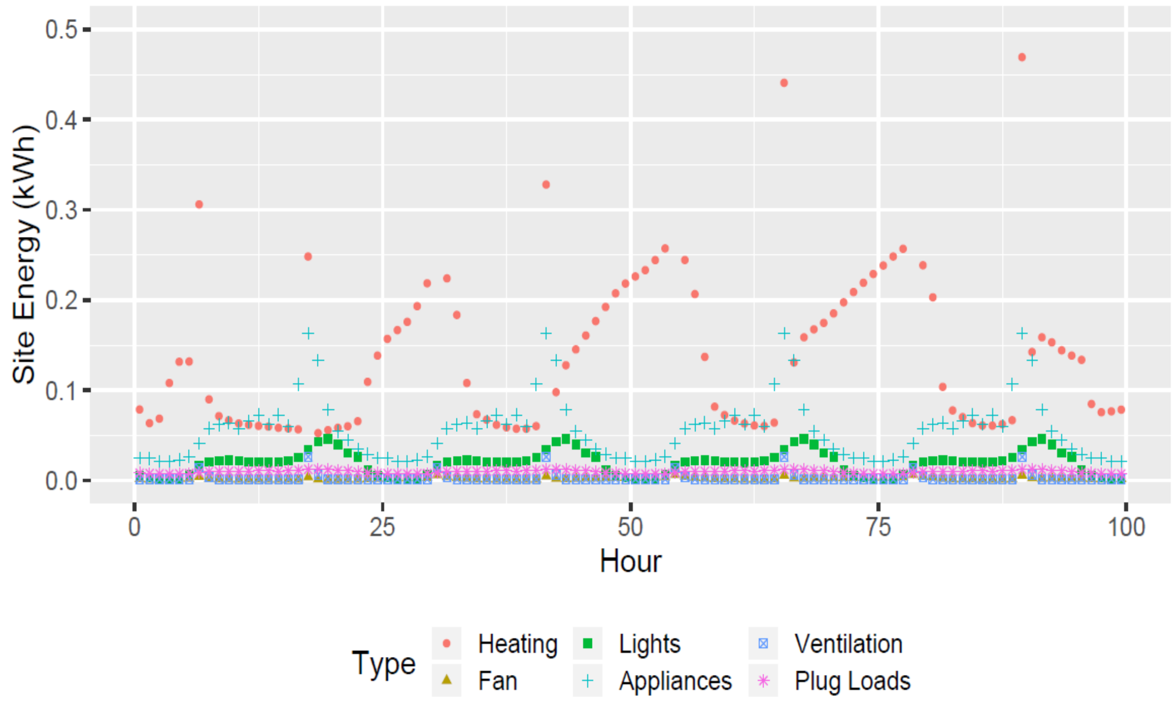

Figure 29: First 100 hours of energy use, by type, for the Pier and Beam Zero-net Energy model.

Heating and appliances and cooking use the most energy in both models. Propane energy use for heating and cooking is found to be the largest energy use for the propane model. The zero-net energy model is simulated using a 1.0 KW PV array.

Table 16: Annual Energy Use for the ZNE with a 1 KW PV Array and Propane Village Design Phase Models. (Cooking for the ZNE model is included in Appliances)

ZNE Model Category	ZNE Annual Totals (kWh)	Propane Model Category	Propane Model Totals (kWh Equivalent)
Total kWh	1,170	Total Electricity (kWh)	550
Heating	400	Propane Heating (kWh Equivalent)	1,800
Fan	10	Fan	40
Lights	150	Lights	150
Appliances	510	Electrical Appliances	250
Ventilation	30	Ventilation	30
Plug Loads	70	Plug Loads	70
Solar PV Production	-1,280	Cooking (kWh Equivalent)	550
Net Energy	-110	Net Energy (kWh Equivalent)	2,890

Table 17 shows the monthly energy use results for the Zero-net Energy tiny home model. The signature pattern of a grid-connected PV house is observed, where the net energy use becomes negative in the summer months in a parabolic shape.

Table 17: Monthly Energy Use Results for the Zero-net Energy Tiny Home Model.

Month	Net Energy Use (kWh)	Solar Production (kWh)	Total Energy Use (kWh)
1	62	79	141
2	27	80	106
3	4	109	112
4	-27	129	102
5	-44	133	89
6	-54	122	68
7	-68	131	63
8	-50	118	68
9	-44	116	72
10	-10	100	90
11	31	86	116
12	62	81	143
Total	-113	1283	1170

Figure 30 shows the total monthly energy use, total solar energy production, and net energy use for the zero-net energy tiny home model.

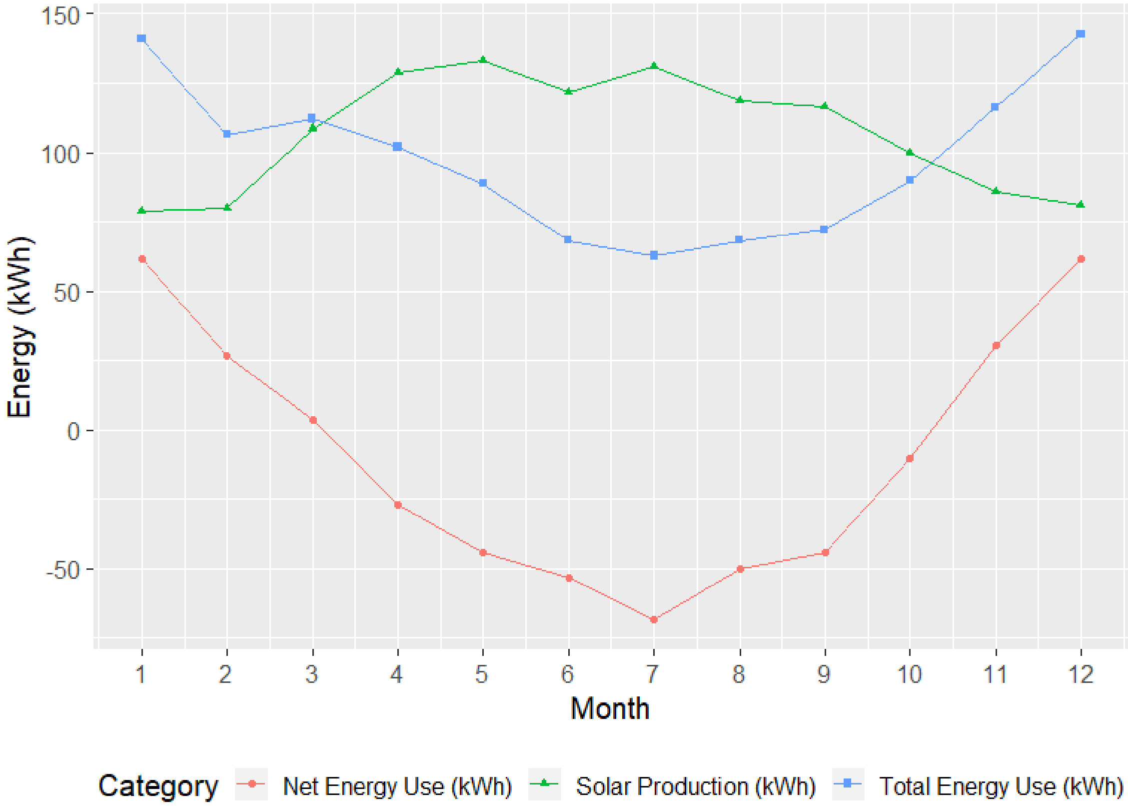

Figure 30: Monthly energy use for the zero-net energy tiny home design model. The lines are added for visual clarity.

<u>Off-grid solar model</u>

Table 18 shows the cost breakdown for the PV and battery system of the off-grid solar model. Under the modeling assumptions, the battery storage system constitutes nearly one half of the lifecycle cost of the combined PV-battery storage system at $12,600.

Table 18: Undiscounted Lifecycle Cost of a Solar Array and Battery Bank for the Off-Grid Solar System with a 4.5 kW PV Array.

System	Parameter	Value	Unit
PV	Total Initial Cost	$13,050	$
	Replacement Costs	$10,800	$
	Inverter Cost and replacement	$1,200	$
	Operation and Maintenance	$0	$
	Salvage	-$8,640	$
	Total Undiscounted Lifecycle Cost	$16,410	$
Battery	Total Initial Cost	$6,000	$
	Replacement Costs	$6,000	$
	Operation and Maintenance	$3,600	$
	Salvage	-$3,000	$
	Total Undiscounted Lifecycle Cost	$12,600	$
Both Systems	Total Undiscounted Lifecycle Cost	$29,010	$

Because this system would cost substantially more than any of the grid-connected cases considered (nearly doubling the lifecycle cost), it is not economically feasible. However, it is important to note that this model was generated using a grid-connected tiny home model with no demand response and a typical load profile. This means that with a different load profile or different energy use assumptions, the answer may change significantly.

Tiny Home Annualized Energy: Individual Use Case

The individual tiny home chosen from the optimization phase used a total 3,000 kWh per year in energy, and achieved zero-net energy with a 2.35 kW solar panel. Because an occupancy of 2-3 people was assumed, a national average hot water draw profile near 33 gallons per day was used. Figure 32 shows that the vast majority of the energy use is due to the electric hot water heater. Consequently, assumptions about the extent of hot water use will significantly affect the results.

A sensitivity analysis was conducted by changing the slab to a pier and beam design with R-38 fiberglass insulation. The annualized energy use results were found to vary by less than 1% for the model considered.

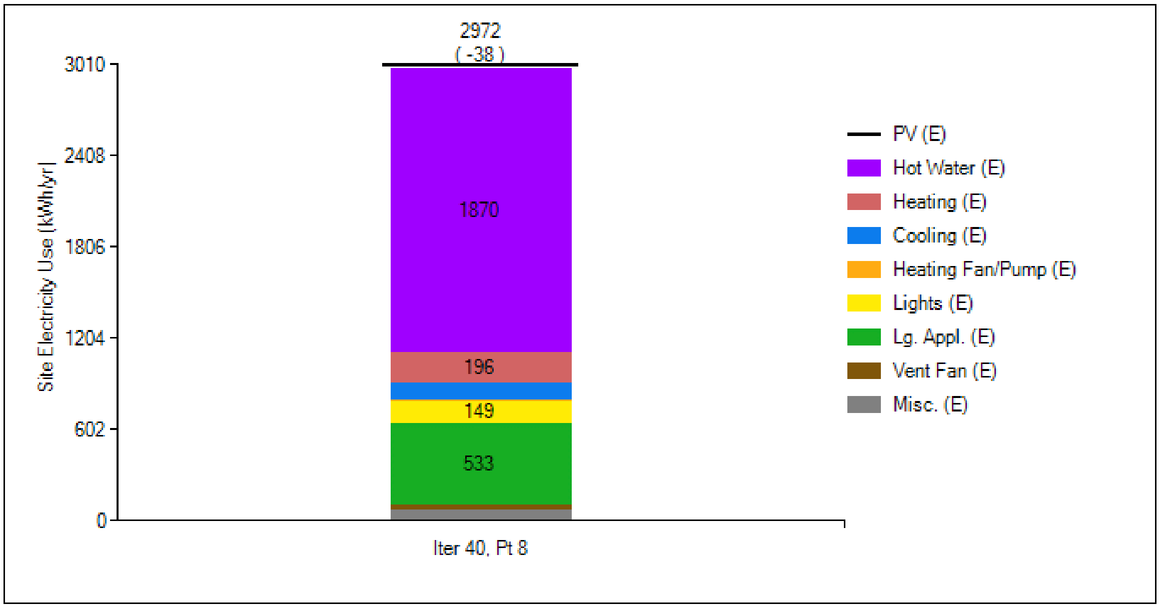

Figure 31: Annualized site energy use, by type, for the individual tiny home model. From top to bottom: the energy use types in each bar graph appear in the same order as the legend to the right. The lines between the bars indicate the change in energy use for each type.

Greenhouse Gas Emissions

The results for greenhouse gas emissions are shown in Table 19. The zero-net energy models achieved the lowest net greenhouse gas emissions, and the lowest total emissions for the tiny home models considered.

Table 19: Greenhouse Gas Emissions, by Model and Energy Type (CO_2 Equivalent)

Model	Total (Metric Tons/Year)	Net Emissions (Metric Tons/Year)
ZNE Tiny Home Model	0.1	0
Propane Tiny Home Model	0.5	0.5
ZNE Individual Model	0.3	0
All Electric Community Services Building	3.2	3.2
Gas-based Community Services	6.7	6.7
Community Services with PV	3.2	1.6
Conventional Gas Model (2,425 Square Feet)	5.1	5.1
Conventional Gas Model (1,575 Square Feet)	3.7	3.7

Lifecycle Cost

The spreadsheet-based analysis and BEopt lifecycle cost analysis were found to vary in their results by less than 10% in all cases, and less than 3% in all cases but one. This shows that the spreadsheet tool that was developed to support this work and enable customization of the assumptions is adequate. In short, analysis supports some confidence in the economic analyses conducted by BEopt, because similar results can be calculated directly. The village zero-net energy tiny home model arrived at an undiscounted life cycle cost of approximately $28,000, while the village propane model resulted in an undiscounted life cycle cost of approximately $22,000 using a spreadsheet, and approximately $24,000 using BEopt. Table 20 shows the life cycle cost analysis results, by model, discount rate, and calculation method, along with the percent difference between methods for each case.

Table 20: Lifecycle Cost Results for the Zero-Net Energy and Propane Village Models

Model	Discount Rate (%)	Spreadsheet-based Life Cycle Cost	BeOpt Life Cycle Cost	Percent Difference
Zero Net Energy Tiny Home Model	0	$28,100	$27,700	1.3%
Zero Net Energy Tiny Home Model	3	$28,400	$28,300	0.3%
Zero Net Energy Tiny Home Model	6	$27,700	$27,700	-0.2%
Propane Model	0	$22,300	$23,700	-5.7%
Propane Model	3	$22,000	$22,700	-3.0%
Propane Model	6	$21,100	$21,400	-1.8%

The undiscounted lifecycle cost for the zero-net energy individual tiny home model was found to vary from approximately $35,300-$35,900. Increasing the discount rate had the effect of lowering the lifecycle cost, most likely due to the discounting of replacement costs of mechanical and PV components late in the assumed analysis period. Table 21 shows the spreadsheet and BEopt results for the individual tiny home model, by discount rate.

Table 21: Lifecycle Cost Results for the ZNE Individual Tiny Home Model

Model	Discount Rate (%)	Spreadsheet-based Life Cycle Cost	BeOpt Life Cycle Cost	Percent Difference
ZNE Tiny Home, Individual Use Case	0	$35,800	$35,400	1.3%
ZNE Tiny Home, Individual Use Case	3	$35,000	$34,900	0.3%
ZNE Tiny Home, Individual Use Case	6	$33,700	$33,700	0.0%

<u>Annualized utility bill results</u>

The zero-net energy tiny home was found to have the lower annualized utility bills in most cases considered, at approximately $100 per year. The propane model was found to have annualized utility bills over three times this amount, at approximately $340 per year. Table 22 summarizes the annualized utility bill results.

The reported results represent the average annual amount in constant 2018 dollars over the 30-year lifecycle of the model. For example, the reported average of $103 for the zero-net energy village model is greater than the amount of $94 calculated for the first year of the model simulation. This is due to energy escalation rates, which were modeled separately from inflation.

Table 22: Annualized Utility Bill Summary Results

Model	Modeled Utility Rate	Annualized Utility Bill ($/Year)
Zero Net Energy Tiny Home: Village Case	Net Metering E-6 Time of Use	$100
Propane Tiny Home: Village Case	E-1 Care Basic	$340
Zero Net Energy Tiny Home: Individual Case	Net Metering E-6 Time of Use	$120
Community Services Building With PV	Net Metering E-6 Time of Use	$4,000
Community Services with Natural Gas	E-1 Care Basic	$3,600
All Electric Community Services	El-1 Care	$5,400
Off-Grid Solar Model	Battery Maintenance	$120

Figure 33 shows the annualized utility bill results over the lifecycle of the design phase tiny home models. Under the NIST escalation rates, the propane model has the highest annual utility bills and experiences the highest overall energy escalation price escalation over its lifecycle.

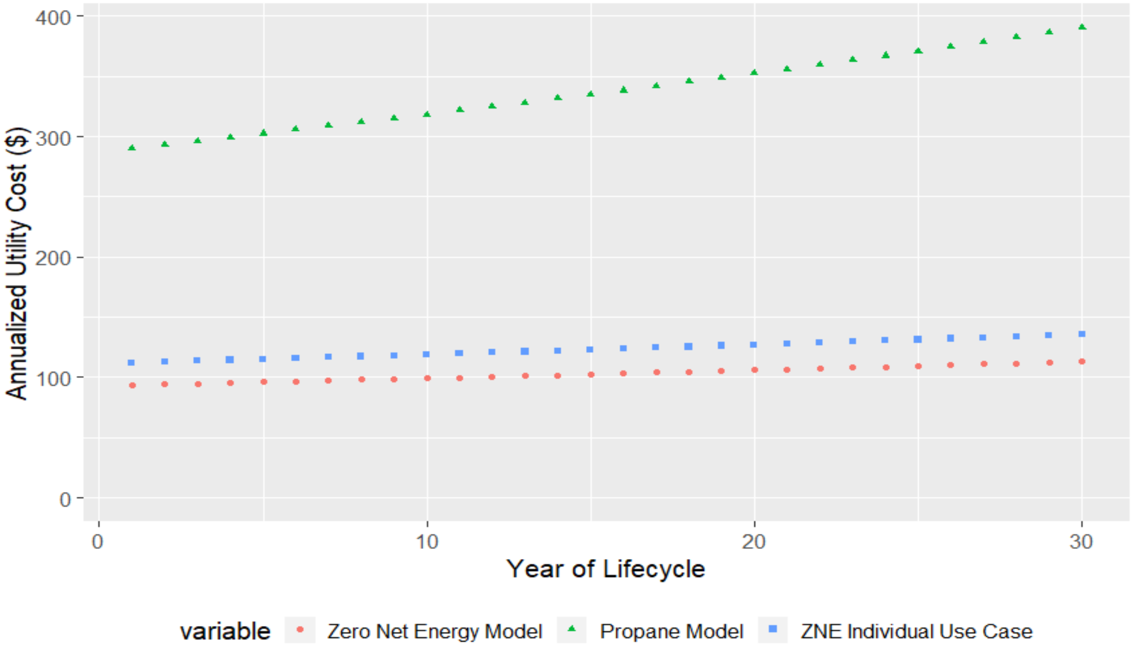

Figure 32: Annualized utility bills for the zero-net energy and propane tiny home models.

Solar PV Sizing and Economics

For the zero-net energy tiny home model considered in the design phase, a solar array of 1 kW most closely approximated zero-net energy. The parametric analysis showed that because of the structure of net metering rates, a system sized for near zero was more economically favorable than a PV system sized to produce excess electricity. The parametric analysis results are shown in Figure 34.

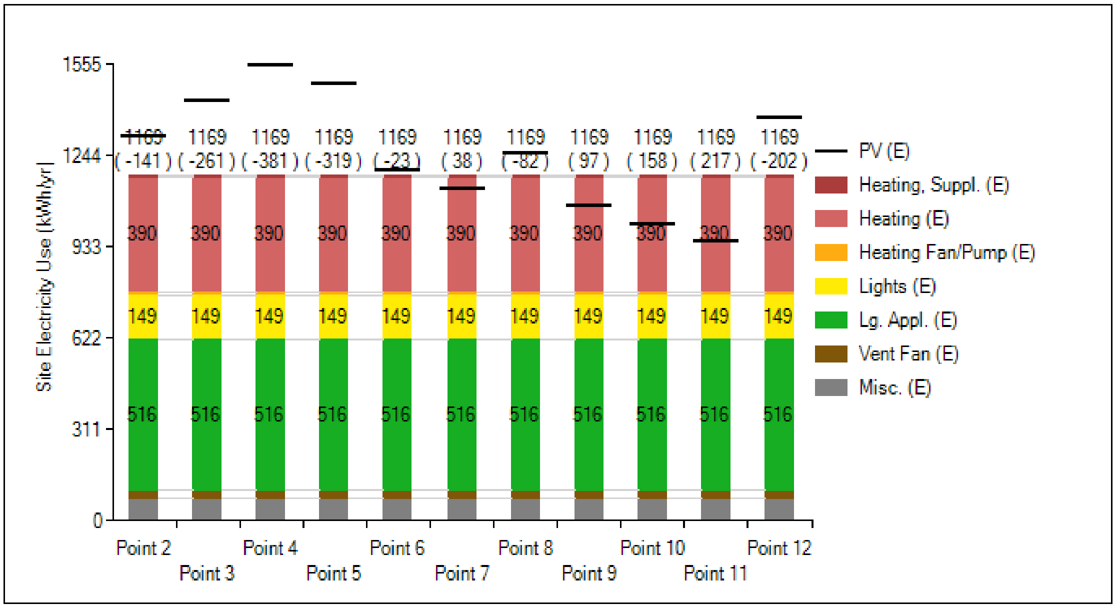

Figure 33: Parametric PV sizing results for the zero-net energy tiny home model. From top to bottom: the energy use types in each bar graph appear in the same order as the legend to the right. The lines between the bars indicate the change in energy use for each type.

The solar PV arrays for each energy model were sized separately from the BEopt spreadsheet; the PV array modeled in BEopt, and the array size calculated using the SEIA methodology is shown in Table 23.

Table 23: Solar PV Panel Sizes, as Modeled in Excel and BEopt

Use Case	PV Array Size from SEIA Method Spreadsheet (kW)	PV Panel Modeled in Beopt (kW)	Percent Error
Community Services Building	13.8	12.8	-7.02
ZNE Village use Case	0.98	1	1.89
PV standalone ZNE Tiny Home	2.49	2.35	-5.57

Table 24 shows the lifecycle cost and levelized cost of energy for each sized solar PV array, by use case and dicount rate. Because the NREL Q1 2016 benchmark of $2.90 per Watt was used for the solar PV cost esimation, the LCOE for each model was only differentiated by discount rate; no scale effects were included, giving an LCOE of $0.10 per kWh for 0%, $0.13 per kWh for 3%, and $0.17 per kWh for 6%.

Table 24: Lifecycle Cost and Levelized Cost of Energy Results, by Model.

Model and Use Case	Discount Rate (%)	Lifecycle Cost ($)	Levelized Cost of Solar Electricity ($/kWh)
Community Services Building PV	0	$35,800	$0.10
Community Services Building PV	3	$33,500	$0.13
Community Services Building PV	6	$32,100	$0.17
ZNE Village use Case	0	$2,600	$0.10
ZNE Village use Case	3	$2,400	$0.13
ZNE Village use Case	6	$2,300	$0.17
PV standalone ZNE Tiny Home	0	$6,500	$0.10
PV standalone ZNE Tiny Home	3	$6,100	$0.13
PV standalone ZNE Tiny Home	6	$5,800	$0.17

Community Services Building Energy Use

The community services building models used between 33,700-42,400 kWh equivalent of energy per year, with the electric models having the lowest site energy use. The all-electric model with no PV was found to be the most expensive in terms of annualized energy use, followed by the PV model and natural gas model. Table 25 gives the energy use for each case, by energy use type. The bottom row gives the average annualized energy bill over the 30-year analysis period for the building, in 2018 dollars. Because the annualized bill total is the uninflated average over the building's lifecycle but includes energy escalation rates, the annualized utility bills in the modeled first year of operation are lower. The PV model, for instance, would cost an estimated $3,640 in its first year of operation.

Table 25: Energy Use and Annual Energy Bill Results for the Community Building

Energy Use Type	PV Model (kWh)	All Electric Model (kWh)	Natural Gas Model (kWh Equivalent)
Miscellaneous	4,700	4,700	4,700
Ventilation Fan	300	300	300
Large Appliances	7,700	7,700	9,800
Lights	2,900	2,900	2,900
Heating Fan	0	0	100
Cooling	900	900	200
HVAC	400	400	2,700
Heating, Supplement	700	700	-
Hot Water	16,100	16,100	21,800
Total	33,700	33,700	42,400
PV	16,400	-	-
Net (Total - PV)	17,200	-	-
Annual Bill Total ($/Year)	$4,000	$5,400	$3,600

The annual hot water use totals over 75,000 gallons of hot water, which corresponds to approximately 11.5 gallons of hot water per person per day. Figure 35 below shows the estimated combined hourly flow rate of hot water at the community services facility for one year. Because the domestic hot water system was modeled as a multifamily unit system with the flowrates combined, there were a few times during the year when non-use intersected, as can be seen by the gaps around hour 5200. These gaps have little practical implication in the results, because variation in the energy use profile from the assumed profile in a real implementation would be expected.

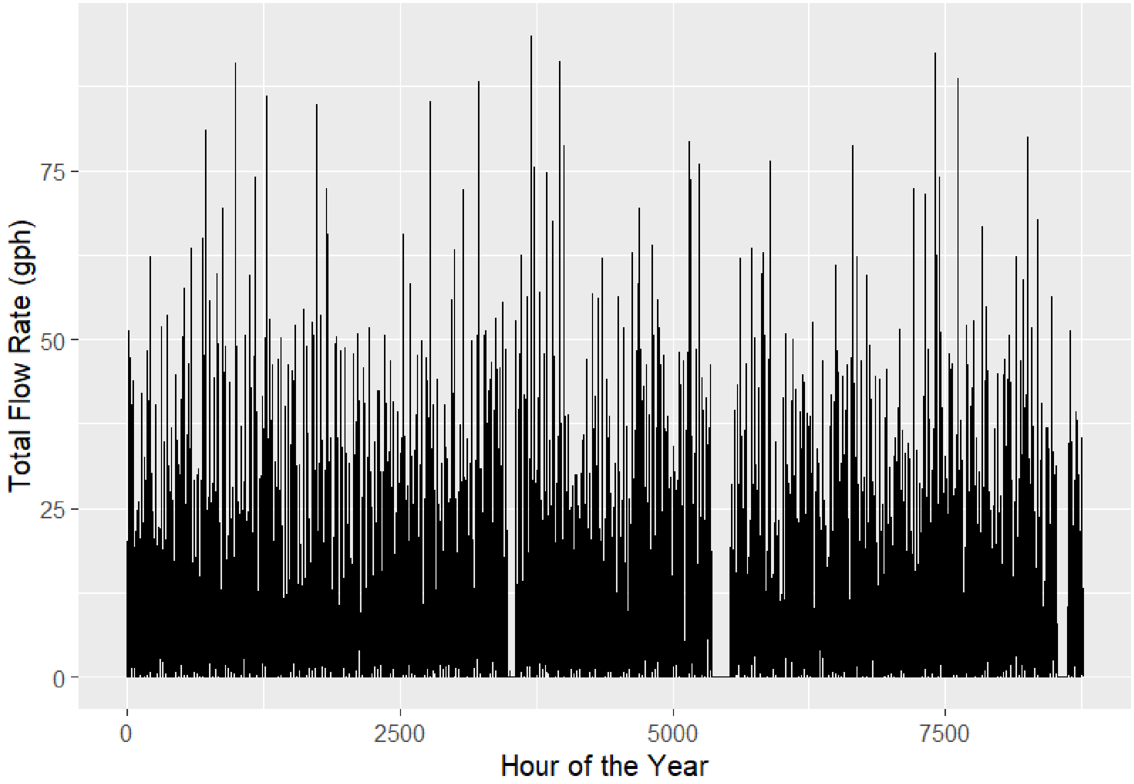

Figure 34: Annual flow rate of hot water simulated at the Community Services Building.

Figure 36 gives the monthly hot water usage of the simulated community services building.

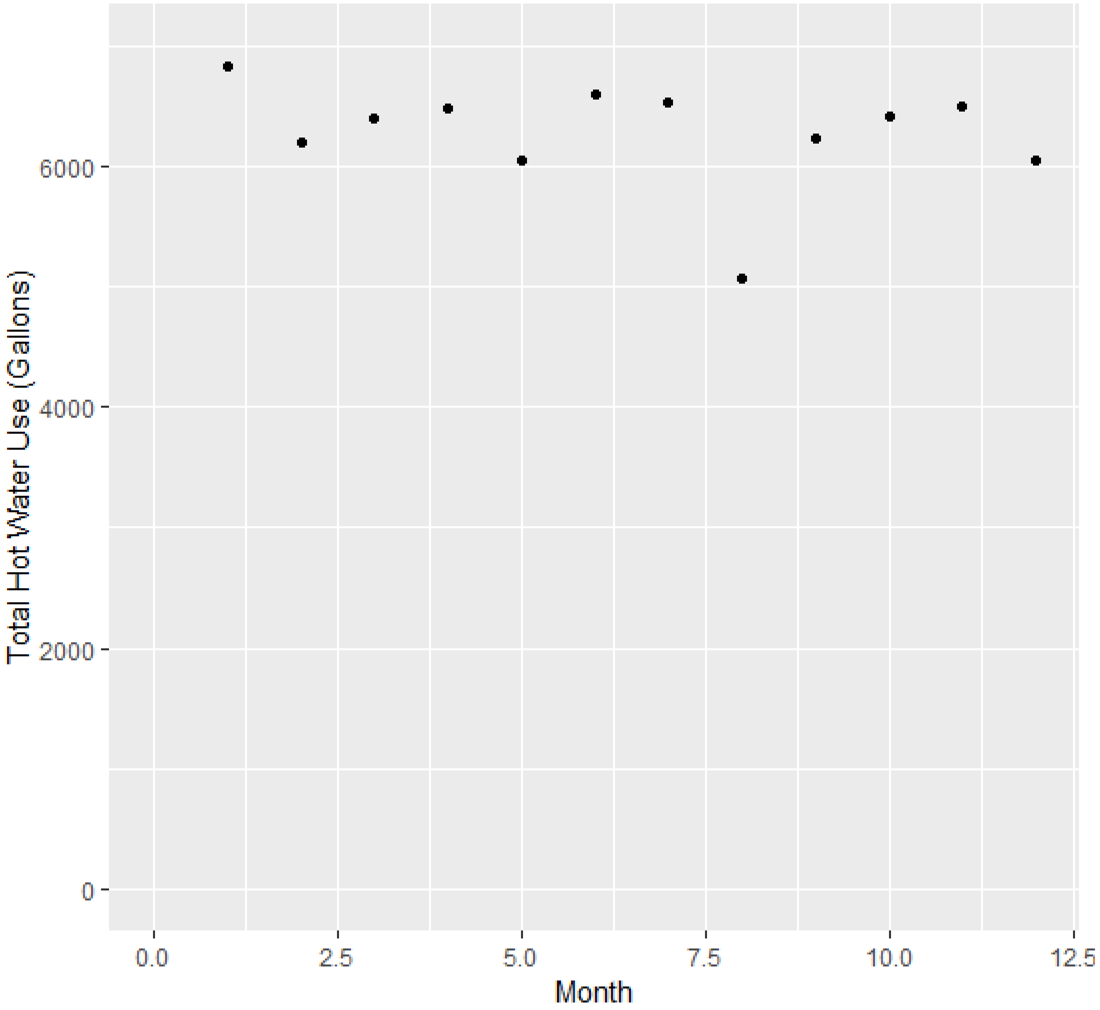

Figure 35: Monthly Hot Water Use at the Community Services Building.

Comparison of Tiny Home Models to a Modeled Conventional Home

The annual energy use for an optimized, pier on beam tiny home with a heat pump water heater is shown in Figure 37. This figure shows source energy, which includes the estimated energy used to produce electricity or natural gas at the plant. This tiny home uses 1.2 million Btu’s of source energy, which is equivalent to approximately 351 kWh per year. The black line indicates the amount of PV energy produced by the PV array. The figure shows that the tiny home consumed 17.8 million Btu’s of source energy total, or approximately 5,214 kilowatt hours.

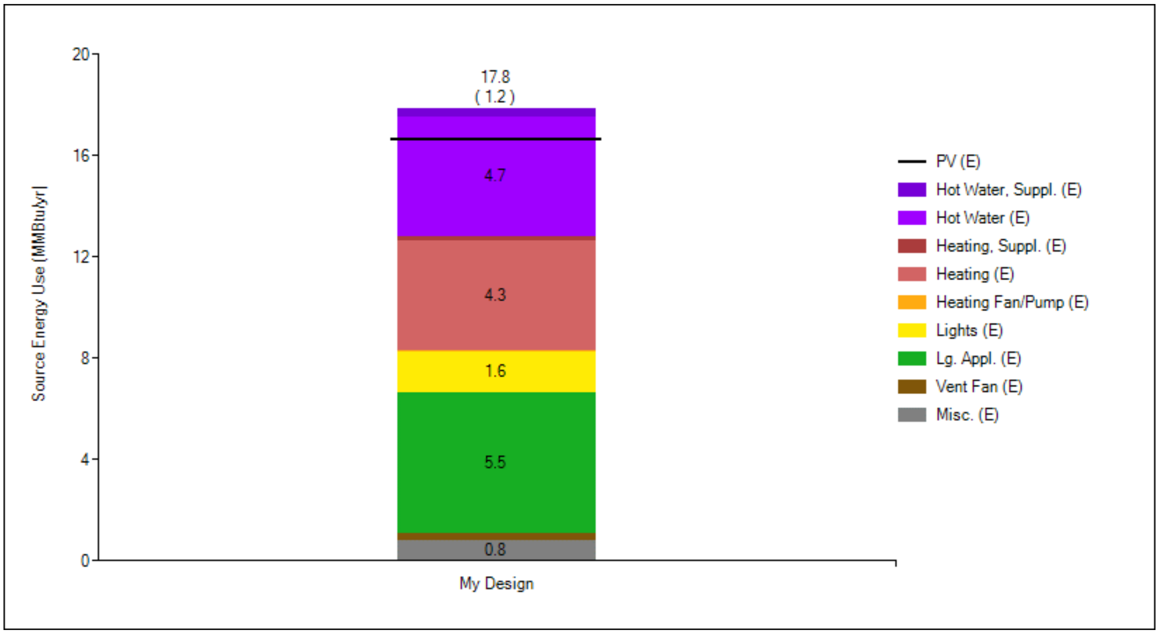

Figure 36: Annual site energy use for a zero-net energy, pier and beam tiny home. The black line indicates the amount of energy produced by a 1.3 kW solar PV panel. From top to bottom: the energy use types in each bar graph appear in the same order as the legend to the right. The lines between the bars indicate the change in energy use for each type.

Figure 38 shows a conventional, slab-on-grade home of 2,425 ft.^{2} with a gas furnace and water heater. The optimized conventional home uses more than three times the annual energy than the tiny home model on a per capita basis—which is to say, if three people are living in the tiny home, and three people are living in the conventional home, then the people in the conventional home are using three times the energy of the tiny home residents. While this conclusion only applies to these two specific models and the assumptions about how much energy the residents are using, it is robust to departures from underlying assumptions. If 6 people were living in the conventional home and 3 people were living in the tiny home, it would still hold true under the energy use assumptions.

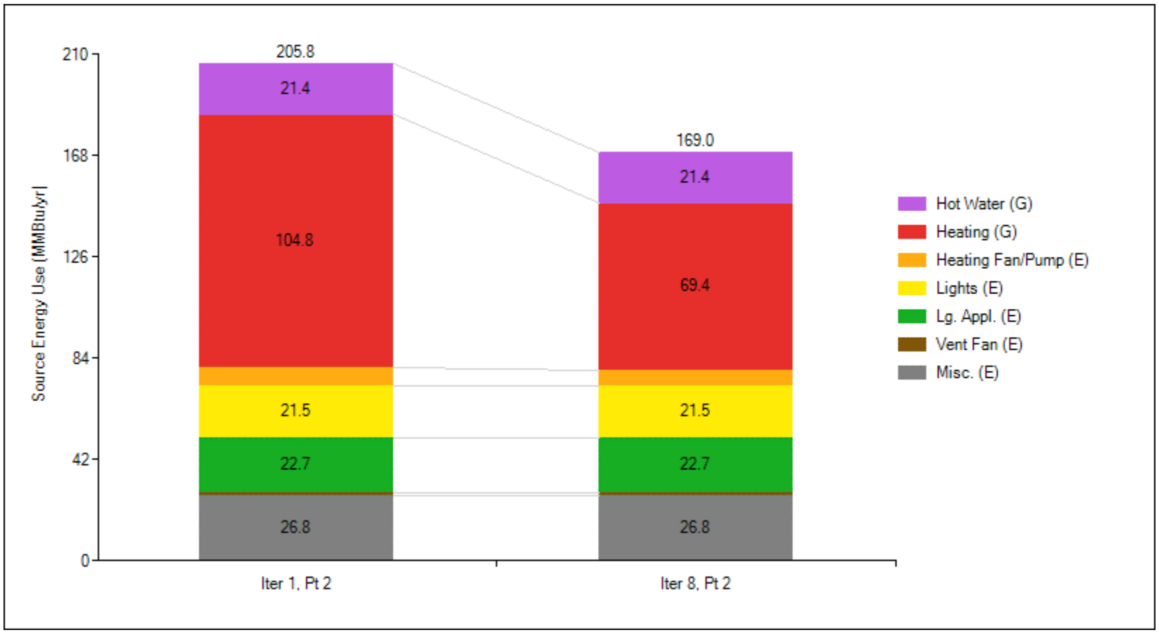

Figure 37: Annual energy use for a conventional, slab-on-grade home. The left total shows a base model without optimization, and the right total shows the model with optimized hot water heating, HVAC, and building insulation. From top to bottom: the energy use types in each bar graph appear in the same order as the legend to the right. The lines between the bars indicate the change in energy use for each type.

Figure 39 shows a frequency distribution of annual source energy use for simulated pier and beam tiny homes with a 1.3 kW solar array. Each point in the frequency distribution corresponds to the results of a different tiny home simulation with a different building envelope and mechanical system configuration. The frequencies at or below zero are zero-net energy, with the remainder being near zero.

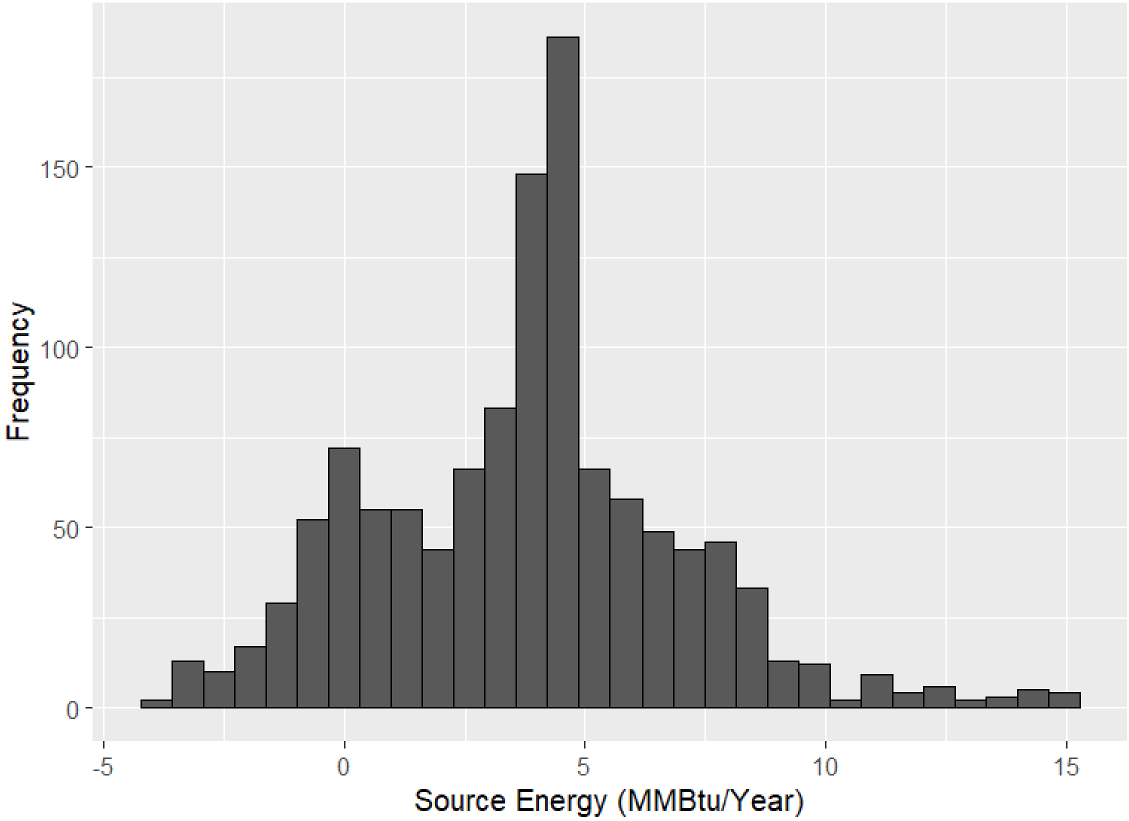

Figure 38: Frequency histogram of net source energy use for pier and beam tiny home simulations with a 1.3 kW solar PV array. The results to the left of zero are 100% zero-net energy (1,188 simulations).

The magnitude of the difference in energy use between the modeled tiny home model and the conventional home model can be seen in Figure 38. In terms of source energy consumption, the tiny home is found to use less than one sixth the energy than the conventional home model, or approximately 16% annually on a source energy basis. The optimization results for tiny homes suggests that the tiny homes modeled generally use less than 25% of the energy of an average-sized residence, regardless of any of the analytical assumptions considered.

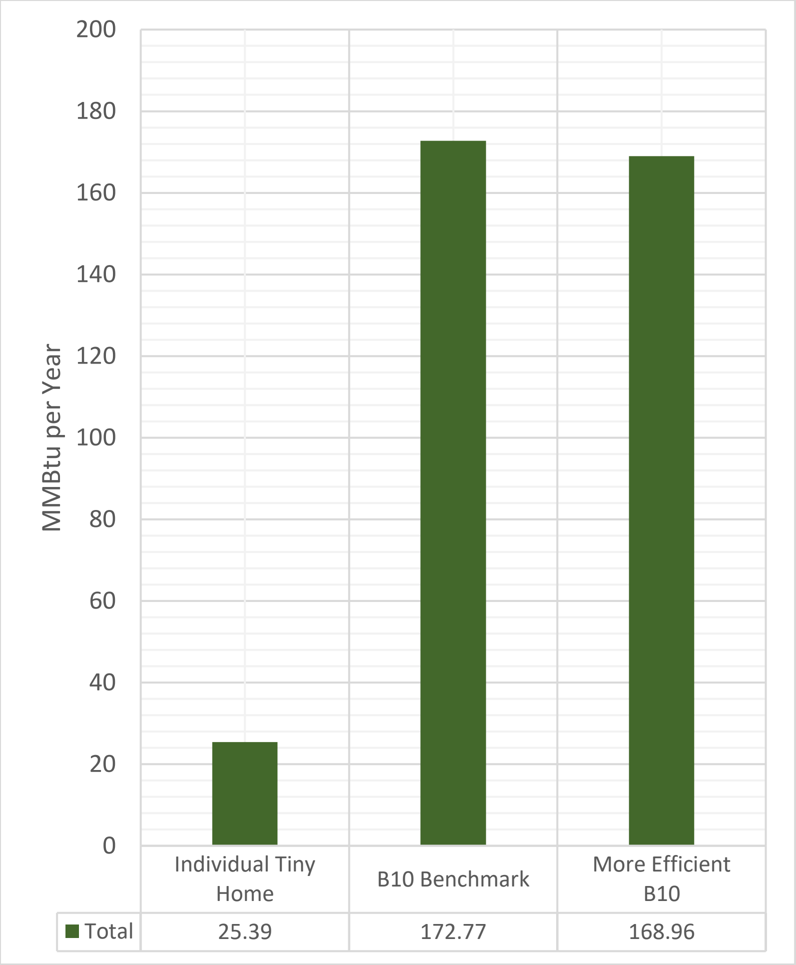

Figure 39: Source-Energy Comparison of a zero-net energy tiny home with a conventional model and more energy efficient version.

A sensitivity analysis on the assumed floor area finds that the conventional home with square footage of the California average of 1,583 square feet reported by the EIA uses 117.4 million Btu's per year, still many times the annual energy use of any tiny homes modeled (Energy Information Administration, 2018).

Sensitivity Analysis

Each parameter listed Tables 26 to 28, below, was modified individually to observe the effect on the results. As described in the methods section, escalation rate sensitivity values were derived from analysis of historical data. When data were in close agreement with NIST methodology projections, a sensitivity value representing a modest variation was chosen. Table 26 below shows sensitivity analysis results for the propane tiny home village model. The sensitivity analysis results were compared with the results reported for a 0% discount rate for each model. This model showed an original lifecycle cost of $23,700, as reported in Table 20. The mortgage parameters were all used together for a simulation with a 25% down payment, 4% interest rate, and mortgage period equal to the project analysis period of 30 years.

Table 26: Sensitivity Results for the Tiny Home Propane Model, Village Use Case with an Original Lifecycle Cost of $23,700.

Parameter	Original Value	Sensitivity Value	Unit	Sensitivity Lifecycle Cost	Percent Change
Down Payment	100.0	25	Percent	$30,400	+30%
Mortgage Interest Rate	0.0	4	Percent	$30,400	+30%
Mortgage Period	0.0	30	Years	$30,400	+30%
Electricity Escalation Rate	0.66	1.90	Percent/Year	$24,200	+2%
Propane Fuel Price	2.43	2.60	$/Gallon	$24,200	+2%

Table 27 below shows the sensitivity analysis results for the village use case, zero-net energy tiny home model. The sensitivity results shown in Table 27 were all compared with the undiscounted lifecycle cost given in Table 20 of $27,700. The original parameters for this case are given in the methods section in Table 10. The results for discount rates of 3% and 6% are located with the original lifecycle cost analysis results. Numbers are estimates taken to 3 significant figures, and so will show differences due to rounding.

Table 27: ZNE Village Use Case Sensitivity Analysis Results with an Original Lifecycle Cost of $27,700.

Parameter	Original Value	Sensitivity Value	Unit	Sensitivity Lifecycle Cost	Percent Change
Down Payment	100.0	25	Percent	$41,400	+50%
Mortgage Interest Rate	0.0	4	Percent	$41,400	+50%
Mortgage Period	0.0	30	Years	$41,400	+50%
Incentives	No Incentive	30% Federal ITC	-	$26,800	-3%
Electricity Escalation Rate	0.66	1.90	Percent/Year	$28,400	+3%

Table 28 below shows the sensitivity analysis results for the individual, slab-on-grade tiny home. The original values are those listed in the methods section for the individual tiny home with a 0% discount rate, and the sensitivity values are those listed in the methods section for the sensitivity analysis. The original value for the undiscounted lifecycle cost, as listed in Table 21, was approximately $35,400. This is the value used in the percent change calculations shown in Table 28.

Table 28: Sensitivity Results for the Individual, Zero-Net Energy Tiny Home with an Original Lifecycle Cost of $35,400.

Parameter	Original Value	Sensitivity Value	Unit	Sensitivity Lifecycle Cost	Percent Change
Down Payment	100.0	25	Percent	$47,300	+30%
Mortgage Interest Rate	0.0	4	Percent	$47,300	+30%
Mortgage Period	0.0	30	Years	$47,300	+30%
Incentives	No Incentive	30% Federal ITC	-	$33,300	-6%
Electricity Escalation Rate	0.66	1.90	Percent/Year	$36,200	+2%

A sensitivity analysis was not conducted on the off-grid solar model, because the model was found to be infeasible for the energy load profile considered. This determination was made by examining changes in the ratio of costs to benefits from the zero-net energy village tiny home model and the off-grid solar model. All other things being equal, the undiscounted energy costs for the off-grid solar model were more than nine times higher than the ZNE village tiny home model.

One additional sensitivity analysis was conducted, which explores the results of increasing utility costs and declining solar costs on the feasibility of the ZNE and propane models. The propane model rate structure was changed to the same Care Program time of use rate as the zero-net energy model, and the energy escalation rate was increased to 3%. Correspondingly, the installed cost of PV for the zero-net energy village use case was decreased to $2.50 per watt. This analysis produced undiscounted lifecycle costs of $27,100 for the ZNE model, and $28,400 for the propane model.

Summary Results

Table 29 below shows the summary economic results for each building. These results show the estimated upfront costs, annual utility costs, and undiscounted lifecycle cost for each building. As described in the methods section, the individual use case tiny home includes hot water and cooking energy use, while the village use case tiny home only includes HVAC, ventilation, lighting, and plug loads. Estimated upfront costs for the community services building lie beyond the scope of the analysis.

Leaving aside the effects of discount rates, mortgages, etc., it is clear that in undiscounted terms, any community services building that exceeds approximately $80,000 in upfront and other non-utility costs over the lifecycle of the building would be economically unfavorable to simply building 6 tiny homes with all energy services included.

Table 29: Summary Economic Results, By Building.

Use Case	Model	Estimated Upfront Cost ($)	Estimated Average Annual Utility Bill ($/Year)	Undiscounted Lifecycle Cost ($)
Village	ZNE Tiny Home	$24,200	$100	$27,700
Village	Propane Tiny Home	$16,600	$340	$22,300
Individual	ZNE Tiny Home (Slab on Grade)	$29,400	$120	$35,800
Village	Community Services Building with PV	-	$4,000	-
Village	Community Services Building - All Electric	-	$5,400	-
Village	Community Services Building - with gas	-	$3,600	-

Table 30 shows summary energy use and greenhouse gas emissions results by building. The building-level results are useful to customize the analysis for a considered tiny home village or use implementation or project.

Table 30: Energy and Greenhouse Gas Emissions Results, by Building.

Use Case	Model	Annual Electricity Consumption	Annual Net Energy Use	Annual Net Greenhouse Gas Emissions
(Unit)	-	kWh per Year	kWh Equivalent per Year	Metric Tons CO_2 Equivalent per Year
Village	ZNE Tiny Home	1,170	-110	0.0
Village	Propane Tiny Home	550	2,890	0.5
Individual	ZNE Tiny Home (Slab on Grade)	3,000	0	0.0
Village	Community Services Building with PV	33,700	17,200	1.6
Village	Community Services Building - All Electric	33,700	33,700	3.2
Village	Community Services Building with Gas	11,600	42,400	6.7

Table 31 shows the estimated average per capita utility bill, net energy use, and greenhouse gas emissions for each case considered. These results assume 18 people living in 6 tiny homes, or 3 people per tiny home. For consistency and ease of comparability, results were computed using the community services model with PV. The primary difference in energy services between the village and individual use case is the inclusion of laundry service in the community services building, and the location of services. In the individual tiny home model, cooking and domestic hot water are included in the tiny home along with HVAC, plug loads, etc., whereas in the community services model, cooking and domestic hot water are included in the community services building.

Table 31: Per Capita Annualized Utility Bill Results

Use Case	Model	Per Capita Estimated Utility Bill	Per Capita Net Energy Use	Per Capita Net Greenhouse Gas Emissions
(Unit)	-	$\frac{\$}{Year}$	$\frac{kWh\ eq.}{Year}$	$\frac{Metric\ Tons\ CO_2\ eq.}{Year}$
Village	ZNE Tiny Home and Community Services Building	$260	920	0.1
Village	Propane Tiny Home and Community Services Building	$340	1,920	0.3
Individual	ZNE Tiny Home (Slab on Grade)	$40	0	0

DISCUSSION

The following discussion section covers the use of BEopt in the building energy modeling of tiny homes, lifecycle cost analysis and utility bills, a comparison of tiny home energy use to per capita energy use, indoor environmental characteristics of models considered, and utility cost and utility rate analysis. The discussion section concludes with recommendations for tiny home implementation, based on the study results.

BEopt and Building Energy Modeling: Considerations

Like any modeling software, the choice of energy analysis tools should always reflect a project or study's ultimate goals. The BEopt GUI offers useful features in terms of simulation capability, functionality, and the organization of results. On the one hand, BEopt's sequential search technique provided in the BEopt GUI enables the efficient optimization of buildings and the synthesis and comparison of simulation results, complete with energy and economic cost breakdowns. The sequential search technique can save a substantial number of building simulations while identifying the least-cost energy savings option (Christensen, et al., 2005). This might be impractical, time-consuming, or far more computationally intensive without an optimization routine. On the other hand, the other simulation engine used in this study, EnergyPlus, contains a wider array of capabilities than the default capabilities of BEopt. Accessing the full functionality of EnergyPlus, therefore, requires customized or batch simulation processes when an EnergyPlus module or object call is not programmed into the BEopt GUI (NREL BEopt Development Team, 2018). This is still possible using BEopt, but it does require substantial knowledge of command-line processes or programming languages, or both (NREL BEopt Development Team, 2018).

For example, EnergyPlus allows modeling green roofs or eco-roofs using an EnergyPlus object called “Material:RoofVegetation” (Department of Energy, 2015). Eco-roofs are one of many compelling environmentally-friendly and healthy building materials that require a more detailed or time-intensive approach to model, simply because less common building materials do not tend to be used as default options or have well-established parameters. One promising area of further study with respect to tiny homes is the collection of thermal and economic data for environmentally friendly building materials (properties, availability, and economic data). This would enable the energy modeling community to model the feasibility of environmentally friendly building materials more easily, and to encourage more widespread adoption of environmentally-conscious building practices.

Another advantage of EnergyPlus is the modeling of phase change materials (PCM). There are options available for modeling PCMs as a wall mass in the BEopt GUI, but they do not consider effects such as hysteresis and subcooling (NREL BEopt Development Team, 2018). The variable thermal conductivity and specific heat of PCMs are modeled in EnergyPlus with the conduction finite difference algorithm (CONDFD) (Department of Energy, 2015). The CONDFD algorithm requires data specifying how enthalpy varies with temperature, which cannot be directly entered into the BEopt GUI.

However, the .idf file that BEopt creates to indicate to EnergyPlus the building parameters to be used in the simulation can be generated by BEopt, manually edited, and subsequently used in EnergyPlus (Tabares-Velasco, et al., 2012). However, since the optimization routine in BEopt might require thousands of simulations, the manual editing would become unworkable and consequently, a programming solution would likely be required for precise or specialized applications.

Overall, BEopt represents an efficient and effective method for lowering the energy use and lifecycle cost of building designs. Further academic research in this area would be well-justified given the possibility of a more widespread adoption of tiny homes.

Lifecycle Cost Analysis and Annual Utility Bills

While both the spreadsheet analysis and BEopt calculations were based on the NIST Lifecycle Handbook 135, there were a few differences that explained variation in the results. Primarily, BEopt automatically adjusts replacement costs for equipment upwards from the original costs (NREL BEopt Development Team, 2018). This was not done in the spreadsheet calculation. In most cases examined, differences between the lifecycle costs reported by BEopt and those calculated using spreadsheet software were less than 3% of the total lifecycle cost.

It is important to understand that differences in annualized utility bills should be viewed in light of the different utility rate structures. For instance, the propane case uses declining block rate structures, while the zero-net energy case uses EL-6 rates used for net metering. These rates change from $0.11 per kWh to $0.25 per kWh depending on the time of day when the electricity is used. This has a pronounced effect on the annualized energy bill results. These rates were chosen because Time of Use rates are used with net metering in California, and were intended to be a realistic analysis in this respect.

Comparison of Tiny Home Models to Average Per Capita Energy Use

Data from the EIA were analyzed to place the tiny home model results in a broader perspective. The average per capita residential consumption in California easily exceeds the energy use of most tiny home models considered, as Figure 41 illustrates. This indicates that tiny homes have very low energy use, because California has the lowest per capita energy consumption of any state, as can be readily observed in comparison to states such as Alaska, which is nearly double. Without accounting for the solar PV energy, these simulations ranged from 11.6-23 million BTUs annually, still substantially lower than the per capita energy use in California for 2016.

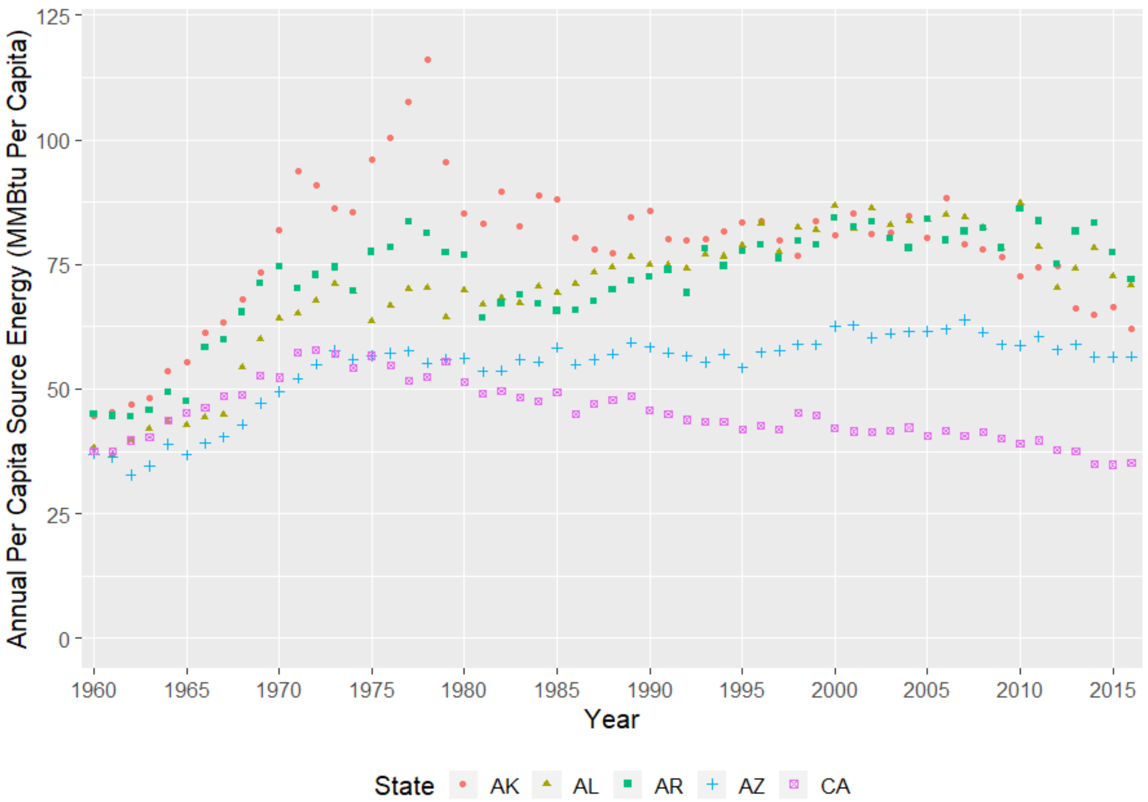

Figure 40: Average per capita residential energy consumption, by state and year. (Data Source: Energy Information Administration, 2019c)

Consequently, while the cost and energy use variation among tiny home models is substantial enough to justify care in making absolute claims about whether one energy model type uses more source energy than another, the energy use comparison between tiny home models and conventional homes is much more consistent. Even accounting for substantial variation in configurations, tiny homes tend to use far less energy per capita than a conventional home on both a source and site-energy basis.

While tiny home occupants, under the assumptions considered, are shown to have less energy use than the California per capita average, the energy use intensity on a square foot basis (Btu/ft.^{2}) is higher under the assumption of a similar level of hot water usage by the occupants. This is most likely because hot water usage is a high share of energy use in many residences, and a similar amount of hot water energy use is being modeled in a smaller square footage. On the other hand, the analysis only considers the energy use of the building after it is built and used, and does not include a full lifecycle analysis of the net energy used to construct the building.

Indoor Environment and Qualitative Characteristics

In order to evaluate the qualitative characteristics of the modeled tiny homes, and differences between the individual and village use cases, the annual indoor temperature and humidity profiles were modeled and compared. Figure 42 shows the annual indoor temperature and relative humidity for the individual, slab-on-grade tiny home. This tiny home was modeled with a dehumidifier. It can be observed that due to the humid coastal climate, the interior humidity set point of 60% serves as an upper boundary for a significant fraction of the year.

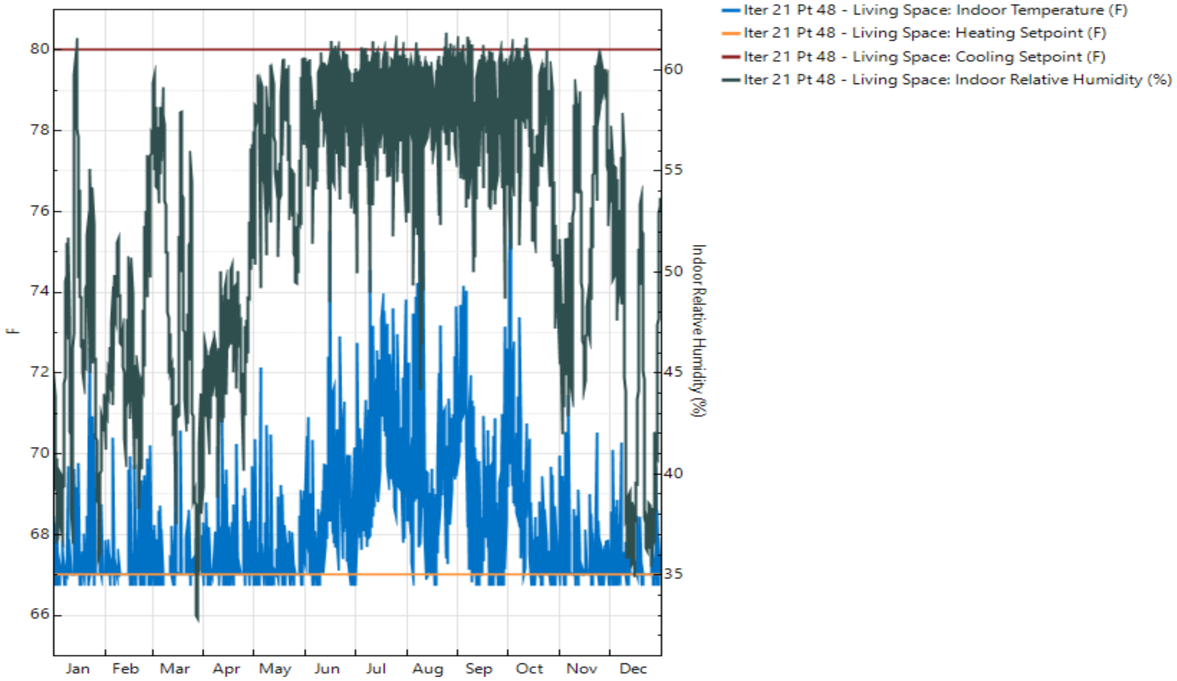

Figure 41: Interior temperature data for the individual case tiny home. From top to bottom: the flat line indicates the interior cooling set point temperature, the next line indicates the indoor relative humidity, then the indoor drybulb temperature, and the interior heating set point temperature.

In contrast, the relative humidity for the village use case tiny home, which was modeled without a dehumidifier, exceeds the set point of 60% for a significant fraction of the year, shown in Figure 43. This result suggests that the village tiny home use case would also require a dehumidifier or further means of interior moisture level control to maintain indoor comfort levels. Because both use cases were modeled with an HVAC system, both succeed in meeting the interior minimum modeled set point temperature of 67 °F.

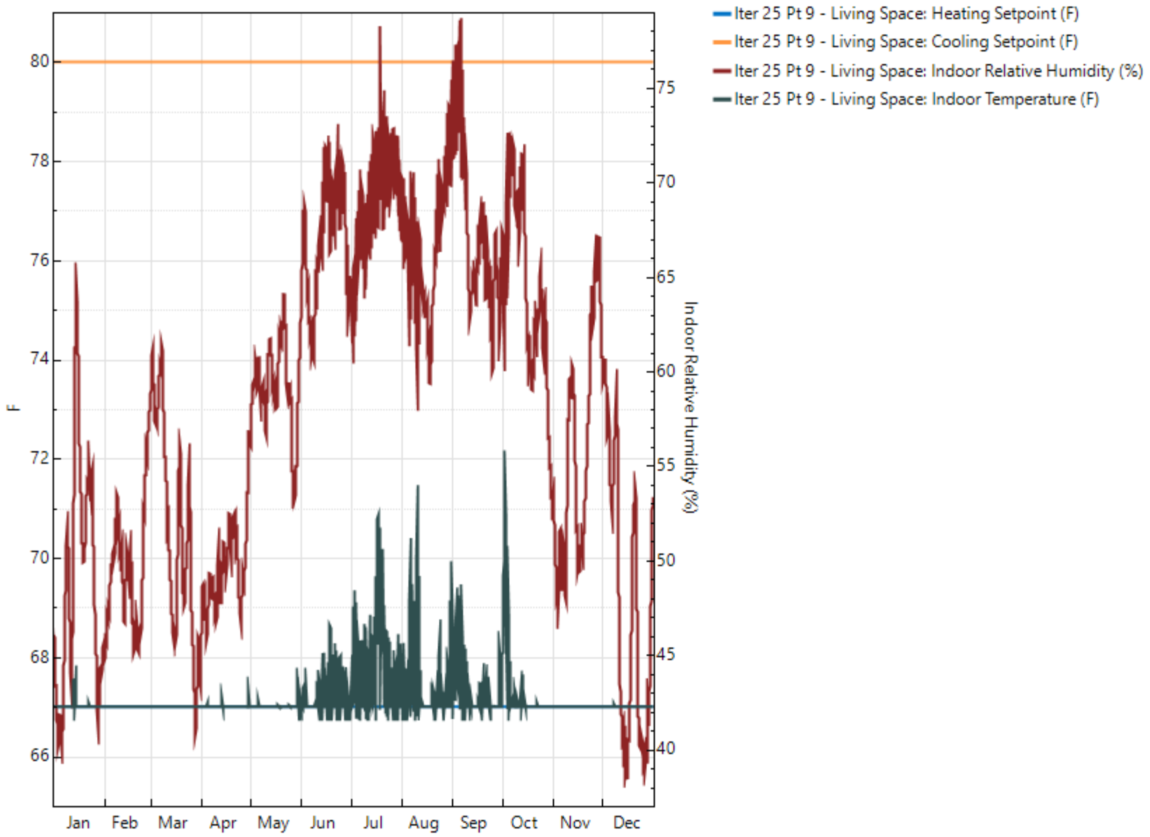

Figure 42: Interior temperature and relative humidity for the zero-net energy village tiny home model. From top to bottom: the jagged line shows the indoor relative humidity, the solid line shows the indoor cooling set point; the next jagged line shows the indoor temperature, and the bottom, flat line shows the heating set point temperature.

The indoor environmental quality results suggest that care should be taken in the design of tiny homes to insure proper interior moisture control, and that with respect to the mechanically ventilated tiny home models considered, a dehumidifier was still useful to maintain an interior relative humidity set point of 60%.

Utility Rate Analysis and Uncertainty

In California, net metering rate schemes are actually too complicated to enter into the Building Energy Optimization Tool GUI exactly. Writing a customized computer program to calculate the annual utility bill given a determined energy load profile is typically feasible. However, BEopt and similar calculation methods are commonly used because in practical applications, any gain in precision from calculating the annual utility bill precisely is contradicted by, or lost from, a number of factors. These include variation in real energy use profiles, changing utility rate structures, and changing utility rates. For instance, the natural gas and energy price peaks observable in Figures 11 and 14 showing propane and natural gas data, respectively, were not modeled exactly in BEopt, only an annual percentage escalation increase. This means that seasonal effects from higher demand and higher prices in the winter season for heating fuel are not reflected in the results. An R script that calculates the annual electricity bill for EL-1 rates given a constant annual electricity rate is given in Appendix H.

Recommendations

Under the assumptions of the analysis, it would initially appear that the propane village tiny home model shows an approximate 17-25% lower lifecycle cost than the zero-net energy tiny home (using a 0% discount rate). However, the models used different utility rates. The propane model’s inverted block rates were economically favorable compared to the EL-6 rates used to model net metering. Because most residential customers in California are shifting to time of use rates (as noted in the literature review), a sensitivity analysis was justifiable.

Changing the propane tiny home model with a 0% discount rate to EL-6 rates (the same rates used to model net metering) increases the lifecycle cost (as reported by BEopt) from $23,665 to $26,100, reducing the difference between models to less than 6%. Adding in a carbon price of $20 per ton reduces the lifecycle cost difference between models to less than 5%. Because the energy price data analysis and literature review find that utility-sourced electricity prices are likely to increase and the cost of solar electricity is expected to decrease, respectively, the zero-net energy tiny home model is recommendable on economic grounds. Zero-net energy tiny homes are also recommendable on health and safety grounds, as they circumvent the health and safety risks of fire or indoor air pollution, respectively, associated with propane.

The economic implications between the zero-net energy village use case model, wherein zero-net energy tiny homes are centered on a community services building, and a standalone model where tiny homes are constructed more as scaled-down residences, are worth careful consideration. Under the analytical assumptions, the individual tiny home that provides running hot water in situ is far more economically favorable than the community services model. Under the assumption of 6 tiny homes with 3 occupants each using a central community services building, the village model adds approximately $18,000 (undiscounted) to the lifecycle cost of the tiny home in annualized utility costs alone. The cheapest community services model is 17% more expensive than the individual zero-net energy tiny home, without even factoring in the initial and maintenance costs of the community services building itself. Even considering that many modeled plug loads could be realistically reduced for the use case, the individual tiny homes are economically favorable.

However, this conclusion must be tempered by practical and code considerations, and the assumption of essentially complete building envelopes with electrical wiring. For a tiny house village intended for temporary habitation to house houseless people, a model with a community services building might, hypothetically speaking, make more economic sense if the cost of the tiny homes is low enough. However, the question then remains that in coastal Humboldt County, these structures would likely either experience significant interior moisture issues or require an electrical wiring configuration consistent with the site zoning, or be exempted from applicable codes by the relevant jurisdiction. A configuration of this sort would bear more resemblance to a campsite with cooking, showering, and laundry facilities accessible in a central building.

CONCLUSIONS

The energy modeling and economic analysis of tiny homes and a supporting building imparted a few primary conclusions worth future consideration. In terms of functionality, BEopt is a powerful tool for determining the energy use of different building configurations, and searching for cost-optimal designs. In this particular study, the construction and mechanical system cost variation was not reflected in the results due to a lack of cost data specific to Humboldt County. Consequently, BEopt is a recommendable application when predicting energy use is more important, or when construction cost parameters are known, but is not designed to predict differences in construction costs. Because the variation and magnitude of these costs are a high percentage of the entire lifecycle cost of the building, the lifecycle cost analysis should be considered appropriately.

In this respect, the energy use estimates, which reflected far more variation in terms of the building design, appear to be substantially more robust to departures from assumptions, for the simple reason that so many different building configurations and mechanical systems were considered. The comparison of simulation results with conventional model simulations and available energy use data show that tiny homes use far less annual energy on a per capita source energy basis.

The zero-net energy tiny home models compared similarly to the conventional tiny home models in terms of lifecycle cost, but tended to have substantially lower monthly bills. Tiny home models were compared to a conventional home model and per capita energy use data from the Energy Information Administration, and it was found that tiny homes use far less energy annually than an average-sized home.

For future studies of the energy characteristics of tiny homes, it is hypothesized that more detail-oriented modeling of environmentally favorable materials would be recommendable for niche or small-scale applications of tiny homes, and that well-established parameter estimates for more obscure environmentally favorable building materials would be useful in the modeling of tiny homes.

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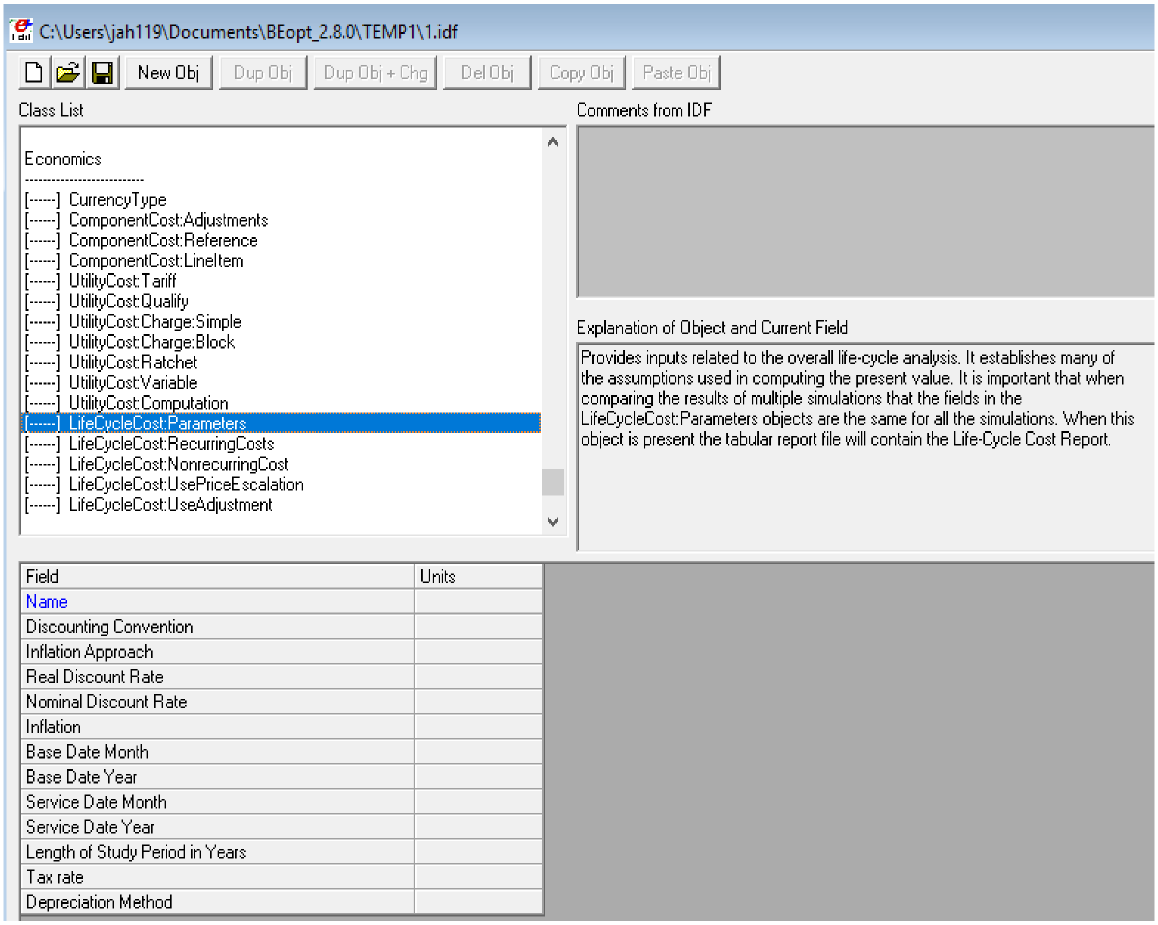
APPENDIX A: Viewing an Input File Generated by BEopt in Energyplus

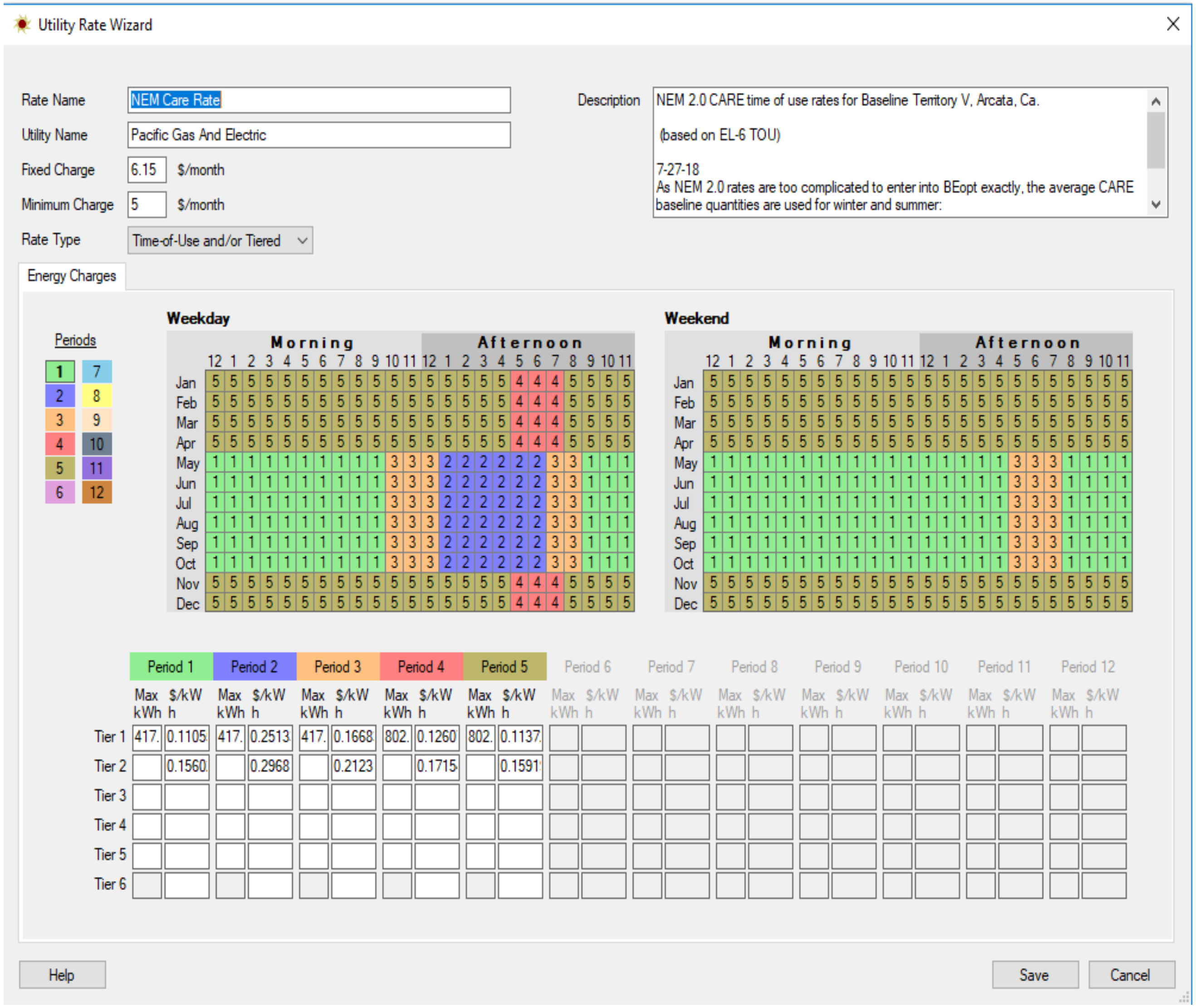


Provides inputs related to the overall life-cycle analysis. It establishes many of the assumptions used in computing the present value. It is important that when comparing the results of multiple simulations that the fields in the LifeCycleCost:Parameters objects are the same for all the simulations. When this object is present the tabular report file will contain the Life-Cycle Cost Report.

Field	Units
Name	
Discounting Convention	
Inflation Approach	
Real Discount Rate	
Nominal Discount Rate	
Inflation	
Base Date Month	
Base Date Year	
Service Date Month	
Service Date Year	
Length of Study Period in Years	
Tax rate	
Depreciation Method	

Figure A1: Image of an Energyplus input file opened in an input file editor. The blank lifecycle cost parameter field indicates that the lifecycle cost calculations must have occurred within the BEopt interface.

APPENDIX B: Economic Parameter Inputs



Rate Name: NEM Care Rate

Utility Name: Pacific Gas And Electric

Fixed Charge: 6.15 $/month

Minimum Charge: 5 $/month

Rate Type: Time-of-Use and/or Tiered

Description: NEM 2.0 CARE time of use rates for Baseline Territory V, Arcata, Ca.

(based on EL-6 TOU)

7-27-18
As NEM 2.0 rates are too complicated to enter into BEopt exactly, the average CARE baseline quantities are used for winter and summer.

Weekday

	Morning												Afternoon											
	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11
Jan	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	4	4	5	5	5	5
Feb	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	4	4	5	5	5	5
Mar	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	4	4	5	5	5	5
Apr	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	4	4	5	5	5	5
May	1	1	1	1	1	1	1	1	1	1	3	3	3	2	2	2	2	2	2	3	3	1	1	1
Jun	1	1	1	1	1	1	1	1	1	1	3	3	3	2	2	2	2	2	2	3	3	1	1	1
Jul	1	1	1	1	1	1	1	1	1	1	3	3	3	2	2	2	2	2	2	3	3	1	1	1
Aug	1	1	1	1	1	1	1	1	1	1	3	3	3	2	2	2	2	2	2	3	3	1	1	1
Sep	1	1	1	1	1	1	1	1	1	1	3	3	3	2	2	2	2	2	2	3	3	1	1	1
Oct	1	1	1	1	1	1	1	1	1	1	3	3	3	2	2	2	2	2	2	3	3	1	1	1
Nov	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	4	4	5	5	5	5
Dec	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	4	4	5	5	5	5

Weekend

	Morning												Afternoon											
	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11
Jan	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Feb	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Mar	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Apr	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
May	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	1	1	1	1
Jun	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	1	1	1	1
Jul	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	1	1	1	1
Aug	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	1	1	1	1
Sep	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	1	1	1	1
Oct	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	1	1	1	1
Nov	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Dec	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5

	Period 1		Period 2		Period 3		Period 4		Period 5		Period 6		Period 7		Period 8		Period 9		Period 10		Period 11		Period 12	
	Max kWh	$/kW h	Max kWh	$/kW h	Max kWh	$/kW h	Max kWh	$/kW h	Max kWh	$/kW h	Max kWh	$/kW h	Max kWh	$/kW h	Max kWh	$/kW h	Max kWh	$/kW h	Max kWh	$/kW h	Max kWh	$/kW h	Max kWh	$/kW h
Tier 1	417.	0.1105	417.	0.2513	417.	0.1668	802.	0.1260	802.	0.1137														
Tier 2		0.1560		0.2968		0.2123		0.1715		0.1591														
Tier 3																								
Tier 4																								
Tier 5																								
Tier 6																								

Figure B1: Net Metering (NEM) Care rates entered into the BEopt GUI.

APPENDIX C: Results and Synopsis of the Heat Conduction Study

This study is intended to show that the modeling of complex heat transfer effects renders the creation of an entirely new building energy modeling program specifically for tiny homes to be infeasible.

The program written to model heat conduction through building insulation used a non-linear algorithm, the Crank-Nicolson algorithm. The algorithm models heat conduction through insulation intended to be used for a raised foundation tiny home. Because the insulation is a planar surface, it is referred to as a plane wall. Heat transfer was modeled using a constant interior set point temperature of 22 °C and a weather data file for Arcata, California. The interior temperature was chosen as 22 °C to be a reasonable value for room temperature inside a tiny home.

Figure 18 shows the nonlinear temperature profile for a 400-square foot surface modeled in ideal conditions for Arcata, California. Because the Crank-Nicolson method numerically approximates the solution to a one-dimensional differential equation (Fourier's law of Heat Conduction), the resulting temperature profile through the modeled surface is non-linear at some points. The insulation surface (intended to be insulation for tiny home flooring) was found to transfer 547.3 kWh of energy per year from the interior to the exterior of the modeled surface. Because the model did not include radiation, convection, and other heat transfer effects, it was concluded that an established building energy modeling program under a pier and beam design would more closely approximate the energy use of a tiny home on wheels (Harkness, unpublished, 2018).

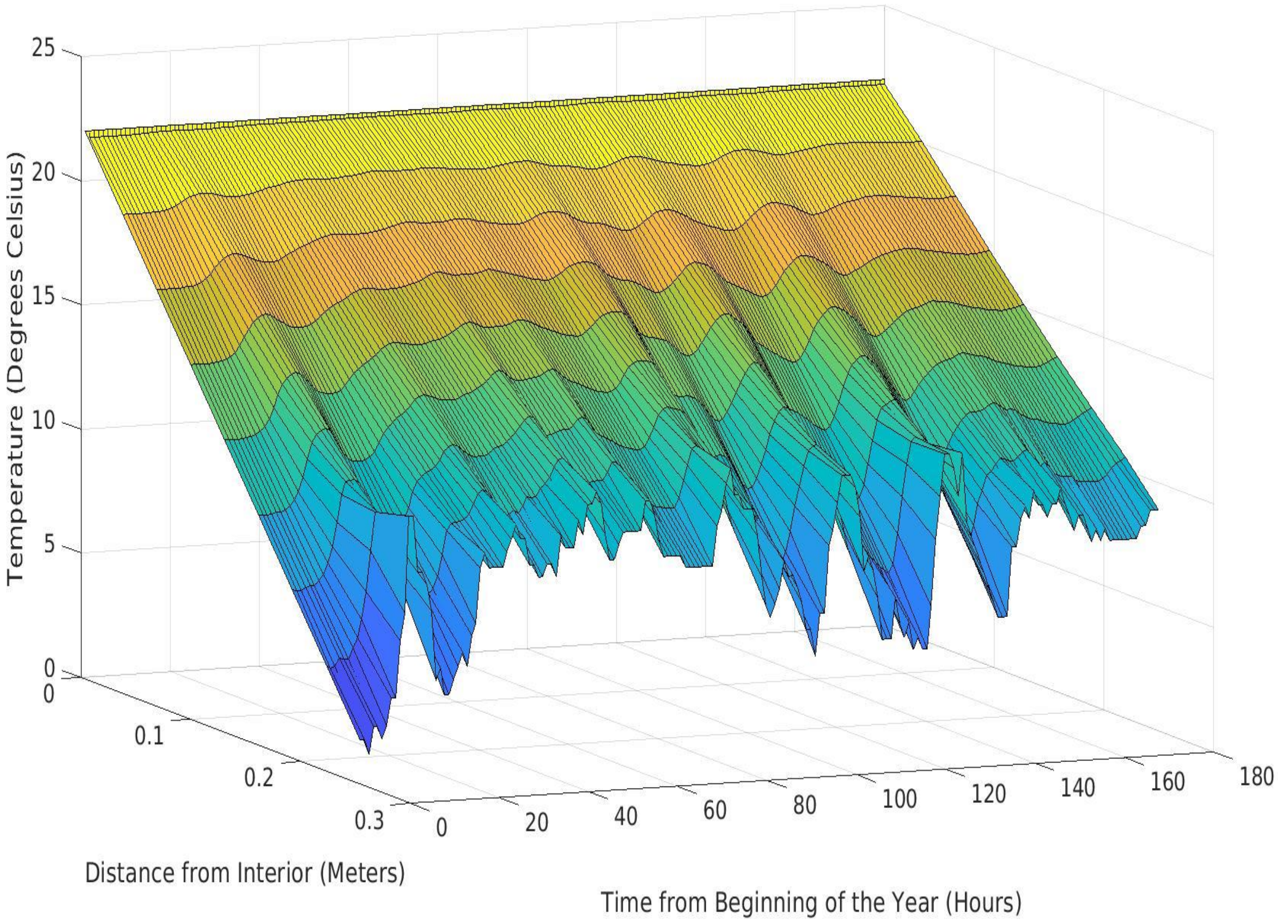
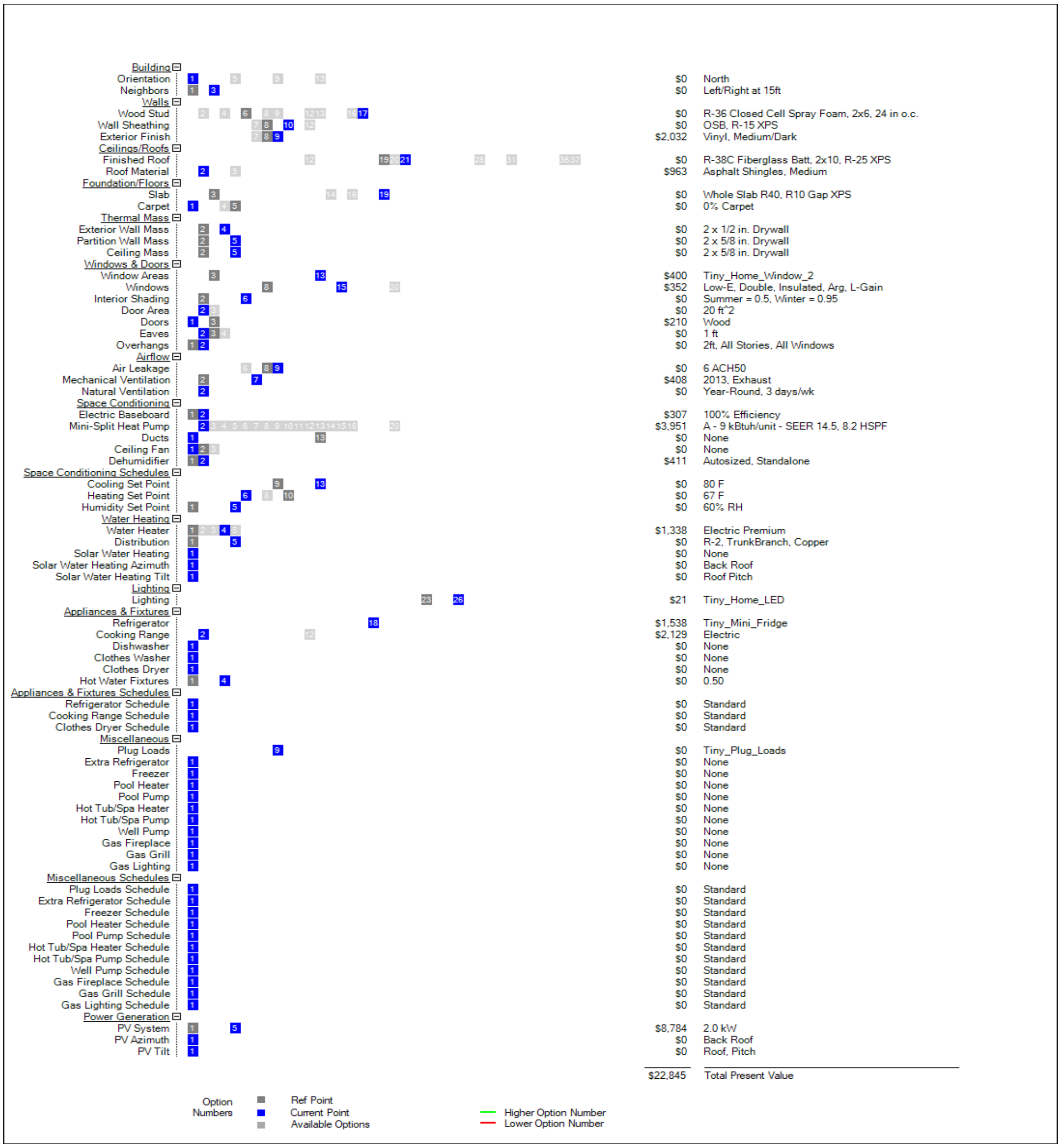


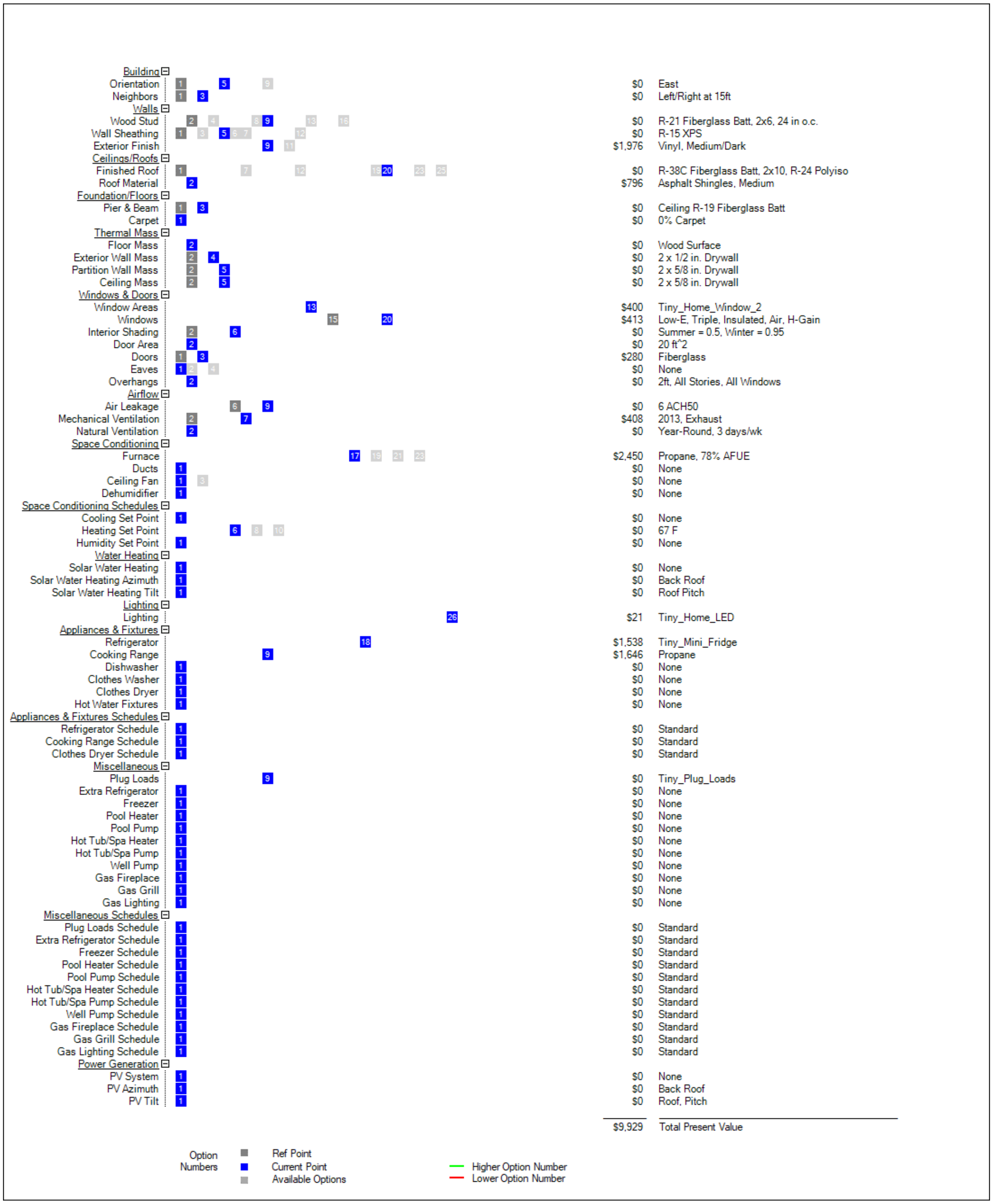
Figure C1: Temperature profile for a 400-square foot, R-38 fiberglass batt modeled in Arcata, California. (Image Source: Harkness, unpublished, 2018)

APPENDIX D: Optimization Parameter Inputs



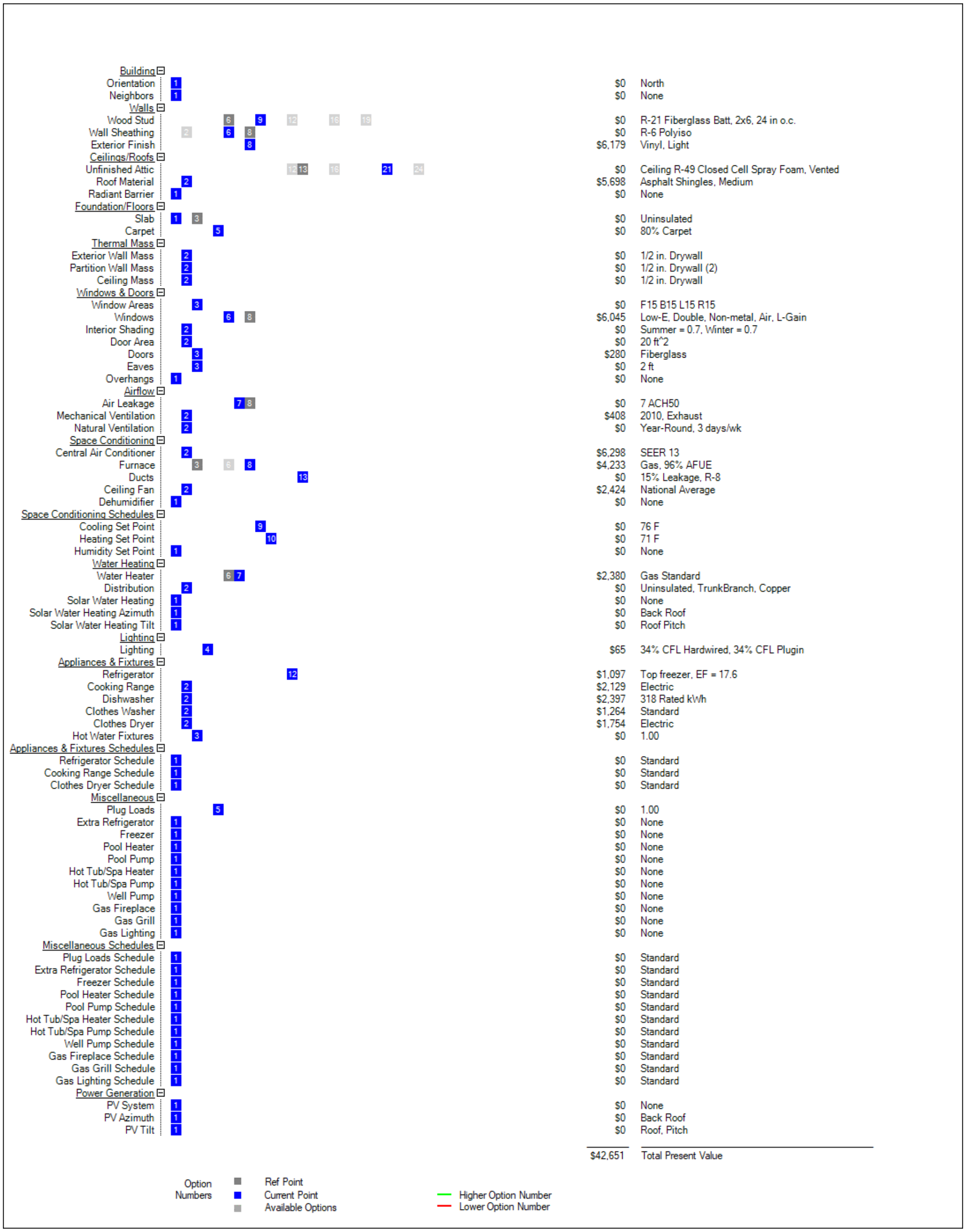
Parameter	Cost	Option
Building		
Orientation	$0	North
Neighbors	$0	Left/Right at 15ft
Walls		
Wood Stud	$0	R-36 Closed Cell Spray Foam, 2x6, 24 in o.c.
Wall Sheathing	$0	OSB, R-15 XPS
Exterior Finish	$2,032	Vinyl, Medium/Dark
Ceilings/Roofs		
Finished Roof	$0	R-38C Fiberglass Batt, 2x10, R-25 XPS
Roof Material	$963	Asphalt Shingles, Medium
Foundation/Floors		
Slab	$0	Whole Slab R40, R10 Gap XPS
Carpet	$0	0% Carpet
Thermal Mass		
Exterior Wall Mass	$0	2 x 1/2 in. Drywall
Partition Wall Mass	$0	2 x 5/8 in. Drywall
Ceiling Mass	$0	2 x 5/8 in. Drywall
Windows & Doors		
Window Areas	$400	Tiny_Home_Window_2
Windows	$352	Low-E, Double, Insulated, Arg, L-Gain
Interior Shading	$0	Summer = 0.5, Winter = 0.95
Door Area	$0	20 ft^2
Doors	$210	Wood
Eaves	$0	1 ft
Overhangs	$0	2ft, All Stories, All Windows
Airflow		
Air Leakage	$0	6 ACH50
Mechanical Ventilation	$408	2013, Exhaust
Natural Ventilation	$0	Year-Round, 3 days/wk
Space Conditioning		
Electric Baseboard	$307	100% Efficiency
Mini-Split Heat Pump	$3,951	A - 9 kBtuh/unit - SEER 14.5, 8.2 HSPF
Ducts	$0	None
Ceiling Fan	$0	None
Dehumidifier	$411	Autosized, Standalone
Space Conditioning Schedules		
Cooling Set Point	$0	80 F
Heating Set Point	$0	67 F
Humidity Set Point	$0	60% RH
Water Heating		
Water Heater	$1,338	Electric Premium
Distribution	$0	R-2, TrunkBranch, Copper
Solar Water Heating	$0	None
Solar Water Heating Azimuth	$0	Back Roof
Solar Water Heating Tilt	$0	Roof Pitch
Lighting		
Lighting	$21	Tiny_Home_LED
Appliances & Fixtures		
Refrigerator	$1,538	Tiny_Mini_Fridge
Cooking Range	$2,129	Electric
Dishwasher	$0	None
Clothes Washer	$0	None
Clothes Dryer	$0	None
Hot Water Fixtures	$0	0.50
Appliances & Fixtures Schedules		
Refrigerator Schedule	$0	Standard
Cooking Range Schedule	$0	Standard
Clothes Dryer Schedule	$0	Standard
Miscellaneous		
Plug Loads	$0	Tiny_Plug_Loads
Extra Refrigerator	$0	None
Freezer	$0	None
Pool Heater	$0	None
Pool Pump	$0	None
Hot Tub/Spa Heater	$0	None
Hot Tub/Spa Pump	$0	None
Well Pump	$0	None
Gas Fireplace	$0	None
Gas Grill	$0	None
Gas Lighting	$0	None
Miscellaneous Schedules		
Plug Loads Schedule	$0	Standard
Extra Refrigerator Schedule	$0	Standard
Freezer Schedule	$0	Standard
Pool Heater Schedule	$0	Standard
Pool Pump Schedule	$0	Standard
Hot Tub/Spa Heater Schedule	$0	Standard
Hot Tub/Spa Pump Schedule	$0	Standard
Well Pump Schedule	$0	Standard
Gas Fireplace Schedule	$0	Standard
Gas Grill Schedule	$0	Standard
Gas Lighting Schedule	$0	Standard
Power Generation		
PV System	$8,784	2.0 kW
PV Azimuth	$0	Back Roof
PV Tilt	$0	Roof, Pitch
	$22,845	Total Present Value

Figure D1: The image shows the input parameters for the slab-on-grade, individual use case tiny home designs. The optimization parameters generated over 1,500 tiny home simulations.



Building		
Orientation	$0	East
Neighbors	$0	Left/Right at 15ft
Walls		
Wood Stud	$0	R-21 Fiberglass Batt, 2x6, 24 in o.c.
Wall Sheathing	$0	R-15 XPS
Exterior Finish	$1,976	Vinyl, Medium/Dark
Ceilings/Roofs		
Finished Roof	$0	R-38C Fiberglass Batt, 2x10, R-24 Polyiso
Roof Material	$796	Asphalt Shingles, Medium
Foundation/Floors		
Pier & Beam	$0	Ceiling R-19 Fiberglass Batt
Carpet	$0	0% Carpet
Thermal Mass		
Floor Mass	$0	Wood Surface
Exterior Wall Mass	$0	2 x 1/2 in. Drywall
Partition Wall Mass	$0	2 x 5/8 in. Drywall
Ceiling Mass	$0	2 x 5/8 in. Drywall
Windows & Doors		
Window Areas	$400	Tiny_Home_Window_2
Windows	$413	Low-E, Triple, Insulated, Air, H-Gain
Interior Shading	$0	Summer = 0.5, Winter = 0.95
Door Area	$0	20 ft^2
Doors	$280	Fiberglass
Eaves	$0	None
Overhangs	$0	2ft, All Stories, All Windows
Airflow		
Air Leakage	$0	6 ACH50
Mechanical Ventilation	$408	2013, Exhaust
Natural Ventilation	$0	Year-Round, 3 days/wk
Space Conditioning		
Furnace	$2,450	Propane, 78% AFUE
Ducts	$0	None
Ceiling Fan	$0	None
Dehumidifier	$0	None
Space Conditioning Schedules		
Cooling Set Point	$0	None
Heating Set Point	$0	67 F
Humidity Set Point	$0	None
Water Heating		
Solar Water Heating	$0	None
Solar Water Heating Azimuth	$0	Back Roof
Solar Water Heating Tilt	$0	Roof Pitch
Lighting		
Lighting	$21	Tiny_Home_LED
Appliances & Fixtures		
Refrigerator	$1,538	Tiny_Mini_Fridge
Cooking Range	$1,646	Propane
Dishwasher	$0	None
Clothes Washer	$0	None
Clothes Dryer	$0	None
Hot Water Fixtures	$0	None
Appliances & Fixtures Schedules		
Refrigerator Schedule	$0	Standard
Cooking Range Schedule	$0	Standard
Clothes Dryer Schedule	$0	Standard
Miscellaneous		
Plug Loads	$0	Tiny_Plug_Loads
Extra Refrigerator	$0	None
Freezer	$0	None
Pool Heater	$0	None
Pool Pump	$0	None
Hot Tub/Spa Heater	$0	None
Hot Tub/Spa Pump	$0	None
Well Pump	$0	None
Gas Fireplace	$0	None
Gas Grill	$0	None
Gas Lighting	$0	None
Miscellaneous Schedules		
Plug Loads Schedule	$0	Standard
Extra Refrigerator Schedule	$0	Standard
Freezer Schedule	$0	Standard
Pool Heater Schedule	$0	Standard
Pool Pump Schedule	$0	Standard
Hot Tub/Spa Heater Schedule	$0	Standard
Hot Tub/Spa Pump Schedule	$0	Standard
Well Pump Schedule	$0	Standard
Gas Fireplace Schedule	$0	Standard
Gas Grill Schedule	$0	Standard
Gas Lighting Schedule	$0	Standard
Power Generation		
PV System	$0	None
PV Azimuth	$0	Back Roof
PV Tilt	$0	Roof, Pitch
	$9,929	Total Present Value

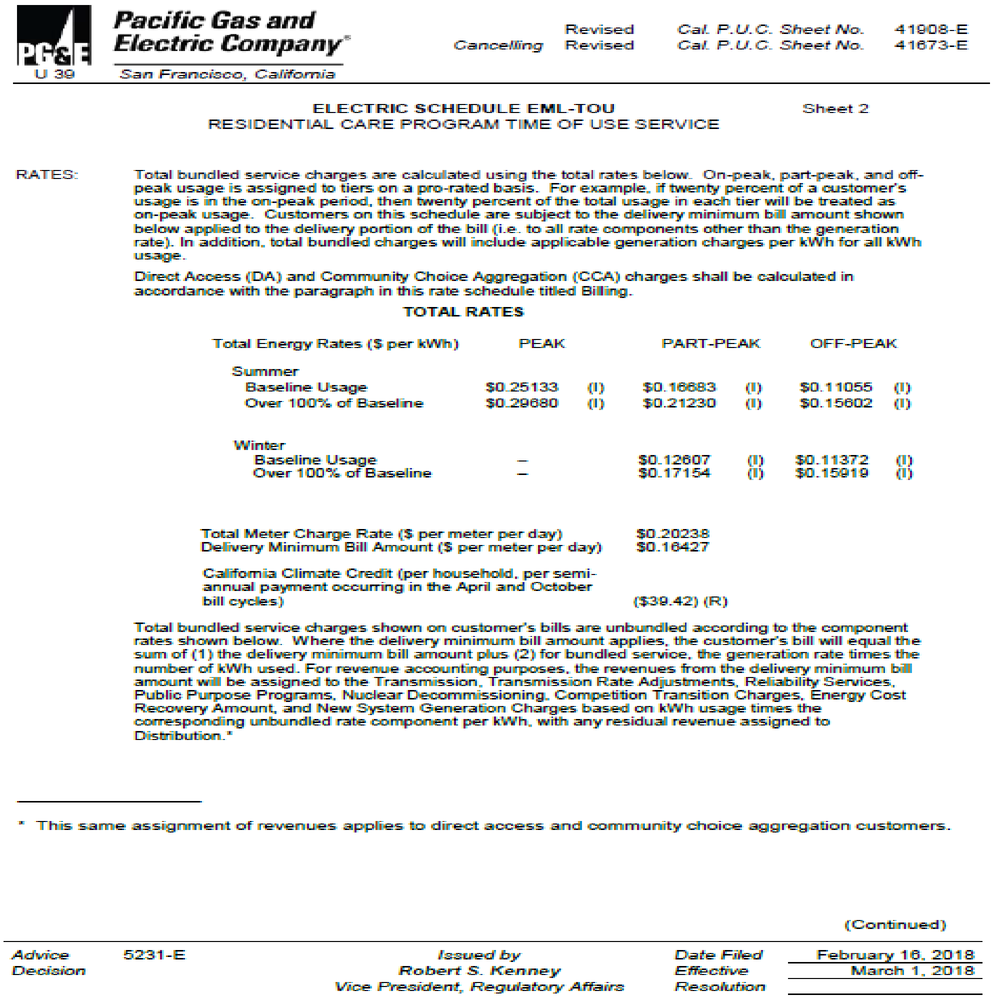
Figure D2: Parameter inputs for the propane tiny home model, village use case. The inputs generated over 980 simulations.



Building			
Orientation	1	$0	North
Neighbors	1	$0	None
Walls			
Wood Stud	6 9 12 16 19	$0	R-21 Fiberglass Batt, 2x6, 24 in o.c.
Wall Sheathing	2 6 8	$0	R-6 Polyiso
Exterior Finish	8	$6,179	Vinyl, Light
Ceilings/Roofs			
Unfinished Attic	12 13 16 21 24	$0	Ceiling R-49 Closed Cell Spray Foam, Vented
Roof Material	2	$5,698	Asphalt Shingles, Medium
Radiant Barrier	1	$0	None
Foundation/Floors			
Slab	1 3	$0	Uninsulated
Carpet	5	$0	80% Carpet
Thermal Mass			
Exterior Wall Mass	2	$0	1/2 in. Drywall
Partition Wall Mass	2	$0	1/2 in. Drywall (2)
Ceiling Mass	2	$0	1/2 in. Drywall
Windows & Doors			
Window Areas	3	$0	F15 B15 L15 R15
Windows	6 8	$6,045	Low-E, Double, Non-metal, Air, L-Gain
Interior Shading	2	$0	Summer = 0.7, Winter = 0.7
Door Area	2	$0	20 ft^2
Doors	3	$280	Fiberglass
Eaves	3	$0	2 ft
Overhangs	1	$0	None
Airflow			
Air Leakage	7 8	$0	7 ACH50
Mechanical Ventilation	2	$408	2010, Exhaust
Natural Ventilation	2	$0	Year-Round, 3 days/wk
Space Conditioning			
Central Air Conditioner	2	$6,298	SEER 13
Furnace	3 6 8	$4,233	Gas, 96% AFUE
Ducts	13	$0	15% Leakage, R-8
Ceiling Fan	2	$2,424	National Average
Dehumidifier	1	$0	None
Space Conditioning Schedules			
Cooling Set Point	9	$0	76 F
Heating Set Point	10	$0	71 F
Humidity Set Point	1	$0	None
Water Heating			
Water Heater	6 7	$2,380	Gas Standard
Distribution	2	$0	Uninsulated, TrunkBranch, Copper
Solar Water Heating	1	$0	None
Solar Water Heating Azimuth	1	$0	Back Roof
Solar Water Heating Tilt	1	$0	Roof Pitch
Lighting			
Lighting	4	$65	34% CFL Hardwired, 34% CFL Plugin
Appliances & Fixtures			
Refrigerator	12	$1,097	Top freezer, EF = 17.6
Cooking Range	2	$2,129	Electric
Dishwasher	2	$2,397	318 Rated kWh
Clothes Washer	2	$1,264	Standard
Clothes Dryer	2	$1,754	Electric
Hot Water Fixtures	3	$0	1.00
Appliances & Fixtures Schedules			
Refrigerator Schedule	1	$0	Standard
Cooking Range Schedule	1	$0	Standard
Clothes Dryer Schedule	1	$0	Standard
Miscellaneous			
Plug Loads	5	$0	1.00
Extra Refrigerator	1	$0	None
Freezer	1	$0	None
Pool Heater	1	$0	None
Pool Pump	1	$0	None
Hot Tub/Spa Heater	1	$0	None
Hot Tub/Spa Pump	1	$0	None
Well Pump	1	$0	None
Gas Fireplace	1	$0	None
Gas Grill	1	$0	None
Gas Lighting	1	$0	None
Miscellaneous Schedules			
Plug Loads Schedule	1	$0	Standard
Extra Refrigerator Schedule	1	$0	Standard
Freezer Schedule	1	$0	Standard
Pool Heater Schedule	1	$0	Standard
Pool Pump Schedule	1	$0	Standard
Hot Tub/Spa Heater Schedule	1	$0	Standard
Hot Tub/Spa Pump Schedule	1	$0	Standard
Well Pump Schedule	1	$0	Standard
Gas Fireplace Schedule	1	$0	Standard
Gas Grill Schedule	1	$0	Standard
Gas Lighting Schedule	1	$0	Standard
Power Generation			
PV System	1	$0	None
PV Azimuth	1	$0	Back Roof
PV Tilt	1	$0	Roof, Pitch
		$42,651	Total Present Value

Figure D3: Optimization parameter inputs for the conventional home optimization. The optimization was used to generate 74 simulations.

APPENDIX E: Pacific Gas and Electric Tariffs Used



Pacific Gas and Electric Company®
U 39 *San Francisco, California*

	Revised	*Cal. P.U.C. Sheet No.*	41908-E
Cancelling	Revised	*Cal. P.U.C. Sheet No.*	41673-E

ELECTRIC SCHEDULE EML-TOU Sheet 2
RESIDENTIAL CARE PROGRAM TIME OF USE SERVICE

RATES: Total bundled service charges are calculated using the total rates below. On-peak, part-peak, and off-peak usage is assigned to tiers on a pro-rated basis. For example, if twenty percent of a customer's usage is in the on-peak period, then twenty percent of the total usage in each tier will be treated as on-peak usage. Customers on this schedule are subject to the delivery minimum bill amount shown below applied to the delivery portion of the bill (i.e. to all rate components other than the generation rate). In addition, total bundled charges will include applicable generation charges per kWh for all kWh usage.

Direct Access (DA) and Community Choice Aggregation (CCA) charges shall be calculated in accordance with the paragraph in this rate schedule titled Billing.

TOTAL RATES

Total Energy Rates ($ per kWh)	PEAK		PART-PEAK		OFF-PEAK	
Summer						
Baseline Usage	$0.25133	(I)	$0.16683	(I)	$0.11055	(I)
Over 100% of Baseline	$0.29680	(I)	$0.21230	(I)	$0.15602	(I)
Winter						
Baseline Usage	–		$0.12607	(I)	$0.11372	(I)
Over 100% of Baseline	–		$0.17154	(I)	$0.15919	(I)

Total Meter Charge Rate ($ per meter per day)	$0.20238
Delivery Minimum Bill Amount ($ per meter per day)	$0.16427
California Climate Credit (per household, per semi-annual payment occurring in the April and October bill cycles)	($39.42) (R)

Total bundled service charges shown on customer's bills are unbundled according to the component rates shown below. Where the delivery minimum bill amount applies, the customer's bill will equal the sum of (1) the delivery minimum bill amount plus (2) for bundled service, the generation rate times the number of kWh used. For revenue accounting purposes, the revenues from the delivery minimum bill amount will be assigned to the Transmission, Transmission Rate Adjustments, Reliability Services, Public Purpose Programs, Nuclear Decommissioning, Competition Transition Charges, Energy Cost Recovery Amount, and New System Generation Charges based on kWh usage times the corresponding unbundled rate component per kWh, with any residual revenue assigned to Distribution.*

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* This same assignment of revenues applies to direct access and community choice aggregation customers.

(Continued)

Advice	5231-E	*Issued by*	*Date Filed*	February 16, 2018
Decision		*Robert S. Kenney*	*Effective*	March 1, 2018
		Vice President, Regulatory Affairs	*Resolution*	

Figure E1: Tariff sheet for the Care Time of Use rate used in the analyses. (Image Source: Pacific Gas and Electric Company, 2019).

Table E1: Rate information for EL-1 rates used in the analysis.

Rate Schedule	**Rate Design**	**Delivery Minimum Bill Amount** (per meter per day)	**Discount** (per dwelling unit per day)	**Minimum Average Rate Limiter** (per kWh per month)
Residential CARE Schedules: EL-1, EML, ESL, ESRL, ETL	CARE Tiered Energy Charges	$0.16427	ESL = $0.06422 ETL = $0.21419	ESL and ETL $0.04632

Table E2: Tier rates for EL-1 rates used in the analysis

Rate Schedule	**Tier 1 ($/kWh)**	**Tier 2 ($/kWh)**	**Tier 3 ($/kWh)**	**California Climate Credit** [2/] (April & Oct Bill)	**"Average" Total Rate** [3/] (per kWh)
Residential CARE Schedules: EL-1, EML, ESL, ESRL, ETL	$0.13453	$0.17767	$0.27510	($39.42)	$0.13073

APPENDIX F: Energy Data Analysis Code

The following R code was used to download electricity data from the Pacific Gas and Electric website to determine a reasonable fuel escalation rate. Code chunks containing URL's for historical electricity data spreadsheets were taken from the site's HTML code and pasted into a .csv file. Excel files containing rate information were downloaded and processed. The resulting rate data were exported to Excel to create graphs. The percentage calculation following the code shows the yearly and overall average fractional percent change in base CARE electricity rate. Code comments are denoted with number marks. Pacific Gas and Electric's website archives were accessed from the indicated URL (https://www.pge.com/tariffs/electric.shtml) on January 9, 2019.

```
######################
#####Data Download####
######################

#####Read in character strings containing URL’s from the PG&E website’s
#####“developer tools tab (stored in excel .csv file)

###Paste directory path containing URL's in .csv file here
URLs_dir <- "E:\\Thesis Draft and Materials, 5-12-18\\Thesis Code
Files\\pgeelectricitytarifffiles.csv"

####Paste path of preferred browser here
browser_path <- "C:/Program Files (x86)/Google/Chrome/Application/chrome.exe"

pa <- "https://www.pge.com/tariffs/"  ###This is the first piece of the data URL

pge <- read.csv(URLs_dir, header = FALSE)

ans <- rep(0,length(pge$V1))  ###Create object for URL fragments
for(i in 1:length(pge$V1)){
temp <- as.character(pge$V1[i])
```

```
for(j in 1:nchar(temp)){
if(substr(temp,j,j+4) == "href="){
temp <- substr(temp,j+6,nchar(temp))
}
if(substr(temp,j,j+3) == "xlsx"){
temp <- substr(temp,1,j+3)
}
if(substr(temp,j,j+2) == "xls" & substr(temp,j, j+3) != "xlsx"){
temp <- substr(temp,1,j+2)
}
}
ans[i] <- temp
}

ans2 <- rep(0,length(ans))
for(i in 1:length(ans)){
ans2[i] <- paste0(pa,ans[i])}  ###Concatenate to create complete URL for download
ans2

for(k in 1:length(ans2)){     ###Loop through completed URL’s to download files
browseURL(ans2[k], browser = browser_path)
}

################################
#####Data analysis, EL-1 Rates##
################################

EL1_dir <- "E:/Thesis Draft and Materials, 5-12-18/PGE Electricity Rates/Residential
Electricity Inclined block rates"

install.packages("xlsx")

setwd(EL1_dir)
library("xlsx")
file_list <- list.files(EL1_dir)     ###object of downloaded files

Care.Base <- rep(0,length(file_list))  #Create an object for each rate tier
Care.Tier2 <- rep(0,length(file_list))
Care.Tier3 <- rep(0,length(file_list))
date <-  rep(0,length(file_list))    #Create an object for each time interval
for(i in 1:length(file_list)){
temp <- read.xlsx(file_list[i],sheetIndex = 1)   #Read in data for each file
Care.Base[i] <- as.numeric(paste(temp[3,6]))  #Read in each rate and
```

```
Care.Tier2[i] <- as.numeric(paste(temp[3,7])) #convert factors to numeric type
Care.Tier3[i] <- as.numeric(paste(temp[3,8]))
date[i] <- as.character(file_list[i])  ##Read in URL containing date range into object
date[i] <- substr(date[i],5,17) ###Reduce to date
}
plot(historical, ylim = c(0,.15))

#Create dataframe containing electricity rates for each tier, by date.
end <- data.frame(Care.Base,Care.Tier2,Care.Tier3,date)
write.csv(end, file = "historical_Care_rates.csv")  #Write to .csv file
```

APPENDIX G: Water Heater Functions Written in R

The following code was used to calculate the theoretical maximum annual volume of hot water a water heating system could produce, based upon the annual energy consumption. The R functions were used to verify that building energy modeling results were consistent with thermodynamic principles. The functions can be easily modified to return an annual hot water production estimate, given the overall average efficiency of a water heater.

```
####Jeff Harkness########
########1-18-19########
#Calculate the Theoretical Maximum Hot Water Output for Water Heaters###########
######Program 1: Gas Water Heaters

gaswh <- function(therms,ef){
set point <- 125 #Degrees Fahrenheit
temp.in <- 58  ###assumed 14 degrees lower than standard interior set point temp.
specific.heat <- 4.184 #KJ/(kg*k)
stp.density <- 998 ##kg/m^3, water at standard temperature-pressure
th.kwh <- 29.3 ###kWh per Therm
delta.t <- set point - temp.in
m3.gal <- 3.7854*(10**(-3))  ###Conversion factor taken from Frank M. White, 2016
joules <- ((therms * th.kwh*ef)*3600)*1000  ###converts therms to Joules
theory.max <- (((joules/4184)/delta.t)/stp.density)/m3.gal ###Gives theoretical maximum
gallons
theory.day <<- theory.max/365  ###Returns the theoretical maximum, in gallons per day
print(c("The theoretical maximum gallons per day is",theory.day,"for the entered number
of therms."))
}


##Program 2: Heat Pump Water Heaters####
####################################
```

```
hpwh <- function(kwh,b){

  set point <- 125 #Degrees Fahrenheit
  temp.in <- 58  ###assumed inside 14 degrees lower than standard interior set point temp.
  specific.heat <- 4.184 #KJ/(kg*k)
  stp.density <- 998 ##kg/m^3, water at standard temperature-pressure
  delta.t <- set point - temp.in
  m3.gal <- 3.7854*(10**(-3))  ###Conversion factor taken from Frank M. White, 2016
  joules <- ((kwh*b)*3600)*1000  ###converts kwh to Joules
  theory.max <- (((joules/4184)/delta.t)/stp.density)/m3.gal ###Gives theoretical maximum gallons
  theory.day <<- theory.max/365  ###Returns the theoretical maximum, in gallons per day
  print(c("The theoretical maximum gallons per day is",theory.day))
}
```

APPENDIX H: Care Rate Utility Analysis Code

The following R code was used to verify the annualized electricity rate calculation reported by BeOpt for the propane tiny home model energy type. The purpose of the analysis is to verify the results and lend transparency to the calculation. Comparison with the reported annual electricity cost for year 1 show that the R code agrees with the reported utility bill to within 1%. The code used to analyze the EL-1 Care electricity rate is given below.

PG & E EL-1 Care rates used for this analysis were downloaded March 20th, 2019, from: https://www.pge.com/tariffs/Res_180301-180831.xls

```
load <- read.csv("E:\\Thesis Draft and Materials, 5-12-18\\Thesis Draft\\Thesis
Simulation Files and Spreadsheets\\Design Simulations\\Results Spreadsheets\\R EL-1
Propane Thesis Case Electricity 3-20-19 .csv",header=TRUE)
colnames(load) <- "net.kwh"
nums <- rep(0,8760)
numdays <- c(31,28,31,30,31,30,31,31,30,31,30,31)
attach(load)
load$hour <- 0
load$hour <- rep(1:24,365)  ##Add Column for Every Hour of the Year
ne <- 0
for(i in 1:length(numdays)){  ###Nested Loops add day column
for(j in 1:numdays[i]){
ne <- c(ne,rep(j,24))
}
}
ne <- ne[-1]
load$day <- ne

mo <- 0   ###Create a months column
for(k in 1:12){
```

```
mo <- c(mo,rep(k,numdays[k]*24))
}
mo <- mo[-1]
load$month <- mo

euse <- tapply(load$net.kwh,load$month,sum)
euse2 <- as.numeric(euse)
Month <- seq(1,12,1)
load2 <- data.frame(Month,euse2)

ans <- rep(0,length(load$euse))
tier.1 <- rep(0,length(load2$euse2))
tier.2 <- rep(0,length(load2$euse2))
tier.3 <- rep(0,length(load2$euse2))
min.mo <- rep(0,length(load2$euse2))

esum <- 8.7
ewint <- 10.6
t1 <- 0.1345
t2 <- 0.1776
t3 <- 0.27510
min.charge <- .16427

for(i in 1:length(load2$Month)){
numkwh <- 0
if(i > 4 & i < 11){
base <- esum
}else{
base <- ewint
}
numkwh <- as.numeric(load2$euse2[i])
baseline <- base * numdays[i]
if(numkwh < baseline){
tier.1[i] <-  numkwh * t1
}
if(numkwh > baseline & numkwh < (baseline * 4)){
tier.2[i] <- ((numkwh - baseline) * t2)
tier.1[i] <- (baseline * t1)
}
if(numkwh > (baseline* 4)){
tier.3[i] <- ((numkwh - (baseline*4)) * t3)
tier.2[i] <- (((baseline*4) - baseline) * t2)
tier.1[i] <- (baseline * t1)
```

```
}
block.charge <- tier.1[i] + tier.2[i] + tier.3[i]
min.mo[i] <- numdays[i] * min.charge
ans[i] <- block.charge + min.mo[i]
block.charge <- 0
}
grand.total <- sum(ans) +  min.charge
min.month <- rep(0,length(load2$euse2))

results <-
data.frame(load2$Month,round(load2$euse2,2),round(tier.1,2),round(tier.2,2),round(tier.
3,2),round(min.mo,2),round(ans,2))
colnames(results) <- c("Month","Energy Use (kWh)","Tier 1 ($)","Tier2 ($)","Tier 3
($)","Monthly Charge ($)","Total ($)")
formattable(results)

bill <- sum(results[,3])
beopt <- 73.91
percent.error <- (bill - beopt)/beopt*100
percent.error
```