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Robustness of Energy Performance of Zero-Net-Energy (ZNE) Homes

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Abstract

Zero-net-energy (ZNE) homes produce an adequate amount of energy on-site to meet their energy demand based on source energy for an entire year. California building energy efficiency standards require new residential buildings started in 2020 to be ZNE. For various reasons, a home designed as ZNE may not achieve ZNE performance in real operation. This study aimed to quantify the robustness of the energy performance of ZNE homes due to weather variability, climate change, and the uncertainty of occupant behavior. A single-family ZNE house, based on the optimal cost-effective design in three California climate zones, was used to develop the EnergyPlus simulation models. Weather variations were considered from a combination of the historical 30 years' actual meteorological year (AMY) weather data, typical year weather data in TMY3, and future weather data based on Intergovernmental Panel on Climate Change scenarios. Three scenarios of occupant behavior from the energy perspective were defined to represent the uncertainty about occupants' activities, comfort requirements, and their adaptive interactions with buildings and systems. In terms of annual source energy, the simulation results of the ZNE homes showed: (1) a decrease of 23–38 percent for occupants with energy austerity behavior and an increase of 120–130 percent for occupants with energy wasteful behavior, compared with the baseline assumption of normal occupants; (2) a variation range of -15 percent to +14 percent for the results using 30-year AMY weather data compared with the baseline results using TMY3 weather data; (3) an increase of 10–13 percent with future weather in Fresno and Riverside and a decrease of 15 percent with San Francisco; and (4) climate change can reduce the gap between the austerity and wasteful consumption. These findings provide insights into how ZNE homes may perform in reality and inform architects, engineers, occupants, and policymakers to pay more attention to occupant behavior on design, operation, and regulations of ZNE homes to ensure energy performance robustness.

Glossary

GHG   Greenhouse gas

ZNE   Zero net energy

IPCC   Intergovernmental Panel on Climate Change

TMY   Typical meteorological year

AMY   Actual meteorological year

TDV   Time dependent valuation

OB   Occupant behavior

CEC   California Energy Commission

HVAC   Heating, ventilation, and air conditioning

SRES   Special Report on Emissions Scenarios

ECM   Energy conservation measures

ZEB   Zero energy building

NEM   Net energy metering

TOU   Time-of-use
CZ   Climate zone

RCP   Representative concentration pathway

GHI   Global horizontal irradiation

PV   Photovoltaic

WGCM The Working Group on Coupled Modeling

GCM   General circulation model

NetCDF   Network common data form

ASHRAE   The American Society of Heating, Refrigerating and Air-Conditioning Engineers

AOGCM   Coupled atmosphere-ocean general circulation model

1.0   Introduction

The building sector consumes more than one-third of global primary energy. In the United States, residential and commercial buildings in 2018 [1] consumed 40 percent of the country's energy. Building energy codes and standards are becoming more stringent, to require existing and new buildings to reduce energy use and carbon emissions.

Zero-net-energy (ZNE) buildings have various definitions and may be based on the site or source energy. *Source energy* is the energy consumed on the site in combination with the energy that is consumed during the extraction, treatment, and transport of the primary fuels, i.e., coal, oil, and natural gas; it accounts for the efficiency of the power plant and energy losses in the transmission and distribution to the site as well. Source energy factors are applied to convert energy delivered and exported on-site into the total equivalent source energy. In this study, we used the source energy conversion factors defined in ASHRAE Standard 105, which covers California.

When on-site renewable energy is exported to the grid as electricity, it replaces electricity that would be required from the grid. Therefore, in ZNE building performance accounting, the same source energy conversion factors are used to quantify the exported energy. The U.S. Department of Energy defines a ZNE building as "an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy" [2]. The California definition for a ZNE building is based on time-dependent valuation (TDV) energy, which is a dynamic accounting of source energy. Zero net energy in TDV is a California Energy Commission (CEC) published definition by which the value of energy consumed by the building over the course of a typical year is less than or equal to the value of the on-site renewable energy generated [3], where the value of energy is represented by the on-site energy use multiplied by the annual 8,760 time-series values of TDV factors. TDV values reflect the mix of electricity supply changes over time. In particular, as more solar photovoltaic (PV) supplies high levels of renewable electricity, the value of the daytime electricity generation is reduced.

As spelled out in the California Energy Efficiency Strategic Plan, the state has high-reaching objectives for the democratization of ZNE buildings. In the residential sector, all new construction will be ZNE by 2020, while for the commercial construction, this requirement will come into effect in 2030.

A building can be designed with a ZNE goal, but may not reach ZNE performance in actual operation every year. The International Energy Agency defines six factors that have the greatest influence on energy consumption of buildings in Annex 53 [4]: (1) weather, (2) building envelope, (3) building energy and services systems, (4) indoor design criteria, (5) building operation and maintenance, and (6) occupant behavior. The second, third, and fourth factors are generally well controlled during the design process; however, yearly weather variation and long term climate change (the first factor) will influence building performance [5–7], and this impact is usually not taken into account, as typical year weather data (e.g., TMY3) are usually used in simulations of ZNE homes to determine optimal design and performance. Building operation and maintenance (the fifth factor) is shown to have a significant impact on building performance, which depends on operation practices adopted for commercial buildings and occupant behavior in residential buildings. Occupant behavior (the sixth factor) is another influential factor for research due to the complexity and inherent uncertainty of occupant energy use styles [8,9].

The yearly weather variations and long term climate change will influence both energy demand and supply in buildings (e.g., more cooling and less heating, and a potential influence on renewable power generation from PV), leading to uncertainty of ZNE home performance. On the other hand, ZNE homes are highly energy efficient in design; they have a highly insulated envelope, high-performance windows, light-emitting diode (LED) lighting, ENERGY STAR appliances, and efficient HVAC systems. Therefore, energy use becomes driven more by occupant behavior than by technologies alone.

1.1 Climate change and creation of future weather data for simulation of ZNE homes

Buildings—including ZNE buildings—are often designed using weather data from remote open areas (e.g., airports near large cities) or historical datasets, which are usually compiled as a typical meteorological year (TMY) weather file. Building performance and solar energy system simulations are clearly undertaken with standardized weather files, which do not generally take climate change into account. A better understanding of the impacts of climate change on building HVAC operation and solar power plants, as well as occupant comfort, will aid financial planning, technology selection, and energy output projections [10].

Climate changes are likely driven by human activities and greenhouse gas (GHG) emissions, which depend highly on energy production, population increase, and economic activity over the next century [11]. Several potential pathways and scenarios have been developed to account for a range of possibilities in the future.

The SRES (Special Report on Emissions Scenarios) are a set of scenarios that were defined by the IPCC (Intergovernmental Panel on Climate Change) in its Third Assessment Report in 2000 [12]. The SRES use a sequential approach to determine 40 scenarios based on socioeconomic futures. Political or legislative actions have no effect during development. Each scenario is categorized into one of the four families (A1, A2, B1, B2), as shown in Figure 1. The A1 scenario represents higher GHG emissions with a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. The A2 scenarios represent medium GHG emissions in a heterogeneous world. The underlying theme is the self-reliance and preservation of local identities. The B1 scenario represents lower GHG emissions with a convergent world of the same global population that peaks in mid-century and declines thereafter. The B2 scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability.
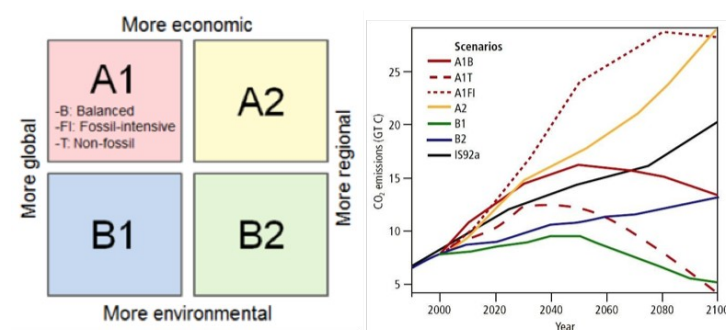

Figure 1. Four families (A1, A2, B1, B2) for the SRES definitions and their emissions [13]

Representative concentration pathways (RCPs), defined in the IPCC Fifth Assessment Report [14], are scenarios that describe alternative trajectories for carbon dioxide emissions and the resulting atmospheric concentration from 2000 to

2100 (Figure 2). The RCPs use a parallel approach to describe four different scenarios—RCP8.5, RCP6.0, RCP4.5, and RCP3-PD (including RCP2.6 and RCP2.9, usually RCP2.6 is used)—based on different assumptions about population, economic growth, energy consumption and sources, and land use over this century. The number represents the radiation forcing (RF) level in watts per square meter (W/m^2). For instance, the RF will be 8.5 W/m^2 under the scenario of RCP8.5, while according to further calculation, the temperature in 2100 will be increased by about 6.9℃. Under these scenarios, the Working Group on Coupled Modeling (WGCM) did some coupled model intercomparison testing to measure the parameters (e.g., time, longitude, latitude, and weather information) globally [15]. The results were stored in NetCDF (network common data form) format as different models (e.g., MIROC5 and HadGEM2-ES).
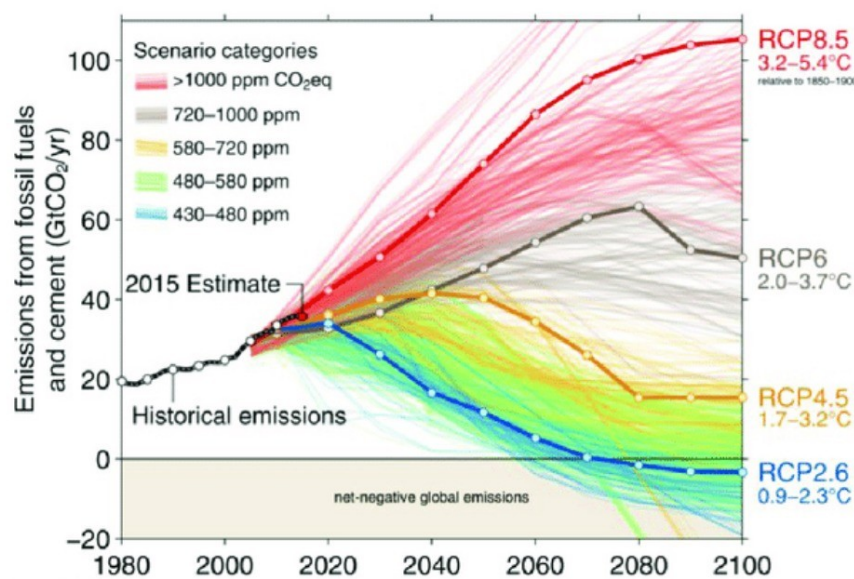

Figure 2. Emissions under different RCPs over the recent century (data: [16][17][18]. Image source: Global Carbon Project)

The morphing method, developed by Belcher et al. in 2005, is a time-series adjustment method for generating future weather data that accounts for projected changes in climate for thermal simulation in buildings. This method is currently employed widely in building simulation research. It combines observed weather data with a certain projection of how the climate would change under different aforementioned emission scenarios. Morphing involves shifting and stretching the variables in the present-day weather time-series that encapsulate the average weather of the future climate while preserving the physically realistic weather sequences of the source data [19]. This method downscales the results from coarse resolution climate models to a fine spatial and temporal resolution applicable to the building thermal simulation.

The main advantage of this morphing method is that it is simple and flexible, so it can be applied across a broad range of climate change scenarios, reducing computational costs compared to traditional numerical modeling. Taking prediction

of the dry bulb temperature as an example, it is simply adjusted through a combination of shifts and stretches. HadCM3 (Hadley Centre Coupled Model, version 3) [20], which is a coupled atmosphere-ocean general circulation model (AOGCM) developed at the Hadley Centre in the United Kingdom, provides changes to monthly mean values of the daily mean temperature, the daily maximum temperature, and the daily minimum temperature. Then, a shift and a stretch are applied to all hourly values within the month to preserve the predicted change in the mean value and the predicted change in the daily mean amplitude for generating the projected time-series dry-bulb temperature distribution.

However, the morphing method has some limitations: the coarse resolution of global climate models and the high degree of uncertainty in predicting future weather conditions compared to other atmospheric models. In addition, its solar radiation prediction is not accurate enough, since a simple shift cannot be applied to solar radiation; even if HadCM3 again predicts an absolute change in the monthly mean value, shifting hourly radiation values leads to either negative radiation values or positive radiation at night. For more details on the morphing procedure, see the original paper by Belcher et al. [19].

A recent study led by Robert and Kummert evaluated the performance of a ZNE residential building in Canada with the future climate [21]. This study demonstrates the use of the morphing method for designing ZNE buildings. The future weather data were used to simulate the performance of a ZNE home in two different locations—Montréal (QC) and Massena (NY)—as it was designed using historical data. In this study, the authors used morphed data with the HadCM3 model and the A2 scenarios. The results showed that the buildings would miss the ZNE target for most of the future years. This can be explained by a significant increase in the cooling system energy consumption in the future due to an increase of outdoor air temperature.

1.2 Occupant behavior impacts on ZNE homes

Recent studies show that as buildings become more energy efficient, the behavior of occupants plays an increasing role in energy consumption [22,23]. Much research has been conducted to understand how people behave and how they operate the systems for controlling their indoor environment and comfort [9,23–26], and more important and practically, how different occupant behaviors influence building energy performance and GHG emissions [5,27–30]. A case study performed by Sun et al. found that occupant behaviors, if adopted as energy conservation measures (ECMs), can save energy as much as 22.9 percent for individual measures and up to 41.0 percent for packages of measures [31]. Hong et al. defined three representative types of occupant behaviors—austerity, standard, and wasteful—and performed building energy simulations to evaluate the impact of occupant behaviors on the energy use of private offices [32]. They found that for a typical single-occupancy office room, the austerity work style could consume 50 percent less energy compared to the standard reference work style, while the wasteful work style would consume up to 90 percent more energy.

Occupant behavior is a leading factor towards uncertainty when evaluating retrofit ECM effectiveness. Hoes et al. performed building energy simulation to evaluate the impact of occupant behavior on ECM savings [33]. They found that in buildings with a passive design (e.g., heavy thermal mass and low window-to-wall ratio) the impact of occupant behaviors becomes even more significant. Sun et al. developed a framework to quantify the impact of occupant behaviors on ECM savings through building performance simulation [34]. They found that occupant behaviors have a much stronger impact on ECMs that involve occupants closely, such as natural ventilation and zonal HVAC control, than on ECMs that are more technology-driven and require little occupant involvement. Considering that ZNE buildings achieve ZNE and indoor comfort mainly through renewable energy and passive ECMs, such as solar radiation and natural ventilation, the impact of occupant behaviors on ZNE buildings' actual performance should be significant.

Past research has been demonstrated that a building designed to be nearly ZNE might lead to higher energy consumption than expected if the assumptions made in the simulation process are not respected during its effective use. Lenoir et al. presented a study investigating the importance of user behavior on the energy performance of high-performance buildings [35]. They compared the data collected through measurements during building operation with data calculated during the design phase, including ventilation and air-conditioning, lighting, plug loads and uninterruptible power supply (UPS), lifts, and ceiling fans. The authors concluded that the differences between the design calculations and the measurements could be as much as 50 percent. A study conducted by Carpino et al. assessed the influence of housing occupancy patterns on the definition of residential ZNE building in Italian climatic conditions [36]. The investigation provides information regarding the effects of human variables (occupants' needs and preferences) on the final energy performance of low energy buildings. It highlights the combination of variables that are important in the definition of nearly ZEB as net-zero source energy. In other words, if occupants are not interacting with the building systems and technologies as expected, the actual energy performance may differ significantly from the initial ZNE design. Therefore, clearly understanding and accurately modeling occupant behavior in buildings is crucial to reducing the gap between design and actual building energy performance, especially for low-energy buildings relying more on passive design features, occupancy controlled technologies, and occupant engagement [37,38].

1.3 Objective and organization of the study

This study aims to quantify the possible building performance (PV generation, energy demand, and overall net performance) variation due to yearly weather and long term climate change, as well as occupant behavior for ZNE homes in three typical climate zones of California. We adopted the source energy definition of ZNE and used the average source factors (3.15 for electricity and 1.09 for natural gas) for the United States defined in ASHRAE standard 105 [39]. The study provides insights into the robustness of ZNE home performance—understanding the risk of performance uncertainty of ZNE homes in reality and reducing the risk by careful

consideration of weather and occupant behavior diversity in the design and operation of ZNE homes.

The remainder of this paper is organized as follows: Section 2 provides a detailed description of the methodology, Section 3 shows the main results and analyses, Section 4 provides more discussion, and Section 5 draws main conclusions.

2.0   Methodology

To simulate and evaluate the impacts of weather variations, climate change, and occupant behavior on the energy performance of ZNE homes, we first adopted ZNE home design developed from a project funded by the CEC for three climate zones in California [40]. Next, we acquired 30 years of AMY weather data and developed future weather data for the three climate zones. Then we defined three scenarios of occupant behavior for ZNE homes. Finally, we ran EnergyPlus (version 8.8) simulations to quantify the influences of various scenarios of weather and occupant behavior on ZNE home performance. Figure 3 illustrates the overall approach and workflow.
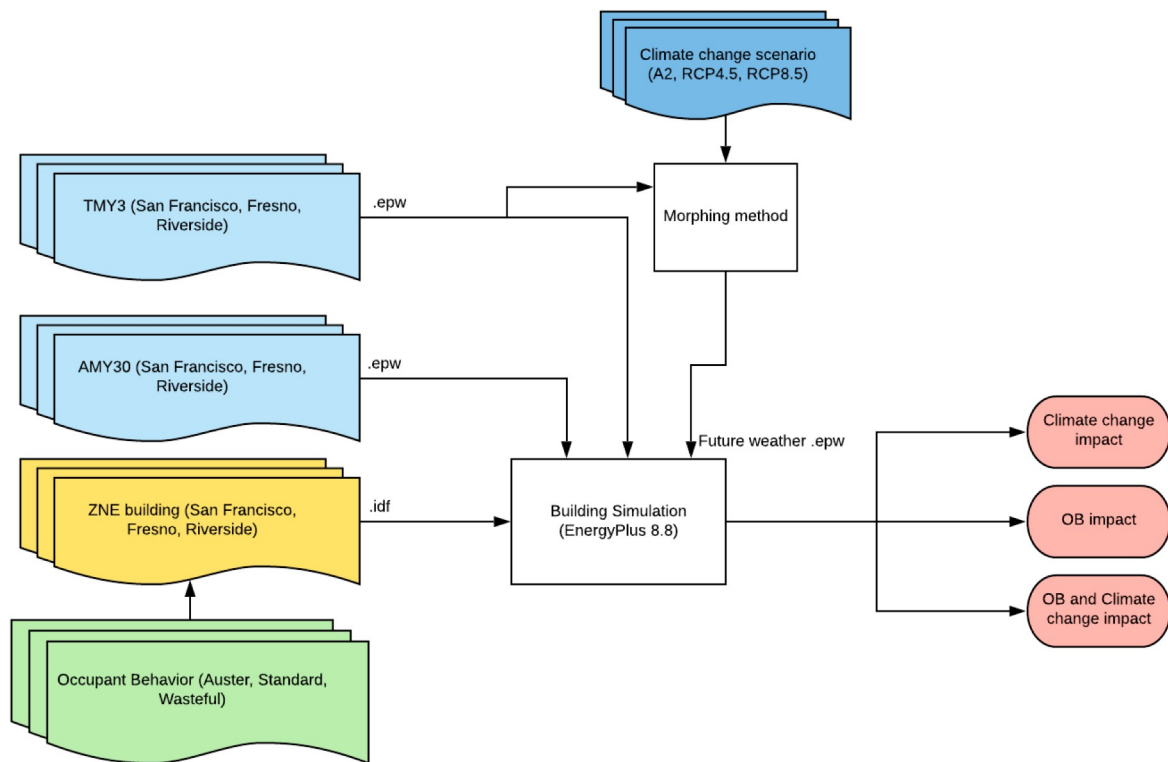

Figure 3. Overall study methodology

2.1   Characteristics of ZNE homes

A single-family home shown in Figure 4 was used for the building energy modeling. This single-family prototype model was developed by the CEC for testing of the California energy efficiency code compliance required for the 2019 California building energy standards, Title 24 [41]. The house is a single story with an attic

and a parking garage. It has three bedrooms and a floor area of 195 m^2 (2,100 square feet [ft^2]), excluding the garage. The CEC Title 24 reference manuals describe underlying assumptions for the standard design of the single-family home prototype building energy model [42,43].
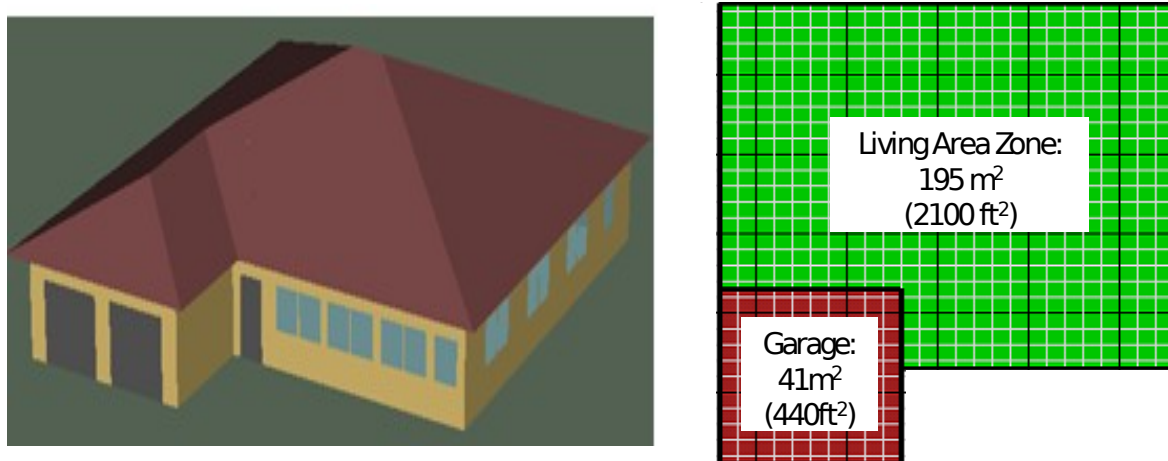

Living Area Zone:
195 m^2
(2100 ft^2)

Garage:
41m^2
(440ft^2)

Figure 4. Prototype single-family energy model for ZNE home analysis

The ZNE technology specification and cost data, TDV metric, and rooftop PV energy export compensation rates were developed to reflect the future conditions in California. Since the ZNE baseline home design is targeted for the 2022 building code and energy efficiency standard guideline, TDV values for 2022 were derived for the ZNE home baseline development [44]. Utility rates were developed based on the TDV-based hourly time-of-use (TOU) electricity rates as a proxy for future utility rates. The electricity exported to the grid from the solar PV was developed based on the anticipation of further evolution of a net energy metering (NEM) policy for rooftop solar [45,46]. ZNE building baseline designs were generated by leveraging the prototype model, energy efficiency measures, TDV metric, utility cost, and PV electricity export rate inputs using the residential building energy simulation tool: BEopt [47]. Using BEopt, we identified cost-optimal efficiency packages for whole-house energy savings along the path to ZNE [48].

Energy use depends on climate conditions. The energy simulation to derive the ZNE baseline used the climate data established by the CEC [49]. The selected climate zones (CZ) for the ZNE home analysis were California CZ 3, CZ 10, and CZ 13 for representative cities of San Francisco, Riverside, and Fresno, respectively. CZ 3 represents a coastal climate with moderate temperatures year-round. CZ 10 represents the Southern California climate for cold winter and warm summer. CZ 13 is for California's Central Valley location, which has high summer daytime temperatures.

The measure packages selected for the ZNE baseline home show that energy efficient home appliances such as clothes dryers, clothes washers, and plug load

reductions from smart controls—as well as hot water pipe insulation, ducts in the conditioned space, advanced HVAC systems, and airtightness—are key measures in general across climate zones. The cooling system was cost-effective high efficiency central air conditioning equipment with a Seasonal Energy Efficiency Ratio (SEER) of 16 and an Energy Efficiency Ratio (EER) of 13.5 that can operate in two speeds of cooling. The ZNE home design has a beneficial impact in reducing the cooling system sizing; for example, the cooling system capacity of a ZNE home in CZ 13 Fresno is 1.4 ton, which is 42 percent less than a typical new non-ZNE home of the same size. A gas furnace with annual fuel utilization efficiency (AFUE) of 92.5 was selected as the cost-effective heating system. Highly insulated walls and attics are advantageous for hot climate zones. Lighting systems and windows in the baseline models offer quite energy efficient technology already, and there is no opportunity for further cost-effective energy savings. Heat pump water heaters and more energy efficient refrigerators and dishwashers are beneficial for all-electric homes, while cooking ranges with advanced technology and condensing tankless water heaters are measures that are cost-effective for mixed-fuel homes. Details of the performance characteristics and incremental cost assumptions for the selected measures are documented in a technical report to the CEC [50].

A broad spectrum of energy efficiency measures were added for the optimization simulation runs. Table 1 summarizes the key characteristics of the selected measures for the ZNE homes, for example, in CZ 13. Photovoltaic panels with different sizes in increments of 0.1 kilowatt (kW) were used in the optimization to find the optimal PV sizing for the most cost-effective point. Rooftop solar PV panels were designed with the azimuth towards the south and tilt aligned with the roof pitch angle. The PV system size was different for the ZNE TDV home design in different climate locations. The optimization simulations determined a 2.5 kW PV system for CZ 03, 2.8 kW system for CZ 10, and 3.4 kW system for CZ 13.

Table 1. Key characteristics of the ZNE single-family home in California Climate Zone 13 (Fresno)

Technology		ZNE Efficiency Measures
Walls	Wood Stud	R-21 Fiberglass Batt, Grade-1
	Wall Sheathing	R-5 Expanded Polystyrene Insulation
	Exterior Finish	Stucco, Medium/Dark
Ceilings/Roofs	Unfinished Attic	Ceiling R-38 + Roof R-19 Grade-1, Vented
	Roof Material	2019 Title-24 Steep Slope Cool Roof
Windows & Doors	Windows	U value 0.30, SHGC 0.23
	Doors	Fiberglass
Airflow	Natural Ventilation	Available for Ventilation and Cooling Load Reduction
	Air Leakage	5 ACH under 50 Pa
	Mechanical Ventilation	Exhaust Fan Meeting 2016 ASHRAE 62.2 requirements
Space Conditioning	Air Conditioner	SEER 16, EER 13.5, 2-speed
	Furnace	Gas Furnace, 92.5% AFUE
	Ducts	In Conditioned Space
Space Conditioning	Heating Setpoint	CBECC RES Heating Thermostat Setpoint
	Cooling Setpoint	CBECC RES Cooling Thermostat Setpoint

~~Schedules~~		
Water Heating	Water Heater	Gas Tankless Water Heater
	Distribution	R-5, Trunk Branch, PEX, Demand
Lighting	Lighting Power	CEC Prototype using LED Lights, 676 kWh/year
Appliances & Fixtures	Refrigerator	Bottom freezer, Energy Factor 15.9
	Cooking Range	Optimized Burner Gas Cooktop / Gas Self-Cleaning Oven Forced Convection
	Dishwasher	DOE Standard Efficiency Dishwasher
	Clothes Washer	Standard Top-loading Baseline 2018 DOE Standard
	Clothes Dryer	Vented Gas with DOE Efficiency Level 2
	Plug Loads	Advanced Power Strips with Infrared and Occupancy Sensor
Power Generation	PV System	3.4 kW
	PV Azimuth	South
	PV Tilt	Roof Pitch Tilt

Note that U value is in Btu/h·ft^2·F and R value is in h·ft^2·F/Btu (1 h·ft^2·F/Btu = 0.1761 m^{2}C/W).

2.2   Development of future weather data for use in energy simulations

To evaluate the influence of climate change on ZNE home performance, generation of consistent future weather data for building simulation is needed. Building simulation uses hourly weather data files, which need to represent the characteristics of the local climate zone. However, most of the future climate model outputs provide monthly data averaged on surface resolutions such as 300 square kilometers (km^2). To downscale the future weather data, the morphing method was used. The method uses recent local weather data and combines it with future climate models to create a realistic future weather file that can be used for building thermal simulations [19]. Details of this method are shown in Figure 3.

Computational tools were developed to generate climate change adapted weather files for any location in the world. This study tested two different morphing tools: the CCWorldWeatherGen [51] and the WEATHERSHIFT [52]. Both use the morphing method developed by Belcher et al. [19] and presented in Section 1.1 Climate change and creation of future weather data for simulation of ZNE homes. CCWorldWeatherGen is a Microsoft Excel-based weather generator. It uses the HadCM3 model and the A2 scenario which is available from the IPCC Data Distribution Centre. A2 is the medium-high emissions scenario, and three future time slices (2020s, 2050s, and 2080s) are studied. WEATHERSHIFT is also a weather forecast tool that adopts the morphing technique; it uses 14 models in the Fifth Assessment Report (AR5) for three future time periods (2026–2045, 2056–2075, and 2081–2100). GCM data are generally available for an average year during these three time periods. For instance, the 2026–2045 period represents the mean weather conditions between 2026 and 2045. The future weather can be calculated for RCP 4.5 and RCP 8.5. RCP 8.5 represents a business as usual scenario, and RCP 4.5 represents a moderately aggressive emissions mitigation scenario. A distribution of the increase of mean temperature for each month is calculated from the 14 models, and the percentile distribution can be chosen. For this study, the warming percentile chosen was 50 percent. This means that among the 14

temperatures generated by the models, the temperature used for the morphism will be an average between the seventh and eighth warmest temperatures calculated. This method should be more accurate than that of CCWorldWeatherGen, which uses only one model (HadCM3).

These two tools were used to generate future weather data in three typical California climate zones: San Francisco, Fresno, and Riverside. Figure 5 shows the morphed temperature with three different scenarios (RCP4.5, RCP8.5, and A2) for the 2080–2099 period in the three locations. The HadCM3 A2 temperature was slightly underestimated, as it represents results for 2080 and not for the 2080–2099 period. The morphed weather files provided hourly values, but to visualize the whole year, monthly averaged values were plotted. Figure 5 also shows the hourly morphed temperature for January 1 in San Francisco during the 2080–2099 period. As expected, the shape of the TMY3 curve stayed the same but is shifted, and the stretching increased the amplitude. Globally, the outdoor temperatures rose to represent the global trend of each climate scenario. Temperatures from the RCP8.5 and A2 scenarios, which are the most pessimistic, were globally higher than temperatures from the RPC4.5 scenario.

Figure 6 shows the global horizontal irradiance (GHI) in the three locations studied during the2080–2099 periods. This variable is important for ZNE homes because it influences solar panel electricity production. On average, the GHI was not significantly modified during the morphing process. Further analysis is provided in the Discussion section below.
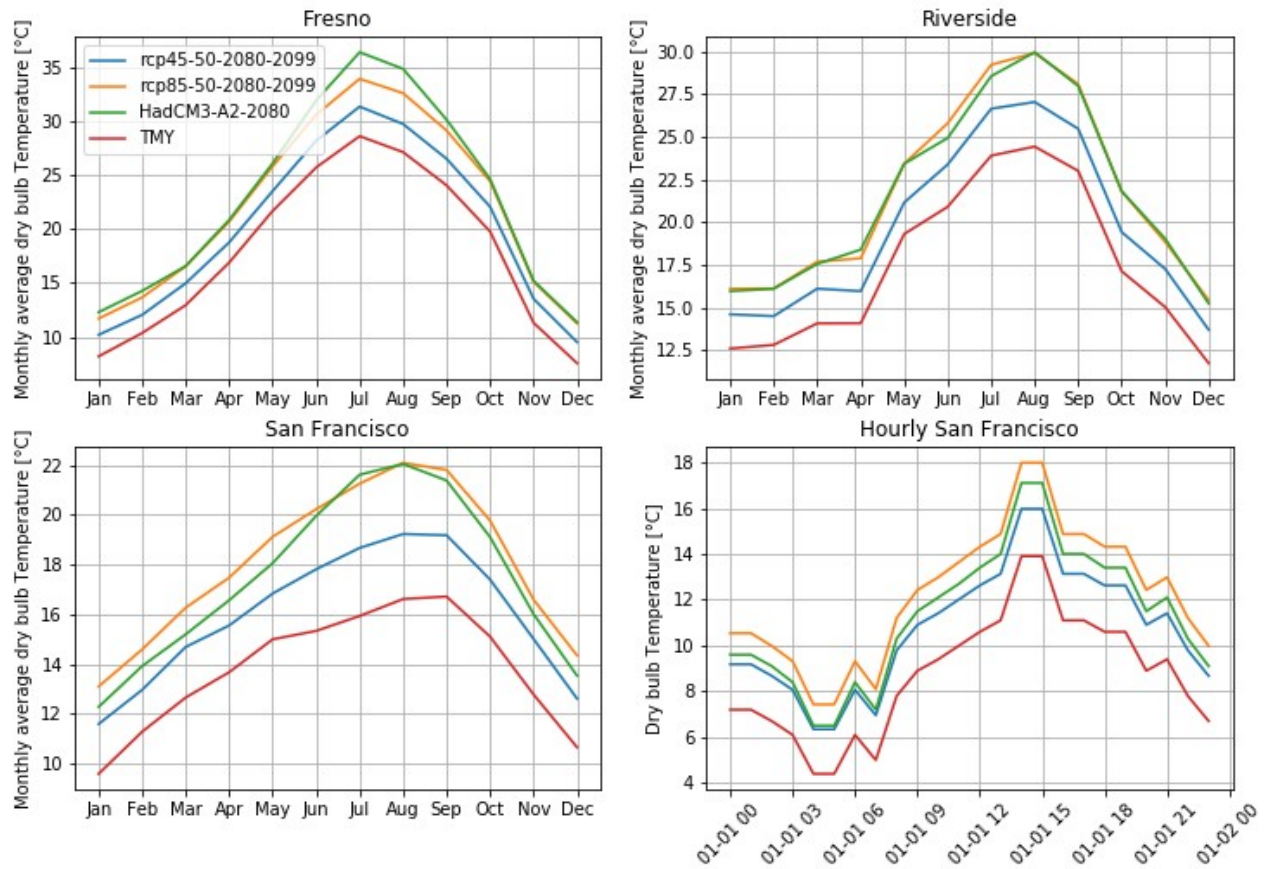
Figure 5. Morphed and TMY3 temperature in Fresno, Riverside, and San Francisco for the RCP8.5, RCP4.5, and A2 scenarios for 2080–2099
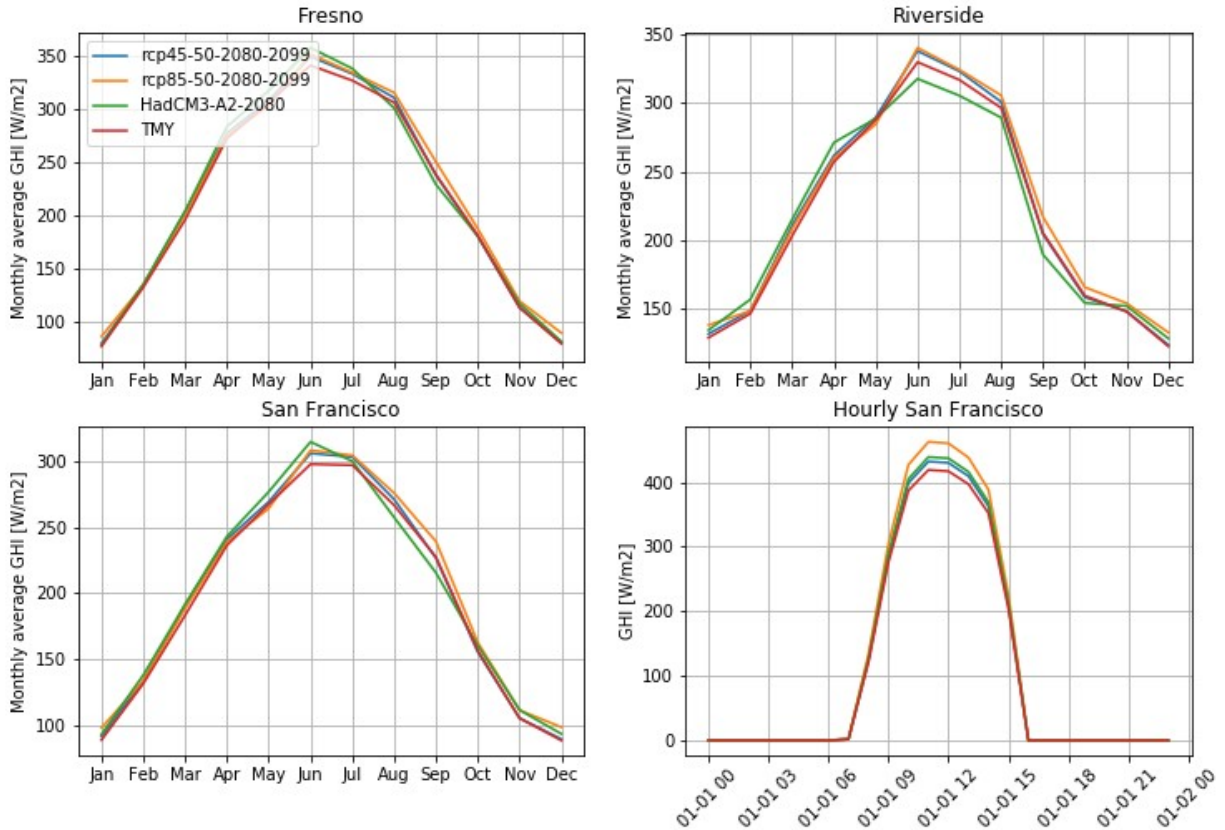
Figure 6. Global horizontal irradiance (GHI) in Fresno, Riverside, and San Francisco for the RCP8.5, RCP4.5, and A2 scenarios for 2080–2099

For the following EnergyPlus simulations, only morphed weather files from Weathershift (RCP4.5 and RCP8.5 scenarios) were used, as they are reasonable predictions and provide a good range for future climate.

2.3   Definition of three scenarios of occupant behavior for ZNE homes

The diversity of occupant behavior makes it challenging to find consistent models. Occupant behavior style can depend on well-known factors such as outdoor conditions (wind, temperature, daylight), but it also depends on occupants' habits, which determine whether they are environmentally responsible in their energy use. Also, not all occupants have the same criteria for thermal comfort; for example, it has been demonstrated that older people are more likely to feel uncomfortable at a given temperature than young people [53].

To represent this occupant behavior diversity and quantify its impact on a ZNE home, we defined three scenarios of occupant energy use behavior for single-family homes: austerity, standard, and wasteful. These refer to the three office workstyles previously proposed by Hong et al. [5,31,34], which we customized for use in residential buildings. These categories tend to define boundary conditions to represent the different levels of energy used to provide occupant comfort. This range of energy consumption can help inform the influence of occupant behavior on ZNE building performance. Descriptions of the three types of occupant behaviors is given below.

1) Austerity occupants are proactive in saving energy. These occupants actively adapt their clothing based on weather conditions, and they use the HVAC wisely to achieve thermal comfort. This can be modeled via a higher cooling setpoint and a lower heating setpoint. Also, austerity occupants are conscientious and try to minimize equipment usage. Thus, all-electric equipment (e.g., light, HVAC, appliances) is supposed to be shut down if the house is unoccupied. In addition, hot water usage is assumed to be reduced by half compared to the average U.S. water consumption. Finally, light is only used if daylight does not provide enough illuminance (set to 300 lux).
2) The standard style represents most occupants in terms of average energy use behavior.
3) The wasteful occupants consume energy at will. They lack the motivation to reduce energy usage. In this case, the HVAC system is assumed to be always ON (cooling and heating setpoint are fixed at 23°C), all equipment is used regardless of whether or not the house is occupied, and hot water usage is assumed to be twice that of the standard hot water user. Also, windows are assumed to remain closed. A case with windows always open was also studied, and that is presented in the Discussion section.

As mentioned, these three scenarios of occupant behavior were based on previous research for office buildings, but were adjusted for residential homes for this study. The occupant behavior models considered for office buildings originally included the adaptive thermal comfort for heating and cooling, lighting control, plug-load control, HVAC system control, and operable windows. For residential homes, the same assumptions were adopted for temperature setpoints and HVAC control because the human interaction with those buildings does not change noticeably by building type. However, light control, control of plug loads, and window operation were modified to better fit a residential environment, and schedules from the single-family prototype presented in Section 2.1 were used in the baseline occupant behavior model. Moreover, hot water system management was added to the list of considerations, by using the standard single-family home schedules defined in California building energy efficiency standards. The different behavior assumptions for these three scenarios are summarized in Table 2. Justifications for the assumptions are provided below.

Table 2. Summary of key assumptions of three occupant behavior scenarios

	Baseline	Energy Austerity	Energy Wasteful
Cooling thermostat setpoint (°C)	24.4 always	26	23
Heating thermostat setpoint (°C)	21.1	18	23

HVAC operation	Scheduled	On only if occupied	Always on
Appliances	Scheduled	On if in use, off if not in use	Always on
Lighting	Scheduled	On if occupied and if illuminance in the room < 300 lux	Always on
Hot water use / bath	Scheduled	Water use is reduced by half	Water use is doubled
Ceiling fan	Switch on if indoor air temperature in > 25.5°C	Switch on if Tin > 25.5°C	Switch on if Tin > 25.5°C
Windows	Closed	Closed	Closed

The standard behavior assumed the cooling setpoint at 24.4°C and the heating setpoint at 21.1°C [34]. The austerity occupants have a wider range, with a cooling setpoint of 26°C and a heating setpoint of 18°C. The wasteful occupants have the same setpoint (23°C) for both heating and cooling [5].

The assumption of hot water usage was based on data from the Residential Energy Consumption Survey (RECS) [54]. Figure 7 shows the distribution and the cumulative probability of the energy consumption of the hot water system in single-family detached houses. Two energy sources (electric and gas) for hot water systems were investigated and plotted separately. Based on this, a probability density function of energy consumption was estimated using the kernel density estimation. The figure shows that 15 percent of families used half the hot water of the average account, and 5 percent of families used double the hot water of the average account. We assumed these two types of water use behaviors represented the boundary conditions.
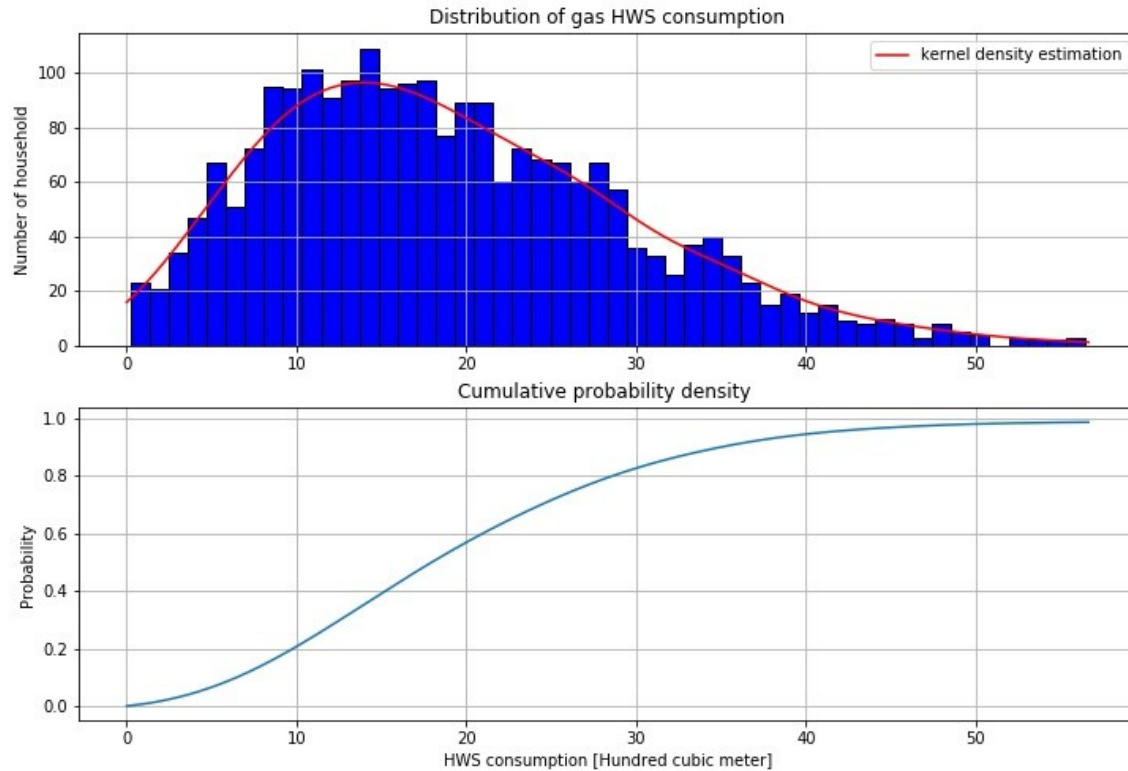
Figure 7. Distribution and cumulative probability density of gas hot water supply (HWS) consumption in single-family houses based on the RECS data

The lighting control of the standard case follows a fixed schedule based on the average use of lighting in residential buildings [55]. For austerity behavior, light usage varies with available daylight. The user switches off the light if the illuminance inside the room is above 300 lux, otherwise, he keeps the same schedule as the standard user [56]. The wasteful user is assumed to keep the lights on all the time.

The use of appliances for the standard case follows a fixed schedule based on Rubin's study [55]. The austerity occupant has the same schedule as the standard occupant when the house is occupied, but is assumed to switch off all appliances (except the freezer and refrigerators) if the house is unoccupied. The wasteful occupant keeps all the appliances on all the time.

3.0   Results

3.1 Impact of climate change on ZNE home performance

We used EnergyPlus version 8.8 to run simulations of the ZNE home models for three different locations (San Francisco, Riverside, and Fresno) using the morphed weather data for two future scenarios (RCP4.5 and RCP 8.5). Figure 8 to Figure 10 represent the detailed net future energy consumption of the ZNE home and the net electricity generated on-site. Two different trends can be noticed. The first is the improvement of the ZNE performance in San Francisco (Figure 8) due to less heating demand and the same cooling demand (i.e., none). The second trend is the

decline in ZNE performance simulated in Riverside (Figure 9) and Fresno (Figure 10) due to more cooling demand and less heating demand.

For San Francisco, as shown in Figure 8, the average net energy estimated for the present day is -1.1 gigajoules (GJ), while the prevision shows a decrease of net energy, reaching -8.6 GJ for the RCP4.5 model and -11.7 GJ for the RCP 8.5 model. In San Francisco, the cooling system is never used during the year because of the mild coastal climate. In the future climate modeled with future weather data, heating system consumption is reduced while the cooling system is still almost unnecessary.

For Riverside, as shown in Figure 9, climate change will also decrease the energy performance of the ZNE home. The trend is very similar to the Fresno case. For the RCP4.5 scenario, there is a slow increase in net energy, but the building still respects the ZNE conditions in the future. However, with the RCP8.5 scenario, the results show that the building will clearly miss the ZNE requirement in the future because of the rise in the cooling system use. Net energy reaches +5.5 GJ in Riverside for the 2080–2099 period.

For Fresno, as shown in Figure 10, climate change will decrease the energy performance of the ZNE home. For the RCP 8.5 scenario, cooling consumption rises faster than the heating reduction. The results show that the building will miss the ZNE target in the future. For the RCP4.5 scenario, the performance is stable, and the building still respects the conditions to be considered as a ZNE building. However, this scenario shows fluctuation: the 2056–2075 period shows a lower net energy than the 2026–2045 and 2080–2099 periods. This problem is due to a peak in solar energy availability (leading to more electricity generation from the rooftop PV) at this period, shown in top left graph. There is no reason to have such a peak at this period (2056–2075), and as a result, it shows one limitation of the morphing method. The morphing method focuses mainly on providing good approximations in future temperatures. However, the prediction of future solar irradiation is inconsistent, and this can explain why the trend for this scenario is different. This issue is mentioned in the Discussion section.
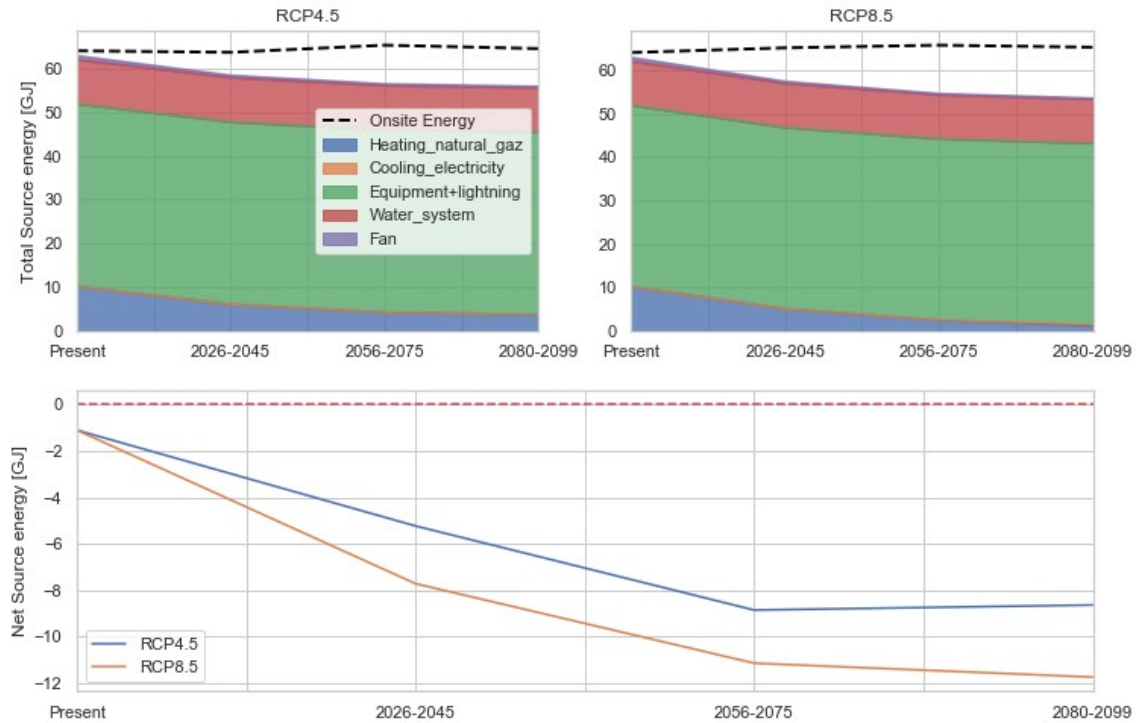
Figure 8. Future source energy consumption and future net source energy in San Francisco for the RCP4.5 and RCP8.5 scenarios
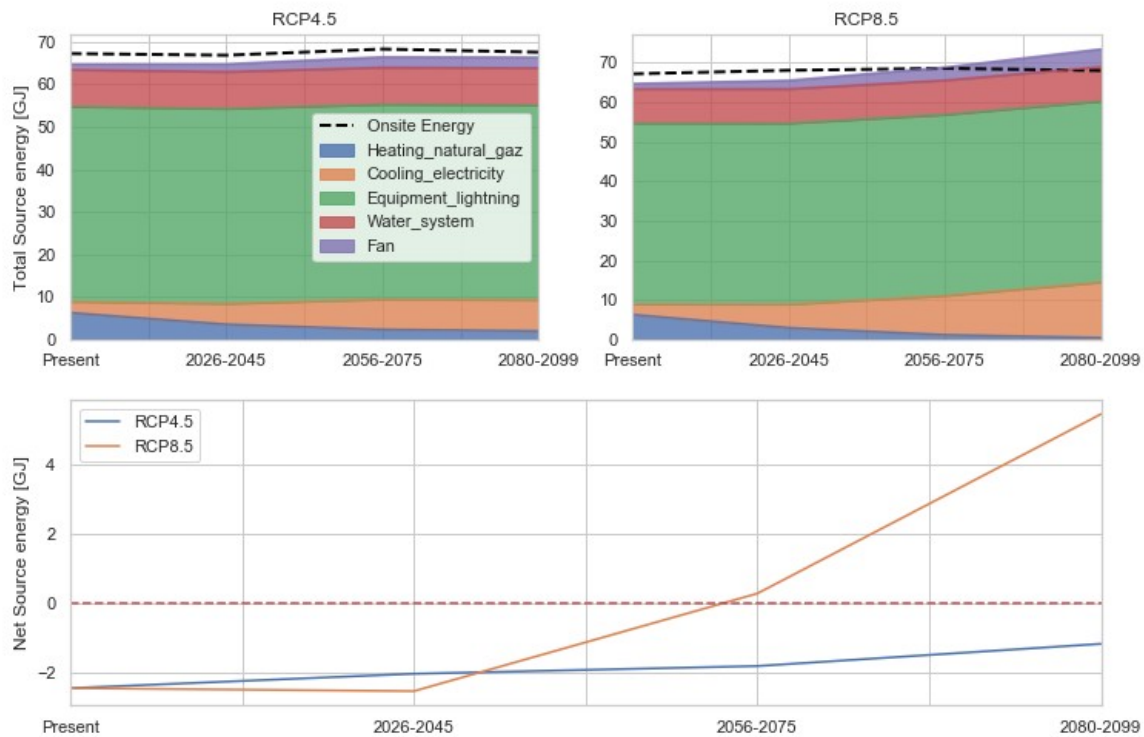

Figure 9. Future source energy consumption and future net source energy in Riverside for the RCP4.5 and RCP8.5 scenarios
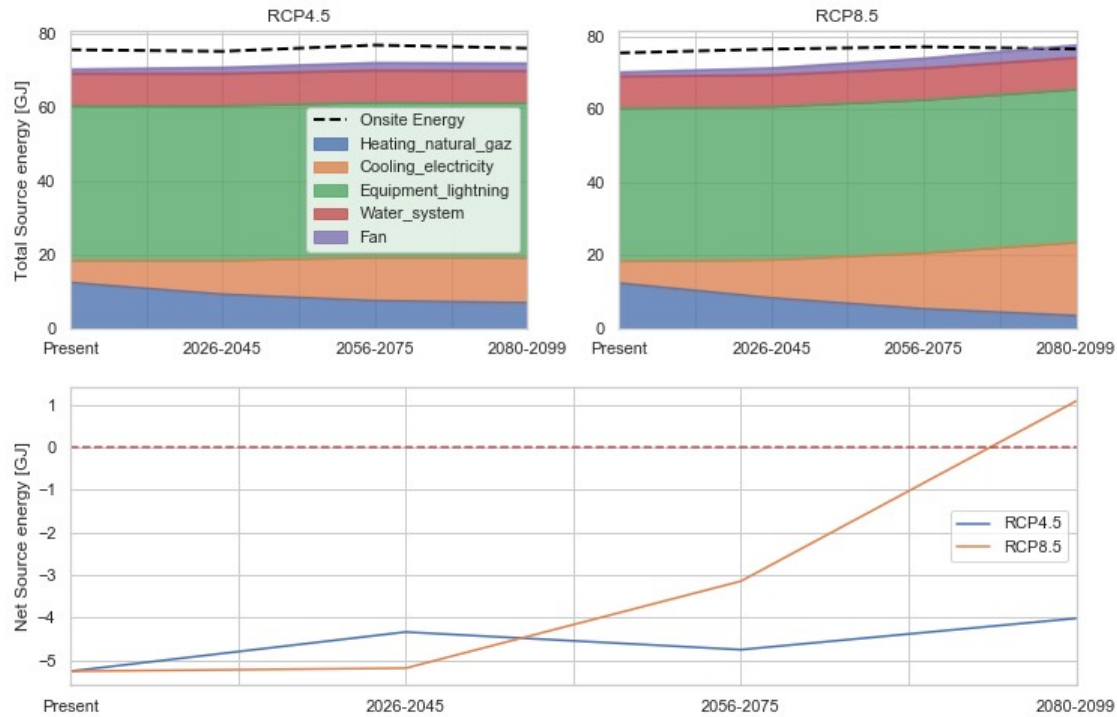
Figure 10. Future source energy consumption and future net source energy in Fresno for the RCP4.5 and RCP8.5 scenarios

3.2   Impacts of occupant behavior on ZNE home performance

This section presents the results of the ZNE home performance simulated with the three different occupant behavior styles. The EnergyPlus simulations were done in three locations (San Francisco, Riverside, and Fresno), and for each location TMY3 and 30 years of AMY weather data were used.

Figure 11 shows the source energy for the three occupant behavior scenarios and for each location cited before using the TMY3 weather data. The trend is almost the same regardless of location. With the wasteful case, the total source energy doubles compared with the standard case. The natural gas heating use represents a substantial increase (threefold for Fresno and fourfold for San Francisco and Riverside). The cooling system also represents one of the main increases (fivefold for Riverside and threefold for Fresno), except for San Francisco, where the cooling is still not used. For all three locations, the lighting energy consumption is about three times higher, hot water system energy doubles as expected, and plug-in equipment energy increases by 60 percent.

With the austerity case, total source energy decreases by about 20 Percent and heating and hot water system is reduced to half for all three locations. With the daylight control, light energy is reduced by 21 percent in Fresno and Riverside and 31 percent in San Francisco. The plug-in equipment consumption does not change significantly, as they are shut down only when the house is unoccupied, which happens only during the holidays in the occupancy schedule used (13 days for the year).
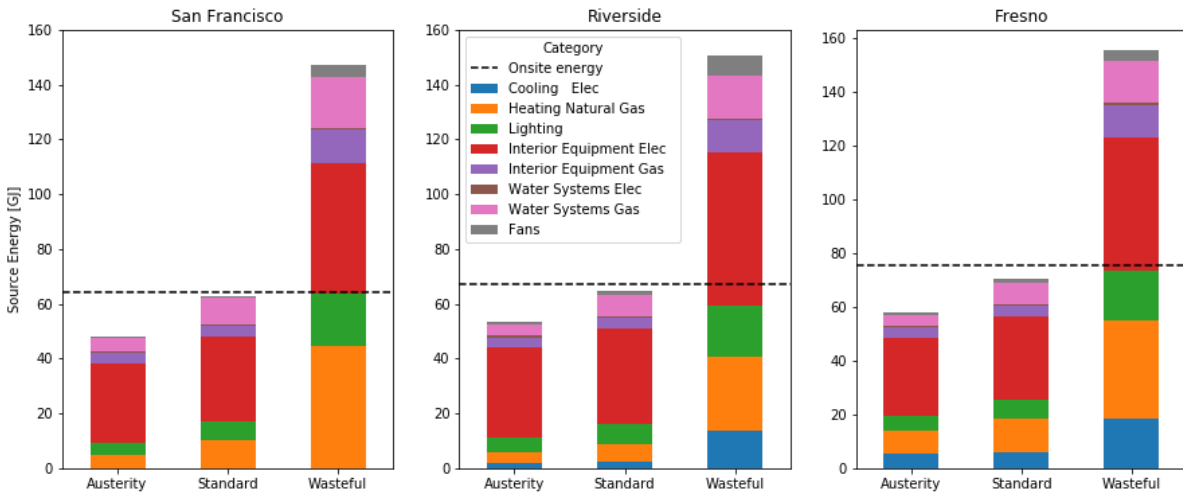
Figure 11. Source energy consumption for three occupant behavior styles in San Francisco, Riverside, and Fresno with TMY3 weather data

3.3   Results of net source energy variations with AMY weather data

Figure 12 shows box plots of the total net source energy variation across the past 30 years (1988–2017) for the three different locations and three different occupant behaviors using the AMY weather data. The same home models were used in the EnergyPlus simulations, with only changes in annual weather data from 1988–2017. The wasteful case was far from the ZNE target, and there was no year when the ZNE goal was achieved. On the opposite end, the austerity case was almost under the ZNE limit for each year. For a given location, the fluctuation of net source energy across the year was more significant for the wasteful style. However, the variation across the year depended also on the location, and it is clear that the ZNE home was more robust in some regions. The ZNE home was more sensitive in the San Francisco region, with a peak-to-peak variation going from 36.7 GJ for the austerity style to 62.42 GJ for the wasteful style. The peak-to peak-variation for Riverside was 19.1 GJ for the austerity style and 29 GJ for the wasteful style. For Fresno, the values are close, with 25.6 GJ for both the austerity and wasteful style. These disparities can be explained by comparing the 30-year AMY (AMY30) average dry temperature across the year. San Francisco had the highest variations in terms of outdoor air temperature.
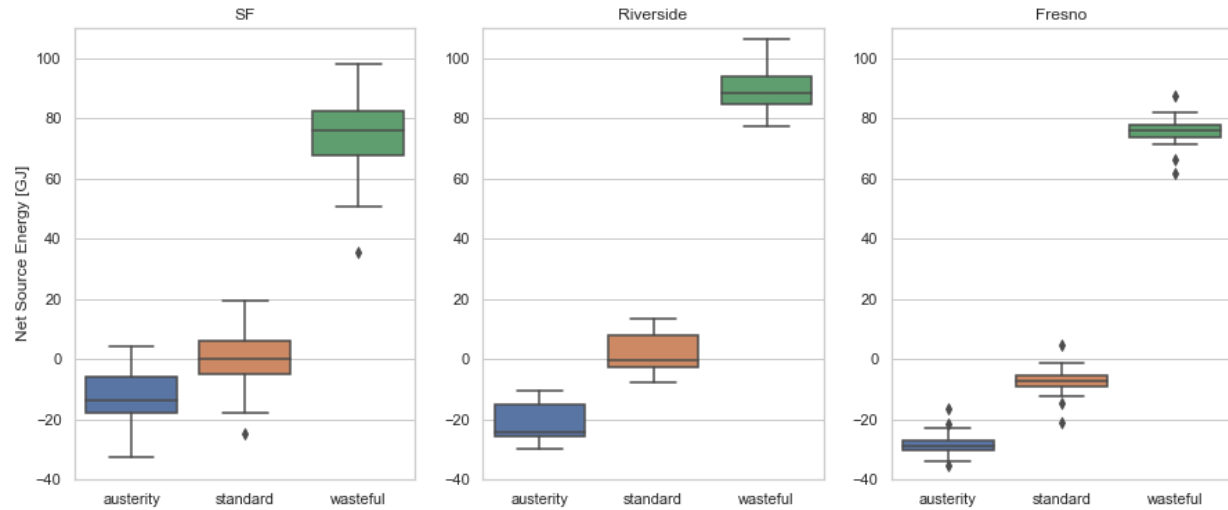
Figure 12. Net source energy across the years in San Francisco, Riverside, and Fresno for the three occupant behavior styles using AMY30 weather data

3.4   Results of peak electricity demand variations with AMY weather data

Figure 13 shows the electricity peak demand variation across years for the three different locations and three different occupant behaviors using AMY30. This electricity demand includes the cooling system, lighting, interior equipment, fans, and domestic hot water pump consumption. For each location the wasteful case's peak demand was twice that of the standard case. In San Francisco, the peak corresponding to each occupant style was exactly the same every year. Of course, the appliance schedules were the same for each year, and appliances represent the most significant part of energy consumption in this zone, as cooling systems are mostly not used. Thus, the peak day represented a day where appliance use was at a maximum. For the other two locations, the use of cooling systems induced variations in the electricity peak across the year.
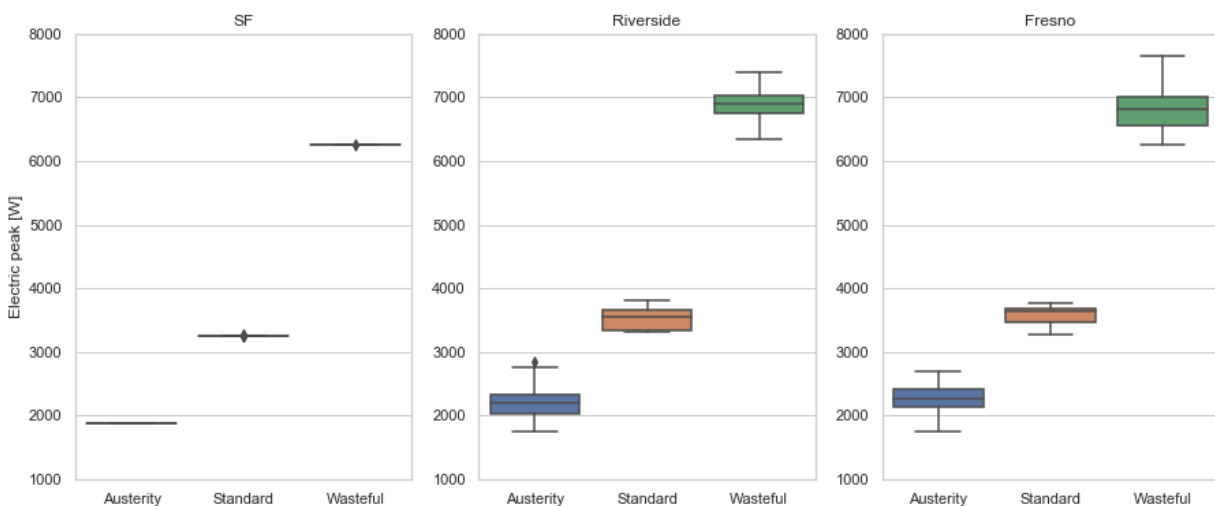

Figure 13. Peak electricity demand across years in San Francisco, Riverside, and Fresno for three occupant behavior styles using AMY30 weather data

3.5 Results combining the impacts of occupant behavior and climate change

Because occupant behavior and outdoor environment are linked, it makes sense to simulate the ZNE performance with different occupant behavior styles under several future climate scenarios and compare them. This section presents the results of the ZNE home performance simulated with the morphed weather data and the three occupant behavior profiles.

Figure 14 shows that in San Francisco, climate change will increase ZNE performance for all occupant behavior styles for both the RCP8.5 and RCP4.5 climate change scenarios. In general, there is a greater increase in ZNE performance with the RCP8.5 scenario, regardless of occupant behavior styles. Among the different occupant behaviors, ZNE performance increases the most under the wasteful style, with 28 GJ in net source energy saved for the RCP8.5 scenario between the present day and 2080–2099 period, and 19 GJ saved for RCP4.5. For the same periods, the standard style saved 10.6 GJ under RCP 8.5, and 7.5 GJ under RCP4.5. Finally, the austerity style shows less savings, with 5.6 GJ for RCP8.5 and 4.3 GJ for RCP4.5. This is because the current San Francisco climate is mild enough that under the austerity style there is almost no need to use the heating system and no need at all to use the cooling system. However, the wasteful style still often uses the heating system currently. Climate change will increase the temperature, reducing the amount of heating used by the wasteful occupants, but it will not change the habits for the austerity occupants, who were already comfortable.

Figure 14 shows also a different trend for Riverside and Fresno. With the RCP4.5 scenario, there will be almost no variations in net energy consumption across time for each occupant behavior style. However, with the RCP8.5 scenario, ZNE performance is reduced in the future for all net energy consumption behavior types. This time, the performance variation under the wasteful style is the lowest, but under the austerity style performance variation is the highest. For the austerity style, the total net source energy gain is 11 GJ for Riverside and 8.6 GJ for Fresno between the present day and the 2080–2099 period. For comparison, the wasteful behavior has a total net source energy gain of about 3.5 GJ for both Riverside and Fresno for the same period. The results imply that in these regions, the climate change impact on the austerity behavior is more sensitive than the wasteful behavior. Finally, the gap between the austerity and wasteful behaviors is reduced in the future. Such results were observed in each case but are more relevant in San Francisco. It implies that climate change should slightly reduce the disparity between occupant behavior styles.
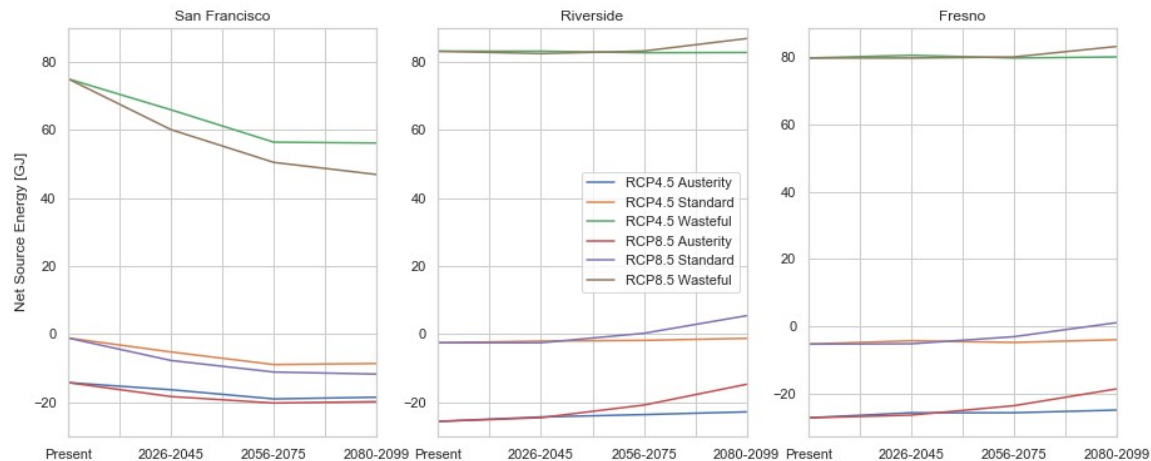
Figure 14. Net source energy in San Francisco, Riverside, and Fresno under different climate scenarios and different occupant behavior styles

4.0   Discussion

Although ZNE homes are defined using the annual net source energy. It is interesting to see the diurnal variations of energy demand and supply on a typical day. Figure 15 shows the electricity consumption and solar PV electricity production in source energy (a source factor 3.15 is used) for the three behavior styles of a typical winter and a typical summer day in Fresno. For each occupant behavior style, two peaks are observed: one is in the early morning before working hours, the other is in the evening after working hours. The morning peak corresponds to more use of appliances, lighting and hot water when occupants wake up, take bath, and prepare breakfast; while the evening peak corresponds to more use of appliances, lighting and hot water when occupants arrive home and prepare dinner. This graph points out that the daily peak demand of electricity usually doesn't match with the solar availability, leading to most of the solar production not used onsite and sold back to the grid (especially in summer). This exported electricity is supposed to replace the electricity from fossil fuel and as a result can be accounted for a negative energy in the ZNE balance calculation.
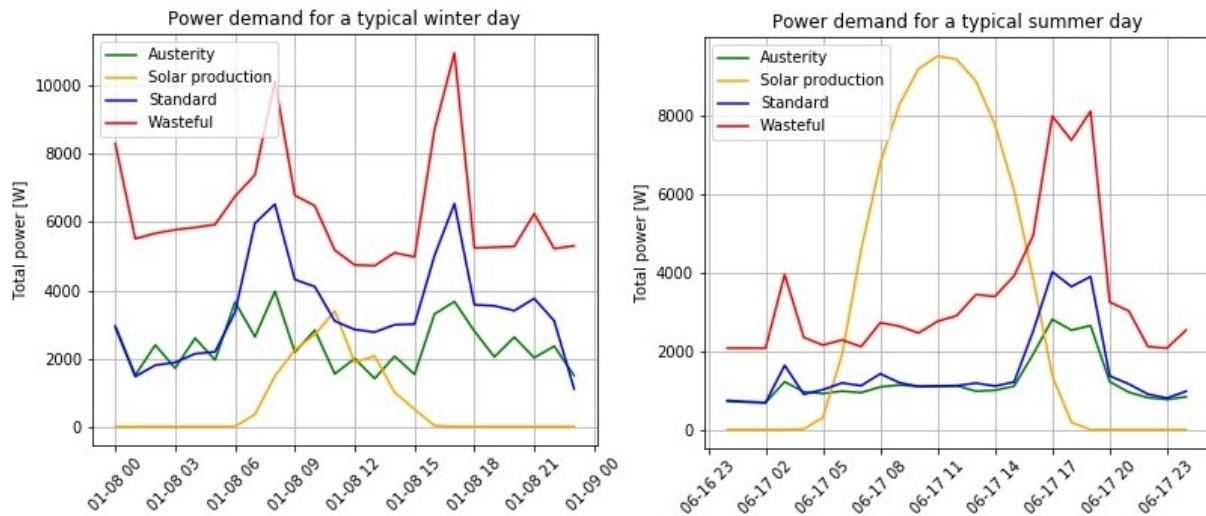
Figure 15. Electricity consumption and solar production for a typical winter day (left) and summer day (right) in Fresno

There are limitations in using the morphing method to create future weather data for building simulations. For each scenario and location, the energy generated by solar panels shows almost no changes in the future. This is because the morphing method focuses mainly on the generation of future temperatures but does not change solar irradiance. This limitation can present some contradictions with provisional results. Crook et al. found that solar panel generation in California could decrease by about 5 percent in the future [57]. Even if this value is not significant, it is not the trend observed by the total on-site electricity generated. Thus, the performance of ZNE homes could be overestimated.

The occupant behavior models have some limitations, as they are simplified compared with the complexity and the diversity of actual human behavior. Indeed, in this study, occupant activities are represented with static profiles. It means that all the interactions with home devices and systems are scheduled (pre-defined), which does not take into account the random pattern of occupant activities. Also, window operating and shading management were not considered, although they may reduce or increase heating or cooling. Thus, it would be interesting to add those interactions in the different occupant behavior models. To have an idea of the windows operating influence on the ZNE home performance, a simulation with wasteful occupants and windows open all the time has been done. The results indicate that the wasteful style can double the energy use if windows are always left open by occupants.

The study evaluated the energy performance robustness of ZNE homes in only three typical California cities. As seen from the results, the local climate influences ZNE home performance. To gain a better understanding of the climate and occupant behavior impacts, more cities should be studied in the future.

The ZNE homes require that annual delivered energy is less than or equal to the on-site renewable exported energy. To ensure this requirement will be met, climate change impacts and occupant variability should not be ignored.

Climate change impacts should be holistically evaluated during the design of ZNE homes. The morphing method used in this study can be used to represent a reasonable estimation of future building performance.

Adaptive measures also can be taken to limit the impacts of occupant behavior. First, ZNE homes can be designed for a wasteful occupant behavior model, to ensure that the ZNE target can be met all the time. This solution is simple but can be expensive. It can be interesting to use more robust methods during the design process. A method developed by Taguchi in the 1940s optimizes, with the stochastic approach, the building design to reduce occupant behavior variability. An example of this approach is to propose a fixed shading device to reduce variability associated with lighting energy use and movable shading. O'Brien and Gunay introduced an application of this method and showed that the impact of occupant behavior on building performance can be reduced [58].

5.0   Conclusions

This simulation study demonstrated that both climate change and occupant behavior significantly impact the energy performance of ZNE homes in California. A ZNE designed house may not achieve ZNE in real operation in the future in some regions, considering climate changes. Occupants who live in a ZNE house can significantly influence its energy use with different energy use behaviors from the simplified assumption used in current baseline practice. In fact, poor occupant behavior can be far more disadvantageous than climate change for the ZNE target, so behavior should be a priority in the design and operation of ZNE homes.

This study's results show that climate change in California will affect ZNE home performance differently depending on the location. In coastal regions where cooling systems are not used, global warming will increase performance due to less heating energy use, while in more arid regions like Fresno or Riverside, performance will decline due to increased cooling energy use. The study estimates that the ZNE target could not be achieved in the future (between 2050 and 2080) for the semi-arid zones (Fresno and Riverside). The results also indicate that diversity in occupant behavior styles can be more disadvantageous for ZNE performance than climate change. It is shown that wasteful style occupants can double energy consumption compared with the standard occupants. By comparison, the most impactful case of climate change increases the standard/baseline energy consumption by 15 percent for the 2080–2099 period.

Finally, the results combining impacts of climate change and occupant behavior show that climate change can reduce slightly the gap between austerity and wasteful consumption. This observation is more pronounced in the coastal region. In regions such as San Francisco, where climate change has a positive ZNE home performance impact, energy use of the wasteful occupants is the most sensitive to

climate change; while for locations where climate change has a negative impact on ZNE home performance, energy use of austerity occupants is the most sensitive.

These findings provide insights into how ZNE homes may perform in reality and inform architects, engineers, occupants, and policymakers to pay more attention to occupant behavior in the design, operation, and regulations of ZNE homes to ensure robust energy performance. The ZNE home design also should be evaluated using future weather data, considering climate change.

Future studies can improve future weather data generation by considering the potential change to solar irradiance due to climate change, and improve the occupant behavior models to include the operation of operable windows and movable shades, as well as the use of stochastic occupant schedules. Extending the method for other climate zones and countries, as well as other residential building types such as multi-family (apartments), can also be worthwhile.

Acknowledgments

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