Approaches to Cost-Effective Near-Net Zero Energy New Homes with Time-of-Use Value of Energy and Battery Storage

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Abstract

California requires all new residential buildings to meet near-net zero energy building (near-NZEB) targets in its building energy efficiency standards (Title 24) starting January 2020. For the first time, rooftop solar PV is required in new homes under three stories tall. While individual technologies are available for energy efficiency and renewable energy, significant challenges exist for scaling up NZEB homes across the State of California. This study presents a novel and holistic modeling and cost-effective analysis of new single-family homes in California to inform the design of cost-effective near-NZEB homes, as well as to guide future updates of Title 24. California’s NZEB homes are defined using the time dependent valuation methodology to evaluate their cost-effectiveness. A comprehensive set of energy efficiency measures, solar PV, and battery storage are considered in the modeling and analysis as well as different net-metering policies for rooftop PV compensation rates for exported power. The BEopt tool with the EnergyPlus simulation engine is used to model and optimize, based on cost, the building designs for all-electric and mixed-fuel single-family homes across all 16 California climate zones. Results show that optimal designs of near-NZEB single-family homes have lower lifecycle costs for both all-electric and mixed-fuel cases in all California climate zones than the 2020 baseline code-compliant homes. Cost-optimal designed all-electric homes are comparable in lifecycle costs to mixed-fuel homes in most climate zones in part because no natural gas infrastructure is needed. For battery storage, electricity rates with a greater degree of time-dependence will improve cost-effectiveness of near-NZEB or full NZEB homes. These findings provide technical and investment insights into the scale up of cost-effective near-NZEB home design in California. The methodology and models can be adopted for other U.S. states or international cities to inform policy making and design of near-net zero energy residential buildings.

Keywords: net zero energy buildings (NZEB); building decarbonization; electrification; energy efficiency; cost-effectiveness; optimization; time dependent valuation
Introduction

1.1 Importance of Building Sector in Global Energy and CO₂ Emissions

Given that buildings and construction sector make up for 36% of final energy use and 39% of energy and process-related CO₂ emissions in 2018 (of which 11% is from the manufacturing of building materials such as cement, steel, and glass) [1], zero energy buildings provide a major opportunity for both energy use and GHG reductions. Residential buildings make up about 73% of total building energy and about 61% of CO₂ emissions with the remainder from non-residential buildings. Building sector GHG reductions are thus a critical segment to address for countries to reach net-zero emission goals by the mid-century.

Many energy-related policies have been developed around the world that encourage more energy efficient buildings and greater onsite renewable energy generation. Net zero energy buildings (NZEB) in particular, have been an active area of research, development, and deployment. Pless et al. classified four different types of NZEBs (Net Zero Site Energy, Net Zero Source Energy, Net Zero Energy Costs, and Net Zero Emissions) [2]. These types are distinguished by whether renewable energy is produced onsite, produced offsite, or purchased offsite, and where energy, costs, or emissions are being counted (i.e., onsite or at power plants). Here, we focus on onsite production case (Net Zero Site Energy) where the general approach is to minimize onsite energy consumption through aggressive energy efficiency and to offset onsite energy consumption with onsite renewable energy generation.

Glossary of Abbreviation

ACE  Avoided-cost for export
ACH  Air change per hour
AFUE  Annual fuel utilization factor
CEC  California Energy Commission
CEE  Consortium for Energy Efficiency
CPUC  California Public Utility Commission
CZ  Climate zone
DOE  Department of Energy
EEM  Energy efficiency measure
EER  Energy efficiency ratio
EF  Energy factor
GHG  Greenhouse gas
HPWH  Heat pump water heater
HSPF  Heating seasonal performance factor
HVAC  Heating, ventilation and air conditioning
MEL  Miscellaneous electric loads
NEM  Net energy metering
NZEB  Net zero energy building
PV  Photovoltaic
RNG  Renewable natural gas
RPS  Renewable portfolio standard
RTO/ISO  Regional transmission organization (RTO)/independent system operator (ISO):
organizations that coordinate, control, and monitor a multi-state electric grid
NPV  Net present value
SEER  Seasonal energy efficiency ratio
SHGC  Solar heat gain coefficient
TDV  Time-dependent valuation
TOU  Time of use
A very similar concept to NZEB is the nearly Zero Energy Building (nZEB) as defined in the European Performance of Buildings Directive (EPBD) [3]. A nZEB is a highly energy efficient building based on annual energy consumption with nearly all of the onsite energy sourced by onsite or nearby energy sources.

Wells et al. describe five generations of net zero energy buildings as 1) green buildings, 2) nearly zero energy buildings, 3) net zero energy buildings, 4) new generation net zero energy buildings incorporating EVs, onsite energy storage, and embodied energy; and 5) future generations including concepts of regenerative buildings and net zero energy districts [4]. They further highlight the lack of universal definitions for net zero energy buildings, a lack of accounting for embodied energy and emissions particularly in the manufacturing of building materials, and a lack of consistency in the treatment of GHG emissions.

Global policies range from NZEB targets for new constructions, deep energy efficiency goals [5], near zero-energy, and zero-carbon buildings. China has set area-based NZEB targets with the construction of demonstration projects of ultra-low-energy and near-zero-energy buildings to reach more than ten million square meters by 2020; Singapore has set aggressive energy intensity goals over best in class buildings (e.g., to achieve improvements in the Energy Efficiency Index (EEI) by 40% – 60% over 2013 best-in-class buildings by year 2030); Japan calls for newly constructed public buildings and standard houses to be zero-energy buildings voluntarily by 2020 and newly constructed buildings and houses are to be zero-energy buildings voluntarily by 2030; British Columbia in Canada sets the target that new buildings must be net-zero energy ready by 2032; and the United Kingdom set the goal that all new homes should be zero carbon from 2016, and all other buildings from 2019.

Feng et al. provide a review of 34 net zero energy buildings and notes that “not all NZEBs are energy efficient buildings, and buildings with ample renewable energy adoption can still achieve NZEB status even with high energy use intensity”[5]. Solar PV was the most common renewable energy source with 30 buildings in this work. Common design features include optimized floor plans, advanced envelopes, and solar shading. Sixteen of the buildings have air source heat pumps, while eight rely solely on fans and evaporative cooling. Energy efficient lighting, advanced lighting controls, and efficient appliances or equipment were commonly deployed. The authors emphasize that stringent building codes and standards would help advanced building envelope technology adoption in NZEBs, that policies and incentives are needed to help building owners overcome the high incremental cost, and that it is important to document the non-energy benefits NZEBs not just the energy savings, including indoor air quality and occupant productivity.

Cost effectiveness of NZEB is an important consideration and the difficulty of identifying cost-saving opportunities can vary depending on the definition used [4]. For example, if offsite electricity generation is considered, the scope of analysis is enlarged and would need to include grid and distribution system costs. Mohamed et al. explore the relative difficulty of fulfilling four different NZEB objectives (NZEB-primary energy, NZEB-site energy, NZEB-CO₂ emission and NZEB-cost) considering five conventional energy systems and seven biomass-based standalone and shared combined heat and power (CHP) systems in Finland [6]. They find NZEB-emission is most readily achieved and NZEB-site least readily achieved, but their findings are expected to vary by geographical region, building and system design, and building loads. Lu et al. reviews the issues related to the design and control of nearly/net zero energy buildings (nZEBs) including design optimization methods, energy storage systems, and model predictive control for fast responses to grid signals [7]. The actual performance of nZEBs is another issue that has been characterized by Zhou et al [8]. They note that several factors can give discrepancies in modeling annual energy consumption and onsite energy generation including variations in equipment type, residential behavior, and hazy weather impinging on solar PV output energy.
Baetens et al. have studied district-level NZEBs to assess electrical challenges at the building and distribution feeder level and characterize issues such as the percentage of self-consumption, peak transformer load per dwelling, and PV supply curtailment [9]. Wells et al. highlight the need for more studies on NZEB economic feasibility, and specific to Australia, a lack of supporting policies for NZEBs and the need for stronger building codes for both residential and non-residential buildings [4].

The United States, Australia, Canada, and New Zealand have the most rooms per household occupant among 40 mostly wealthy countries studied by the Organization for Economic Cooperation and Development and the average size of new homes in these four countries are close to or exceed 2,000 square feet (185.8 square meters) [10]. The work here on single-family new homes is thus most applicable to those countries, but the methodology described here can also be applied to other countries with smaller single-family homes.

This study provides an up-to-date account of NZEB-related policies in California, helps to address the gap in the research literature on the economic feasibility of NZEBs, and provides a novel treatment of the value that battery storage can provide to nearly-NZEBs in California.

1.2 Climate and NZEB Policies in California

The economy of the State of California is the largest in the United States, boasting a $3.1 trillion gross state product as of 2019. If California were a sovereign nation in 2019, it would rank as the world's fifth largest economy [11]. California is a worldwide testbed for low-cost strategies and low-greenhouse gas (GHG) policies for a future decarbonized economy. The state has extremely aggressive GHG reduction goals for 2030 with a 40 percent economy-wide GHG reduction target [12] from the 1990 level and an 80 percent reduction goal in 2050 by Executive Order S-3-05 [13]. More recently, the state has set the target of 60 percent renewable portfolio standard (RPS) for the electricity sector in 2030, a zero GHG emissions target in the electricity sector by 2045 [14], and then state governor Jerry Brown announced a goal of net-zero carbon emissions statewide by 2045 (Executive Order B-55-18) [15].

In the building sector, California passed two statutes addressing decarbonization in 2018: Senate Bill (SB) 3232, specifically targeting building decarbonization, and Assembly Bill (AB) 1477, which targets GHG emissions reductions from building heating and includes support for disadvantaged communities [16,17]. California Senate Bill 1383 requires the reduction of high global warming potential refrigerants by 40 percent below 2013 levels by 2030 [18]. California previously had set the policy goal of all new homes to be net zero energy homes by 2020 [19] and all new commercial buildings to be NZEB by 2030.

California’s “Title 24 building code” is a collection of building energy efficiency standards designed to ensure that new and existing buildings in California continue to achieve greater energy efficiency [20]. The California Energy Commission (CEC) updates Title 24 standards every three years to raise the minimum building energy efficiency requirements for new buildings and major renovations. Title 24 encompasses 16 California climate zones (CZs) [21]. Figure 1 shows the California climate zone map and Table 1 lists reference cities and their climate characteristics of winter (December/January/February) and summer (June/July/August) average temperature, annual heating degree days with a base of 18 °C (HDD18C), annual cooling degree days with a base of 10 °C (CDD10C), winter mean global horizontal solar irradiance (GHSI) and summer GHSI. HDD18C is a measure of how much in °C and how long in days, outside air temperature is lower than the base temperature (18 °C). CDD10C is a measure of how much in °C and how long in days, outside air temperature is higher than the base temperature (10 °C). Title 24 promotes cost-effective energy efficiency measures (EEMs) to achieve greater energy efficiency and to reduce energy supply requirements. Beginning with the 2005 standards update, time-dependent valuation (TDV) has been used for the cost-effectiveness evaluation for Title 24. The concept behind TDV is that energy savings should be valued differently depending upon which hours
of the year the savings occur (e.g., electricity during summer peak hours is much more expensive than other times), to better reflect the actual costs of energy to consumers, to the utility system, and to society [11]. TDV is a series of annual 8760 hourly values for electricity cost and natural gas cost for each of the 16 California CZs that considers source energy and GHG impacts, transmission and distribution system impacts, and time of day energy impacts and is described in greater detail below.

Figure 1 Sixteen California Building Climate Zones [22]
Table 1 California 16 Climate Zones for Title 24 Building Energy Efficiency Standards [22]

<table>
<thead>
<tr>
<th>CZ</th>
<th>Reference city</th>
<th>Winter average temperature [°C]</th>
<th>Summer average temperature [°C]</th>
<th>HDD18C [°C·day]</th>
<th>CDD18C [°C·day]</th>
<th>Winter mean GHSI [W/m²]</th>
<th>Summer mean GHSI [W/m²]</th>
<th>Climate condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Arcata</td>
<td>8.9</td>
<td>13.2</td>
<td>2,705</td>
<td>515</td>
<td>80</td>
<td>241</td>
<td>Mixed - Humid</td>
</tr>
<tr>
<td>2</td>
<td>Santa Rosa</td>
<td>9.1</td>
<td>18.9</td>
<td>1,699</td>
<td>1,587</td>
<td>95</td>
<td>311</td>
<td>Warm - Marine</td>
</tr>
<tr>
<td>3</td>
<td>Oakland</td>
<td>11.1</td>
<td>17.1</td>
<td>1,602</td>
<td>1,430</td>
<td>98</td>
<td>297</td>
<td>Warm - Marine</td>
</tr>
<tr>
<td>4</td>
<td>San Jose-Reid</td>
<td>11.5</td>
<td>19.9</td>
<td>1,301</td>
<td>1,929</td>
<td>103</td>
<td>318</td>
<td>Warm - Marine</td>
</tr>
<tr>
<td>5</td>
<td>Santa Maria</td>
<td>10.9</td>
<td>15.8</td>
<td>1,817</td>
<td>1,192</td>
<td>127</td>
<td>297</td>
<td>Warm - Marine</td>
</tr>
<tr>
<td>6</td>
<td>Torrance</td>
<td>13.4</td>
<td>20.5</td>
<td>908</td>
<td>2,335</td>
<td>128</td>
<td>279</td>
<td>Warm - Marine</td>
</tr>
<tr>
<td>7</td>
<td>San Diego-Lindbergh</td>
<td>15.2</td>
<td>18.3</td>
<td>685</td>
<td>2,479</td>
<td>139</td>
<td>286</td>
<td>Warm - Marine</td>
</tr>
<tr>
<td>8</td>
<td>Fullerton</td>
<td>14.9</td>
<td>21.1</td>
<td>715</td>
<td>2,728</td>
<td>125</td>
<td>296</td>
<td>Warm - Humid</td>
</tr>
<tr>
<td>9</td>
<td>Burbank-Glendal</td>
<td>13.6</td>
<td>23.3</td>
<td>874</td>
<td>2,757</td>
<td>127</td>
<td>312</td>
<td>Warm - Humid</td>
</tr>
<tr>
<td>10</td>
<td>Riverside</td>
<td>13.2</td>
<td>24.4</td>
<td>941</td>
<td>2,845</td>
<td>131</td>
<td>314</td>
<td>Warm - Humid</td>
</tr>
<tr>
<td>11</td>
<td>Red Bluff</td>
<td>9.8</td>
<td>26.8</td>
<td>1,474</td>
<td>2,849</td>
<td>94</td>
<td>324</td>
<td>Warm - Dry</td>
</tr>
<tr>
<td>12</td>
<td>Sacramento</td>
<td>10.5</td>
<td>23</td>
<td>1,439</td>
<td>2,327</td>
<td>88</td>
<td>321</td>
<td>Warm - Marine</td>
</tr>
<tr>
<td>13</td>
<td>Fresno</td>
<td>10.6</td>
<td>27.2</td>
<td>1,376</td>
<td>3,003</td>
<td>89</td>
<td>325</td>
<td>Warm - Dry</td>
</tr>
<tr>
<td>14</td>
<td>Palmdale</td>
<td>7.6</td>
<td>27.2</td>
<td>1,625</td>
<td>2,835</td>
<td>138</td>
<td>333</td>
<td>Warm - Dry</td>
</tr>
<tr>
<td>15</td>
<td>Palm Springs</td>
<td>14.9</td>
<td>31.6</td>
<td>441</td>
<td>5,119</td>
<td>138</td>
<td>314</td>
<td>Very Hot - Dry</td>
</tr>
<tr>
<td>16</td>
<td>Blue Canyon</td>
<td>3.8</td>
<td>20.6</td>
<td>2,974</td>
<td>1,468</td>
<td>108</td>
<td>332</td>
<td>Mixed - Dry</td>
</tr>
</tbody>
</table>

Three related policies in California in addition to the 2019 Title 24 building code are also important to note: “reach codes”, recent bans on the use of natural gas in new building construction in several cities in California, and $200 million total announced funding to support building decarbonization efforts in 2019-2022 under state Assembly Bill 1477.

“Reach codes” (CEC 2020) refer to a local requirement for new buildings that go beyond the state code (2019 Title 24). These can include higher efficiency, electrification measures, enabling measures such as electric panel upgrades, energy saving water conservation measures, and energy auditing requirements per specified
schedules depending on the building type. One notable local requirement is the “Low Carbon Concrete Code” enacted in Marin County, California, in 2019 which establishes building standards GHG content in concrete (Marin County 2019).

Berkeley, California was the first city in the U.S. to ban natural gas in new buildings, and more than 40 cities in the state have banned or limited natural gas in new buildings (St. John 2020), although the Berkeley ordinance is being challenged in court [26].

Two laws were passed in 2018 related to reducing greenhouse gas emissions from buildings, State Bill 1477 and Assembly Bill 3232. SB 1477 funds two programs (BUILD and TECH) aimed at reducing greenhouse gas emissions associated with buildings, while AB 3232 requires state agencies, by 2021, to assess the feasibility of reducing the greenhouse gas emissions of California’s buildings 40 percent below 1990 levels by 2030. SB 1477 provides $50 million annual funding for four years from state cap and trade revenues for the BUILD and TECH programs. The BUILD program provides direct incentives for near zero GHG emission technologies such as electric heat pump HVAC systems and heat pump water heaters, and targets new housing with a requirement that 30% of funding is disbursed in low-income residences. TECH has the strategic focus to foster long-term changes in new construction and retrofits, contracting, and the appliance marketplace, targeting market development programs and upstream and midstream audiences, e.g., appliance vendors and contractors.

1.3 Net Zero Energy Buildings

Conceptually, a NZEB building is one where the quantity of the energy produced by onsite renewable energy resources is equal to the quantity of the energy consumed annually by the building. NZEB buildings have various definitions and may be based on annual site or source energy. The U.S. Department of Energy (DOE) defines a NZEB building as “an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the onsite renewable exported energy [27]. The California definition for NZEB is based on annual TDV energy (“TDV-NZEB”), which considers the time-dependent valuation of energy [28] (State of California 2016) and an hourly equation below:

Based on the unit of a single project, a NZEB building is one in which the value of the energy produced by onsite renewable energy resources is equal [or greater] to the value of the energy consumed annually by the building measured using the time-dependent valuation (TDV) metric.

\[
\sum_{h=1}^{8760} (TDV_h (consumption_h - generation_h)) \leq 0
\]

TDV values for electricity can shift the value of onsite renewable energy such as rooftop solar photovoltaic (PV) to having higher or lower values depending on the hour of the day.

TDV is based on a series of annual hourly values for electricity cost (and monthly costs for natural gas) in a given weather year. TDV values are developed for each of the 16 climate zones in California. The key components of the electricity TDV factors include both variable and fixed costs:

- Marginal Cost of Electricity (variable by hour) using the PLEXOS production simulation dispatch model (developed by Energy Exemplar). The price shape from the production simulation model is then adjusted to reflect the natural gas price forecast as well as the following non-energy costs: transmission and distribution, emissions, ancillary services, and peak capacity.
- Revenue Neutrality Adjustment (fixed cost per hour). The remaining, fixed components of total annual utility costs that go into retail rates (taxes, metering, billing costs, and so forth) are then calculated and spread over all hours of the year. The result, when added to the hourly marginal cost of electricity, is
an annual total electricity cost valuation that corresponds to the total electricity revenue requirement of the utilities.

For each climate zone, the marginal cost of electricity is calculated as the sum of seven components (generation energy, system capacity, ancillary services, system losses, transmission and distribution capacity, CO$_2$ emissions, and avoided renewable resources). Each of these components are estimated for each hour in a typical weather year and forecasted into the future for 30 years. The 30-year present values of the forecasts are calculated with a 3% real discount rate. More detailed description of these inputs can be found in Sontag et al. [29].

Meeting full NZEB or TDV-NZEB requirements in California has proven to be difficult for several reasons. Building the requisite capacity (in kW) of rooftop PV would over generate solar power during early afternoons, potentially exacerbating the “duck curve” problem in California [30] and would add much higher initial costs. The over-generation would be especially large in the mixed fuel case where the PV would be sized to offset both electric and natural gas TDV. Moreover, such an implementation for the mixed fuel case would not address policy objectives for energy savings and greenhouse gas (GHG) reduction since natural gas end uses would continue to generate CO$_2$ emissions and the PV capacity required to offset natural gas TDV would not reduce natural gas energy consumption. Thus the 2019 Title 24 building code’s prescriptive measure for rooftop PV sizing requires that site level PV generation only offset the site-level electricity consumption for a mixed fuel home, and the PV size required for an all-electric home is stipulated to be the same PV size as that for a mixed fuel home of the same area. We refer to the required new homes in California starting January 2020 as “near-NZEB” homes, which do not exactly meet the full NZEB requirement based on TDV, but the annual onsite electricity generation is close to the annual electricity consumption, e.g., within 5-10%.

NZEB homes can be built as mixed-fuel homes consisting of a mix of natural gas-fired and electricity-powered appliances or as all-electric homes. Mixed-fuel homes are the most common type of new homes in California historically and typically use natural gas for heating such as space heating, water heating, and cookstoves. All-electric homes use electricity for all end uses including space heating, water heating, cooking, drying, etc., and typically do not include a gas line to the home. Renewable energy supply options include “on-site renewable energy” and “community renewable energy” for NZEB homes [31]. Both mixed-fuel and all-electric homes can have onsite rooftop solar PV, while community renewables can refer to various energy supply options: (1) renewable natural gas (RNG) together with rooftop PV, and (2) “community solar,” or “shared solar” in the case of all-electric homes. RNG refers to methane derived from biogas emissions primarily from landfills, municipal solid waste, wastewater plants, and dairy plants. Community solar refers to a solar PV installation at a nearby site separate from the site of the home, a portion of whose output is associated with one residential home. A greater role for energy storage is expected in the near term, with expected cost reductions in battery storage [32].

All-electric homes are receiving increasing attention because when they are coupled with low-carbon intensity electricity, which can provide large reductions in GHG emissions compared to mixed-fuel homes. Benefits and barriers to achieving all-electric NZEB homes, and supportive policies to all-electric homes from a national perspective [33,34]. They find that electrification of end uses in buildings is most cost-effective in new residential buildings, where a single heat pump can provide heating and cooling, and gas infrastructure costs can be avoided (e.g., in new all-electric buildings or communities). The study found that many existing policies bear on electrification, sometimes in unintended ways. Rapid and widespread electrification would require revisions to numerous policies, including electricity rate design, building codes and appliance standards, incentives, outreach, education, and energy efficiency program targets that require a reduction of total electricity usage. The study highlights that key potential policy enablers include time-of-use rates, NZEB
building codes, demand response programs, and payments for flexible loads. Davis Energy Group et al. presents cost-effectiveness for all-electric designs that exceed the requirements of the 2016 Title 24 building code [35]. A key difference from the current study is that their analysis uses a customer-based lifecycle cost approach to evaluating cost-effectiveness based on utility rates with a rooftop solar compensation policy, whereas the CEC’s lifecycle cost methodology uses TDV as the primary metric for energy accounting. PV systems are sized in two ways: (1) to offset approximately 80 percent of estimated annual electricity consumption in a mixed-fuel (gas/electric) home, or (2) to offset 100 percent of estimated annual building site electricity use (total kWh) for mixed-fuel or all-electric homes. The second case is very close to NZEB for all-electric homes. In all cases for residential buildings, all-electric homes are found to be cost effective from the life cycle cost perspective. A recent study by Mahone et al. assesses the energy savings, GHG reductions, impacts on the electric grid, and overall economics of residential building electrification for customers across several regions of California [36]. E3 modeled the performance and costs of both all-electric new construction homes and existing homes retrofitted with heat pump heating, ventilation, and air conditioning (HVAC) systems and heat pump water heaters. These were compared to mixed-fuel homes. The study finds that all-electric new construction homes result in savings of $130–$540 per year relative to a mixed-fuel home. There are cost savings for developers from the elimination of costs to lay down gas lines, as well as to homeowners, who will see lower utility bills. Narayanamurthy et al. examined the impacts of NZEB communities on the distribution grid [37]. The study details the design, deployment, construction, sale, and occupancy of 20 homes built to California Title 24 NZEB standards with electrified heating. The goal of their study was to understand if the transformers, laterals, load blocks, and feeders had sufficient capacity using today’s planning methods. To alleviate the distribution impact, these homes were set up with controllable loads and with behind-the-meter energy storage [38]. Key takeaways were that the control strategy of energy storage could either strengthen, or in some cases accentuate, distribution problems, and that modeling tools still have a way to go to address the prominent or “needle” peaks or spikes in power demand that will be more common in future buildings.

A study by Navigant Consulting Inc. (2015) examined the costs of TDV-NZEB single-family homes in Southern California, starting from 2016 Title 24 standards and considering mixed-fuel and all-electric fuel configurations [39]. Since this study adhered to the TDV-NZEB requirement that NZEB homes must offset 100 percent of their TDV consumption, the resultant mixed-fuel homes have large PV sizes that can overproduce electricity during certain periods of the year.

About 7,000 nominally NZEB homes were built in California through 2017, compared to a new construction volume of about 150,000 new housing units per year through 2020 [19]. With the new requirements of 2019 Title 24 building code, there is the need to further investigate the cost reduction potential of near-NZEB new homes and the question of whether full TDV-NZEB homes can make economic sense for all-electric homes.

With California’s SB 100 target for high levels of renewable electricity, there is aggressive deployment of solar PV and wind turbine to generate an increasing portion of clean electricity for the grid, leading to: (1) the electricity supply side becomes more dynamic, and (2) changing California’s peak electricity demand from traditional 12-3pm of the early afternoon of day to 4 - 9 pm of late afternoon or early evening of the day, reducing the value of electricity generation at midday, this type of analysis also required revised TDV values for 2022 to incorporate these changes to the grid.

To address the research question of what can provide cost-effective near-NZEB homes for California, as well as to inform the 2022 updates to California Title 24 building energy efficiency standards, this study aims to provide an update-to-date NZEB home cost-effectiveness analysis across all 16 California climate zones using an early version of 2022 TDV values developed by the research team and considering the
evolutionary net energy metering (NEM) policy that reflects lower compensation rates for exported electricity to the grid from solar PV. The study also quantifies the benefits of the behind-the-meter electricity storage for various building system control schemes. The remaining portion of the paper covers methodology in Section 2, results and analysis in Section 3, discussion in Section 4, and conclusion and future work in Section 5.

2 Methodology for NZEB Home Modeling and Cost-effectiveness Analysis

The cost-effectiveness evaluation of NZEB homes is based on the optimization of NZEB home designs to minimize life cycle cost considering technology costs and utility costs based on the 2022 TDV values. For this project, the research team updated TDV values for the 2022–2052 period, which approximates time-dependent energy costs under currently adopted policies (including 50 percent renewable portfolio standard by 2030) and the California Energy Commission’s (CEC) 2017 Integrated Energy Policy Report (IEPR) mid-demand case forecasts.

Figure 2 illustrates the time-varying shape of TDV values across an average day, the various TDV components, and the evolution of TDV values from 2016 and 2019 to the present case (2022). Figure 2 shows that the peak hour shifts slightly later than the TDV values used in the 2019 Title 24 Building Code cycle, with lower energy costs in the middle of the day due to greater quantities of solar electricity and a higher overall peak.

Detailed building energy modeling is conducted using the BEopt tool which uses EnergyPlus as the simulation engine. Figure 3 illustrates the NZEB home modeling and cost-effectiveness analysis workflow. The workflow starts with the prototype NZEB home model development. The study adopted various energy efficiency measures for the homes and developed cost data for the selected measures. Since the cost-
effectiveness analysis is targeted for the state’s 2022 code cycle, we used the 2022 future energy rates based on updated TDV values for the lifecycle energy cost analysis. The utility rates were developed for different California climate zones reflecting the energy grid and renewable portfolio dynamics, and in anticipation of further evolution of NEM policy for rooftop solar [40], assumes lowers compensation rates for exported electricity from solar PV to the grid. We then conducted parametric building energy simulations for each climate to find measures packages of cost-effective homes. The cost-effective home designs are found from energy-related life cycle cost optimization, and the minimum cost home is selected for the most cost-effective home [41]. Finally, we expanded the cost-effectiveness analysis to include electric battery storage, which can further help improve the cost-effectiveness of NZEB homes. Multiple battery costs and operation scenarios are explored to capture hourly dynamics of electricity usage by home, generation by the PV system, and controlled charge and discharge of the battery system.

Figure 3 Workflow of the NZEB Home Modeling and Cost-Effectiveness Analysis

2.1 Energy Modeling and Simulation
The prototype residential single-family home developed by the CEC [42] was adopted in the residential building energy modeling and simulation tool: BEopt (Building Energy Optimization Tool) [43] for the energy performance evaluation, parametric simulation run, and cost optimization. The prototype single-family home is a single-story building with three bedrooms. BEopt is a computer program designed to find cost-optimal building designs along the path to a NZEB. The optimal path to NZEB extends from a base case to the NZEB through a series of energy-saving building designs and energy generation systems with minimal energy-related costs. BEopt provides a set of measures in various categories to specify options to be considered in the optimization and calculate energy savings relative to a reference. BEopt uses the EnergyPlus simulation engine and a sequential search technique to automate the process of identifying optimal building designs along the path to NZEB.
Figure 4 shows the prototype single-family home modeled in BEopt. The prototype energy model has 195 m² of living space and a 41 m² of garage with a floor height 2.7 meter and a roof area of 256 m². The home boundary terrain is suburbs. The number of occupants is 2.6 based on the CEC reference single-family home [42]. It has wood-framed structure and pitched roof with attic space and the insulation requirement is different for climate ones. Mixed-fuel homes have a central air-conditioning system for cooling, natural gas furnace for heating, and tankless hot water systems for domestic hot water. All-electric homes use heat pump systems for space cooling and heating and hot water heat pump system for domestic hot water.

BEopt uses EnergyPlus as the underlying building energy simulation engine and provides capabilities to evaluate the energy performance of residential building designs and identify cost-optimal efficiency packages for whole-house energy savings along the path to NZEB. BEopt provides energy performance analysis based on residential building characteristics, such as architecture, envelope, HVAC systems, appliances, occupancy-related operations, reflecting climates, and tariffs. BEopt calculates the annualized energy-related lifecycle cost of the building design with efficiency measure packages. Note that battery storage was not modeled in BEopt; rather, it was modeled using a separate module after cost-optimal building designs were generated by BEopt.

The annualized energy-related lifecycle cost is calculated by annualizing the cash flows. The total cost for the cash flows includes total cost of ownership for 30 years, which includes home construction costs, mortgage payments, equipment replacement costs, energy costs, and residual values. The present worth ($PW$) is the cash flow by converting the total cost for each year to the value at the beginning of the analysis period ($N$) according to:

$$PW = \sum_{k=0}^{k=N} \frac{TotalCost_{year=k}}{(1 + d_n)^N}$$

where $TotalCost_{year=k}$ is the total cost in year $k$, and $d_n$ is the discount rate. The annualized energy-related lifecycle cost is determined by annualizing the $PW$ using the discount rate ($d_r$), according to:

$$\text{Annualized Energy Related Lifecycle Cost} = \frac{PW(d_r)}{1 - \frac{1}{(1 + d_r)^N}}$$
The lifecycle cost of home designs includes the EEMs cost, replacement cost, and energy cost. Key cost inputs include capital and installation costs of EEMs and the rooftop PV system. Also, the energy cost reflects the assumed policy regime for PV compensation rates, which the customer credit for providing electricity back to the grid at times when the generation from PV is greater than the usage by the home electricity demand. The measure cost data are primarily based on NREL’s National Residential Efficiency Measures Database [44] supplemented by expert elicitation inputs [45]. Utility rates use the TDV-based hourly rates for electricity as a proxy for future electricity rates and a fixed annual rate of increase for natural gas to 0.0546$/kWh. The TDV-based hourly electricity rate approach is consistent with the state’s current codes and standards rulemaking process. For the study, the electricity hourly rate is based on the projected 2022 TDV values that reflect the future electricity grid conditions [46].

In this study, we assume a continued trend to less favorable policy subsidization for rooftop PV ownership due to the rapidly falling price of PV and equity concerns about helping solar customers at the expense of non-solar customers. The key policy parameter here is the compensation rate that solar PV owners receive for each kWh of excess solar generation or the hourly difference in solar generation above hourly electricity demand. Prior to 2016, net metering policy in California provided export compensation at the retail rate in $/kWh. In 2016, “NEM 2.0” was implemented and the export compensation rate in $/kWh was reduced by a small adjustment, to the retail rate minus a “non-bypassable” charge [47]. Lu et al. introduced the cost impact of the exported electricity from hourly imbalance from electricity generation and consumption load profile [48]. Here, we assume a PV export rate that is less favorable than NEM 2.0, or that exported power is compensated at the “avoided cost for export” (ACE) or to the retail rate minus a retail rate adjustment. The following retail rate adjustments are assumed by investor-owned utility in dollars per kilowatt-hour ($/kWh): Pacific Gas and Electric (PG&E) at $0.131/kWh; San Diego Gas and Electric (SDG&E) at $0.118/kWh; and Southern California Edison (SCE) at $0.131/kWh [47]. For clarity, under the NEM2.0 policy case, the non-bypassable charge is $0.02 per kWh, and the bill credit for excess generation in NEM2.0 is the retail rate less this non-bypassable charge. For example, if the retail rate is $0.22/kWh for a given hour of the year, then 1 kWh of excess generation at that hour is compensated by $0.20 (or 22 cents less 2 cents). Under the “avoided cost for export” policy case, if the retail rate is $0.22/kWh for a given hour of the year, then 1 kWh of excess generation is $0.089 at that hour (or 22 cents less 13.1 cents) for PG&E customers.

The avoided cost of electricity is the marginal cost required to deliver a unit of electricity in a given time frame. Utility retail rates are designed to recover these costs plus other costs (fixed, administrative, etc.) not explicitly tied to supplying a specific kWh of electricity. Under Avoided Cost for Export, a home’s solar energy exported back to the grid is compensated at avoided cost, i.e., the true value being provided to the grid. This reflects a policy trend in moving away from crediting grid exports at the full retail rate. The avoided cost for export values are based on the E3 Avoided Cost Model (https://www.ethree.com/tools/acm-avoided-cost-model/) that forecasts long-term marginal costs to evaluate the cost-effectiveness of distributed energy resources (DERs) such as energy efficiency, distributed generation, storage, and demand response.

Other underlying assumptions use inflation rate 2.4 percent, a discount rate 3 percent, and no tax credit of capital cost for PV for the lifecycle cost calculation.

2.2 Baseline Model and NZEB Measures

The baseline home energy model uses the prototype single-family home (Figure 4) with the 2019 Title 24-compliant requirements for each California climate zone. Then, energy savings and cost impacts for cost-effective energy-efficient homes were compared to this baseline home. 46 energy efficiency measures from 22 categories were identified as promising technology options for optimal pathways to NZEB homes in a variety of contexts. For the cost-effectiveness analysis, the measures include cost for materials and labor and
usage lifetimes. Table 2 shows available measures for BEopt cost-effectiveness optimization simulations and baseline model input values, for example, for climate zone 3. The full list of measures and their detailed measure performance characteristics and cost assumptions are documented in the CEC technical report [45].

Table 2 Energy Efficiency Measures Available for Cost-effectiveness Optimization

<table>
<thead>
<tr>
<th>Measure category</th>
<th>Available measures for BEopt optimization</th>
<th>Baseline model value for example in CZ03 (San Francisco Bay Area)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall wood stud</td>
<td>• R-23</td>
<td>R-21</td>
</tr>
<tr>
<td></td>
<td>• R-33</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• R-45</td>
<td></td>
</tr>
<tr>
<td>Wall sheathing</td>
<td>• R-10</td>
<td>R-5</td>
</tr>
<tr>
<td></td>
<td>• R-12</td>
<td></td>
</tr>
<tr>
<td>Ceiling / Roof</td>
<td>• R-38</td>
<td>R-30</td>
</tr>
<tr>
<td></td>
<td>• R-49</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• R-60</td>
<td></td>
</tr>
<tr>
<td>Roof material</td>
<td>• Cool roof solar reflectance 0.40</td>
<td>Solar reflectance 0.2</td>
</tr>
<tr>
<td>Windows</td>
<td>• U-value 1.42 W/m²K, SHGC 0.23</td>
<td>U-value 1.7 W/m²K, SHGC 0.23</td>
</tr>
<tr>
<td></td>
<td>• U-value 1.25 W/m²K, SHGC 0.44</td>
<td></td>
</tr>
<tr>
<td>Air leakage</td>
<td>• 4 ACH at 50 Pascal</td>
<td>5 ACH at 50 Pascal</td>
</tr>
<tr>
<td></td>
<td>• 3 ACH at 50 Pascal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• 2 ACH at 50 Pascal</td>
<td></td>
</tr>
<tr>
<td>Central air conditioner</td>
<td>• SEER 15 EER 13,</td>
<td>SEER 14 EER 11.7</td>
</tr>
<tr>
<td></td>
<td>• SEER 16 EER 13 2-speed</td>
<td></td>
</tr>
<tr>
<td>Air Source Heat pump</td>
<td>• SEER 15 HSPF 8.5</td>
<td>SEER 14, HSPF 8.2</td>
</tr>
<tr>
<td></td>
<td>• SEER 18 HSPF 9.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• SEER 22 HSPF 10.0</td>
<td></td>
</tr>
<tr>
<td>Gas furnace</td>
<td>• AFUE 92.5%</td>
<td>AFUE 78%</td>
</tr>
<tr>
<td>Ducts</td>
<td>• Duct located in conditioned space</td>
<td>Duct R-8 in unfinished attic with 5% leakage</td>
</tr>
<tr>
<td>Natural gas hot water heater</td>
<td>• Gas condensing tankless heater EF 0.92</td>
<td>Gas tankless heater EF 0.82</td>
</tr>
<tr>
<td>Electric hot water heater</td>
<td>• HPWH EF 3.7</td>
<td>HPWH EF 2.8</td>
</tr>
<tr>
<td>Hot water distribution</td>
<td>• R-5 PEX pipe</td>
<td>R-2 PEX pipe</td>
</tr>
<tr>
<td>Refrigerator</td>
<td>• Refrigerator with bottom freezer 21.3</td>
<td>Refrigerator with bottom freezer 15.9</td>
</tr>
<tr>
<td>Natural gas cooking range</td>
<td>• Gas cooktop with optimized burner EF 0.7, oven EF 0.12</td>
<td>Gas cooktop EF 0.5, oven EF 0.085</td>
</tr>
<tr>
<td>Electric cooking range</td>
<td>• Electric induction cooktops EF 1.3, oven EF 0.25</td>
<td>Electric cooktop EF 1.0, oven EF 0.2</td>
</tr>
<tr>
<td>Dishwasher</td>
<td>• 86 kWh/unit/year</td>
<td>111 kWh/unit/year</td>
</tr>
<tr>
<td></td>
<td>• 69 kWh/unit/year</td>
<td></td>
</tr>
<tr>
<td>Clothes Washer</td>
<td>• Front-loading CEE Tier 3 EF 2.9</td>
<td>Top-loading baseline EF 1.6</td>
</tr>
<tr>
<td>Natural gas clothes dryer</td>
<td>• Vented gas dryer EF 4.7</td>
<td>Vented gas standard EF 3.2</td>
</tr>
<tr>
<td></td>
<td>• Vented gas dryer EF 5.0</td>
<td></td>
</tr>
</tbody>
</table>
One of the most challenging end-uses to address in new construction is miscellaneous electric loads (MELs) that are electricity consumption from plug-in electric equipment. MELs constitute about 2,000 kWh/year in a typical home, with about 13 percent growth projected by 2030 [49]. Standby loads, which comprise about 25 percent of MEL end uses [50] are often targeted for energy efficiency improvements because they contribute limited value to homeowners. Lawrence Berkeley National Laboratory (LBNL) has estimated that 30 percent of standby loads can be eliminated through occupant behavior [51]. There is also room for improvement when MELs are in active mode but not in use, such as when television is left on in another room. Convenient methods for homeowners to easily or automatically turn off electronic devices that are not in use can have a significant impact on MEL energy, but there can be a trade-off with occupant satisfaction if such controls react improperly. MELs have not generated much attention in building energy standards because builders have limited ability to control them. Despite the challenges, there are a few promising energy efficiency measures available for addressing MELs using smart controls and other technologies [52]. We identified two viable market-ready MELs reduction measures: (1) advanced power strips with occupancy sensors to turn off devices based on total power fluctuations for all connected devices if the room is unoccupied, and (2) occupant behavior leveraging smart plugs and smartphone applications. These measures have demonstrated the potential for both MEL energy savings (6 and 16 percent, respectively) and strong market acceptance [53]. Some key modeling assumptions for this work are summarized in Table 3.

<table>
<thead>
<tr>
<th>Item</th>
<th>Baseline Case</th>
<th>Optimized Case (corresponding to results shown in this work)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prototype single-family homes</td>
<td>California Energy Commission 195m² (2100ft²) model</td>
<td>California Energy Commission 195m² (2100ft²) model</td>
</tr>
<tr>
<td>Cases modeled</td>
<td>California Building Code-compliant (2019 Title 24) homes: mixed-fuel new homes; and all-electric new homes using BEopt</td>
<td>Mixed-fuel and all-electric homes that consider more energy efficient measures and more rooftop solar PV using BEopt</td>
</tr>
<tr>
<td>Energy prices</td>
<td>Projected utility rates based on preliminary estimates for 2022 time-dependent valuation</td>
<td>Projected utility rates based on preliminary estimates for 2022 time-dependent valuation</td>
</tr>
<tr>
<td>Rooftop solar incentive policy</td>
<td>Excess generation compensated at “avoided-cost” (less favorable than NEM 2.0)</td>
<td>Excess generation compensated at “avoided-cost” (less favorable than NEM 2.0)</td>
</tr>
<tr>
<td>Solar PV installed cost</td>
<td>$3.00/kW</td>
<td>$3.00/kW</td>
</tr>
<tr>
<td>Battery 30-year NPV Costs*</td>
<td><strong>Average Cost, No Reduction:</strong> $2,856/kWh</td>
<td><strong>Average Cost, Reducing over Time:</strong> $1,684/kWh</td>
</tr>
<tr>
<td>---------------------------</td>
<td>---------------------------------------------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td><strong>Climate zones</strong></td>
<td>Home cases above modeled in each of 16 California climate zone</td>
<td>Home cases above modeled in each of 16 California climate zone</td>
</tr>
</tbody>
</table>

*Battery cost notes:

1. Average Cost, No Reduction; based on Lazard 4.0 cost of storage (https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2018/); installed in 2023, O&M costs for 20-year lifetime reported by Lazard; replaced in 2043, O&M costs for remaining 10 years of NPV; assumes no reduction in storage costs throughout timeframe
2. Average Cost, Reducing over Time; Same schedule as Scenario 1; 2023 and 2043 costs are 64% and 47% of 2018 costs, respectively
3. Low Cost, Reducing over Time based on Tesla Powerwall 2.0 costs collected online; installed in 2023, 2033, and 2043 with 10-year lifetime; no O&M costs, same cost decline as Scenario 2

and where the 30-year NPV is the sum of the following two components:

\[
\text{Present value of install costs} = \text{reduction factor}_{2023} \times \frac{\text{install cost}}{(1 + \text{rate})^0} + \text{reduction factor}_{2043} \times \frac{\text{install cost}}{(1 + \text{rate})^{20}}
\]

\[
\text{Present value of O&M costs} = \frac{\text{O&M cost}_1}{(1+\text{rate})^1} + \cdots + \frac{\text{O&M cost}_{29}}{(1+\text{rate})^{29}}
\]

3 Results and Analysis

3.1 EEMs and Solar PV

Figure 5 shows the energy cost savings for all-electric (left) and mixed-fuel (right) single-family prototype homes in California climate zone 13 to illustrate the cost-effectiveness optimization results. The x-axis represents TDV energy savings, while the y-axis represents the annualized energy-related lifecycle cost that integrates energy cost and added measure capital cost. The top left points are reference points that represent 2019 Title 24 compliant homes with energy efficiency measures and solar PV. The charts show that initially adding energy efficiency measures can contribute to reducing energy-related costs compared to the reference
design point. Although incremental energy efficiency measures and PV costs contribute to higher first costs, reduced energy costs from energy savings and electricity generation have greater impacts on the lifecycle cost reduction. The charts show the minimum annualized energy-related lifecycle cost (center-bottom points) and the saving percentage of TDV energy on the X-axis. The cost-optimal home is achieved with various energy efficiency measures and a certain level of the PV system. From this cost-optimal building design point, the charts show alternative cost-optimal points with increased cost by adding more PV to achieve the NZEB home at the right side from the minimum point. The right-most point labeled “ZNE [NZEB] Home” is the home design achieving the TDV-NZEB (full NZEB) home. Other climate zones show similar patterns in the energy cost saving slope to achieve the cost-optimal home and added costs by adding more PV to achieve the NZEB as observed from Figure 5.

![Figure 5 Cost-Effectiveness Optimization Results for Single-Family Homes in CZ 13 (left: all-electric homes, right: mixed-fuel homes)](image)

While the optimized points labeled “ZNE [NZEB] Home” meet the policy goal of TDV-NZEB compliance, their PV systems need to be designed to meet the home’s TDV energy consumption, which makes the PV system oversized in excess of site-level electricity demand. For mixed-fuel homes, the TDV-NZEB home needs to have the solar PV system oversized to offset both electricity and natural gas consumption with PV electricity generation. This does not meet the state’s grid harmonization goals since they overproduce electricity.

Figure 6 shows the annual electricity consumption for all-electric homes (left) and annual electricity and natural gas consumption for mixed-fuel homes (right) across all California climate zones for 2019 Title 24 compliance single-family homes, which are the top-left points in Figure 5. The compliance homes have rooftop solar PV systems, and PV sizing is based on the mixed-fuel home that offsets the annual site-electricity consumption for each climate zone, and this PV sizing is applied to all-electric homes per the Title 24 prescriptive requirement. The white narrow bar represents the electricity generation kWh from the PV system for each climate, and values at the top are the PV system capacity in kW. Figure 7 shows energy consumption and PV energy generation for the cost-optimal residential building designs, which are the cost-effective home in Figure 5. These homes are cost-optimal designs that integrate energy efficiency measures and rooftop solar PV as a function of TDV energy savings. A wide spectrum of energy efficiency measures is added for the optimization simulation runs. PV panels with different sizes in increments of 0.1 kW are used in the optimization to find the optimal PV sizing for the most cost-effective point. Figure 8 shows energy consumption and generation for TDV-NZEB home designs, which represent NZEB (“ZNE”) home in Figure 5. For both all-electric and mixed-fuel homes, the rooftop solar PV system overproduces onsite electricity. Note that even in the all-electric case, the solar PV system overproduces onsite electricity because the hourly
TDV values provide less value for solar PV in the middle of the day compared to the TDV values of the electricity consumed at the evening hours, which makes the PV system needs to be designed oversized to fully compensate the TDV valuation of onsite electricity consumption.

Figure 6 2019 Title 24 Compliant Home Electricity / Natural Gas Consumption and PV Electricity Generation for 16 California Climate Zones (left: all-electric home, right: mixed-fuel home)

Figure 7 Cost-optimal Home Electricity / Natural Gas Consumption and PV Electricity Generation (left: all-electric home, right: mixed-fuel home)

Figure 8 TDV-NZEB Homes Electricity / Natural Gas Consumption and PV Electricity Generation (left: all-electric home, right: mixed-fuel home)
Figure 9 shows the lifecycle cost of the cost-optimal designs for all-electric (left) and mixed-fuel (right) prototype homes, which are the cost-effective home from Figure 5. The lifecycle cost refers to the total cost of ownership for 30 years, which includes home construction initial investment costs, mortgage payments, replacement costs, energy bill payments, and residual values. The construction costs only include the subset of building components that are related to the energy efficiency measures for the envelope, HVAC system, hot water system, lighting system, and appliances and do not include costs associated with land costs, permitting, plumbing pipes, natural gas pipes (for mixed-fuel homes), and any infrastructure-related costs. A range of infrastructure costs is shown for mixed-fuel homes, as natural gas connection costs need to be considered when comparing to all-electric homes. These costs can vary, depending on the degree of infrastructure required, but typically vary from about $1,000 to $10,000 per home. The mixed-fuel home (right) from Figure 9 shows this cost range for the natural gas-related infrastructure costs, centered at an assumed median point of $3,000 per home infrastructure cost. All-electric homes benefit from avoiding the cost of building natural gas infrastructure to the home.

The most lifecycle cost-effective all-electric homes generally include more energy efficient heat pumps for heating and cooling and additional rooftop solar PV than mixed-fuel homes. Figure 7 shows that an average of 1 kW additional PV system sizing for all-electric homes compared to mixed-fuel homes. All-electric homes potentially have higher upfront initial construction costs with increased PV system sizing but yields lower lifecycle costs compared to mixed-fuel homes.

The measure packages selected for the most cost-effective home designs show that energy efficient home appliances such as clothes dryers, clothes washers, dishwashers, refrigerators, and plug load reductions from smart controls, as well as hot water pipe insulation, advanced HVAC systems, and airtightness are key measures in general across climate zones and fuel types. We find energy efficiency measures that provide lifecycle cost savings in all climate zones and for all fuel types: plug load reductions (smart controls), hot water pipe insulation (R-5), and HVAC ducts located in conditioned space, and energy-efficient appliances including clothes washers (standard front-loading Consortium for Energy Efficiency (CEE) Tier 3) and refrigerators with bottom freezer (energy factor 21.3). For all-electric homes, high-efficiency heat pump systems (e.g., SEER 22 and HSPF 10) and energy-efficient clothes dryers (vented electric EF 4.5) are beneficial. For mixed-fuel homes, clothes dryers (vented gas combined EF3.48) and energy-efficient cooking ranges (max tech gas cooktops) are beneficial and colder climate zones would benefit from more energy-efficient gas furnaces (92.5 percent AFUE). Table 4 shows the selected energy efficiency measures and PV capacity that enables the most cost-effective homes both for all-electric and mixed-fuel homes as an example for CZ13.
Table 4 Selected Energy Efficiency Measures and PV capacity for the Cost-optimal All-electric and Mixed-fuel Homes in CZ13

<table>
<thead>
<tr>
<th>Category</th>
<th>All-electric homes</th>
<th>Mixed-fuel homes</th>
</tr>
</thead>
</table>
| EEMs     | • Air Source Heat Pump: SEER 22, HSPF 10  
          | • Ducts: In conditioned space  
          | • Hot Water Pipe Insulation: R-5  
          | • Refrigerator: Bottom freezer EF 21.3  
          | • Dishwasher: Energy Star  
          | • Clothes Washer: Front-loading CEE Tier 3 EF 2.9  
          | • Clothes Dryer: Vented Elec EF 3.93  
          | • Plug Loads: Optimal occupant behavior with smart control | • Central Air Conditioner: SEER 16 EER 13.5 2-speed  
          | • Ducts: In conditioned space  
          | • Hot Water Pipe Insulation: R-5  
          | • Cooking Range: Gas Cooktop Max Tech  
          | • Clothes Dryer: Vented Gas EF 3.48  
          | • Plug Loads: Advanced Power Strips with IR and occupancy sensor |
| PV capacity | • 4.0 kW | • 3.4 kW |

We find that well-insulated walls and attics are advantageous for hot climate zones. Lighting systems and windows in the baseline models offer quite an energy-efficient technology already, and there is no opportunity for further cost-effective energy savings. Triple-pane windows with low-emissivity are not yet cost-effective due to their high cost, but higher production rates could reduce costs significantly in the future. 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. Heat pump water heaters are cost-effective for all-electric homes, and not that the all-electric 2019 Title 24-compliant homes have electric heat pump water heaters from code requirements. Also, we observe the cost-minimum mixed-fuel homes can have reduced PV systems compared to PV sizing for 2019 Title 24-compliant homes that are designed to offset the annual site electricity consumption since the efficiency measures reduce the site electricity consumption. However, the PV electricity generation is greater than the home’s electricity demand during the daytime. Figure 10 illustrates the annual average hourly profile of the electricity demand (blue line), and natural gas demand (in red line) and PV electricity generation (yellow line) for all-electric homes and mixed-fuel homes in CZ 13, which shows electricity overproduction during the daytime especially when PV generation peaks during noon time while home electricity demand is moderate. Although they are the most cost-effective homes that minimize the energy-related lifecycle cost, there are hours that PV electricity generation is not aligned to grid harmonization. Figure 11 compares the energy-related lifecycle cost differences between different PV electricity over-generation export policies, one with the NEM 2.0 which is the current California policy and avoided-cost for export used for the cost-effectiveness analysis in this paper. The current policy NEM 2.0 is favorable to consumers when PV modules are added from the code-compliant homes. It shows that the policy under the avoided cost for export is less favorable to home owners as it provides less credit for electricity exported. Integration of the electricity battery can help mitigate this grid harmonization problem and improve the cost-effectiveness from the charge and discharge control [54]. The next section discusses the adoption of battery systems.
3.2 Cost-Effectiveness of Battery Storage for NZEB Homes

Home energy modeling and simulation enables finding the energy-related cost-optimal home design. The cost-optimal homes are designed with a set of energy efficiency measures along with a solar PV system carefully sized to offset home TDV electricity consumption. The battery storage can store the electricity generated from the PV and dispatch when electricity cost is expensive, which potentially improves the energy cost-effectiveness. The storage analysis provides the optimal size of residential battery storage systems and the level of the cost-effectiveness for NZEB homeowners. The cost-effectiveness analysis used the TDV methodology with 2022 TDV values. The underlying assumptions include that each residential battery storage system can only charge from a rooftop PV system and that the PV system is sized to offset no greater than the building’s electricity annual load. This is consistent with battery storage requirements for the Title 24 compliance credit, as well as California’s NEM and Self-Generation Incentive Program (SGIP) rules [47,55].
Battery storage systems are assumed to have a two-hour duration, i.e., kWh equal to the rated power in kW multiplied by two. Any exports from solar PV and battery storage to the grid are assumed to be compensated at the avoided cost for export rate as described previously.

The most cost-effective home design based on the building energy simulation (the cost-effective home from Figure 5) was used as the baseline for the storage analysis. This design point typically falls short of TDV-NZEB for both all-electric and mixed-fuel homes. The battery storage analysis can be viewed as a post-processing analysis to study the extent to which battery storage can be added to produce net benefits and the degree to which TDV-NZEB can be achieved with the addition of a battery storage. Note that this is a two-step process in this case and is not a global optimization of energy efficiency measures, rooftop PV size, and battery storage since battery storage cannot be modeled in BEopt (while EnergyPlus does model electric battery). The storage system dispatch control scenarios were developed to capture price signals as follows:

1. Optimal dispatch, which assumes that each battery is dispatched to maximize TDV values in each hour of the year, with perfect foresight.
2. Shuffled dispatch, which assumes that each battery dispatches against hourly TDV values from a similar day, by shuffling the same day of the week within the same month.
3. Time of use (TOU) dispatch, under which batteries are assumed to dispatch in response to on-peak and off-peak TOU periods.
4. Basic dispatch, under which batteries are assumed to charge on solar PV net exports and discharge when load again exceeds PV production.
5. Backup dispatch, which assumes that batteries are only used to provide backup power. According to reports from Itron, Inc., and E3 evaluating California’s SGIP, this was the most common use case for residential battery storage as of the end of 2017 [56].

Figure 12 shows the the Optimal, Shuffled, and TOU rates from a sample day. The same algorithm is used for these three scenarios with the only difference being the rate signal against which the battery is dispatched. The battery dispatch from each scenario is valued with the Optimal rate signal, so the dispatch signal closest to Optimal will be most valuable. Accordingly, Optimal dispatch is most valuable, followed by Shuffled dispatch, which uses the Optimal signal from a similar day, and finally TOU, which averages the signal over a long time horizon.

Figure 13. Battery dispatch signal chart or the electricity rate signal against which the battery is dispatched
The battery storage cost data has a significant uncertainty in the future. We applied three different battery cost trajectories for the cost-effectiveness analysis.

1. An average cost, with no reduction case, which assumes costs cited in Lazard’s Levelized Cost of Storage Analysis – Version 4.0 (Lazard, 2018) for systems installed in 2023 and does not assume any reduction in battery storage costs when systems are replaced in 2043.

2. An average cost, reducing overtime case, which begins with the same costs as the above case, but assumes 2023 and 2043 costs are 64 percent and 47 percent of 2018 costs, respectively [57].

3. A low cost, reducing overtime case, which uses recent Tesla Powerwall 2.0 installed costs collected online, and assumes the same percentage cost reduction at the average cost, reducing overtime case.

Two use case sensitivities with current TOU rates are used to approximate how battery storage would optimally dispatch and be compensated under existing 4 pm–9 pm TOU rates of the investor-owned utility that corresponds to each climate zone.

1. Current TOU rate under NEM 2.0, which reflects current policy, compensating grid exports from PV or battery storage at the retail rate less a non-bypassable charge

2. Current TOU rate under avoided cost for exports, which reflects the anticipated trend in grid export compensation policy, compensating grid exports at the average avoided cost for each TOU period

3.2.1 Battery Storage Sizing

While rooftop PV has an established sizing convention of installing a capacity that will offset the building’s annual load, residential battery storage does not have such a well-defined rule of thumb. The best battery size for a given household depends on many factors, including desired and/or achievable battery control or dispatch behavior, building load, and market availability. Current guidance on battery sizing in the 2019 Title 24 Residential Compliance Manual requires batteries to be at least 5 kWh to be eligible for compliance credit. It also requires batteries to be operated with control strategies to provide cost savings to the grid and customer to varying degrees. No upper limit on sizing is specified in Title 24, but in practice, the size is limited by diminishing marginal net benefits, as costs continue to increase while additional benefits begin to decline as battery size increases.

Because this analysis views battery storage through the lens of Title 24 cost-effectiveness, each battery case is optimally sized to maximize net benefits to the homeowner, subject to the parameters of that case. That is, the battery’s charging and discharging are valued with TDV values to calculate the battery’s net present value (NPV) benefits, and the upfront and ongoing costs of purchasing and maintaining a battery for 30 years are subtracted from these benefits to arrive at the system’s net benefits. Net benefits are calculated for a range of battery capacities (minimum 2 kWh), and the size that yields the highest net benefits is selected as the optimal size.

3.2.2 Battery Storage Analysis Results

The battery storage analysis revealed that under the Basic and TOU dispatch scenarios, battery storage cannot achieve TDV-NZEB. Battery storage responding to more dynamic price signals (i.e., under shuffled and optimized dispatch algorithms) can achieve TDV-NZEB (see Figure 14), though these solutions may not be cost-effective to homeowners. This is because basic and TOU dispatch controls are not as effective in capturing storage arbitrage value.
Further, if compensated under current TOU electricity rates and NEM policies, battery storage is not projected to be cost-effective to home owners, even assuming storage costs reduce over time (see Figure 15). The timing of the TOU periods and magnitude of the rates do not provide a sufficient signal or compensation to generate enough arbitrage value to offset battery costs. Because the penalties for exporting in the avoided cost for export use cases are about four times higher than the non-bypassable charges in the NEM 2.0 use cases, battery storage provides more energy cost savings under avoided cost for exports than under NEM 2.0.

Electricity retail rate structures are uncertain over the 30-year time frame. For this analysis, electricity consumed behind the meter by the building’s load is valued at the full TDV, while electricity exported from residential solar to the grid is valued at the avoided cost for export rate. Solar PV systems are sized to be cost-
effective as Figure 7 indicates, for each California climate zone, batteries may only charge on rooftop solar PV.

Each battery case is optimally sized to maximize net benefits (TDV benefit minus battery costs) to the homeowner. Figure 16 shows the optimal sizes of 64 battery use cases (4 use cases by 16 CZs) installed in a mixed-fuel home under at average cost, with no cost reduction. Figure 17 shows the corresponding total net benefits. The use cases in Figure 16 and Figure 17 illustrate that if battery storage costs do not decline, optimally sized battery storage systems would be very small, and few use cases would provide net benefits to the homeowner if battery storage was valued using TDV values. In Figure 16, the optimal capacity of all but two systems is the analysis’s minimum size of 2 kWh: any additional capacity would be more costly than beneficial. As shown in Figure 17, the total net benefits of these systems are negative for all but three systems, i.e., only three of these use cases are cost-effective, and by small margins.

Figure 16 Optimal Sizing of 2-hr Battery (Minimum 2 kWh) for Average Cost, No Reduction Case, Mixed-Fuel Homes
Figure 17 TDV Benefits Less Battery Costs (30-year NPV) for Average Cost, No Reduction, Mixed-Fuel Homes (the y-axis is 30-year NPV of TDV rate bill savings from battery dispatch less battery install and maintenance costs)

If battery storage costs decline from present average costs, optimal battery sizes and associated TDV net benefits are expected to increase. Figure 18 shows the same home as Figure 17, this time assuming that battery costs come down according to the Average Cost, Reducing over Time case. This analysis begins with the same costs as the Average Cost, No Reduction case, but assumes 2023 and 2043 costs are 64 percent and 47 percent of 2018 costs, respectively. Under this cost trajectory, battery storage is optimally sized above the 2 kWh minimum for many use cases. As shown in Figure 19, some of these use cases show positive cost-effectiveness margins.

Figure 18 Optimal Sizing of 2-hr Battery (Minimum 2 kWh) for Average Cost, Reducing over Time, Mixed-Fuel Homes

Figure 18 Optimal Sizing of 2-hr Battery (Minimum 2 kWh) for Average Cost, Reducing over Time, Mixed-Fuel Homes
Also notable is the variation in optimal battery size and net benefits, depending on climate zone and use case. Three factors cause this variation:

- **Climate zone:** Variation of timing in PV generation, load, and TDV peaks results in different battery storage arbitrage values by climate zone.
- **Dispatch algorithm:** Dispatch algorithms responding to more granular pricing signals provide more arbitrage value per kWh of battery storage, and improved dispatch leads to larger batteries if sized to maximize TDV net benefits.
- **Building load:** Optimally sized batteries are larger for homes with higher electric load (and therefore larger PV systems to offset annual kWh). Larger all-electric homes will see larger optimally sized battery storage systems.

We also find that if a home builder sizes the battery (or is mandated to size the battery) to maximize net benefits under one dispatch method, but then operates the battery using a less optimal dispatch method or as a backup, the situation could result in net costs. Figure 20 illustrates how total net benefits change with battery capacity under the five modeled dispatch methods. The diamonds represent the battery size that maximizes net benefits for the relevant dispatch method. In this example, an optimally sized battery under Optimal dispatch would be 9.5 kWh and would net $5,380 in TDV arbitrage value over 30 years if operated under Optimal dispatch (i.e., with perfect foresight in response to an hourly signal that perfectly matches TDV). However, if the homeowner operates the 9.5 kWh battery under shuffled, TOU, or basic dispatch, it would result in $2,400 net benefits, $4,530 net costs, or $4,450 net costs, respectively.
critically important to ensure that new buildings are as close to TDV-NZEB as possible and can be built cost-effectively since a building’s lifetime can exceed 50 years. In a future with a zero- to near-zero-emissions electricity sector, much lower CO₂ emissions can be achieved with all-electric homes compared to mixed-fuel homes. Given the sharply falling prices of rooftop solar PV and battery storage, it is critically important to characterize these dynamically changing factors and evaluate their impacts on the cost-effectiveness of new NZEB homes. Key findings are summarized by topic as follows.

4.1 NZEB Home Design

New all-electric homes with cost-optimal designs have lower costs on a 30-year lifecycle basis than 2019 Title 24-compliant all-electric reference homes for all climate zones; similarly, cost-optimized designs for new mixed-fuel homes have lower lifecycle costs than 2019 Title 24-compliant mixed-fuel reference homes in all climate zones. Energy efficiency measures such as vented electric clothes dryers (EF 4.5), ducts in conditioned space, hot water pipe insulation (R-5), and plug load reduction measures (with optimal occupant behavior and smart controls) are beneficial to achieve cost-effectiveness of future all-electric NZEB homes. Vented gas clothes dryers (EF 3.48), advanced gas cooktops, ducts in conditioned space, and hot water pipe insulation (R-5) are cost-effective for mixed-fuel homes throughout California climate zones. For all-electric homes, high-efficiency heat pump systems (e.g., SEER 22 and HSPF 10) are found to be cost-effective for climate zones with high cooling energy demand.

Lifecycle costs of a new all-electric home with cost-optimized designs are comparable to cost-optimized mixed-fuel homes across most climate zones. However infrastructure costs of all-electric homes are reduced by avoiding the costs of the natural gas pipeline infrastructure. Note that the mixed-fuel home heating fuel type is assumed to be using conventional pipeline natural gas.

All-electric single-family homes with cost-optimized designs have a larger size solar PV system by an average of 1 kW compared to mixed-fuel homes, which helps offset the increased electricity consumption for all-electric homes. When the annual total solar PV electricity generation is greater than the annual total site electricity consumption, cost-effectiveness cannot be achieved under the less generous solar PV compensation policy assumed here (avoided cost for export). Full TDV-NZEB homes can be achieved by oversizing solar PV systems (without storage) to offset the TDV of the building’s annual site energy usage with the TDV of onsite generated electricity from PV. However, this violates the NEM policy that solar PV output should not exceed the site electricity consumption, as excess exported electricity from oversized PV is not aligned to grid harmonization goals.

4.2 Battery Storage

Battery storage benefits are strongly dependent on assumptions for control algorithms and future battery costs. Batteries can bring single-family homes to TDV-NZEB with net benefits under aggressive price reduction scenarios. For residential storage to contribute to California’s NZEB goals and be cost-effective to home owners, the implementation of storage control algorithms must consistently and reliably respond to price signals that are more closely aligned with TDV values than current TOU electricity rate structures and with less favorable NEM compensation than the current NEM 2.0 policy. This could be achieved through, for example, dynamic pricing with some assurance of customer response, direct utility control, aggregation services, and/or NEM policy that compensates exported electricity at an avoided cost.

If storage is dispatched according to current utilities’ TOU periods, or is assumed to charge during times of solar PV net exports and discharge when the load exceeds PV production, then storage cannot achieve TDV-NZEB. Conversely, battery storage which is assumed to respond to TDV price signals added to cost-
optimized home designs can achieve TDV-NZEB. Optimal battery size and associated net benefits vary greatly, depending on climate zone, dispatch algorithm, and home electric load.

If compensated under current TOU rates and NEM 2.0 policies, storage is not projected to be cost-effective to the participant even if storage costs reduce over time. If storage systems are instead compensated according to TDV values and sized to maximize net TDV benefits, then potential benefits from storage depend upon future storage cost trajectories. If storage costs do decline from present average costs, assuming that 2023 and 2043 costs are 64 percent and 47 percent of 2018 costs, respectively, then storage generally sees net TDV benefits.

Finally, while co-optimizing battery and PV sizing may be relevant for off-the-grid, commercial, or utility-scale systems, it is not necessary here. In residential applications with NEM (including the Avoided Cost for Exports NEM policy we used in this study), PV is so cost-effective that the PV sized to offset the building’s annual energy consumption is always the system that provides the most cost savings. Even larger systems would yield greater savings, but NEM statutes restrict PV systems sized beyond this point. Under the conditions considered in this study, there are no cases in which reducing PV size with the same or different size of battery would increase net benefits.

4.3 Policy Implications

Here we highlight key policy sensitivities and policy implications from this work. There is a high sensitivity of lifecycle costs on NEM policy regime with higher LCC costs for the NEM 2.0 successor policy modeled here (“avoided cost for export” for solar power exported to the grid). A more attractive payment for exported power will make all-electric new homes more cost effective, but this needs to be balanced with the falling prices for rooftop solar PV installation and equity concerns of subsidizing solar PV owners at the expense of non-solar customers.

Highly energy efficient appliances are found to be beneficial to overall cost effectiveness but states cannot require appliance standards that are more stringent than Federal appliance standards. A starting point for this is to encourage or require Energy Star rated large appliances for new homes.

This study highlights several common measures that are cost effective that should be prioritized for inclusion in the next building code cycle in California, for example, ducts in conditioned space, hot water pipe insulation (R-5), and plug load reduction measures. Miscellaneous plug loads are an increasing fraction of energy use and their regulation and/or provisions to contain their energy use are increasingly important.

If the overarching policy goal is decarbonization (which is targeted by California), NZEB metrics should focus more on CO₂ emission reduction rather than energy savings. One proposed approach is to apply a higher carbon price to the cost effectiveness calculations, and to update zero-net energy goals to reflect zero net carbon goals whereby the overarching policy goal is for carbon emissions associated with a buildings’ energy use should net to zero over the course of a year [58].

This work also finds that storage systems optimized to maximize net TDV benefits are often smaller than the current Title 24 minimum size of 5 kWh. This should be considered by policymakers in California as part of any market analysis performed to support the inclusion of battery storage in building codes. TOU rates that capture actual costs such as those based on the time-dependent valuation described here can better enable storage benefits.

4.4 Model Generalization

Although key modeling assumptions of this study are based on the California context and its building energy codes and policies, the modeling methodology can be adjusted for use in other U.S. states as well as
other countries. For example, the prototype single-family home can be customized (including geometry, use patterns, efficiency level) based on local representative homes; the weather data used in EnergyPlus simulations can be changed to local weather data; the efficiency levels of EEMs or types of EEMs can be modified to suit the local context; all pricing input (e.g., energy price, costs of EEMs, PV) can be changed to local market values. The use of BEopt tool is convenient, but other tools can be potentially used, for example the jEPlus tool (jEPlus.org), which is open source and provides parametric runs and optimization. To study NZEB for other building types, e.g., multi-family residential or office buildings, their appropriate prototype building models can be developed and used.

4.5 Limitations

Some limitations of the study are described here. These also represent opportunities for further work and model development.

Cost effectiveness calculations, in general, may not capture all costs or benefits, and these costs and benefits may change over time, which is hard to capture in a single study. On the cost side, installed costs of electric heat pump equipment could change in the future – for example, installation costs could drop with higher volumes of installed equipment, more economies of scales in manufacturing heat pump equipment, and/or greater competition among contractors. Similarly, the operational costs for mixed fuel homes could increase if carbon prices increase and were priced into the cost of fossil fuels such as natural gas. The study does not consider any additional costs incurred by impacts to the electricity supply, transmission, or distribution system. A greater electricity demand overall could lower the cost per unit of electricity in the long run, but in the short run may increase electricity costs if, for example, upgraded distribution system components are required. On the benefits sides, the study does not quantify any potential benefits (or costs) of non-energy factors such as health, comfort, productivity, or resilience. For example, switching away from fossil-fuel burning appliances could result in better indoor air quality for all-electric homes due to the elimination of any in-home combustion of fuel, and homes with larger rooftop solar PV systems could have higher resilience benefits to electricity grid outages compared to homes without solar PV or homes with smaller solar PV systems (assuming that the solar PV system could be islanded or isolated from the grid). With “smarter” end uses and homes in the future, all-electric homes could have the added flexibility of loads that can be shifted in time (or demand shifting) to better align with favorable time-of-use electricity rates or peak times of rooftop solar PV output. This could also reduce operational costs of all-electric homes. Technologies for communication, coordination, and customer controls are starting to appear, but in addition, RTO/ISO markets and aggregation of these services by the utility or third party providers need further development.

Cost/benefit analysis of other types of home design such as passive homes and prefabricated homes is important to quantify for initial costs, life-cycle costs, and embodied CO$_2$ emissions in comparison to the “conventional” home designs presented here, for example. For the overall goal of decarbonized buildings and transportation, it would be very interesting to look at the addition of electrified transportation (plug in electric vehicle or plug in hybrid electric vehicle) in the context of an all-electric home in terms of integrated costs, air quality benefits, and resilience benefits for example. Thermal storage concepts and emerging technologies is another area that could be investigated in addition to the battery storage presented here.

Extensions of this type of study could be made to multi-family residential buildings and commercial buildings, and beyond that to community-scale or city-scale modeling for both new buildings and the retrofitting of existing buildings.
5 Conclusions

This paper presented a novel study on the cost-effectiveness of near-NZEB new homes in California, United States. The cost-optimized home designs can reduce the lifecycle costs for all-electric and mixed-fuel homes compared to their all-electric and mixed-fuel 2019 Title 24-compliant homes for all California climate zones. We find that all-electric homes are comparable in lifecycle costs to mixed-fuel homes for most California climate zones, considering cost savings from avoided natural gas infrastructure. The cost-effectiveness of the all-electric near-NZEB homes depends on the capital costs of heat pumps and electric heat pump water heaters and the PV export compensation. Rooftop solar PV improves the cost-effectiveness of near-NZEB homes, but its benefit is reduced with lower compensation rates for excess power. Battery storage improves the cost-effectiveness of near-NZEB homes if there is a lower battery cost in the future, a favorable TDV-based hourly electricity rate structure, and a moderate degree of controllability. These findings provide guidance for future updates of California’s energy efficiency standards and inform policies on electrification and the adoption of renewable energy for new residential buildings.

Future research includes passive homes, thermal storage integration, and prefabricated components as additional strategies to achieve NZEB new homes in California. As weather variations and occupant behavior can significantly influence the actual performance of NZEB homes, it is important for future research to study the robustness of NZEB performance and characterize its driving factors to inform risk assessment, as well as the adoption of technologies for design and operational strategies of NZEB homes. Evaluating the resilience of NZEB homes under extreme weather events (e.g., heat waves, cold snaps) can also inform the design and operation of NZEB homes. Another potential research topic is a residential energy district that serves multiple homes taking advantage of temporal load diversity across individual homes and economies of scale. For example, combined heat and power systems, self-contained distributed energy systems that provide both onsite power and heating, can improve cost-effectiveness where there is sufficient year-round heating load, and waste heat from a power generation unit could be used for water heating throughout the year.

Although this NZEB study was conducted for new homes in California, the methodology and models can be adopted for other U.S. states and international cities if they, like California, push for NZEB homes considering time-dependent energy valuation.

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