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Approaches to Zero Net Energy Cost Effectiveness in New Homes

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PREPARED BY:

Primary Authors:

Max Wei[1]
Sang Hoon Lee[1]
Hung-Chia Yang[1]
Sarah Price[1]
Jeff Greenblatt[1]
Tianzhen Hong[1]
Brian Conlon[2]
Lucy McKenzie[2]
Zachary Ming[2]
Bob Hendron[3]
Alea German[3]

[1]Lawrence Berkeley National Laboratory
One Cyclotron Road
Berkeley, California 94720
Phone: 510-486-4000
http://www.lbl.gov

[2]E3
44 Montgomery St,
San Francisco, CA 94104
Phone: 415-391-5100
http://www.ethree.com

[3]Frontier Energy
1000 Broadway #410
Oakland, CA 94607
Phone: 510-444-870
http://www.frontierenergy.com

Contract Number: EPC-16-002

PREPARED FOR:
California Energy Commission

Brad Williams
Project Manager

Virginia Lew
Office Manager
ENERGY EFFICIENCY RESEARCH OFFICE

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Drew Bohan
Executive Director

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Approaches to Zero Net Energy Cost Effectiveness in New Homes is the final report for the Pathways to More Cost-Effective ZNE Homes project (Contract Number: EPC-16-002) conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

This report summarizes detailed modeling of new residential zero net energy homes in California to provide information for future Title 24 building codes using the state's time dependent valuation method. The researchers derived an updated set of time dependent valuation values for 2022 to more accurately estimate future energy costs, and rooftop photovoltaic compensation rates for exported power were assumed to be less favorable than the current net energy metering policy to emulate future anticipated state policy. The project used Building Energy Optimization Tool software to provide cost-optimized building designs for all-electric and mixed-fuel single-family homes across all 16 California climate zones and for eight-unit multifamily buildings in 3 climate zones. The researchers performed detailed modeling for onsite battery storage and precooling to evaluate the cost effectiveness of these measures under various assumptions for future battery costs and control algorithms.

The research found that optimally designed single-family and multifamily homes result in lower customer lifecycle costs for all-electric and mixed-fuel cases in all climate zones studied, but generally with higher initial costs. Optimally designed all-electric single-family homes are comparable in lifecycle costs to mixed-fuel homes in most climate zones, and single-family and multifamily homes can benefit from not having to build natural gas infrastructure to the home. Lower future battery costs and a moderate degree of controllability can enable cost-effective battery storage with a wider range of battery sizes than currently permitted in California. For precooling, a single-day control schedule can optimize precooling to achieve a large fraction of the benefits. For battery storage and daytime precooling, electricity rates with a greater degree of time-dependence will enable greater potential benefits.

Keywords: zero net energy homes, building decarbonization, electrification, energy efficiency, cost-effective zero net energy homes, battery storage, demand shifting, demand response, precooling

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EXECUTIVE SUMMARY

Introduction

California is a pre-eminent testing ground for low-cost and low-greenhouse gas (GHG) energy strategies for a decarbonized economy. The state has aggressive economywide GHG reduction goals for 2030, 2045, and 2050 with a 40 percent reduction target for 2030 from the 1990 level and an 80 percent reduction goal in 2050. More recently, the state set the target of zero GHG emissions from the electricity sector by 2045, and then-Governor Edmund G. Brown, Jr. announced a goal of net zero carbon emissions statewide by 2045.

In the building sector, California passed legislation in 2018 specifically targeting GHG emissions reduction from building heating. California also requires the reduction of high global warming potential refrigerants in the state by 40 percent below 2013 levels by 2030. For new homes, the state set a policy goal of zero net energy new homes by 2020 and zero net energy new commercial buildings by 2030. California's Title 24 Energy Code (Title 24) has become successively more stringent over time with greater accommodation for electric appliances, and for the first time, 2019 Title 24 building code has a prescriptive requirement that all new homes have rooftop solar photovoltaic.

Project Purpose

California's GHG emissions reduction goals and the overarching goal of decarbonizing the state's entire economy, and the building sector, necessitate that new buildings have emissions as close to zero as possible and are cost effective to build. This report examines the most cost-effective options for achieving zero net energy homes for future building code cycles that will support California's GHG reduction goals.

In a future with zero to near-zero electricity sector emissions, lower carbon dioxide emissions can be achieved with all-electric homes compared to mixed-fuel homes (that is, homes with appliances that are supplied by both conventional natural gas and electricity). The falling prices of rooftop solar photovoltaic and battery storage and the increasing availability of supply options such as community solar and renewable natural gas will affect zero net energy new home cost-effectiveness and must be considered in plans for achieving state emissions reduction goals.

This study explores the following questions with the goal of informing future state building codes and standards:

1. What is the cost-effectiveness of all-electric homes compared to mixed-fuel homes, considering anticipated policy revisions for rooftop solar compensation and updates to key inputs in cost-effectiveness methods?
2. What are the viability and policy considerations and/or barriers for community renewable energy supply sources (community solar and renewable natural gas)?
3. What are the benefits and cost impacts of battery storage and precooling?
4. What are the policy implications of these research findings?

Project Approach

The approach of this work included: (1) conducting an expert elicitation process among key stakeholders such as builders and utility contacts (expert elicitation refers to formal procedures for obtaining and combining expert judgments and is not a simple survey instrument); (2) using the National Renewable Energy Laboratory Building Energy Optimization software tool, BEopt, for building energy modeling and cost optimization; (3) providing technoeconomic analysis and policy considerations for community renewables; and (4) performing a detailed sensitivity study for battery storage and precooling impacts as a function of battery storage cost, battery controllability, and precooling control schedules. Since building modeling results are targeted for the 2022 code cycle, lower compensation rates are assumed for exported electricity from solar photovoltaic ("avoided cost for exports") in anticipation of further evolution of net energy metering policy for rooftop solar.

Building energy modeling is based on three prototype buildings used by the California Energy Commission (CEC): two single-family homes and one multi-family building. Optimized building designs are generated using BEopt, which uses the EnergyPlus simulation engine. BEopt calculates the life-cycle cost of building energy efficiency measures including capital and operating costs. Key inputs include the set of candidate energy efficiency measures, building measure costs, utility rates, rooftop photovoltaic capital costs, fixed charges, and net photovoltaic compensation rates.

The time-dependent value-based time-of-use rate approach is most consistent with the state's current codes and standards rulemaking process. Time dependent values for electricity and natural gas are based on the concept that the value of a unit of energy consumed or energy generated varies depending on the time of day and the season of the year. However, the CEC is evaluating cost-effectiveness options for the 2022 code cycle that are based on source-energy and/or that provide more direct weighting to reductions in GHG emissions. In this work, the researchers computed and used newly derived time dependent valuation values for 2022 for the cost-effectiveness analysis since alternative cost-effectiveness metrics and methods were not available.

Policy analysis for community solar and renewable natural gas supply options included an assessment of current and future policies for community solar and renewable natural gas, an assessment of future available supply and costs, and competing demands for renewable natural gas.

Scenarios for battery storage included future battery costs and the degree of controllability of battery operation. Precooling effects are provided as a function of precooling set-point temperature schedules.

Project Results

The project resulted in several key findings summarized here, described in more detail in Chapter 5, and include results on all-electric and mixed-fuel new homes costs; community renewables; battery storage; precooling; and policy implications. Key input assumptions that differ from current assumptions for 2019 Title 24 homes include the use of updated time-dependent values for 2022 and the assumption of avoided cost for exports for rooftop solar photovoltaic compensation rather than the more favorable net energy metering 2.0 compensation. Some key findings include:

- New all-electric homes with cost-optimized designs have lower costs on a 30-year life-cycle cost basis than 2019 Title 24–compliant all-electric reference homes for all climate zones; similarly, cost-optimized designs for mixed-fuel new homes have lower life-cycle costs than 2019 Title 24–compliant mixed-fuel reference homes in all climate zones.
- New all-electric homes with cost-optimized designs are comparable to cost-optimized mixed fuel homes on a life-cycle cost basis across most climate zones and have significantly lower carbon dioxide emissions. All-electric home costs can benefit from reduced infrastructure costs for gas lines.
- Community solar — systems where electricity production is shared by more than one household — present an alternative zero net energy pathway with the potential for lower cost to Californians compared to onsite rooftop solar photovoltaics (PV). However, existing community solar programs are not financially attractive to participants and do not adequately satisfy CEC zero net energy compliance criteria. There is an important opportunity for the development of new community solar programs that are cost-effective for participants, improve non-participant impacts relative to the status quo, and satisfy CEC zero net energy compliance criteria.
- Using renewable natural gas for zero net energy compliance presents significant challenges in cost-effectiveness, competing demands in hard-to-decarbonize sectors (industry, trucking), and supply uncertainties.
- For residential storage to contribute to the state's zero net energy goals and be cost-effective to the participant, storage control algorithms must consistently and reliably respond to price signals that are more closely aligned with time-dependent values than current time-of-use rates and with less favorable net energy metering compensation for grid exports than the current net energy metering 2.0 policy.
- An optimized precooling schedule that dynamically chooses a setpoint schedule each day to minimize time dependent valuation costs (hourly net load multiplied by time-dependent values) often uses more kilowatt-hours (kWh) than the base case setpoint schedule.
- An optimized precooling schedule could save up to 26 percent of net time dependent valuation by shifting electricity consumption from high-cost evening peak periods to lower cost afternoon hours and reducing the amount of power that is exported to the grid at low avoided cost compensation.
- The research team finds that a single setpoint schedule for all days that is customized by climate zone could provide much of the precooling cost savings provided by an optimized schedule, while being simpler to implement and not requiring forecasting.

Policy Implications

- All-electric homes are attractive for their lower overall carbon dioxide emissions than mixed-fuel homes and are cost effective for all climate zones compared to all-electric 2019 Title 24 compliant homes.
- With tighter building shells and energy-efficient lighting, energy-efficient large appliances (clothes dryers and washers, dishwashers, refrigerators, cooktop stoves, and ovens) and

plug loads (miscellaneous electric loads) are increasingly important for life-cycle energy costs.

- With the intent to provide more viable community solar zero net energy compliance options, the research team provides two potential designs including a ratepayer-funded green tariff and an upfront green tariff.
- Storage systems optimized to maximize net time dependent valuation benefits are often smaller than the current Title 24 minimum size of 5 kWh and common commercially available sizes like the 13.5 kWh Tesla Powerwall.
- Several policy elements are needed to realize the savings from precooling in new residential construction: the installation of occupant controlled smart thermostats in new construction; sufficiently time-differentiated price signals to customers or to aggregators to encourage customers to pre-cool; and greater customer education efforts to communicate the financial and comfort benefits of precooling and reiterate customer control and opt-out options.

Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

The research team is transferring the knowledge produced through this study in several ways. First, this report discusses the methods and results in detail. Second, the team presented the project results in a panel at the 2018 American Council for an Energy-Efficient Economy Summer Session, "Net Zero: Moving Beyond 1 Percent of Homes," in Pacific Grove, California. The conference provided an opportunity for stakeholders to meet and discuss the effects of electrification on cost-effectiveness of zero net energy homes, provide feedback on technical inputs of this work, and learn about best-practice implementations for all-electric, zero net energy and "zero energy-ready" homes, or those that are at least 40 percent to 50 percent more energy efficient than a typical new home. Lawrence Berkeley National Laboratory will present the project results in various stakeholder meetings, including the American Society of Heating, Refrigerating and Air-Conditioning Engineers 2020 Building Performance Analysis Conference & SimBuild in Chicago, both in August 2020.

Technical advisory committee members — stakeholders from utilities, government agencies, and academia — helped to develop assumptions and review results during development and in final form. The committee's participation ensured that they understood the benefits of this work and can use the results to direct future programs and studies.

Finally, Lawrence Berkeley National Laboratory anticipates publishing the results of this analysis in a journal publication in 2021.

Benefits to California

This research is important to ratepayers because it provides cost-effective zero net energy designs for all-electric and mixed-fuel homes and identifies the conditions under which battery storage and precooling options can be cost-effective. All-electric designs, if adopted by contractors, architects, building owners, residents, and property owners, can lower annual energy costs and realize an average of 38 percent annual carbon dioxide savings compared to mixed-fuel family homes. All-electric homes with onsite solar or community solar agreements could insulate consumers from future volatility in natural gas prices and increasing electricity prices from the grid.

Increasing the adoption of all-electric zero net energy homes across California will improve the health and safety of ratepayers by reducing criteria pollutants from natural gas combustion. Reduction of natural gas consumption by broader adoption of alternatives such as electrically powered heat pump-based water heating and space heating, will improve consumer and neighborhood safety by reducing natural gas distribution, possible leakage, and combustion for onsite heat generation.

Transitioning to zero net energy all-electric new single-family and multi-family homes by 2023 would result in more than 50 metric tons of carbon dioxide cumulative savings from 2023–2050, with about 0.62 billion therms of natural gas savings in 2050, resulting in 3.3 million metric tons net carbon dioxide savings in 2050. These calculations assume 4.9 million new all-electric zero net energy homes from 2023 to 2050, or about 175,000 homes per year, and corresponds to about 127 therms per year of natural gas savings and about 0.67 metric tons of carbon dioxide savings per year per home.

All-electric homes with onsite solar PV coupled with electricity storage offer the potential for greater ratepayer resiliency, fewer power outages, and reduced potential hazards associated with power outages. For example, ratepayers can still receive air conditioning service during a heat wave-induced power outage. As "distributed heating" technologies (onsite photovoltaic systems and heat pump heating) become more prevalent, consumers would rely less on the natural gas system and the electricity grid.

This research also sets the groundwork for the future Title 24 building cycle with new time dependent valuations for 2022 and a "high renewables" time dependent valuation case with a lower GHG target in 2030 of 30 million tonnes of carbon dioxide electricity in the electricity sector, new zero net energy building designs, and new battery storage and precooling cases.

CHAPTER 1: Introduction

California is a pre-eminent testing ground for low-cost and low-greenhouse gas (GHG) energy strategies for a decarbonized economy. The state has aggressive economy-wide GHG reduction goals for 2030 and 2045 with a 40 percent reduction target for 2030 from the 1990 level (Senate Bill 32, Pavley, Chapter 249, Statutes of 2016) and an 80 percent reduction goal in 2050 (Executive Order S-3-05, 2005). More recently, the state set the target of zero GHG emissions from the electricity sector by 2045 (Senate Bill 100, De León, Chapter 312, Statutes of 2018) and then-Governor Edmund G. Brown, Jr. announced a goal of net zero carbon emissions statewide by 2045 (Executive Order B-55-18, 2018). In the building sector, California passed legislation in 2018, specifically targeting GHG emissions reduction from building heating (Assembly Bill 3232, Friedman, Chapter 373, Statutes of 2018). California also requires the reduction of high global warming potential refrigerants in the state by 40 percent below 2013 levels by 2030 (Senate Bill 1383, Lara, Chapter 395, Statutes of 2016). For new homes, the state has the policy goal of zero net energy new homes by 2020 (California Energy Commission and California Public Utilities Commission 2015) and zero net energy new commercial buildings by 2030. Title 24 building codes have become successively more stringent with greater accommodation for electric appliances, and for the first time, 2019 Title 24 building code has a prescriptive requirement for all new homes to have rooftop solar photovoltaic (PV).

Zero Net-Energy Definition

Zero net energy (ZNE) buildings have various definitions and may be based onsite or source energy (United States Department of Energy [USDOE] 2015). The California definition for ZNE, "TDV-ZNE," is based on time dependent valuation (TDV) factors (State of California 2016):

> "Based on the unit of a single project, a ZNE building is one in which the value of the energy produced by onsite renewable energy resources is equal to the value of the energy consumed annually by the building measured using the time dependent valuation (TDV) metric."

TDV values for electricity can shift the value of onsite renewable energy such as rooftop solar PV. TDV values are also expected to change as the mix of electricity supply changes over time. In particular, as more solar PV is brought online per the SB 100 target for high levels of renewable electricity, the value of electricity generation at midday is reduced. The TDV method also results in extreme hourly spikes in electricity valuation that may not be reflected in utility prices.

ZNE Design and Energy Supply Options

Table 1 shows ZNE design and energy supply options. The first row shows that ZNE homes can be built as "mixed-fuel" consisting of a mix of natural gas-fired and electricity powered appliances or as all-electric homes. Mixed-fuel homes have historically been the most common type of new home and typically use gas[1] for heating applications such as space heating, water heating, and cooking (stoves). All-electric homes use electricity for heating, cooling, cooking, drying, and other purposes and typically do not include a gas line to the home.

Table 1: Zero Net Energy Design and Energy Supply Options

	Mixed-Fuel (Gas & Electric Home)	**All-Electric Home (Electricity for heating, air conditioning, cooking, drying, etc.)**
Onsite Solar PV	Natural Gas + Rooftop PV	All-Electric + Rooftop PV
Community Renewables	Renewable Natural Gas + Rooftop PV	All-Electric + Community Solar

Table 1 shows a comparison of ZNE design and energy supply options for mixed-fuel and all-electric homes.

Source: Lawrence Berkeley National Laboratory

The first column of Table 1 shows energy supply options for ZNE homes. Both mixed-fuel and all-electric homes can have onsite rooftop solar PV, while "community renewables" refers to two specific 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 emissions (CH_4) primarily from landfills, municipal solid waste (MSW), wastewater plants, and dairy operations. Community solar refers to a solar PV installation at a site near but separate from the site of the home, a portion of whose output is associated with one residential home. Technology options thus are limited to "in-paradigm" or conventional options and do not include options such as combined heat and power (CHP), distributed heating, hydronic heating, or synthetic natural gas (SNG) derived from hydrogen and carbon dioxide (CO_2).

New ZNE homes from 2015 onward are expected to make up about 32 percent of housing stock by 2050 (M. Wei et al. 2019) and from 10 to 28 percent of the natural gas demand and about 28 percent of the electricity demand[2] in 2050. Though new housing starts were only 130,000 per year in 2018 compared to nearly 14 million housing units,[3] they are projected to increase by about 10 percent per year the next few years.[4]

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[1] "Gas," as referred to here, and in the context of ZNE new homes, refers to natural gas. The report uses this nomenclature for simplicity.

[2] The fraction of new ZNE home energy demand versus total residential demand in 2050 is dependent on several factors including the rate of retrofits and the rate of electrification in new and existing homes. The ranges given here are for scenarios with high electrification and no electrification and with almost all existing homes retrofitted by 2050.

[3] https://factfinder.census.gov/faces/nav/jsf/pages/community_facts.xhtml?src=bkmk, accessed December 31, 2018

[4] *Los Angeles Times* article: http Scope: SF, MF, 15 California climate zoness://www.latimes.com/projects/la-pol-ca-next-california-economy/

Grid Harmonization

As more solar PV is added to the grid from both centralized solar, concentrating solar thermal, and rooftop PV, there is greater recognition of the need for "grid harmonization," or the concept that additional resources added to the grid should take into account the need to maintain grid stability, reliability, and maximal use of grid resources. The well-documented California net load curve, or "duck-curve" (Figure 1), is one important manifestation of the issues arising from adding increasing amounts of intermittent renewable solar and wind resources to the grid.

Figure 1: California Net Load Curve

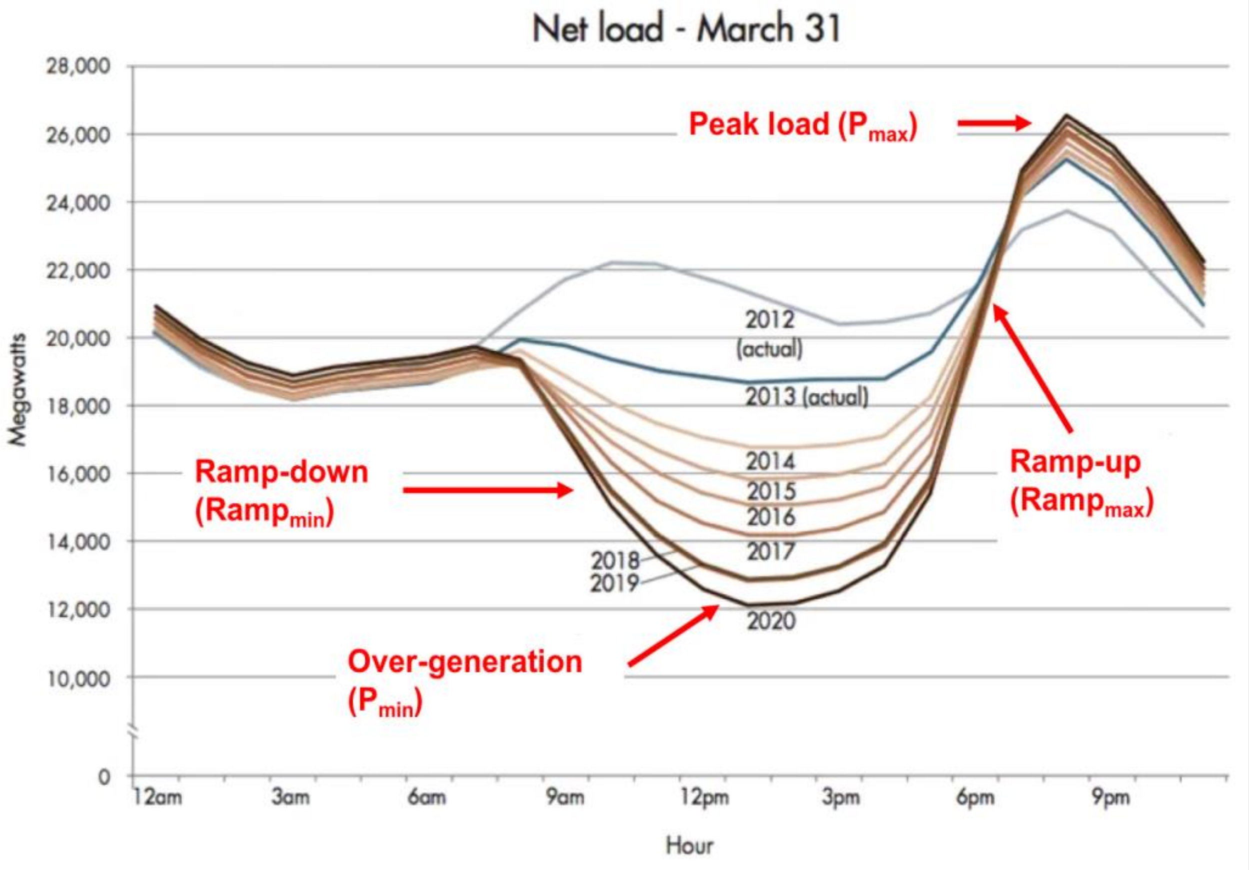

Figure 1 shows the California average hourly net load curve, in megawatts, for 2014.

Source: California Independent Systems Operator 2014

"Net load" is defined as total system load minus generation from wind and solar. Figure 1 shows net load in 2012 and 2013 and projected net load in subsequent years. For increasing amounts of solar generation with its diurnal shape of early afternoon peaking output, the duck curve highlights four important problems:(1) over-generation during the early afternoon; (2) high evening peak load; (3) sharp mid-morning down-ramps; and (4) substantial evening up-ramps.

Current net energy metering (NEM) policy does not allow a rooftop solar PV whose annual output exceeds site-level electricity demand in kilowatt-hours (kWh). For the duck curve, several mitigations are pertinent in the case of ZNE homes with their increasing amounts of solar PV: (1) flexible loads or demand shifting as in precooling a home or shifting electric vehicle charging to better coincide with solar peak output times; and (2) energy storage, such as battery storage or thermal storage to store electricity during peak daytime hours for use later in the day.[5]

A greater role for energy storage is expected in the near term with anticipated cost reductions in battery storage (Kittner et al, 2017 and Lazard, 2019). Similarly, precooling can facilitate greater use of solar PV output by shifting cooling demand in the late afternoon or early evening to earlier in the day. Thus, it is important to model potential benefits of energy storage and precooling.

Key Research Questions

This study explores the following key questions with the goal of informing future state building codes and standards (for example, 2022 Title 24 building code):

1. What is the cost-effectiveness of all-electric homes compared to mixed-fuel homes, considering anticipated future policy revisions for rooftop solar compensation and updates to key inputs in cost-effective methods?
2. What are the viability and policy considerations and/or barriers for community renewable energy supply sources (community solar and RNG)?
3. What are the benefits and cost effects of battery storage and precooling?
4. What are the policy implications of the resultant research findings?

Report Organization

The remainder of this report is organized as follows: Chapter 2 describes the study approach; Chapter 3 summarizes key findings; Chapter 4 discusses technology, knowledge, and market transfer activities; and Chapter 5 discusses conclusions and areas for follow-up work. Several appendices provide study assumptions and additional technical details.

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[5] Systemwide, a number of additional approaches can contribute to mitigation of these issues including increasing regional coordination, renewable generation diversity, more flexible non-solar and non-solar generation resources, and use of over generated power for chemical storage, for example, power to gas or power to hydrogen.

CHAPTER 2:
Project Approach

Time Dependent Valuation Update for 2022

Currently, California Title 24 building codes and energy efficiency standards are developed based upon the cost-effectiveness of energy efficiency measures in new buildings. The standards promote measures that have a positive benefit-cost ratio from a modified participant cost perspective. The project team is aware that the California Energy Commission (CEC) is reviewing the use of this method, but this report uses the existing, cost-effectiveness-based method. Given the likely changes to this method, the research team did not provide total resource cost test results in this report.

Beginning with the 2005 standards update, TDV has been used in the cost-effectiveness calculation for Title 24. The concept behind TDV is that energy efficiency measure savings should be valued differently depending on the specific hours of the year in which the savings occur, to better reflect the actual costs of energy to consumers, to the utility system, and to society. While the details of the Title 24 TDV method can be complex, at its root the concept of TDV is quite simple: it holds the total cost of energy constant at forecasted retail price levels but gives more weight to on-peak hours and less weight to off-peak hours.

TDV is based on a series of annual hourly values for electricity cost (and monthly costs for natural gas) in a given weather year.[6] TDV values are developed for each of the 16 climate zones.[7] The key components of the electricity TDV factors include:

- Marginal Cost of Electricity – *variable by hour* – The shape of the hourly marginal cost of generation is developed using the CEC’s 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 of energy: 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,

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[6] In official updates, TDV values are matched to CEC-adopted typical weather year files for the 16 California climate zones. Because this analysis required weather-correlated data for zones outside of California, these projected TDV values were matched to 2013 historical weather to ensure consistent conditions across the West.

[7] Note that these use CTZ weather files used in the calculation of 2019 TDV values.

transmission and distribution capacity, CO_2 emissions, and avoided renewable resources) each of which is summarized in Table A1 in Appendix A. 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

TDV are calculated in life cycle dollars per unit of energy for each hour and climate zone in California. For the purposes of building code compliance, they are converted to units of kBTU/kWh and kBTU/therm using fixed multipliers. This is done because of a long-standing precedent of using 'source energy' factors in building code analysis, which is familiar with many practitioners. In addition, conversion to energy units prevents confusion between a long-term estimate of consumer bill savings based on a California average over 30 years and specific customer bill savings in a specific year and location.

Updates for 2022 Base Time dependent valuation

For this project, the research team calculated two sets of TDV values for the 2022–2052 period:

1) A "Base Case" set, which approximates energy costs under currently adopted policies (including 50 percent renewable portfolio standard by 2030) and the CEC's 2017 *Integrated Energy Policy Report* (IEPR) mid-demand case forecasts
2) A "Higher Renewables" set, which uses the California Public Utilities Commission (CPUC) Integrated Resource Plan (IRP) 30 million metric tons (30MMT) by 2030 case, resulting in a California Independent System Operator (California ISO) generation portfolio corresponding to a nearly 70 percent renewable portfolio standard (RPS).

Figure 2 and Figure 3 show hourly 2022 TDV values under the two cases, averaged across the full year. In both cases, the peak hour shifts slightly later than the TDV values used in the CEC's 2019 Title 24 Building Code cycle, with lower energy costs in the middle of the day and a higher overall peak. The Higher Renewables case shows higher average TDV values in each hour, due primarily to higher RPS and capacity values (and despite lower energy costs in the middle of the day during higher solar production). Appendix A provides additional detail on these cases.

Figure 2: Average Day Base Case 2022 Time dependent valuation Components, Climate Zone 12

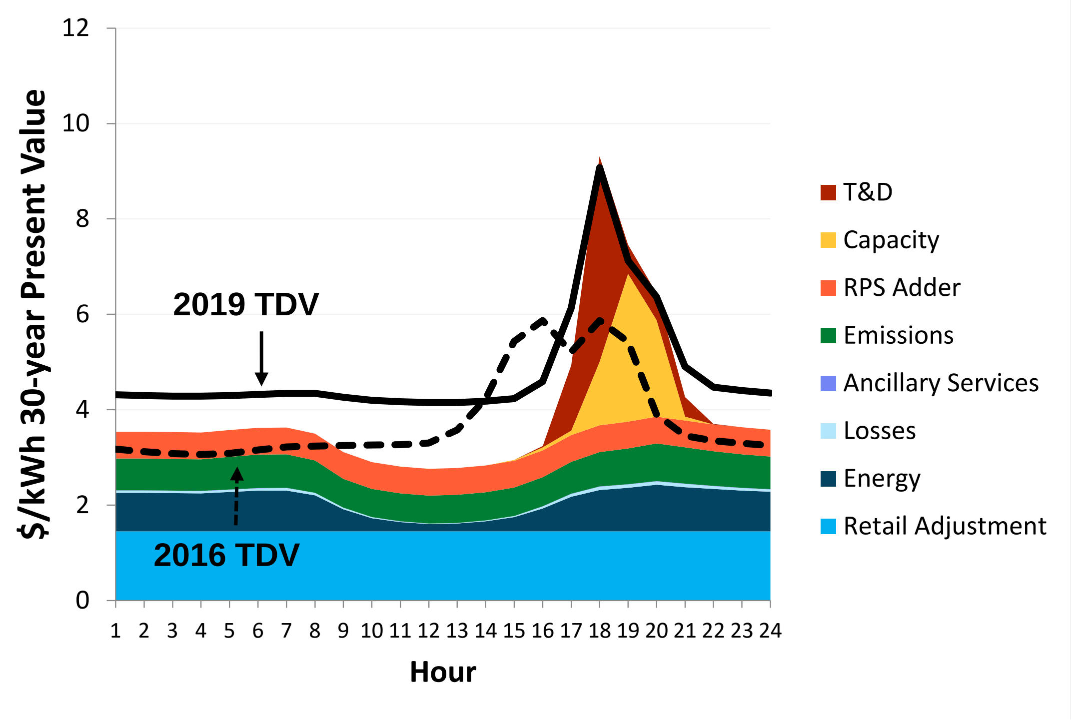


Figure shows the base case 2022 TDV components across an average day in climate zone 12. The total 2022 TDV is the sum of all components in each hour.

Source: Lawrence Berkeley National Laboratory

Figure 3: Average Day Higher Renewables 2022 Time dependent valuation, Components Climate Zone 12

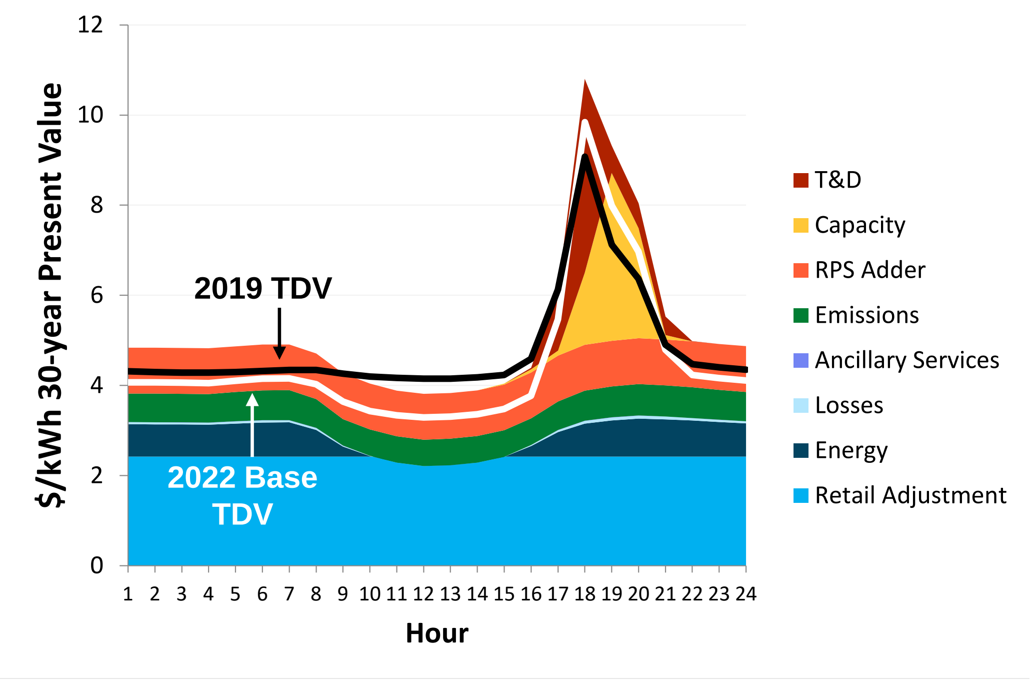


Figure shows the higher renewables scenario 2022 TDV components across an average day in climate zone 12.

Source: Lawrence Berkeley National Laboratory

Energy Modeling Approach

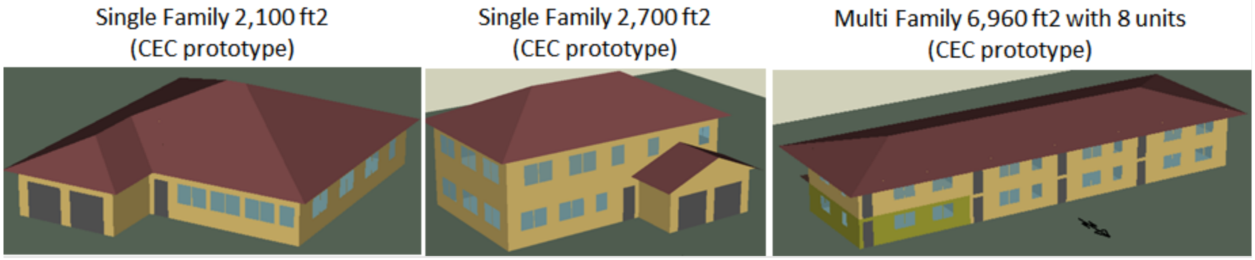
BEopt Modeling Tool

The residential building energy modeling uses BEopt. BEopt provides capabilities to evaluate residential building designs and identify cost-optimal efficiency packages for whole-house energy savings along the path to ZNE. BEopt offers energy performance simulation of the single energy efficiency design, parametric runs, and cost-based optimizations for both new construction and existing home retrofits of single-family and multi-family buildings. BEopt provides energy performance analysis based on the residential building characteristics, such as architecture; heating, ventilating, and air conditioning (HVAC) systems; appliances; and occupancy-related operations, reflecting climates and tariffs. The National Renewable Energy Laboratory (NREL) developed BEopt; its underlying simulation engine uses the U.S. DOE's EnergyPlus. The use of BEopt tool for energy analysis is described in detail in an earlier Navigant report (Navigant Consulting Inc 2015).

Residential Prototype Energy Models

Building energy modeling is based upon three prototype residential buildings shown in Figure 4: two single-family homes and one multi-family building.[8] These prototype models were developed by the CEC for testing of the Alternative Calculation Method with the compliance CBECC-Res software (CEC 2015).

Figure 4: Prototype Buildings for Modeling in BEopt



Single Family 2,100 ft2 (CEC prototype)

Single Family 2,700 ft2 (CEC prototype)

Multi Family 6,960 ft2 with 8 units (CEC prototype)

Figure shows the three prototype buildings used for energy modeling in this study.

Source: Lawrence Berkeley National Laboratory

Modeling Assumptions

BEopt calculates the annualized energy-related life-cycle-cost of the building design with efficiency measure packages. The energy-related cost includes the measure cost, utility costs, and replacement costs.

Key inputs include the set of energy conservation measures, measure costs, and rooftop PV capital costs, fixed charges, and net PV compensation rates. Input cost assumptions are a key aspect of ZNE homes. For this work, costs are primarily based on NREL's National Residential Efficiency Measures Database (NREL, 2018b) supplemented by additional sources including expert elicitation inputs. For this study, utility rate inputs use TDV-based time of use (TOU) electricity rates as a proxy for future utility rates. Note that a fixed annual rate was used for

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[8] The research team also developed a prototype 18-unit multi-family building but run-times in BEopt were untenably long and more critically, unstable, and the decision was made to drop this case.

natural gas rates (average TDV-based rate) since BEopt does not allow seasonally varying natural gas rates.

The BEopt tool finds optimal measure packages using TDV-based life-cycle energy costs. The research team finds that the TDV-based hourly utility rate approach is the most consistent with the state's current codes and standards rulemaking process, although the CEC is evaluating cost-effectiveness options for the 2022 code cycle that may be based on source-energy and/or provide more direct weighting to GHG emissions reductions. The TDV utility rate is based on the projected 2022 TDV values, which provides 8760-hour utility rates. Solar PV electricity generation surplus power compensation rates use 2017 avoided cost for export (ACE) rates using the following retail rate adjustments 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 (CPUC 2018) to reflect NEM policy evolution of less favorable rooftop PV compensation. Hourly CO_2 emission factors are derived by the Energy and Environmental Economics Inc. (E3) team, using the emission rates methodology from the 2019 TDV update.[9]

Annualized energy-related costs are the annualized energy related cash flows, which include full annualized utility bills plus annualized capital cost values over 30 years for the improved cost case, subtracted from the costs for the reference case (Title 24 energy efficiency prescriptive case with PV). Cash flows consist of equipment capital costs, installation costs, replacement costs, utility bill payments, and residual values. Key assumptions include the following: inflation 2.4 percent, discount rate 3 percent, energy escalation 0 percent, and no tax credit of capital cost for PV incentives. Community solar costs, bio-methane supply curves, and natural gas demand projections are based on the literature (Jaffe 2016) and draw upon other studies by research team member E3 (Energy and Environmental Economics Inc. 2018).

Title 24 Measures and ZNE Measures

Promising efficiency measures for both single-family and multi-family homes were identified for each California climate zone, along with realistic estimates of the installed cost of each measure. An initial screening was performed by Frontier Energy to develop a manageable set of candidate measures that could be included in a more formal optimization process. Measures with a lower cost per TDV savings than PVs using CBECC-Res were prioritized in the measure selection process. The final pre-screened measures and costs were used as inputs to the BEopt models that predicted optimal pathways to ZNE in a variety of contexts.

Approximately 22 measures were considered but ultimately rejected for the final optimization process for one of the following reasons:

- Low energy savings relative to cost based on the team's experience

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[9] Hourly systemwide average natural gas heat rates for each year (MMBtu/MWh) are multiplied by the carbon content of natural gas (tons/MMBtu) to produce hourly emissions rates for grid electricity (tons CO_2/MWh), not yet accounting for RPS energy. For each year, this set of hourly emissions rates are weighted by a unitized renewable generation shape and multiplied by that year's RPS percentage target to produce the average rate of avoided CO_2/MWh from RPS. For each year, this average rate of avoided CO_2/MWh from RPS is subtracted from the initial hourly rates, which results in the final hourly CO_2 emission rates of grid electricity.

- Highly uncertain technical performance or cost
- Impossible to model accurately in BEopt
- Redundancy (for example, R-40 insulation when R-38 and R-42 are included)

The baseline for all energy simulations was the prescriptive requirements of the 2019 update to Title 24, Part 6. Energy savings and cost impacts for ZNE measures were analyzed relative to this baseline. Because the measure selection process for this project occurred in parallel to the Title 24 rulemaking process, the research team encountered some challenges keeping the baseline up to date. In some cases, new options in BEopt were necessary to match the specific requirements of Title 24, but BEopt provides sufficient flexibility to simulate nearly all code requirements accurately. Some of the ZNE measures were more challenging to model in BEopt, especially in the context of large multi-family buildings with centralized systems. Similar difficulties were encountered when developing cost models for some of the newer technologies on the path to ZNE. The following sections discuss the technical and cost details of the baseline and ZNE measures considered for this project. Battery storage and precooling were not modeled in BEopt but were separate analysis modules that were characterized after cost-optimal building designs were generated by BEopt.

2019 Title 24 Updates

Several updates were made to the Title 24 Part 6 prescriptive requirements during the 2019 code change cycle. The updates relevant to the simulations performed for this study are summarized by end-use category in Tables A-4 through A-7 in Appendix A. Final changes to the 2019 alternative calculation method were not available prior to the modeling phase of this project and are not necessarily reflected in the results.

ZNE Measures

A broad range of energy efficiency measures was included as options for achieving ZNE. The performance characteristics and incremental cost assumptions are summarized in Tables A-8 through A-11 in Appendix A. All incremental costs are relative to the corresponding prescriptive requirements of the 2019 update to Title 24, as specified earlier in Tables A-4 through A-7 in Appendix A.

Several viable options were not included in the final BEopt analysis for various reasons as described in Appendix A: mini-split heat pumps in single-family homes; slab insulation and central heat pump water heaters (HPWH) and solar hot water for multi-family buildings. Limitations of BEopt energy modeling for these measures are discussed in Appendix A

Miscellaneous Electric Loads

One of the most challenging end uses to address in new construction is miscellaneous electric loads (MELs). MELs constitute about 2000 kWh per year in a typical home, with about 13 percent growth projected by 2030 (Energy Information Administration 2015). Standby loads, which comprise about 25 percent of the MELs end use (U.S. DOE 2011a), are often targeted for energy efficiency improvements because they contribute limited value to homeowners. LBNL has estimated that 30 percent of standby loads can be eliminated through optimal occupant behavior (LBNL 2019). There is also room for improvement when MELs are in active mode but not in use, such as when a 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 California building energy codes because builders have limited ability to control them. California Title 20 appliance standards and the Energy Star program have made significant progress improving the efficiency of specific product categories, but technology changes so rapidly that it is difficult for regulatory and certification programs to keep pace. Despite the challenges, a few promising energy efficiency measures are available for addressing MELs using smart controls and other technologies.

The research team identified two viable market-ready MELs reduction measures that appear to have the potential for both significant energy savings and strong market acceptance:

1. **Tier 2 advanced power strips with infrared and occupancy sensor**. A Tier 2 advanced power strip with occupancy sensor turns off devices based on total power fluctuations (constant power indicates standby mode) for all connected devices if the room is unoccupied. Devices are also shut down if there is a lack of remote-control activity, again when the room is unoccupied, which saves active mode energy.
2. **Optimal occupant behavior, smart plugs with smartphone**. Smart plugs or sockets with energy monitoring can be used with smartphones and/or voice recognition systems. This technology makes it much more convenient for occupants to identify individual MELs that are high energy users at any given time and turn them off through voice commands or remotely using a smartphone.

Several emerging technologies for reducing MELs were investigated, but despite promising savings projections, were deemed to be insufficiently developed or unproven in occupied homes:

- Direct current (DC) networks for better compatibility with PV, battery charging (15 percent MELs savings achievable today, 25 – 50 percent at maturity)
- Low energy ground-fault circuit interrupters (GFCI) (25 percent of GFCI power)
- Efficient security systems (2 percent of security system power)
- Low standby remote-control systems (5 percent savings, presumably for relevant systems)
- Variable power wi-fi (25 – 50 percent savings for wi-fi)
- Power management user interface (5 percent of MELs)
- Mobile design practices applied to other plug loads (10 percent of MELs)

- ZNE-ready plug loads (2 percent of MELs)
- Gaming system efficiency (1 percent of MELs)
- Wide bandgap power supplies (1 percent of MELs)
- Energy savings and cost estimates are shown in Table 2 for the two near-term measures. Additional details and BEopt inputs for the measures are included in Table A-12 Appendix A. The emerging technology measures just listed were not included in the optimization process because cost is impossible to predict with confidence.

Table 2: Estimated Cost and Savings for Two Miscellaneous Electric Loads Options

Measure	First Cost	Percent Reduction in MELs	Annual Electricity Savings
Advanced Power Strips with Occupancy Sensor (2)	$126	6 percent	134 kWh
Smart Plugs (10), Smart Phones, Voice Recognition	$420	16 percent	358 kWh

Source: Lawrence Berkeley National Laboratory

Storage Analysis Approach

Battery Storage

The research team assessed (a) the optimal size of residential battery storage systems and (b) the cost-effectiveness to the participant (the party that purchases the storage). Both outcomes were analyzed using the CEC's existing TDV method for two future sets of TDV values: the "Base 2022" case and "Higher Renewables" case (as previously described) for the years 2023 – 2052.

Electricity retail rate structures are uncertain over the 30-year time frame used in the CEC's Title 24 analyses, so TDV values are used to capture the theoretical costs of energy to the homeowner, assuming rates are designed to capture these costs and as in the BEopt building modeling.

The research team's analysis was run assuming:

- Each residential battery storage system can only charge from a rooftop PV system, and that PV system is sized to offset the building's electricity annual load. This is consistent with requirements for receiving Title 24 compliance credit, as well as California's NEM and Self-Generation Incentive Program (SGIP) rules.
- Battery storage systems have a two-hour duration, that is, system capacity in kilowatt-hours equal to the rated electrical power in kilowatts (kW) multiplied by two.
- Any exports from solar PV and battery storage to the grid are compensated at avoided system cost, that is, the TDV values without the retail rate adder.

In addition to these assumptions, the research team ran:

- Two home sizes: 2,100 and 2,700 square-foot (ft2) single-family homes. Homes modeled were with the input home designs taken at the cost minimum of BEopt output. This design point typically falls short of TDV-ZNE for both all-electric and mixed-fuel homes, and 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-ZNE can be achieved with the addition of 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 is not a modeled measure in BEopt.

- Five battery use cases, intended to capture response to less sophisticated price signals (details in Appendix A):
    - Optimized Dispatch, which assumes that each battery is dispatched to maximize TDV values in each hour of each year, with perfect foresight
    - Shuffled Dispatch, which assumes that each battery dispatches against hourly TDV values from a similar day (approximating forecast error), by "shuffling" days of TDV values among other days that share the same day of the week and month, i.e., random reassignment of TDV days within the same month and day of the week.
    - TOU Dispatch, under which batteries are assumed to dispatch in response to on-peak and off-peak TOU periods
    - Basic Dispatch, under which batteries are assumed to charge on solar PV net exports and discharge when load again exceeds PV production
    - 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[10]
- Three battery storage cost trajectories, to capture the significant uncertainty in future storage prices:
    - An "Average Cost, with No Reduction" case, which assumes costs cited in Lazard's "Levelized Cost of Storage Analysis – Version 5.0" (Lazard 2019) for systems installed in 2023 and does not assume any reduction in battery storage costs when systems are replaced in 2043
    - An "Average Cost, Reducing Over Time" case, which begins with the same costs as the Average Cost, with No Reduction case, but assumes 2023 and 2043 costs are 64 percent and 47 percent of 2018 costs, respectively[11]
    - A "Low Cost, Reducing Over Time" case, which uses recent Tesla Powerwall 2.0 installed costs collected by LBNL and assumes the same percentage cost reduction as the "Average Cost, Reducing Over Time" case
- Two use case sensitivities with current TOU rates, to approximate how battery storage would optimally dispatch and be compensated under existing 4:00 to 9:00 p.m. TOU rates of the investor-owned utility that corresponds to each climate zone (CZ):

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[10] See "Self Generation Incentive Program Reports," http://www.cpuc.ca.gov/general.aspx?id=7890.

[11] Based on a forthcoming journal paper by Amol Phadke, et al. of LBNL.

  - Current TOU rate under NEM 2.0, which reflects current policy, compensating grid exports from PV or battery storage at the retail rate less non-bypassable charges
  - Current TOU rate under ACE, which reflects the anticipated trend in grid export compensation policy, compensating grid exports at the average avoided cost for each TOU period

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 be at least 5 kWh to be eligible for compliance credit. It also requires batteries to operate under one of three control strategies, which are designed 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.[12]

An alternative method of sizing battery storage to meet TDV-ZNE was analyzed as a sensitivity. This method increases battery storage size under different use cases until the annual electricity TDV value produced by the PV and battery storage arbitrage zeroes out the TDV value of the building's annual electric load.

Precooling Analysis Approach

The team ran an analysis on precooling methods. The analysis was designed to capture the cost-effectiveness to the participant, using TDV values, of different cooling strategies that can be used to ensure the indoor temperature does not exceed a maximum comfort threshold of 78°F(26°C), which is an industry standard threshold, currently used in the CEC's Title 24 residential building simulation software CBECC Res.

The research team modeled three thermostat setpoint schedules:

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[12] For example, consider the following case: 2,100 ft^2 mixed-fuel home in CZ 10 under Base 2022 TDV values, operating with Optimized Dispatch in the Average Cost – Reducing over Time battery cost scenario. This battery maximizes its net benefits at a 9.5 kWh size, so the net benefits provided by a 9.5 kWh battery operating under these conditions is are shown for this case.

1. Base: The thermostat is dispatched such that the home's temperature is permitted to rise above the 78°F (26°C) comfort threshold when the building is unoccupied. This matches the base setting in CBECC Res.
2. Constant 78°F (26°C): The thermostat is dispatched such that the home's temperature may not rise above 78°F (26°C).
3. Precooling: The thermostat is dispatched such that the home is cooled below 78°F (26°C) and allowed to drift back up to a 78°F (26°C) threshold to avoid coincidence of cooling load with peak TDV hours. This schedule often uses more kWh than the Base schedule but saves TDV by:
    - Shifting electricity consumption from high-grid-cost evening peak periods to lower cost afternoon hours.
    - Using excess energy from rooftop PV systems, reducing grid export penalties.

To model these schedules, the team undertook the following steps:

1. The minimum cost building prototypes from the BEopt analysis were selected for mixed-fuel and all-electric 2,100 ft^2 homes in all 16 CZs and 2,700 ft^2 in 3 CZs (38 prototypes total). In EnergyPlus, the team simulated annual hourly loads of these buildings with 14 different cooling setpoint schedules for each house prototype: Base, Constant 78, and 12 precooling schedules (Figure 5). The precooling setpoints were selected by varying the temperature and length of precooling before the TDV peak period.
2. For each day of the year, the "Optimal" precooling schedule was selected, that is, the schedule that resulted in the lowest net TDV (net load multiplied by TDV).
3. The team compared the annual net TDV of these optimized precooling schedules against the net TDV of the same house prototypes operated under the Constant 78°F (26°C) and Base setpoint schedules for the entire cooling season.
4. The team compared the annual net TDV of individual precooling schedules against Optimal and Base set point schedules.
5. The analysis was repeated using current and feasible TOU rate structures[13] in place of TDV values to determine whether precooling provides bill savings under rates that are less granular and dynamic than hourly TDV values.

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[13] PG&E E-TOU-B for climate zones 1-5, 11-13; SCE TOU-D-4-9PM for climate zones 6, 8-10, 15, 16; SDG&E TOU-DR-SES for climate zones 7, 14.

Figure 5: Cooling Setpoint Schedules for Optimal Precooling Selection

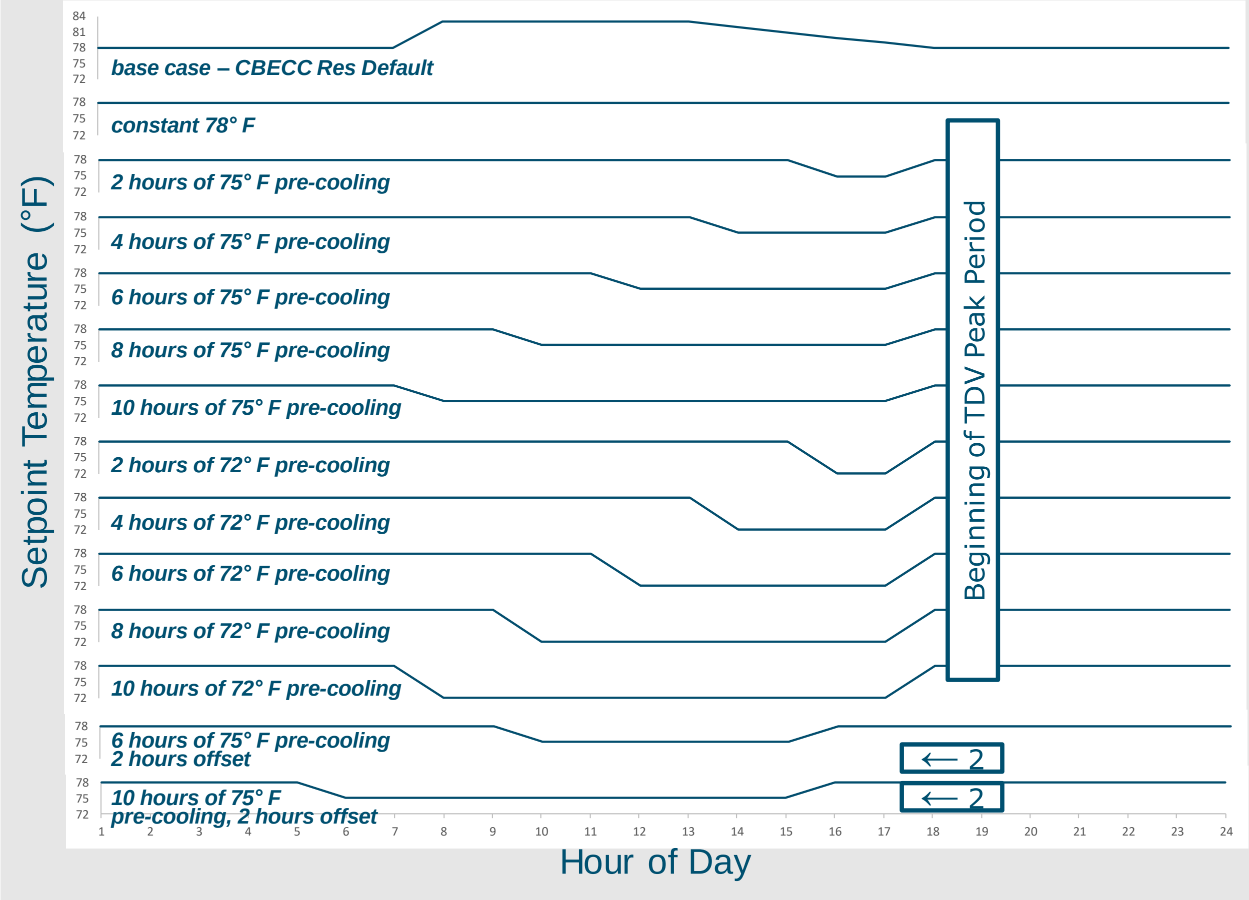

Figure shows optimal precooling schedules based on time of day.

Source: Lawrence Berkeley National Laboratory

Community Renewables Approach

Renewable Natural Gas

The research team examined the potential to replace conventional natural gas with RNG. RNG in this case is assumed to be pipeline-quality methane sourced from biomass. RNG can be produced from various biomass sources and various biochemical pathways, and can be used as a substitute for, or blended with, fossil-based natural gas uses, including building end-uses, transportation, electricity production, and industrial heating. Though RNG combustion emits greenhouse gases in the same manner as combusting fossil-based (or "conventional") natural gas, CO_2 produced by RNG combustion does not result in a net increase over natural emissions from biomass decomposition. In addition, RNG production can create lower total upstream emissions, due to avoided fossil-based extraction and processing-related emissions, and for some RNG sources, methane capture and conversion to CO_2. The California Air Resources Board's (CARB) greenhouse gas inventory assumptions define RNG as a carbon neutral fuel source, that is, CO_2 produced by RNG combustion does not result in a net increase over natural emissions from biomass decomposition. Currently, most RNG is sourced from landfills, municipal solid waste, wastewater treatment plants, and dairies.

Under the simple definition of a ZNE home — one that produces as much energy as it consumes over the course of a year — a home cannot be zero net energy while using more energy that is produced off site than is generated on site, over the course of a year. However, in Title 24 2019 building energy efficiency standards, the CEC has provided a more flexible definition that allows for ZNE compliance using off-site gas production and/or off-site, community-based solar. The research team's assumption in this investigation is that the CEC will continue to allow off-site energy production for ZNE homes and will assess a mixed-fuel home as ZNE compliant as long as it only uses energy sources that are classified by state agencies as carbon neutral.

E3 used their PATHWAYS model,[14] with data from Jaffe (Jaffe, et al., 2016) and the U.S. DOE's Billion-Ton Report (Langholtz, Stokes, & Eaton, 2016) to create forecasted RNG supply curves for California in 2030. E3 has also estimated economywide RNG demand curves as part of their prior PATHWAYS analyses for California, to assess how much of the resource may be needed to meet the state's climate goals.

E3 further estimated the potential demand for RNG from new residential construction were it to be required for ZNE compliance in mixed-fuel homes. They used two sources:

1. Annual gas consumption per new home. Estimates of annual household site natural gas consumption for the single-family , multi-family and mobile home types in the Western region were taken from the U.S. Energy Information Administration (EIA) Residential Energy Consumption Survey (Energy Information Administration, 2013).
2. The number of new homes. Estimates of new homes of each type added annually were obtained from the CEC's 2015 IEPR report mid-demand statewide housing forecast.

The research team compares these demand curves with supply curves for RNG to form conclusions about the feasibility and cost of requiring RNG for ZNE compliance in new residential construction. The research team also provides an analysis of the TDV cost-effectiveness from the participant's perspective for:

- New mixed-fuel-with-RNG residential construction versus the CEC's 2019 prescribed home.
- New mixed-fuel-with-RNG residential construction versus new all-electric (this analysis incorporates fuel costs only, that is, it excludes infrastructure cost differences).

Community Solar

The research team performed a qualitative analysis, backed by simple back-of-the-envelope calculations and figures from other literature, to assess the potential benefits of community solar for ZNE compliance. They used three criteria to assess these potential benefits:

1. Ability to provide ZNE compliance at a lower cost.
2. Ability to provide a potential option for ZNE compliance where rooftop solar PV is infeasible.
3. Ability to reduce costs to ratepayers who do not install solar PV.

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[14] For more details on E3's PATHWAYS model, see https://www.arb.ca.gov/cc/scopingplan/california_pathways_model_framework_jan2017.pdf

Expert Elicitation

An expert elicitation is a structured process for collecting subjective estimates of uncertain quantities based on the careful assessment by experts who are knowledgeable about the issue of interest (in this case, the building cost of ZNE homes) through a series of interviews with experts (Meyer & Booker 2001; Morgan 2014). Interviews can be performed in different modes, and the most common way to collect an expert judgment is through face-to-face elicitation. Expert elicitation has become increasingly common as a tool to develop credible estimates when data are lacking or when it involves projections of future conditions that are very different from the current status quo. This approach is intended to capture a representation of the views of informed experts rather than deriving a probability distribution of estimates with statistical significance; therefore, the appropriate number of experts to be included in an expert elicitation depends heavily on the topic.

ZNE building is a relatively new area in the United States, and currently, only a few states have pledged to adopt ZNE policy goals within the next couple of decades. Even in California, which currently mandates the highest building energy efficiency standards in the nation, the number of new housing starts that can achieve ZNE remains low.[15] The future prospect of building technologies used in ZNE homes and the degree to which policy support is needed to achieve a higher level of ZNE adoption partially depends on the future costs of building ZNE homes. While data on current costs related to building ZNE homes are already sparse, future cost estimates are close to non-existent. In this study, the research team sought inputs from experts from custom and production home building sectors and policy analysts to obtain a range of perspectives on ZNE home adoption in California as well as cost estimates of building ZNE homes.

Survey Design

The expert elicitation was designed to address the following research questions to help the CEC make informed decisions related to ZNE policy:

- What are the current and future cost estimates of building measures for residential ZNE construction? And what are the key cost reduction areas for TDV-ZNE implementation?
- What are the relative costs of all-electric versus mixed-fuel homes?
- What is the potential for community renewables, storage, and demand response in ZNE implementation?
- What are the market barriers and key challenges for ZNE implementation?

The survey was structured into three main sections: (1) costs related to building measures, (2) costs related to non-building components, and (3) costs related to an entire ZNE home. Last, the elicitation concluded with a section of open-ended questions. The research team intentionally separated the costs between building measures and non-building components because little focus has been put on soft costs in most ZNE studies and the team wanted to elicit experts' insights to address market barriers related to soft costs of building ZNE homes.

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[15] According to the Net Zero Energy Coalition's 2017 Inventory Report, California remains a volume leader in ZNE residential buildings in the U.S., with around 5,300 units in stock in 2017. Report available at: http://netzeroenergycoalition.com/zero-energy-inventory/

In the section focused on building measures, the team included a total of 16 buildings measures, which are based on efficiency features mandated by Title 24. The section focused on non-building components consists of design costs, permitting expenses, inspection costs, marketing costs, construction-related costs, utility infrastructure costs, and an option for experts to add other cost items if they see fit. Current cost estimates were elicited for each building measure and non-building component. However, given the high level of uncertainty and subjectivity embedded in future cost estimates, experts were asked to select only up to five building measures and two non-building components for which they felt comfortable providing future cost estimates. In addition, the research team explicitly asked experts about any emerging building technology or innovative development in each category that may potentially have a significant impact on cost reduction in ZNE homes. In the section focused on the entire ZNE home, the team asked experts two sets of questions. The first set asked about the cost difference between building a Title 24 code-compliant home and a ZNE home as of 2017. The second set of questions asked about the future cost of building a ZNE home in 2021 and 2026 compared to the cost of building a ZNE home in 2017. More details on the survey protocol can be found in Appendix C. The final version of the expert elicitation questionnaire is included in Appendix D.

CHAPTER 3:
Project Results

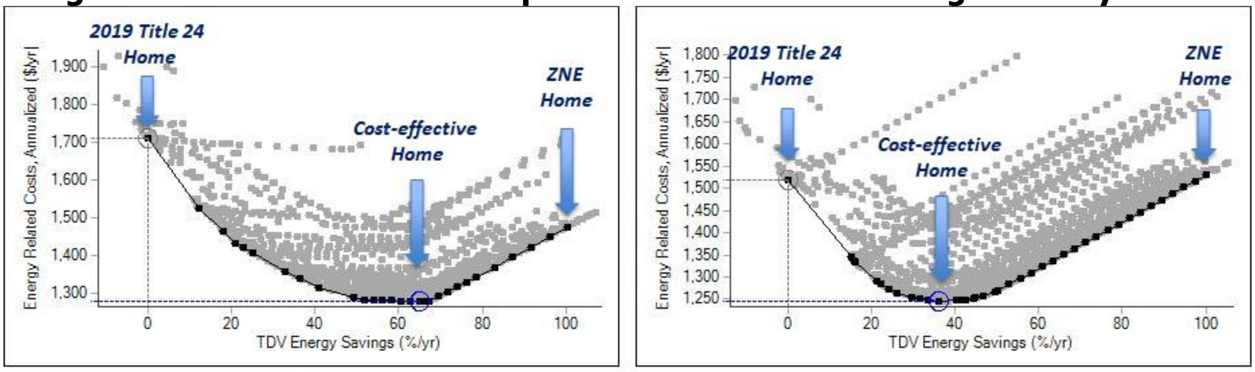
Energy Model Simulation Results

The research team conducted building energy simulations using BEopt 2.8 for the CEC's residential prototype models of single-family 2100 ft^2 and 2700 ft^2 homes and two-story multi-family eight-unit buildings. The BEopt baseline energy models were set for Title 24 2019 standard. The team conducted optimization simulations to find the most cost-effective ZNE homes. For the cost optimization, all the measures used input data assumptions for the cost for materials and labor and included usage lifetimes for end-use appliances. Before starting the BEopt optimization modeling, reference designs for 2019 Title 24–compliant homes were developed in BEopt and energy usage by end use was compared with output from CBECC-Res until they were in reasonable agreement. The annual total site energy difference between the BEopt baseline models and the CBECC-Res standard designs were within 10 percent.

Cost Effectiveness of All-Electric vs. Mixed-Fuel Homes

Figure 6 shows the cost/TDV saving charts for all-electric (left chart) and mixed-fuel (right chart) single-family 2,100 ft^2 prototype homes in Climate Zone 13 to illustrate the cost-effectiveness optimization simulation results by BEopt.

Figure 6: Cost-Effectiveness Optimization Results for Single-Family Home



All-electric

Mixed-fuel

Figure shows the cost optimization for a prototype single-family 2100 ft^2 home in climate zone 13 (left: all-electric home, right: mixed-fuel home).

Source: Lawrence Berkeley National Laboratory

Note that the mixed-fuel home heating fuel type is assumed to be conventional pipeline natural gas in the BEopt modeling results. The X axis represents TDV savings compared to the reference point while Y axis represents the annualized energy related cost that integrates utility cost and added measure capital cost. Each dot represents the simulation result of a home design with a set of measures. The curve represents a Pareto front for thousands of home design simulations and the black dots are cost optimal designs to allow a different level of the TDV energy savings preference. The top left points are reference points that represent 2019 Title 24 compliant homes for energy efficiency measures and solar PV. The cost versus TDV saving charts show that initially adding energy efficiency measures can contribute to reducing energy related costs compared to the Title 24 2019 reference point. Although incremental measures and PV costs contribute to higher first costs, reduced utility costs from energy savings and generation have greater effects on the life-cycle cost reduction. The charts show the minimum energy related cost (center-bottom points), as well as the saving percentage of TDV energy on the X axis. From this cost-optimal building design point, the charts show that adding more PV increases costs. To meet the TDV-based definition for ZNE homes (TDV-ZNE), the solar PV system is oversized to offset electricity and natural gas TDV consumption with PV electricity generation in excess of site-level electricity demand (right-most points labeled "ZNE Home"). While the optimized points labeled "ZNE Home" in Figure 6 meet the policy goal of TDV-ZNE compliance, their PV systems are oversized and in violation relative to the state's NEM sizing constraints and do not meet the state's grid harmonization goals since they overproduce electricity.

Figure 7 shows TDV-based energy consumption and TDV values from PV electricity generation with rooftop solar PV for all-electric (left) and mixed-fuel (right) homes for Title 24 2019 reference points for all California climate zones. The rooftop solar PV sizing is based on the mixed-fuel home that offsets the annual site-electricity consumption, and this PV sizing is applied to all-electric homes for baseline points per the Title 24 prescriptive requirement.

Figure 7: Reference Points: Electricity/Natural Gas Consumption and Photovoltaic Electricity Generation

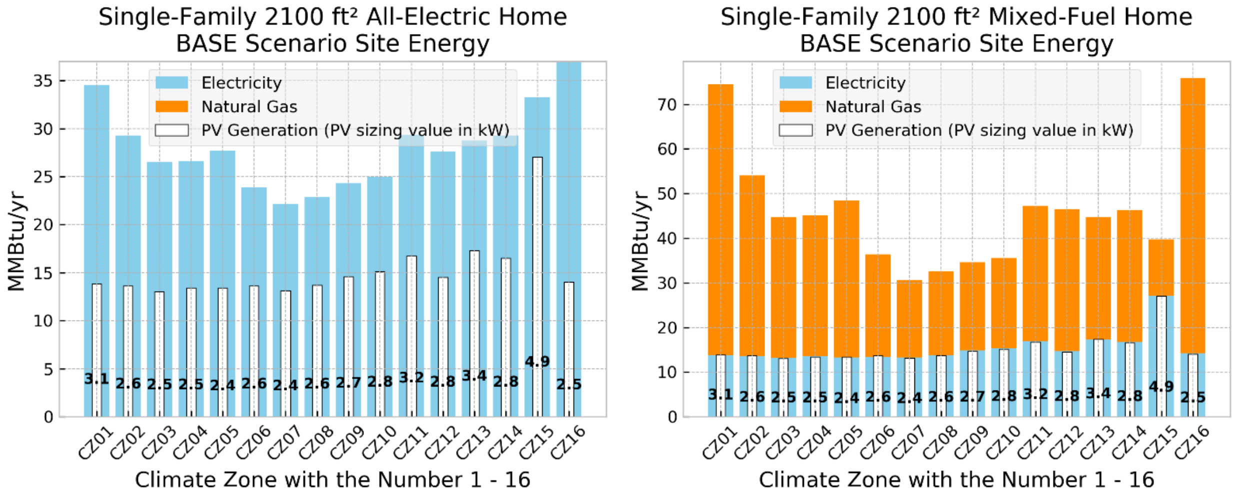
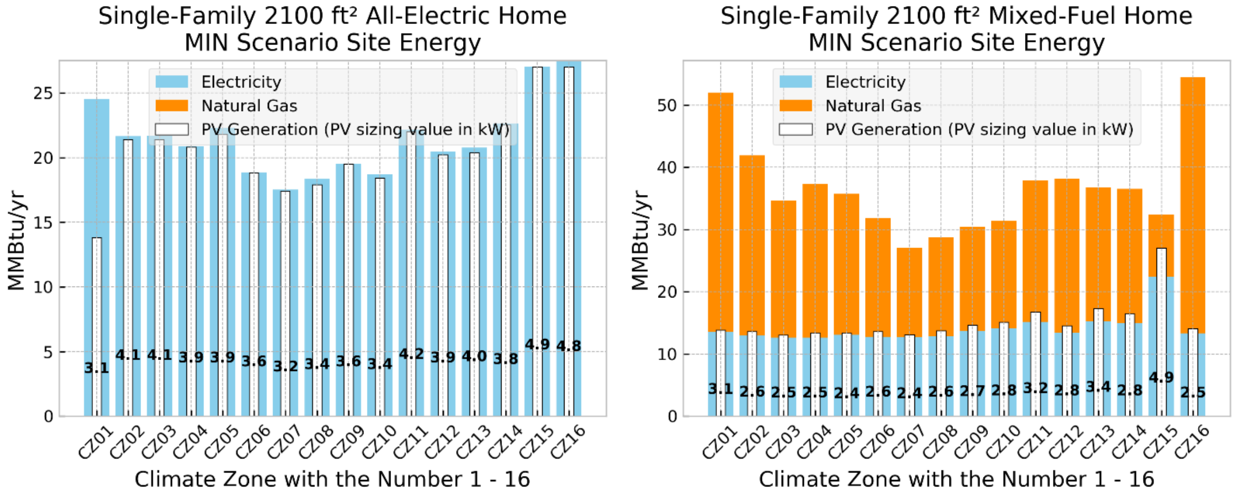


Figure shows reference points for a prototype single-family 2100 ft^2 home showing electricity, natural gas consumption and PV electricity generation (left: all-electric home, right: mixed-fuel home).

Source: Lawrence Berkeley National Laboratory

Figure 8 shows the annual electricity and natural gas consumption and PV energy generation for the cost-optimal residential building design that integrates 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: Cost-Effective Minimum Points: Electricity/Natural Gas Consumption and Photovoltaic Electricity Generation


Single-Family 2100 ft² All-Electric Home MIN Scenario Site Energy

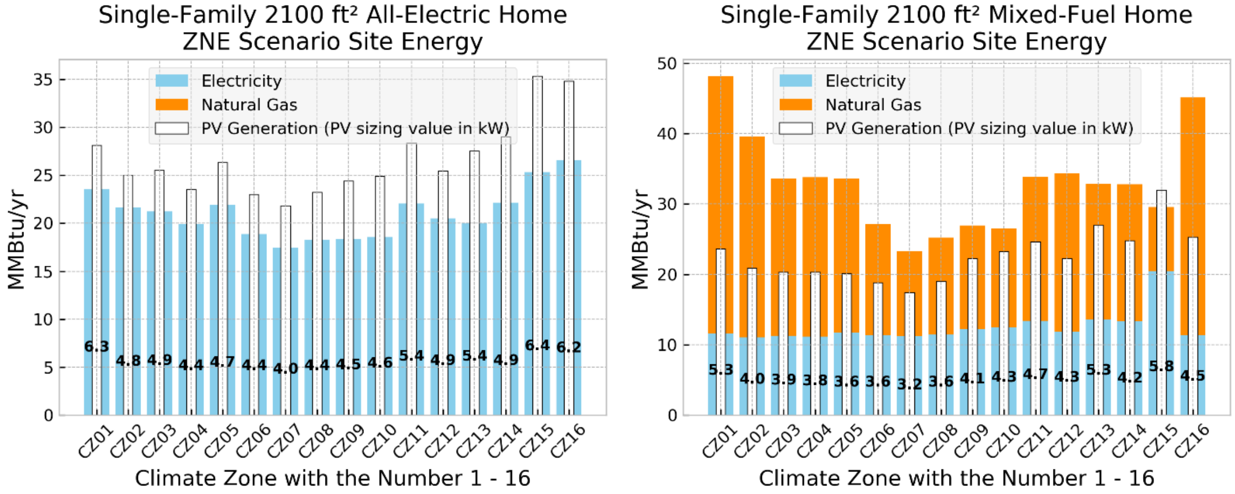
Single-Family 2100 ft² Mixed-Fuel Home MIN Scenario Site Energy

Figure shows the cost-effective minimum points for a single-family 2100 ft^2 showing the electricity, natural gas consumption and PV electricity generation (left: all-electric home, right: mixed-fuel home).

Source: Lawrence Berkeley National Laboratory

Figure 9 shows energy consumption and generation for TDV-ZNE home designs. For both all-electric and mixed fuel homes, the rooftop solar PV system overproduces electricity and is in violation of NEM requirements. Note that even in the all-electric case, the solar PV system overproduces electricity because the hourly shape of TDV values described in Chapter 2 provides less value for solar PV in the middle of the day and the PV system must be oversized to fully compensate the TDV value of onsite electricity consumption.

Figure 9: Time dependent valuation-Zero Net Energy Points: Electricity/Natural Gas Consumption and Photovoltaic Electricity Generation


Single-Family 2100 ft² All-Electric Home ZNE Scenario Site Energy

Single-Family 2100 ft² Mixed-Fuel Home ZNE Scenario Site Energy

Figure shows the TDV-ZNE points for a single-family 2100 ft2 home showing electricity, natural gas consumption and PV electricity generation (left: all-electric home, right: mixed-fuel home).

Source: Lawrence Berkeley National Laboratory

Figure 10 shows the life-cycle cost and Figure 11 the initial construction cost of the cost-effective designs for all-electric (left) and mixed-fuel (right) prototype single-family 2100 ft^2

homes. The life-cycle cost refers to the total cost of ownership for 30 years, which includes mortgage payments, replacement costs, utility bill payments, and residual values. The underlying assumptions include 30 years of the project analysis period, 3 percent of the discount rate, 4 percent of the mortgage interest rate, and 28 percent of the marginal income tax rate used for annual tax deductions. The initial construction cost refers to the initial investment cost to build the house including construction materials and labor costs. A range of infrastructure costs is shown for mixed-fuel homes, as natural gas connection costs must be considered when comparing to all-electric homes. These can vary depending on the degree of infrastructure required but typically vary between $1,000 and $10,000 per home. The mixed-fuel home chart from Figure 10 and Figure 11 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, and all-electric single-family home life-cycle costs are comparable to mixed-fuel homes in most climate zones (Figure 10) with an average of 38 percent less annual GHG emissions than mixed-fuel homes. All-electric homes are less favorable compared to mixed-fuel homes in climate zones with high heating demand and low cooling demand (for example, CZ01 and CZ16) since the lack of cooling operation reduces the heat pump cost savings that can accrue from operation in both heating and cooling modes.

Figure 10: Life-Cycle Cost of All-Electric and Mixed-Fuel Homes at Cost-Optimal Design Point

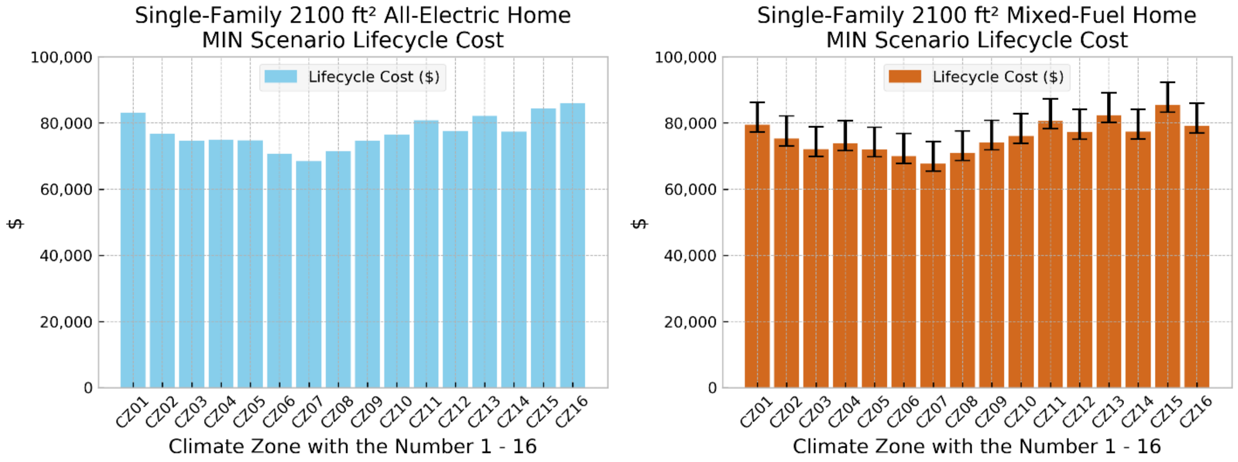


Figure shows lifecycle cost of all-electric and mixed-fuel single-family 2100 ft^2 homes at cost-optimal design point for all California climate zones, using 2022 TDV values and avoided cost for solar PV exports (left: all-electric home, right: mixed-fuel home).

Source: Lawrence Berkeley National Laboratory

Figure 11: Initial Cost of All-Electric and Mixed-Fuel Homes at Cost-Optimal Design Points

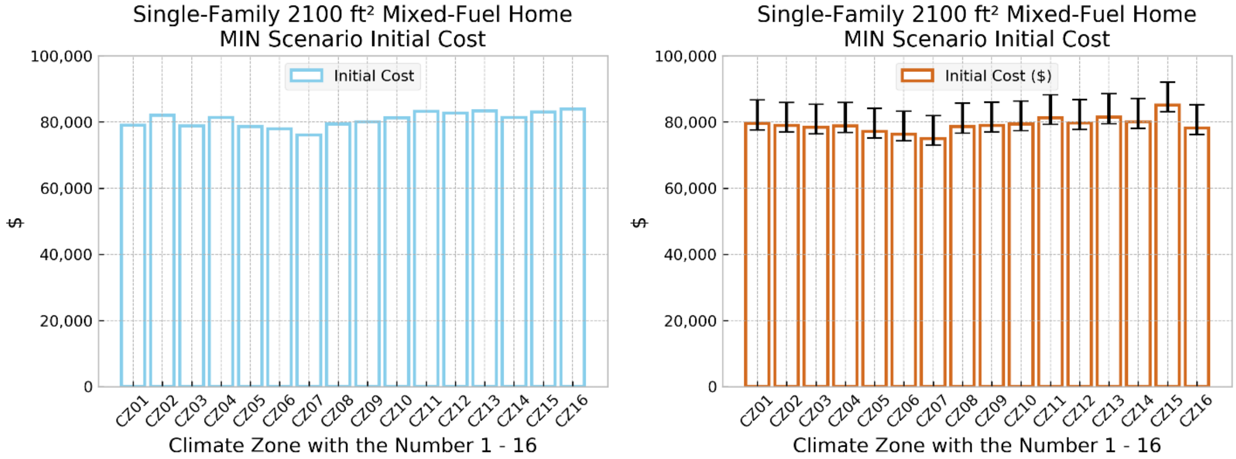


Figure shows initial cost of all-electric and mixed-fuel single-family 2100 ft^2 homes for all California climate zones at cost-optimal design points (left: all-electric home, right: mixed-fuel home).

Source: Lawrence Berkeley National Laboratory

All-electric single-family new homes (2100 ft^2) can realize life-cycle cost savings compared to 2019 Title 24–compliant all-electric homes using updated TDV values for 2022 and less generous net energy metering solar PV compensation (avoided cost for exports rather than the current NEM 2.0. The life-cycle cost minimum of all-electric homes generally includes more energy efficient heat pumps for heating and cooling and an average of 1kW more of additional rooftop solar PV than mixed-fuel homes. This results in higher upfront initial construction cost but lower life-cycle costs as shown in Table B-15 in Appendix B. Life-cycle cost savings from cost minimum designs vary from $3,697 to $10,797 across all climate zones, but initial costs are from $2,235 to $10,081 higher. The research team finds several energy efficiency measures that provide life-cycle cost savings in all climate zones: ducts in conditioned space, plug load reduction (optimal occupant behavior with smart control), hot water pipe insulation (R-5), and more energy efficient clothes dryers (vented electric CEF 4.5). Most climate zones would also benefit from more energy efficient clothes washers (standard front-loading CEE Tier 2) and more energy efficient refrigerators (bottom freezer, EF 21.3).

Similarly, mixed-fuel homes with more aggressive efficiency measures can realize life-cycle cost savings but with increased initial costs. Life-cycle cost savings from cost minimum designs compared to Title 24–compliant homes vary from $1,151 to $9,142 across all climate zones, but initial costs are from $1,887 to $4,397 higher. The cost-minimum mixed-fuel homes can have smaller PV systems than Title 24–compliant homes, which are designed to offset the annual site electricity consumption, since the efficiency measures decrease site electricity consumption. The research team finds several measures that provide life-cycle cost savings in all climate zones: ducts in conditioned space, hot water pipe insulation (R-5), more energy efficient clothes dryers (vented gas CEF 3.48), and more efficient cooking ranges (max tech gas cooktops). Several climate zones would also benefit from more energy efficient gas furnaces (92.5 percent AFUE) and central air conditioning (SEER 15-16).

Figure 12 shows CO_2 emissions for 30 years of all-electric and mixed-fuel single-family 2100 ft^2 homes with cost-optimal designs for all California climate zones. Hourly CO_2 emission factors from E3 were used for the CO_2 emission calculation for electricity consumption, and 11.7 pounds CO_2/therm emission factor was used for the natural gas CO_2 emissions. CO_2 emissions reflect the net electric load after PV generation for each hour. All-electric homes have an average of 38 percent lower emissions.

Figure 12: CO_2 Emissions for All-Electric and Mixed-Fuel Homes at Cost-Minimum Design Points

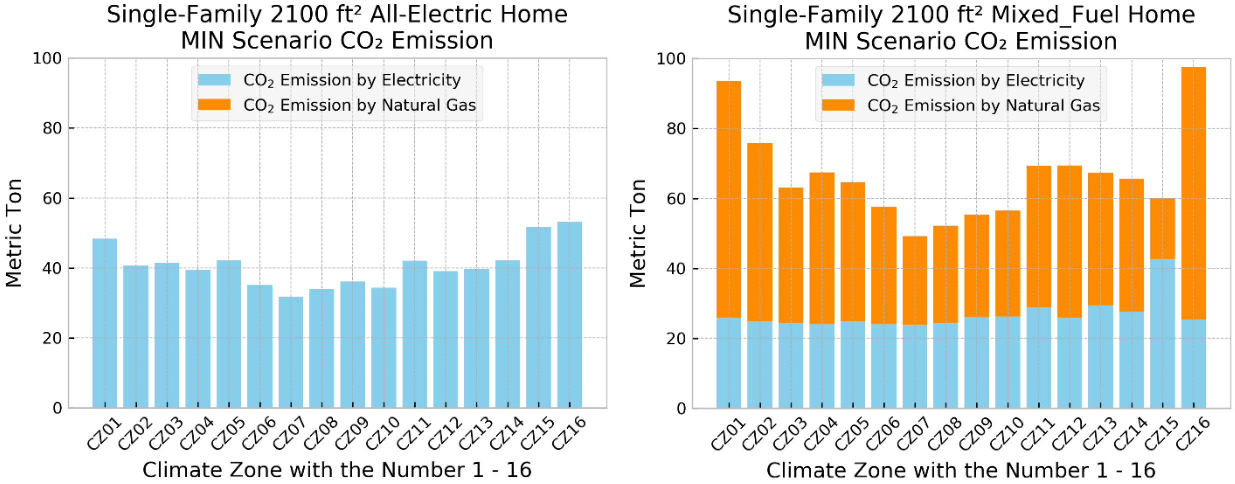


Figure shows CO_2 emissions for all-electric and mixed-fuel single-family 2100 ft^2 homes for all California climate zones at cost-minimum design points (left: all-electric home, right: mixed-fuel home).

Source: Lawrence Berkeley National Laboratory

Tables B-3 and B-4 in Appendix B show the measures selected for the most cost-effective home designs for the single-family 2100 ft^2 all-electric and mixed-fuel homes respectively.

The packages show that energy efficient home appliances such as clothes dryers and clothes washers, plug load reduction from smart controls, hot water pipe insulation, ducts in finished space, advanced HVAC systems, and air tightness are general key measures throughout climate zones and fuel types. Energy efficient walls and attics are advantageous for hot climate zones. Lighting systems and windows in the baseline models offer energy efficient technology, and there is no opportunity for further cost-effective energy savings. Triple pane windows with low-emissivity technology that minimizes heat from outside in the summer and retain indoor heat 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.

The all-electric prototype models have heat pump water heaters (HPWH). A more energy efficient HPWH is beneficial for all-electric homes for larger single-family homes and multi-family buildings.

Figure 13 and Figure 16 show the simulation results for single-family, 2700 ft^2 homes and multi-family eight-unit buildings, respectively, for annual electricity and natural gas consumption and PV energy generation in climate zones 3, 10, and 13. Each figure shows site energy consumption and PV electricity generation for all-electric and mixed-fuel design homes for different climate zones representing 2019 Title 24 compliant designs (left). The energy performance of the most cost-effective homes and ZNE homes are included for 2700 ft^2 homes but only the cost-effective design for multi-family buildings. Note that BEopt optimization simulation run time takes more than seven days (using 2.5 gigahertz [GHz] CPU and 36 core processor computer) for multi-family buildings, which limited the scope of the optimization to find the minimum cost-effectiveness designs.

Figure 14 and Figure 17 show the life-cycle cost of the cost-effective scenarios for all-electric (left) and mixed-fuel (right) prototype single-family 2700 ft^2 homes and multi-family eight-unit building. The mixed-fuel single-family home includes natural gas connection costs varying between $2,000 and $16,0000. Multi-family buildings are assumed to have a natural gas connection cost that ranges from $500 to $2,000 per unit. Figure 15 and Figure 18 show initial cost.

For eight-unit all-electric multifamily homes (CZ03, CZ10, CZ13), the research team finds that cost-optimized homes can have designs that have lower life-cycle cost than Title 24–compliant all-electric baseline homes with $3,156 to $5,346 in lower life-cycle cost but an increased initial cost of $1,844 to $2,692 on a per unit basis (Table B-2 in Appendix B). Compared to the reference Title 24–compliant homes, cost-minimum all-electric homes in all three climate zones have more efficient mini-split heat pumps, air leakage at two to three air changes per hour (ACH), R-5 hot water pipe insulation, and more efficient refrigerators (bottom freezer EF 19.8) and clothes washers and dryers (front loading CEE Tier 2 and vented electric CEF 4.5, respectively).

Similarly, eight-unit mixed-fuel multi-family homes (CZ03, CZ10, CZ13) can achieve lower life-cycle costs than Title 24–compliant mixed-fuel baseline homes with $963 to $1,887 lower life-cycle costs but with an increased initial cost of $1,390 to $1,954 on a per unit basis (Table B-2 in Appendix B). Compared to the reference Title 24–compliant design cost, cost-minimum homes in all three climate zones have air leakage at two ACH, vented unfinished attic with ceiling R-49 Gr-1 cellulose, R-5 hot water pipe insulation, plug loads with smart control, and more energy efficient refrigerator, cooking range, and clothes dryer (bottom freezer EF 19.8, gas cooktop max tech, and vented gas CEF 3.48, respectively). In the warmer climate zones (CZ10, CZ13), a radiant barrier and more efficient central air conditioner are also installed (SEER 15).

For multi-family home cost-optimal designs (CZ03, CZ10, CZ13), the research team finds that all-electric initial costs can be lower than those of mixed-fuel homes from the elimination of ducts and the adoption of ductless mini-split heat pumps. All-electric life-cycle costs are slightly higher than mixed-fuel costs since per unit cost savings for avoided natural gas infrastructure are lower than for single-family homes. Assuming natural gas infrastructure savings ranging from $500/unit to $2,000/unit, the team estimates about 4 to 6 percent or 2 to 4 percent higher life-cycle costs respectively for all-electric multi-family homes compared to mixed-fuel homes.

Figure 13: Single-Family Electricity/Natural Gas Consumption and Photovoltaic Electricity Generation

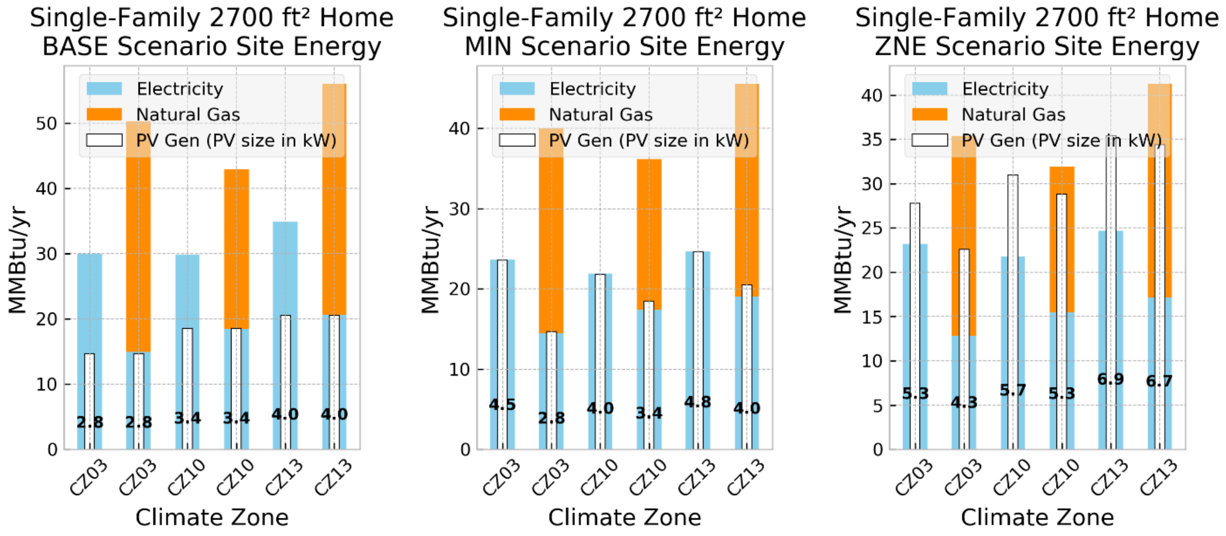


Figure shows modeled electricity use, natural gas use, and PV generation for the 2700 ft^2 single family model (left: baseline, center: cost-optimized, right: ZNE).

Source: Lawrence Berkeley National Laboratory

Figure 14: Life-Cycle Cost at Cost-Optimal Design Points — All-Electric and Mixed-Fuel Single-Family Homes

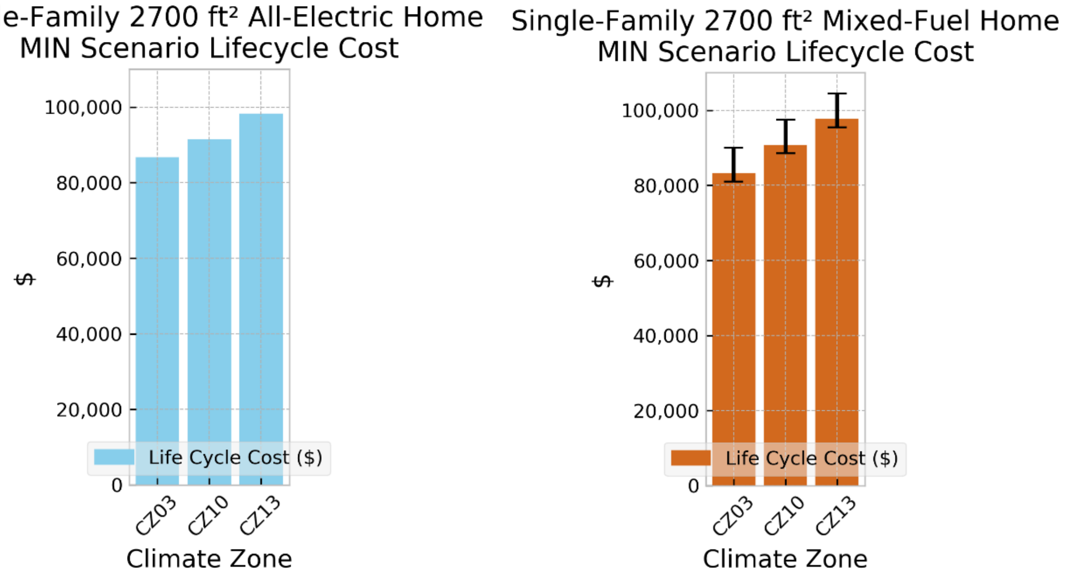


Figure shows life-cycle cost of all-electric and mixed-fuel single-family 2700 ft^2 homes for California climate zones 3, 10, and 13 at cost-optimal design points, using 2022 TDV values and avoided cost for solar PV exports (left: all-electric home, right: mixed-fuel home).

Source: Lawrence Berkeley National Laboratory

Figure 15: Initial Cost of All-Electric at Cost-Optimal Design Points — Mixed-Fuel Single-Family Homes

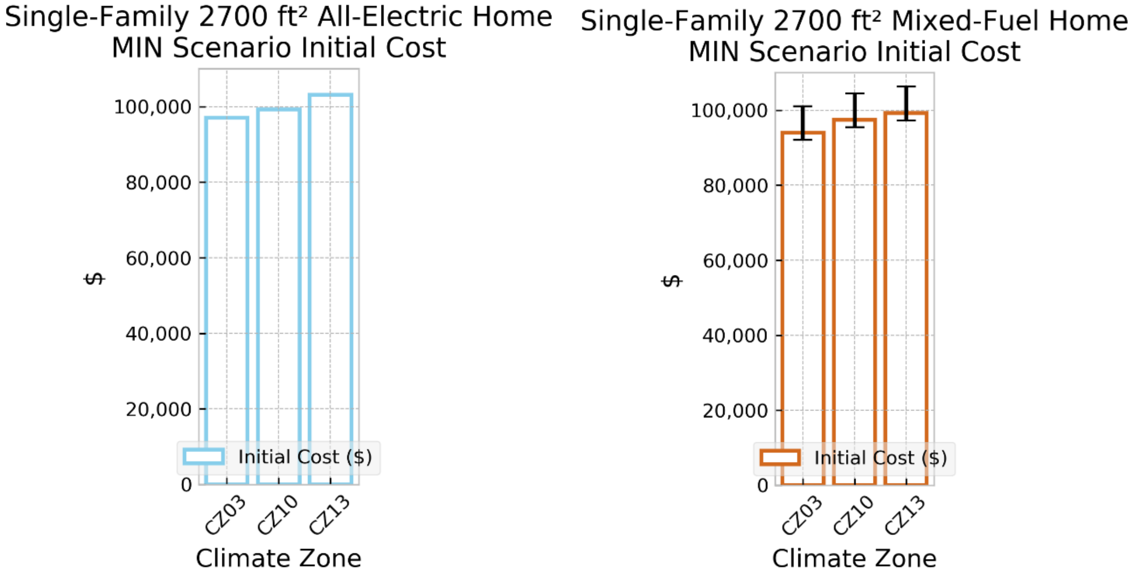


Figure shows Initial cost of all-electric and mixed-fuel single-family 2700 ft^2 homes for California climate zones 3, 10, and 13 at cost-optimal design points (left: all-electric home, right: mixed-fuel home).

Source: Lawrence Berkeley National Laboratory

Table B-6 in Appendix B shows the measures selected for the most cost-effective home designs for 2700 ft^2 single-family homes in climate zones 03,10,13 for all-electric and mixed-fuel homes, and Source: Lawrence Berkeley National Laboratory

Table B-7 shows the measures for the most cost-effective multi-family 8-unit all-electric building.

Table B-8 in Appendix B shows the selected measures for the multi-family eight-unit buildings.

The packages show that energy efficient home appliances such as clothes dryers, clothes washers, plug load reduction from smart controls, hot water pipe insulation, ducts in finished space, advanced HVAC systems, and air tightness are key measures throughout climate zones and fuel types.

Figure 16: Multi-Family 8-Unit Building Electricity/Natural Gas Consumption and Photovoltaic Electricity Generation for Baseline and Cost-Optimal

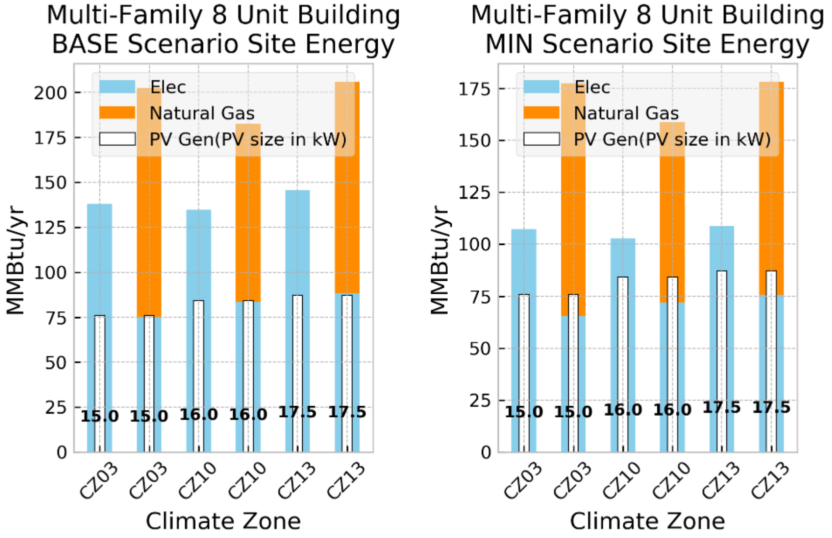


Figure shows modeled electricity use, natural gas use, and PV generation for the multi-family 8-unit model (left: baseline, right: cost-optimized).

Source: Lawrence Berkeley National Laboratory

Figure 17: Life-Cycle Cost and Cost-Optimal Design Points — All-Electric and Mixed-Fuel 8-Unit Multi-Family Building

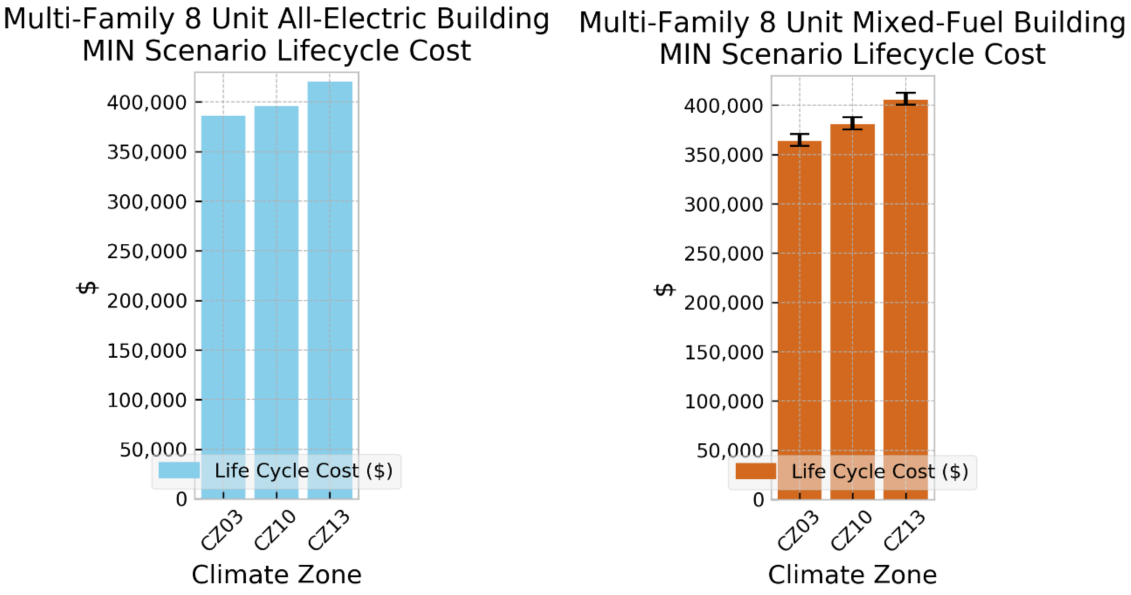


Figure 17 shows life-cycle cost at cost-optimal design points for all-electric and mixed-fuel 8-unit multi-family buildings for California climate zones 3, 10, and 13 (left: all-electric building, right: mixed-fuel building).

Source: Lawrence Berkeley National Laboratory

Figure 18: Initial Cost at Cost-Optimal Design Points — All-Electric and Mixed-Fuel 8-Unit Multi-Family Buildings

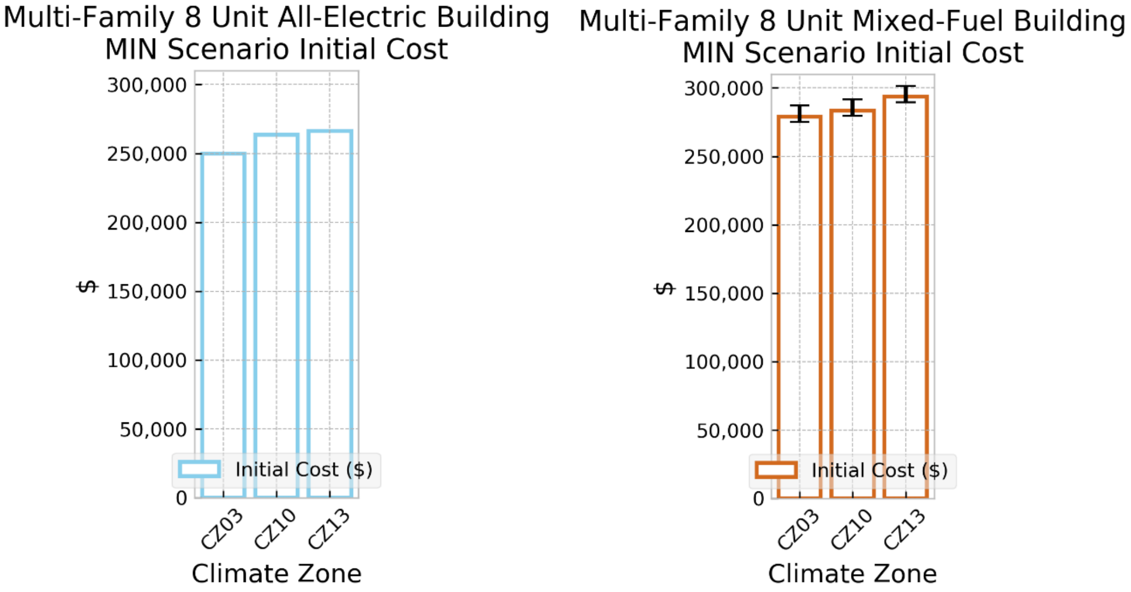


Figure 18 shows the initial cost at the cost optimal design points for all-electric and mixed-fuel 8-unit multi-family buildings for California climate zones 3, 10, and 13 (left: all-electric home, right: mixed-fuel home).

Source: Lawrence Berkeley National Laboratory

BEopt Measures for Cost-Effectiveness

This section shows the energy and CO_2 emission savings effect of frequently selected individual efficiency measures for cost-optimal designs: large appliances, plug load reduction, air source heat pump, duct, and hot water pipe insulation. Large appliances include dishwashers, clothes dryers, clothes washers, and refrigerators. Figure 19 shows how individual measures can save electricity and CO_2 emissions relative to the 2019 Title 24–compliant baseline home— for example, a 2100 ft^2 all-electric home for climate zone 13. High efficiency air source heat pumps and ducts in finished space show the highest energy savings. Plug load reduction from optimal occupant behavior with smart control technology also has a high electricity saving potential. Among major appliances, clothes dryers show high energy savings, followed by refrigerators with bottom freezers. All measures were then modeled to see the integrated impact of all measures on electricity and CO_2 emission savings.

Figure 20 illustrates hourly CO_2 emission profiles (annual average) for the selected package of measures in climate zone 13, which shows a night-time demand peak and appreciable peak reduction for this set of cost-optimal design measures.

Figure 19: Climate Zone 13 Results of Cost-Effectiveness Measures on Electricity and Carbon Dioxide Emission Savings

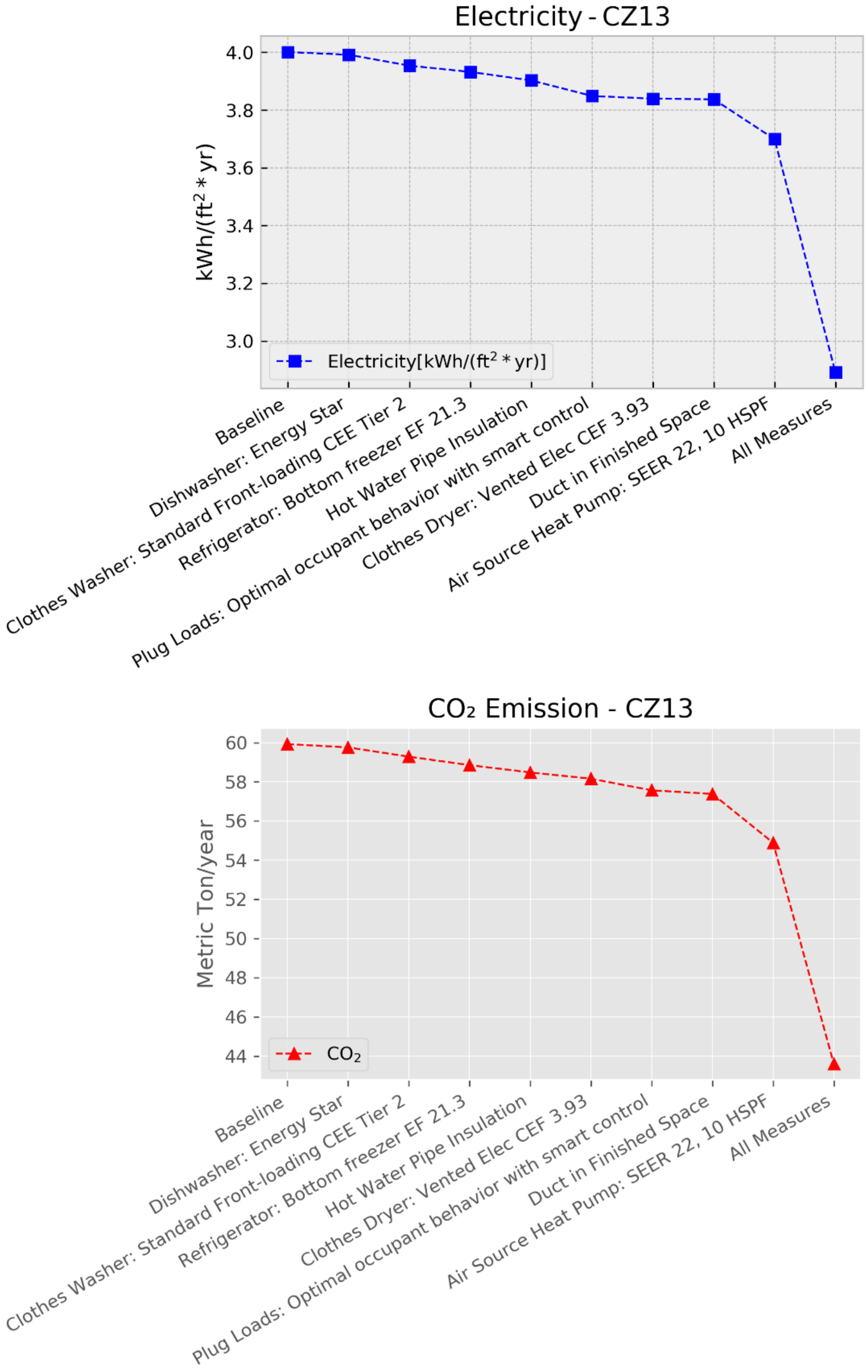


Figure 19 shows the electricity (top) and CO_2 emission (bottom) savings of individual measures at the cost-optimal design point for a 2100 ft^2 all-electric home for California climate zone 13.

Source: Lawrence Berkeley National Laboratory

Figure 20: Annual Average Hourly Profile — Carbon Dioxide Emissions for Individual Measures and Measure Package

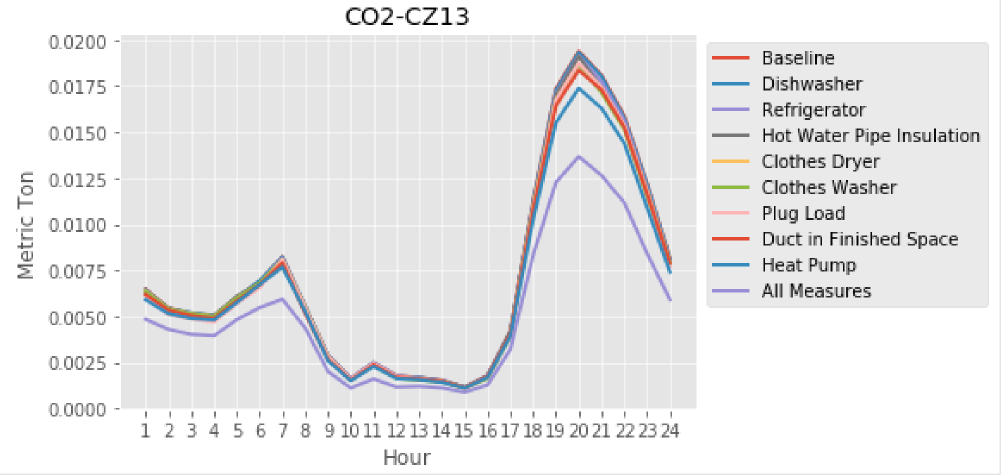


Figure 20 shows the annual average hourly CO_2 emission profiles for the indicated measures in California climate zone 13.

Source: Lawrence Berkeley National Laboratory

Photovoltaic Orientation Sensitivity

The baseline prototype models have PV systems with south-facing module orientation, which generates the most electricity generation as shown in Figure 21 (left) for a single-family 2100ft^2 all-electric home at the cost-effective design point. PV module orientation to the southwest is the most beneficial to reduce the utility cost under the TDV 2022-based hourly pricing utility rate structure, followed by a west-facing orientation. As shown in Chapter 2, electricity generation in the late afternoon has a greater value for the life-cycle cost optimization with the TDV metric, benefitting these two orientations. Figure 21 (right) shows the life-cycle cost for different PV module orientations.

Figure 21: Photovoltaic Electricity Generation by Module Orientation and Effect on Life-Cycle Cost

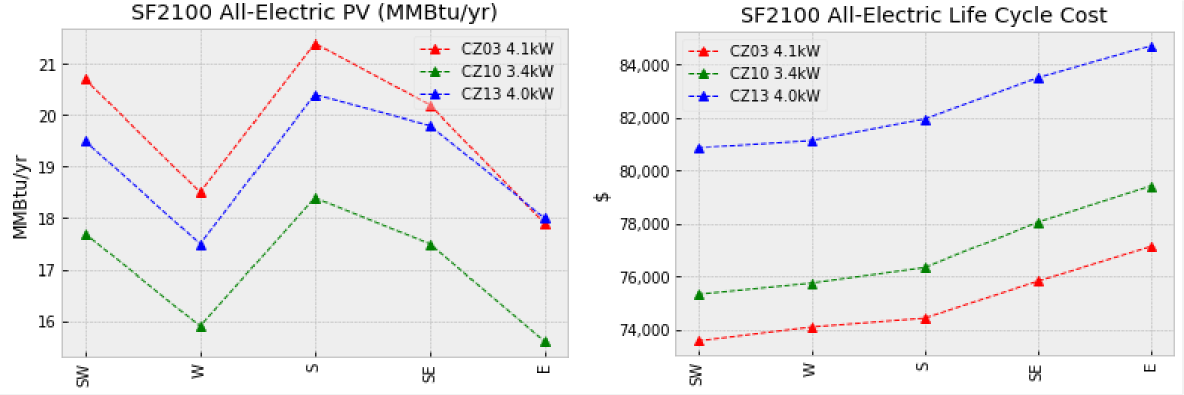


Figure 21 shows the annual electricity generation (left) and the life-cycle cost (right) for a single-family 2100ft^2 all-electric home at the cost-effective design point as a function of PV module orientation.

Source: Lawrence Berkeley National Laboratory

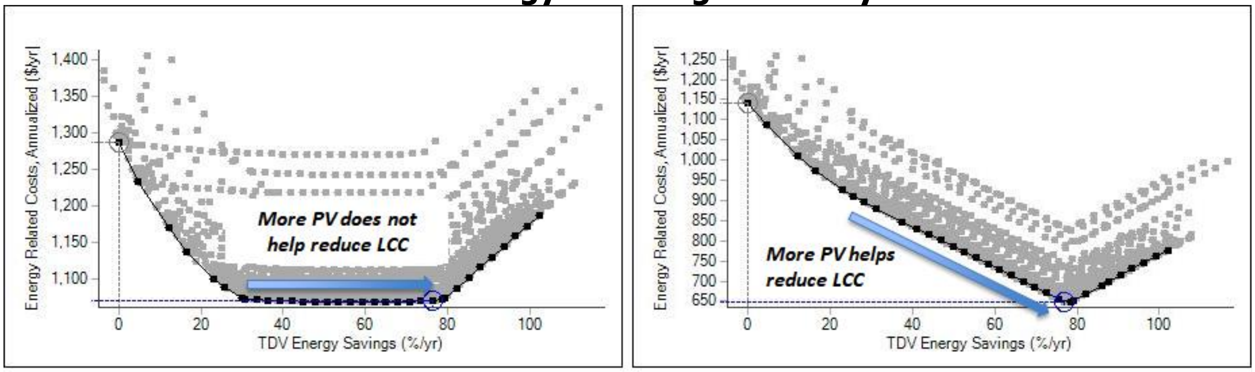
Photovoltaic Export Rate Sensitivity: Avoided Cost for Export versus Net Energy Metering 2.0

The baseline analysis uses the avoided cost for export (ACE) rate for hours when PV electricity generation exceeds electricity demand. The team compared this ACE rate to NEM 2.0 rates for climate zones 3, 10, and 13. Under NEM 2.0, there is a component known as non-bypassable charges (Pacific Gas & Electric: 0.023 $/kWh, San Diego Gas & Electric: 0.021 $/kWh, Southern California Edison: 0.019 $/kWh). The compensation rate for grid exports in this case is the retail rate reduced by the non-bypassable charges. Consumers earn much less credit under the ACE rate structure, where electricity exported from residential solar to the grid is valued at the TDV value less the retail rate adder.

Figure 22 shows the single-family 2100 ft^2 all-electric home in climate zone 3 under ACE (left) and NEM 2.0 (right) PV electricity export rate. The left optimization chart under ACE rate shows that adding more PV does not help reduce energy-related costs since there are many hours for which PV electricity generation is greater than the home electricity consumption, and, for those hours, consumers earn much less credit than what they pay for electricity. However, the cost optimization under NEM 2.0 illustrates that the exported electricity is still beneficial to reduce the utility bill for consumers. Figure 23 shows the total life-cycle cost differences between ACE and NEM2.0 rates, showing that NEM2.0 is more favorable to consumers when PV modules are added in moving from the base point to the minimum cost points.

All-electric home designs and costs are a sensitive function of NEM assumptions. Assuming a NEM 2.0 regime with higher compensation for PV exports, all-electric single-family home life-cycle cost savings vary from $7,200 to $8,200 for climate zones 3, 10, and 13 at the cost-minimum design point compared to the case of avoided cost for export as net energy bill savings would be much higher under NEM 2.0.

Figure 22: Energy-Related Cost Optimization Under Avoided Cost for Export and Net Energy Metering 2.0 Policy



Avoided Cost for Export

Net Energy Meter 2.0

Figure 22 shows the single-family 2100 ft^2 all-electric home in climate zone 3 under the avoided cost for export (left) and the NEM 2.0 (right) PV electricity export rate.

Source: Lawrence Berkeley National Laboratory

Figure 23: Life-Cycle Cost Under Different Photovoltaic Electricity Overgeneration Export Policies

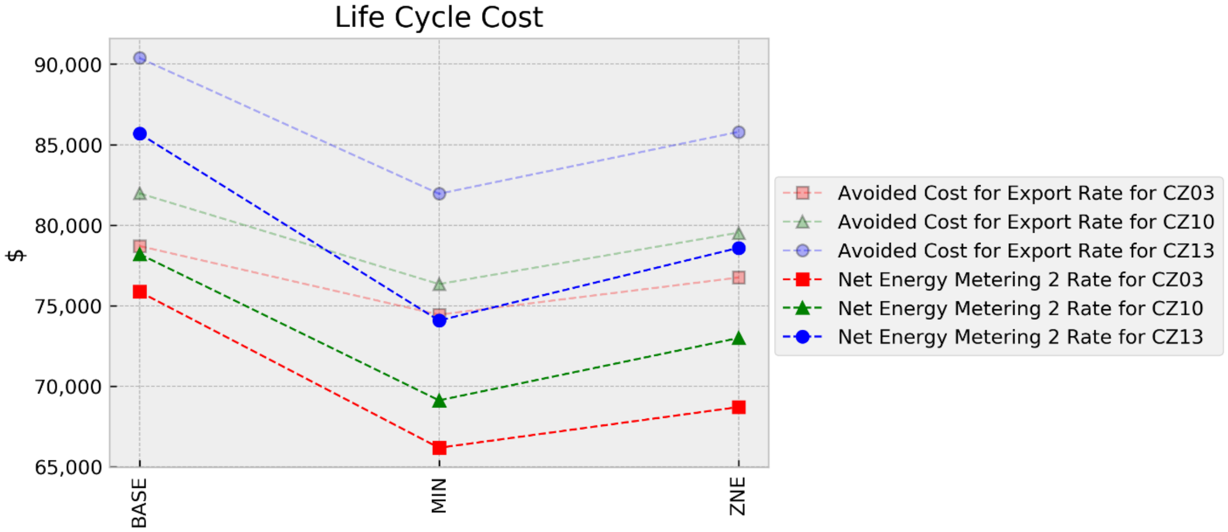


Figure 23 shows the total life-cycle cost differences between avoided-cost for export and NEM2.0 rates, showing that NEM2.0 is more favorable to consumers when PV modules are added from the base design points to the minimum cost points. (2100 ft^2 single family home).

Source: Lawrence Berkeley National Laboratory

Time Dependent Valuation Sensitivity: 2022 Base Case versus Higher Renewables Case

TDV values are important inputs when conducting the cost-effectiveness optimization simulation. The research team uses TDV values derived for 2022 for the baseline optimization analysis. A sensitivity analysis was also performed to compare the cost-effectiveness under this base case versus the Higher Renewables TDV case described in Chapter 2. Figure 24 compares the life-cycle cost with the baseline TDV 2022 values compared to Higher Renewables TDV case values. The life-cycle cost at the minimum cost point is between $700 and $1700 higher for the Higher Renewables TDV case.

Figure 24: Life-Cycle Cost Under 2022 Base Case versus Higher Renewables Case

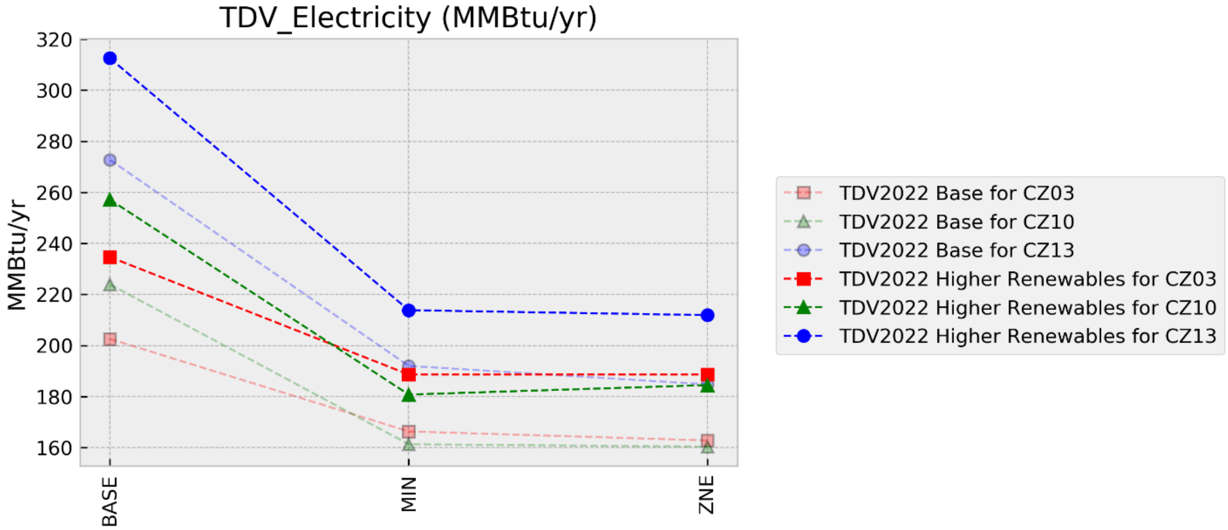


Figure 24 compares the life-cycle cost for the baseline TDV values for 2022 compared to those values for the Higher Renewables TDV case.

Source: Lawrence Berkeley National Laboratory

Storage

The research team analyzed two forms of energy storage: battery storage and precooling. The buildings used in this storage analysis are the BEopt minimum cost home designs for the specified fuel type, square footage, climate zone, and TDV sensitivity.

Battery Storage

The team's analysis revealed that under Basic and TOU dispatch, battery storage cannot achieve TDV-ZNE (that is, cannot enable the building to consume and produce equal amounts of electricity TDV over each year). Battery storage responding to more dynamic price signals (such as under Shuffled and Optimal dispatch algorithms) can achieve TDV-ZNE (see Figure 25), though these solutions may not be cost-effective to the participant. While batteries dispatching against more dynamic price signals could achieve TDV-ZNE, batteries operating with Basic and TOU dispatch could not, as they are not as effective in capturing storage arbitrage value.

Figure 25: Selection of Time-Dependent Value-Zero Net Energy Battery Size

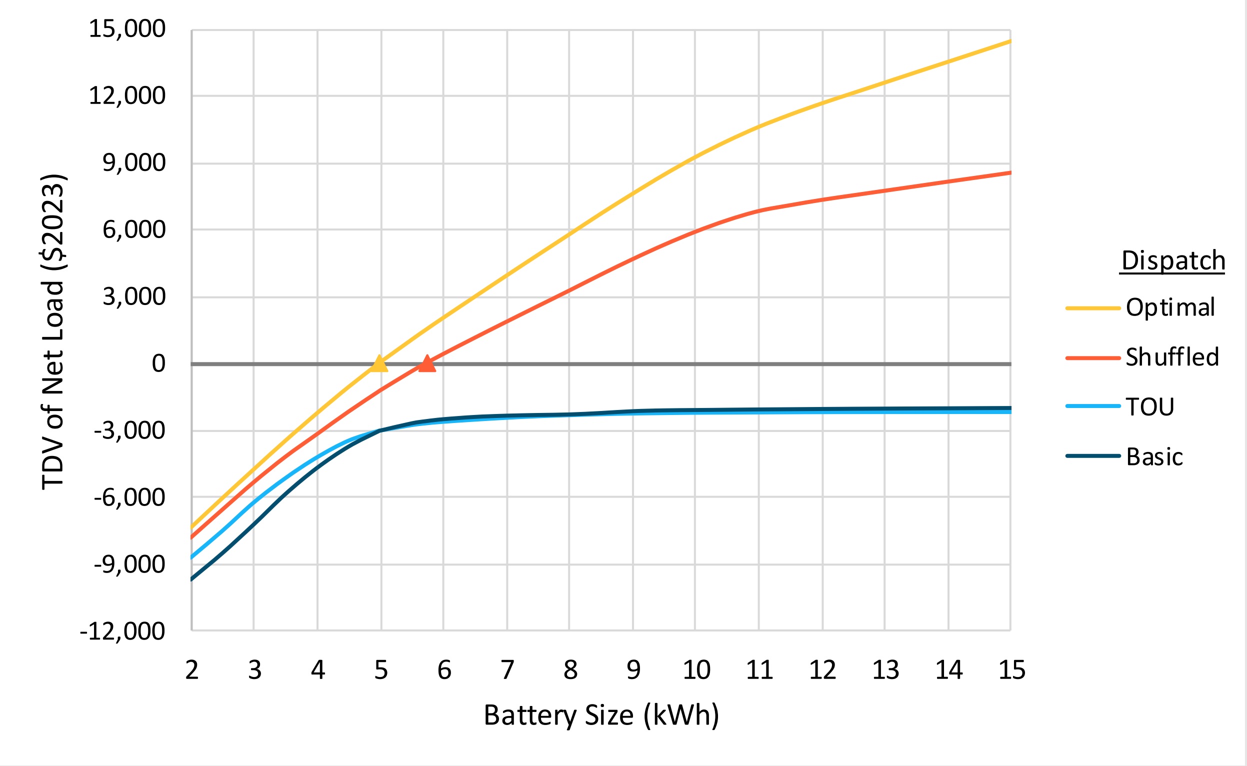


Figure 25 shows the TDV of net load as a function of battery size for four different dispatch algorithms for 2100 ft^2 Mixed Fuel home, Base 2022 TDV, CZ 10 (triangles indicate battery size at which TDV-ZNE is reached).

Source: Lawrence Berkeley National Laboratory

Further, if compensated under current TOU rates and NEM policies, battery storage is not projected to be cost-effective to the participant, even assuming storage costs reduce over time (see Figure 26).[16] The timing of the TOU periods and magnitude of the rates do not provide sufficient signal or compensation to generate enough arbitrage value to offset battery costs. Because the penalties for exporting in the avoided cost for exports use cases are about four times higher than the non-bypassable charges in the NEM 2.0 use cases, battery storage provides more bill savings under avoided cost for exports than under NEM 2.0.

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[16] That is, even assuming 2023 and 2043 costs are 64 percent and 47 percent of 2018 costs, as in the "Average Cost – Reducing Over Time" case.

Figure 26: Storage Net Bill Savings Less Battery Costs (30-Year Net Present Value)

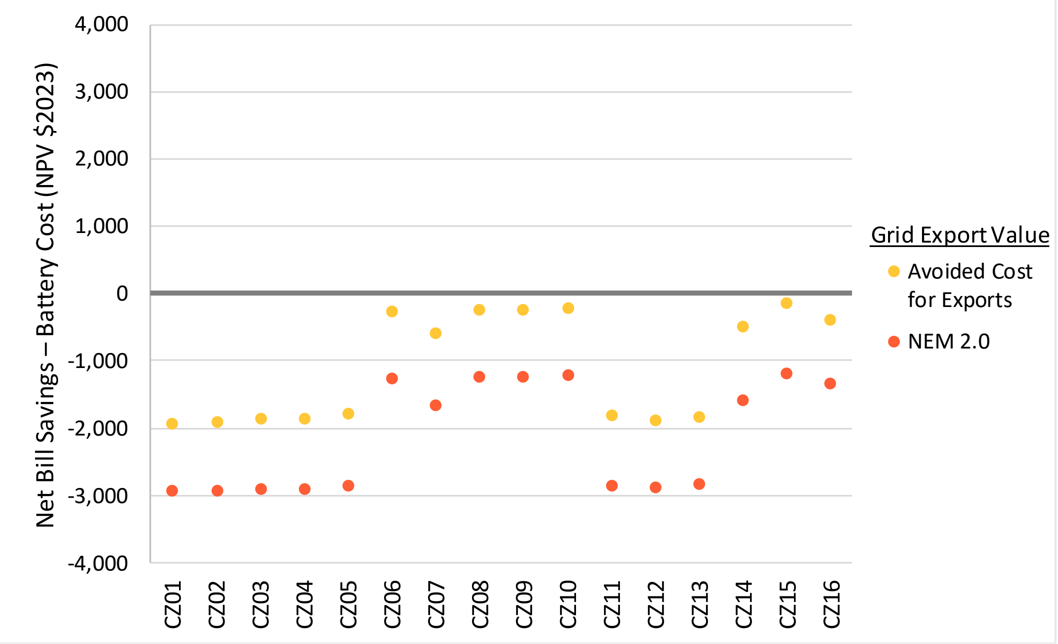

Figure 26 shows storage net bill savings less Battery Costs (30-year NPV) assuming Average Cost-Reducing over Time battery cost and 2100 ft^2 Mixed Fuel Home with current TOU rates

Source: Lawrence Berkeley National Laboratory

Given that electricity retail rate structures are uncertain over the 30-year time frame used in the CEC's Title 24 analyses, the research team sought to further analyze cost-effectiveness under the TDV framework. 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 TDV, less the retail rate adder (the avoided cost portion of the TDV). PV systems are sized to offset the building's annual electricity load. This analysis further assumes that batteries may only charge on rooftop solar PV, as this is a requirement for receiving Title 24 compliance credit.

Recall that the analysis used five different battery use cases (see Storage Control Algorithms in Appendix A for details):

1. Optimized Dispatch, which assumes that each battery is dispatched to maximize TDV values in each hour of each 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. 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 used only 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.[17]

In this analysis, battery storage value generally comes from:

1. Avoiding generation and distribution capacity peaks: value comes from displacing grid electricity consumption with battery electricity during high TDV periods
2. Avoiding "export penalties": because PV generation is more valuable serving building load than when exported to the grid, battery storage provides value by shifting solar energy that would have been exported to a time when the building would have been consuming energy from the grid
3. Energy arbitrage: in the future, penetration of solar generation is expected to be high enough that the difference in energy prices between hours with and without solar generation (particularly in the spring when system load is low) could be large enough to provide arbitrage value

In this analysis, each battery case is optimally sized to maximize net benefits (TDV value minus battery costs) to the homeowner. Figure 27 shows the optimal sizes of 64 battery use cases (4 use cases by 16 CZs) installed in a 2100 ft^2 mixed-fuel home under Base 2022 TDV values, Average Cost, with No Cost Reduction. Figure 28 shows the corresponding total net benefits.

The use cases in Figure 27 and Figure 28 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 27, 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 28, the total net benefits of these systems are negative for all but three systems — that is, only three of these use cases are cost-effective, and by small margins.

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[17] See "Self Generation Incentive Program Reports," http://www.cpuc.ca.gov/general.aspx?id=7890

Figure 27: Optimal Sizing of Two-Hour Battery, Minimum 2 Kilowatt-Hour, Average Cost – No Reduction

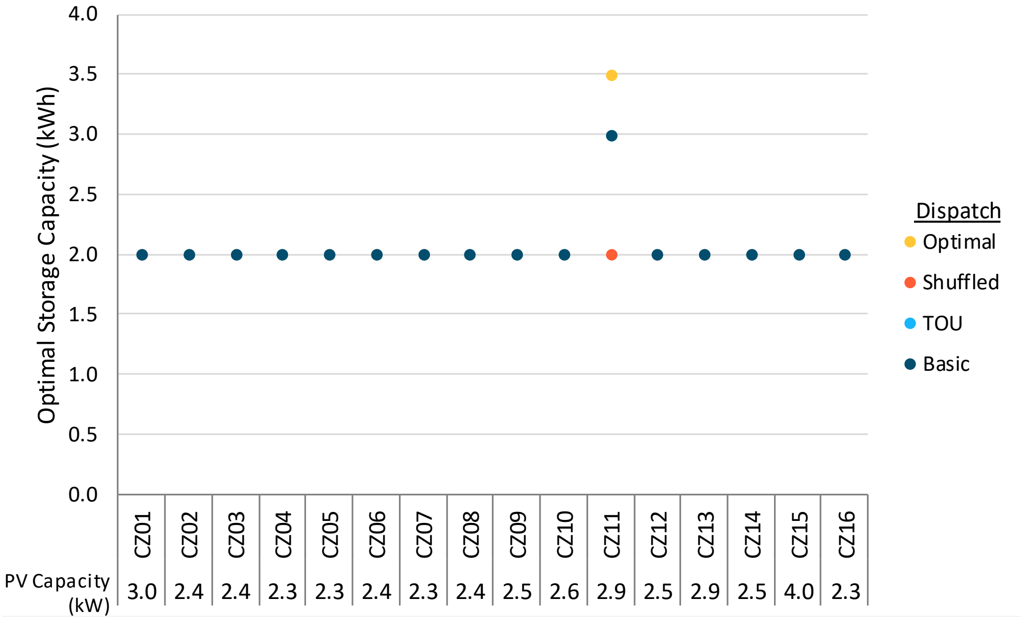

Figure 27 shows the optimal sizing of 2hr battery (minimum 2kWh) for the Average Cost-No Reduction battery cost case, 2100 ft^2 Mixed Fuel Home, Base 2022 TDV Values.

Source: Lawrence Berkeley National Laboratory

Figure 28: Time dependent valuation Benefits Less Battery Costs, 30-year Net Present Value, Average Cost – No Reduction

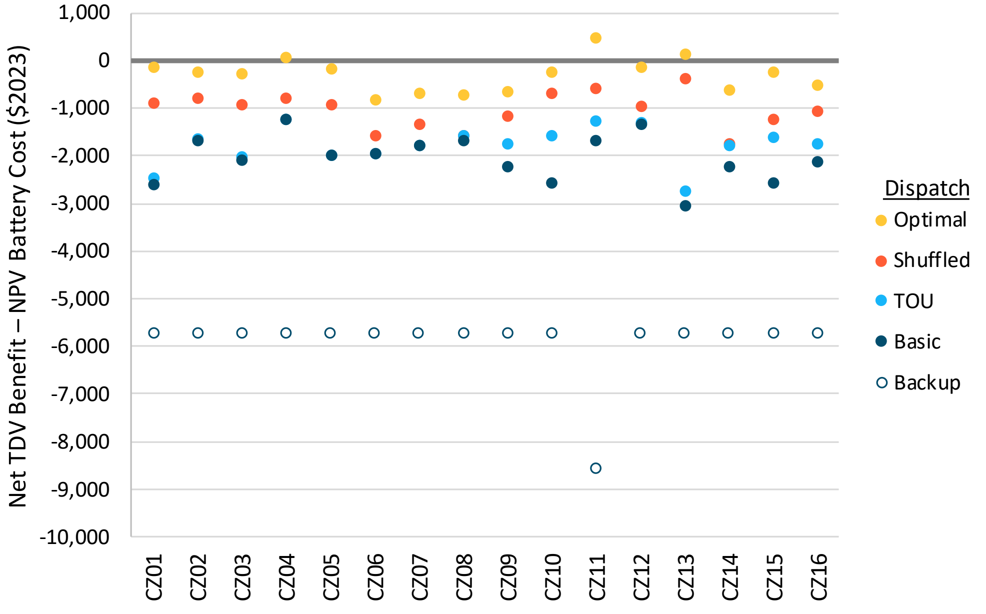

Figure 28 shows Net TDV Benefits Less Battery Costs (30-year NPV) for the Average Cost-No Reduction battery cost case, 2100 ft^2 Mixed Fuel Home, Base 2022 TDV

Source: Lawrence Berkeley National Laboratory

If battery storage costs decline from present average costs, optimal battery sizes and associated TDV net benefits are expected to increase. Figure 29 shows the same home as Figure 28, this time assuming that battery costs come down according to the Average Cost-

Reducing over Time case.[18] Under this cost trajectory, battery storage is optimally sized above the 2kWh minimum for many use cases. As shown in Figure 30, some of these use cases show positive cost-effectiveness margins.

Figure 29: Optimal Sizing of Two-Hour Battery, Average Cost-Reducing Over Time

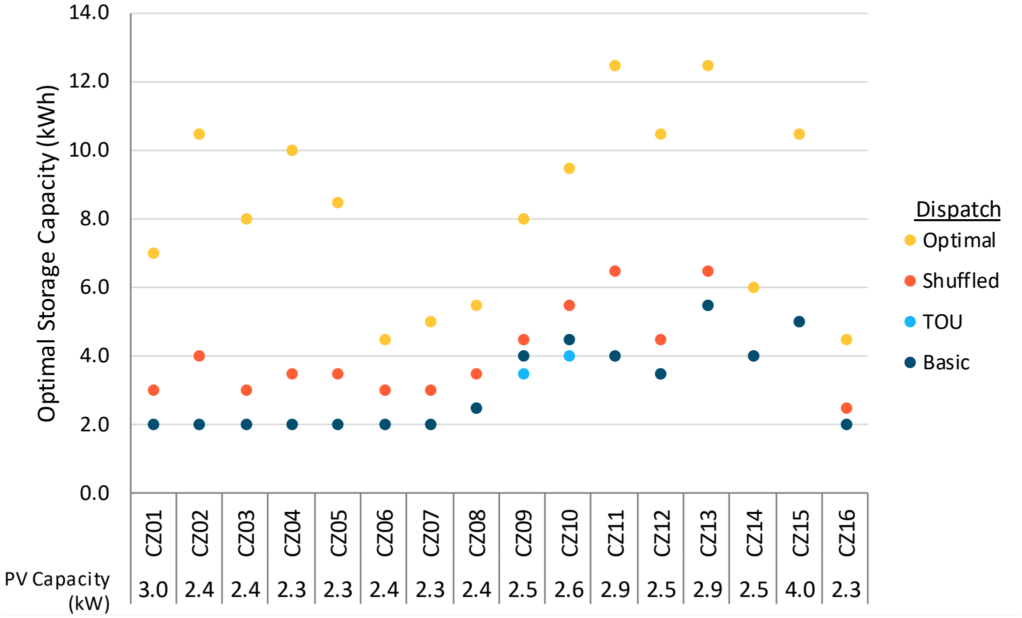

Figure 29 shows the optimal Sizing of 2hr Battery (Minimum 2kWh) with the Average Cost-Reducing over Time battery cost case, 2100 ft^2 Mixed Fuel Home, Base 2022 TDV

Source: Lawrence Berkeley National Laboratory

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[18] Recall that this case begins with the same costs as the "Average Cost, with No Reduction" case, but assumes 2023 and 2043 costs are 64 percent and 47 percent of 2018 costs, respectively

Figure 30: Time dependent valuation Benefits Less Battery Costs, 30-year Net Present Value, Average Cost-Reducing Over Time

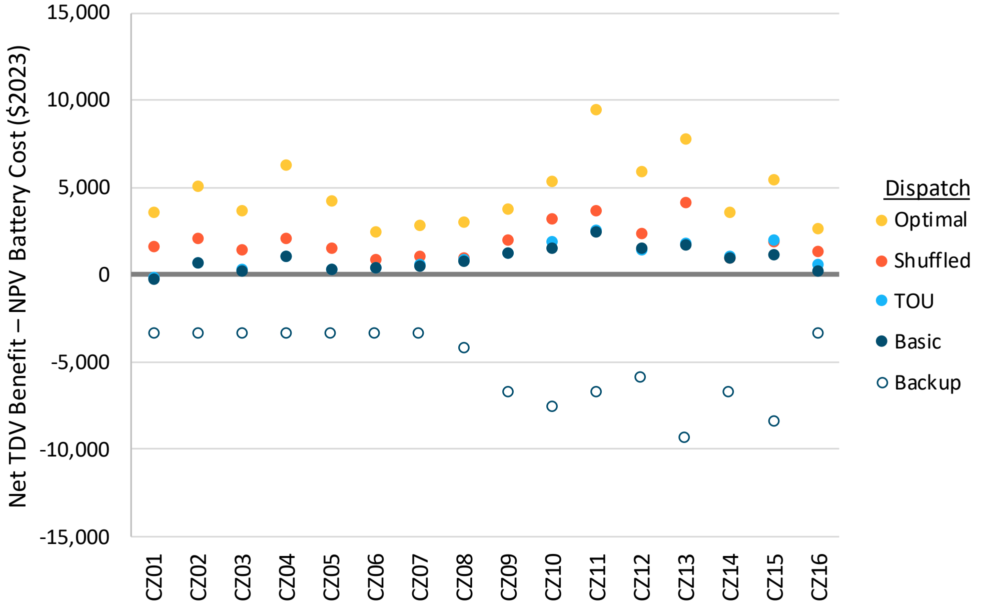

Figure 30 shows Net TDV Benefits Less Battery Costs (30-year NPV) for the Average Cost-Reducing over Time battery cost case, 2100 ft^2 Mixed Fuel Home, Base 2022 TDV

Source: Lawrence Berkeley National Laboratory

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 value by CZ
- 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. See Figure B-1 and Figure B-2 in Appendix B.

The research team also finds that if the 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 backup, it could result in net costs. Figure 31 illustrates how total net benefits change with battery capacity under the four 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 (that is, 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 provide $2,400 net benefits, $4,530 net costs, or $4,450 net costs, respectively.

Figure 31: Selection of Optimal Battery Size: Average Cost-Reducing Over Time

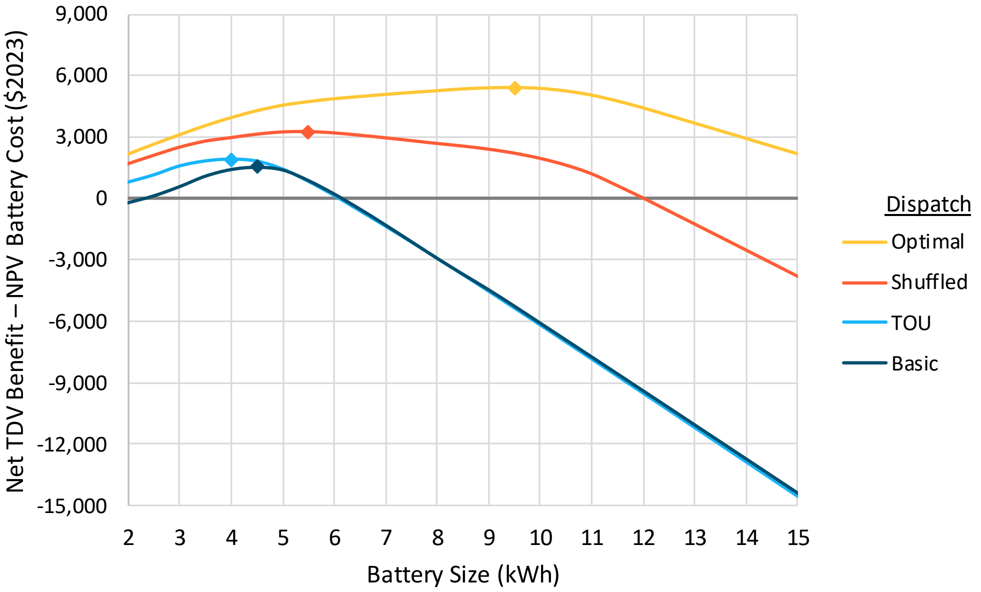

Figure 31 shows if a home builder sizes the battery (or is mandated to size the battery) to maximize net benefits under one dispatch method, but then operates the battery using a less optimal dispatch method or as backup, it could result in net costs.

Source: Lawrence Berkeley National Laboratory

A further implementation issue is the small size of optimal battery storage systems found in this analysis relative to the current Title 24 minimum size of 5 kWh and common commercially available sizes like the 13.5 kWh Tesla Powerwall. This should be considered by the CEC as part of any market analysis performed to support the inclusion of battery storage in building codes.

The research team also ran a sensitivity analysis using the Higher Renewables 2022 TDV values. As shown in Figure 32 with higher penetration of renewables, residential battery storage could become cost-effective in some CZs, even with no cost reduction (not shown in the figure). This is because battery storage is expected to see more arbitrage value per kWh under high renewables, especially with more optimized dispatch. Less advanced dispatch methods may not be able to capture the additional arbitrage value in the peaky Higher Renewables TDV as well as Optimal dispatch. In interpreting these Higher Renewables results, it is important to consider the broader storage market. Though the peakier TDV values seen in the Higher Renewables case may be more favorable to residential battery storage, this higher arbitrage value could also encourage the installation of additional grid-level or commercial behind-the-meter storage. While services provided by residential storage differ somewhat from those of larger batteries, an influx of lower-cost (due to economies of scale) non-residential energy storage could soak up some of the arbitrage value, reducing the cost-effectiveness of residential storage.

Figure 32: Optimal Sizing of Two-Hour Battery and Time Dependent Valuation Net Benefits Less Battery Costs

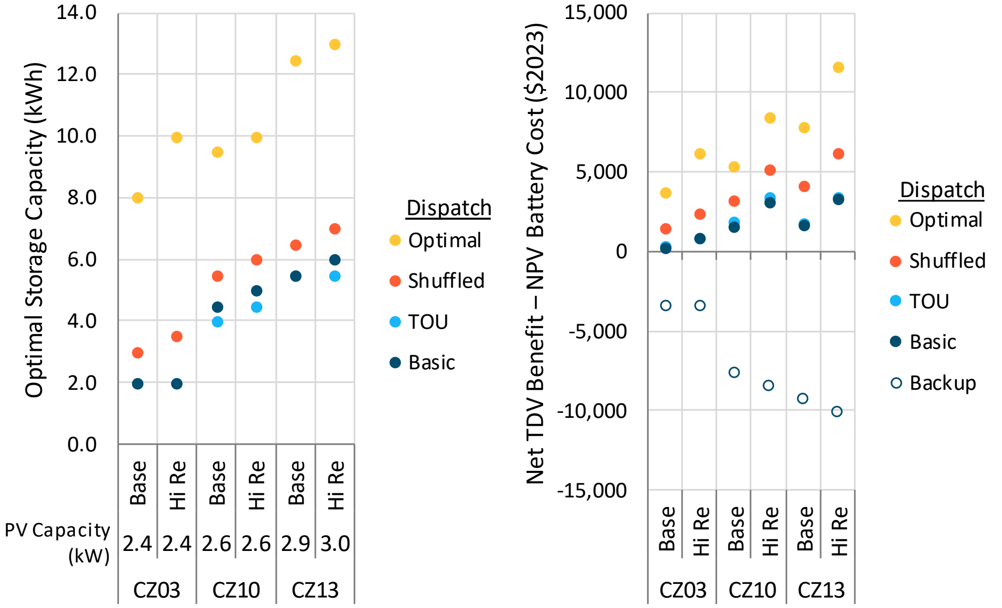

Figure 32 shows that optimal storage capacity (left) and TDV Net Benefits less Battery Costs (right) are nearly always higher with Higher Renewables 2022 TDV than Base 2022 TDV, for the Average Cost-Reducing over Time battery cost scenario, 2100 ft^2 Mixed Fuel Home

Source: Lawrence Berkeley National Laboratory

The research team ran a final, more optimistic case on battery storage costs by starting with today's lowest battery storage costs (rather than the industry average) and assumed that these costs will decline in the future.[19] Then the battery size that maximizes TDV net benefits could be quite large and provide large net benefits (see Figure B-1 through Figure B-4 in Appendix B).

A final and important caveat to this analysis is that it does not compare the cost-effectiveness of residential battery storage to precooling or to distribution system-sited battery storage. Though residential battery storage is cost effective to the homeowner under some dispatch methods, battery cost trajectories, and climate zones, it may not be cost effective compared to larger scale storage sited at the distribution system, or compared to other potential forms of load management such as precooling or load shifting from electric vehicles. Ongoing analysis by E3 for the California Public Utilities Commission is delving further into the question of cost-effectiveness of residential- and commercially sited storage versus distribution system-sited battery storage.

Precooling

Precooling provides similar benefits to battery storage. Whereas batteries store low-cost electricity to discharge when electricity costs are high, precooling arbitrages low and high electricity costs by storing cool air in advance of later, more expensive hours. Both forms of

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[19] See description of "Low Cost-Reducing Over Time" in Methods chapter

storage cause the home to use more energy in aggregate due to efficiency losses but reduce costs to the grid (and to the customer, if price signals correlate with grid costs).

Precooling often uses more kWh than the Base setpoint schedule,[20] but saves electricity costs in two main ways, as illustrated in Figure 33.

1. Precooling shifts electricity consumption from high-cost evening peak periods to lower cost afternoon hours.
2. Because precooling is more coincident with rooftop solar PV generation than Base Case cooling, the energy that would have been exported to the grid at low avoided cost compensation is used by the building's load.

Figure 33: Example Day of Base Cooling Load vs. Precooling Load

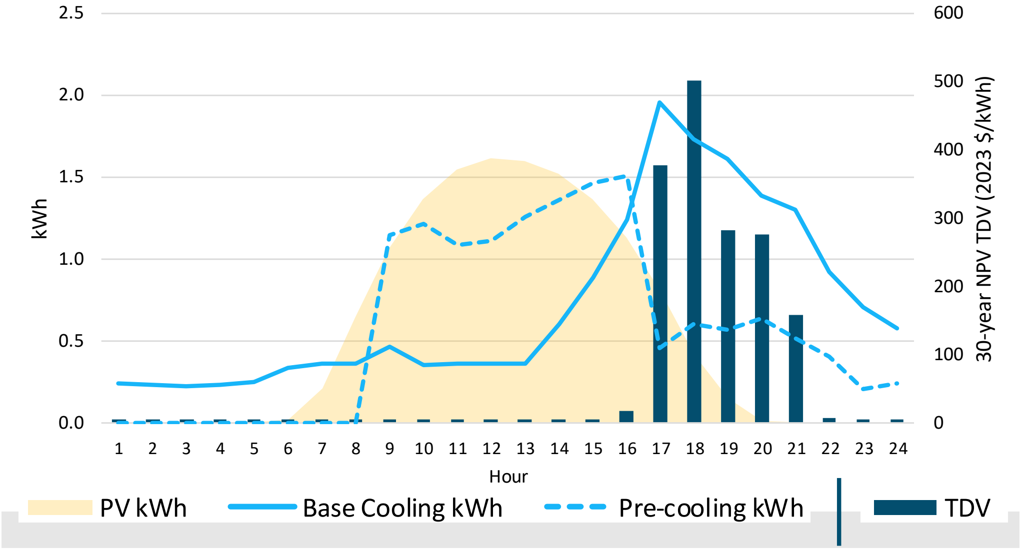

Figure 33 shows how precooling can shift demand to earlier in the day, better aligning cooling load with solar PV output and avoiding hours with high TDV values.

Source: Lawrence Berkeley National Laboratory

The Base Case cooling setpoint schedule in the California Building Energy Code Compliance residential standards compliance software (CBECC-Res) was designed to save energy by not running air conditioning when the building is unoccupied during midday. However, with higher penetration of solar depressing midday energy costs and rooftop solar required by Title 24, even setting the thermostat to constant 78°F (26°C) could be less expensive than the Base schedule. For example, for the all-electric 2100 ft^2 home in CZ 10, the Constant 78°F (26°C) schedule adds 44 kWh of annual net load relative to the Base Case (1 percent of gross load in Base Case), but saves $672 in TDV net costs (5 percent less than Base Case) over the 30-year lifetime.

To further investigate the potential for precooling, the research team simulated annual hourly building loads under 14 different cooling setpoint schedules (described in Chapter 2). For each

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[20] Recall that under this setpoint schedule, the thermostat is dispatched so that the home's temperature is permitted to rise above the 78° comfort threshold when the building is unoccupied. This Base setpoint schedule matches the base setting in CBECC Res building simulation software for the 2019 Title 24 standards.

day, the setpoint schedule with the lowest TDV costs (hourly net load multiplied by TDV values) was selected to make up an Optimal setpoint schedule. Figure 34 and Figure 35 show how the annual net load and net TDV costs vary by CZ between the Base, Constant 78°F (26°C), and Optimal precooling setpoint schedules. CZs 1, 3, and 5 have little to no cooling load. In most CZs, Optimal precooling uses the most kWh, followed by Constant 78, and then the Base Case (which has a net load of zero in each CZ because PV systems in this analysis are sized to offset annual electricity loads). However, Optimal precooling shows the least TDV costs, followed by Constant 78° F (26°C), and then the Base Case. The exception is hot, arid CZ 15, where Optimal precooling is still the least cost option, but a Constant 78°F (26°C) schedule is higher cost than the Base Case.

Figure 34: Annual Net Load Comparison of Cooling Schedules by Climate Zone

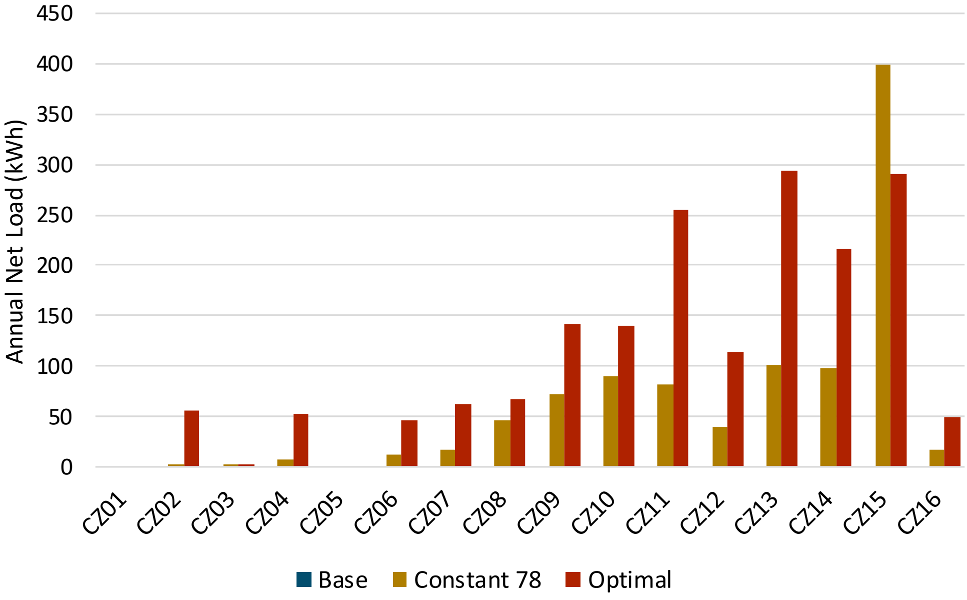


Figure 34 shows annual net load for 2100 ft^2 Mixed Fuel Homes under three different cooling schedules. In most CZs, the Optimal precooling schedule uses the most kWh.

Source: Lawrence Berkeley National Laboratory

Figure 35: 30-Year Net Time Dependent Valuation Cost Comparison of Cooling Schedules by Climate Zone

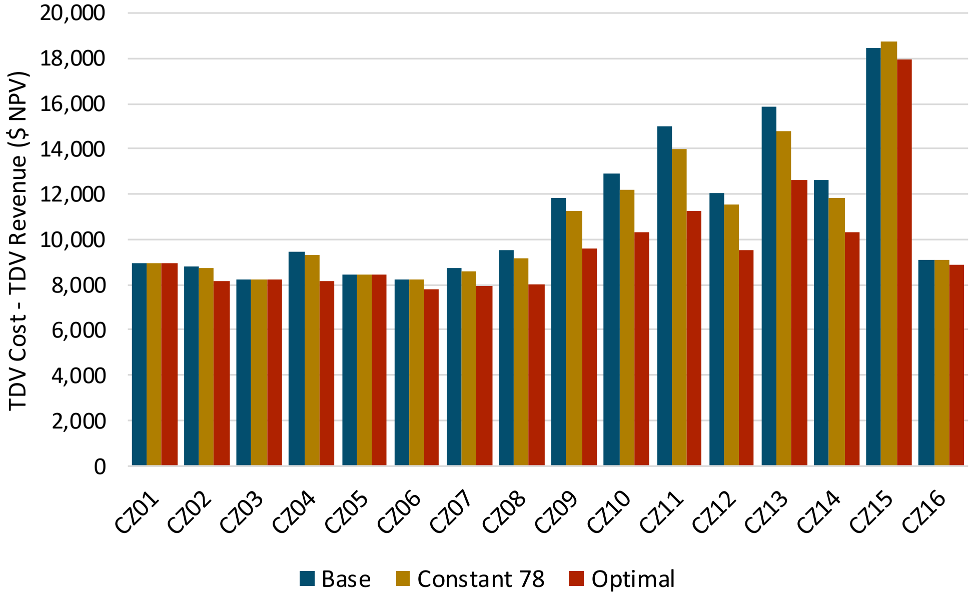
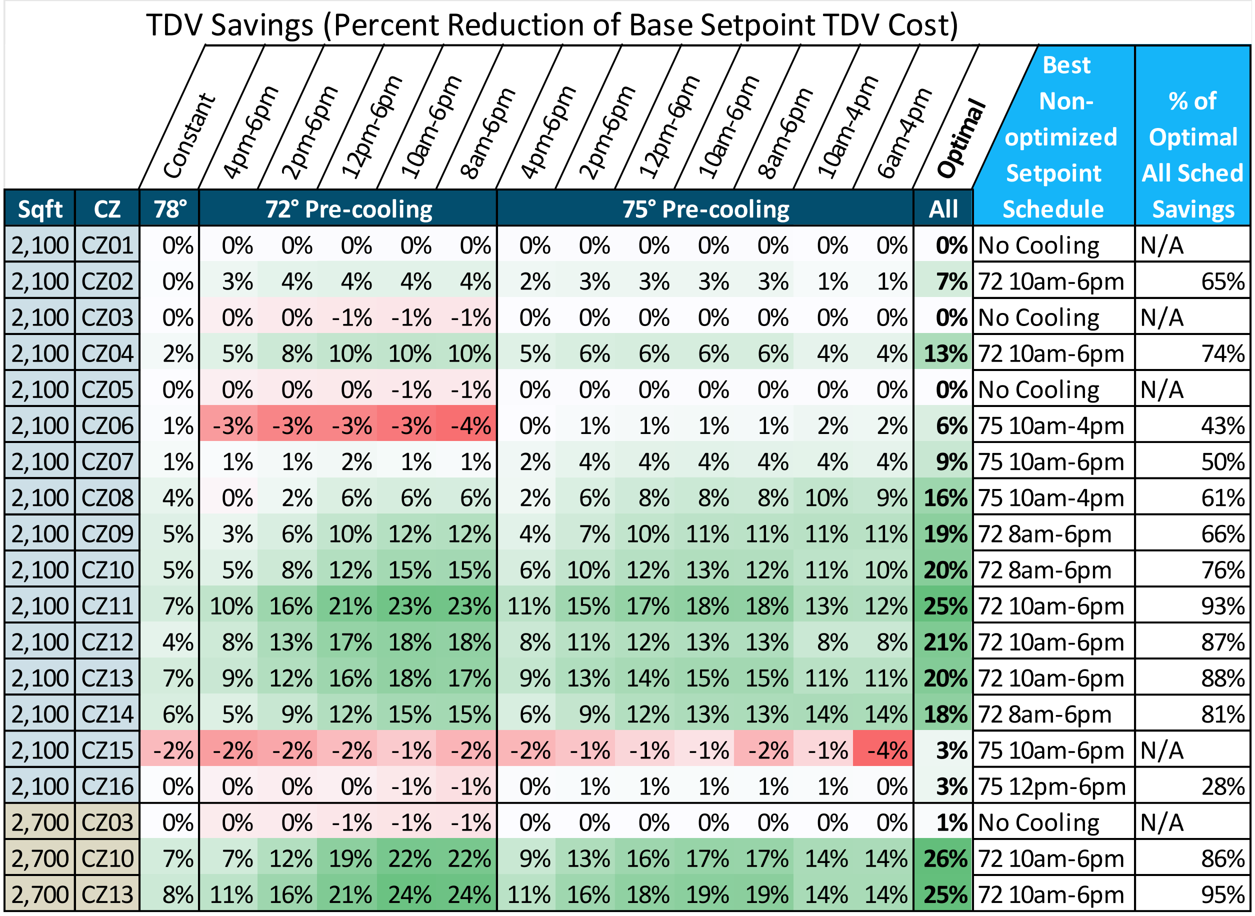


Figure 35 shows that although Optimal Cooling Schedule uses more energy (Fig. 34), the net TDV costs are lower than the Base case and the Constant 78°F (26°C) Case for for 2100 ft^2 Mixed Fuel Homes in all climate zones.

Source: Lawrence Berkeley National Laboratory

This Optimal precooling analysis uses perfect foresight of cooling loads and TDV values, which is impossible to replicate in practice. However, further analysis revealed that a single setpoint schedule for all days could provide most of the precooling savings. As shown in Figure 36, in all but 3 of the 14 home types, an individual precooling setpoint schedule can return much of the Optimal precooling bill savings. Longer (8:00 a.m. – 6:00 p.m., 10 hours) and cooler (72°F [26°C]) precooling setpoint schedules tend to create more savings. Selecting one precooling schedule may provide most of the benefits as daily optimal selection and be simpler to implement.

Figure 36: 30-Year Net Time Dependent Valuation Cost Savings of Individual and Optimal Precooling Schedules Relative to Base Cooling



TDV Savings (Percent Reduction of Base Setpoint TDV Cost)

Sqft	CZ	78°	72° Pre-cooling					75° Pre-cooling							All	Best Non-optimized Setpoint Schedule	% of Optimal All Sched Savings
		Constant	4pm-6pm	2pm-6pm	12pm-6pm	10am-6pm	8am-6pm	4pm-6pm	2pm-6pm	12pm-6pm	10am-6pm	8am-6pm	10am-4pm	6am-4pm	**Optimal**		
2,100	CZ01	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	**0%**	No Cooling	N/A
2,100	CZ02	0%	3%	4%	4%	4%	4%	2%	3%	3%	3%	3%	1%	1%	**7%**	72 10am-6pm	65%
2,100	CZ03	0%	0%	0%	-1%	-1%	-1%	0%	0%	0%	0%	0%	0%	0%	**0%**	No Cooling	N/A
2,100	CZ04	2%	5%	8%	10%	10%	10%	5%	6%	6%	6%	6%	4%	4%	**13%**	72 10am-6pm	74%
2,100	CZ05	0%	0%	0%	0%	-1%	-1%	0%	0%	0%	0%	0%	0%	0%	**0%**	No Cooling	N/A
2,100	CZ06	1%	-3%	-3%	-3%	-3%	-4%	0%	1%	1%	1%	1%	2%	2%	**6%**	75 10am-4pm	43%
2,100	CZ07	1%	1%	1%	2%	1%	1%	2%	4%	4%	4%	4%	4%	4%	**9%**	75 10am-6pm	50%
2,100	CZ08	4%	0%	2%	6%	6%	6%	2%	6%	8%	8%	8%	10%	9%	**16%**	75 10am-4pm	61%
2,100	CZ09	5%	3%	6%	10%	12%	12%	4%	7%	10%	11%	11%	11%	11%	**19%**	72 8am-6pm	66%
2,100	CZ10	5%	5%	8%	12%	15%	15%	6%	10%	12%	13%	12%	11%	10%	**20%**	72 8am-6pm	76%
2,100	CZ11	7%	10%	16%	21%	23%	23%	11%	15%	17%	18%	18%	13%	12%	**25%**	72 10am-6pm	93%
2,100	CZ12	4%	8%	13%	17%	18%	18%	8%	11%	12%	13%	13%	8%	8%	**21%**	72 10am-6pm	87%
2,100	CZ13	7%	9%	12%	16%	18%	17%	9%	13%	14%	15%	15%	11%	11%	**20%**	72 10am-6pm	88%
2,100	CZ14	6%	5%	9%	12%	15%	15%	6%	9%	12%	13%	13%	14%	14%	**18%**	72 8am-6pm	81%
2,100	CZ15	-2%	-2%	-2%	-2%	-1%	-2%	-2%	-1%	-1%	-1%	-2%	-1%	-4%	**3%**	75 10am-6pm	N/A
2,100	CZ16	0%	0%	0%	0%	-1%	-1%	0%	1%	1%	1%	1%	1%	0%	**3%**	75 12pm-6pm	28%
2,700	CZ03	0%	0%	0%	-1%	-1%	-1%	0%	0%	0%	0%	0%	0%	0%	**1%**	No Cooling	N/A
2,700	CZ10	7%	7%	12%	19%	22%	22%	9%	13%	16%	17%	17%	14%	14%	**26%**	72 10am-6pm	86%
2,700	CZ13	8%	11%	16%	21%	24%	24%	11%	16%	18%	19%	19%	14%	14%	**25%**	72 10am-6pm	95%

Figure 36 shows that a non-optimized single setpoint schedule can realize a high fraction of precooling savings obtained from optimal setpoint scheduling in most climate zones.

Source: Lawrence Berkeley National Laboratory

Like battery storage, precooling also provides value by avoiding grid consumption at peak periods and shifting PV generation to be consumed behind the meter instead of exporting to the grid for low compensation. Because dynamic rates enable this value, the project team designed TOU rate sensitivities like the ones in the battery storage analysis. Along with the optimal setpoint selection for each day using TDV values shown above, this selection was performed using TDV values averaged into TOU periods of current rates and two versions of 30-year NPV of current TOU rates: grid exports valued at ACE and grid exports valued at retail less non-bypassable charges (NEM 2.0).[21]

If customers see current TOU rates rather than TDV values, then cost savings to customers and the grid from precooling are much lower. The muted price signals in current TOU rates lack enough variation between TOU periods to provide arbitrage value for precooling (see Figure 37). The current TOU rate with NEM 2.0 provides the lowest savings because there is little incentive for precooling to avoid PV exports.

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[21] TDV and TDV averaged by TOU period cases also value grid exports at avoided cost.

Figure 37: 30-Year Net Time Dependent Valuation Cost Savings of Precooling with Optimal Setpoint Selection Under Rate Structure Sensitivities

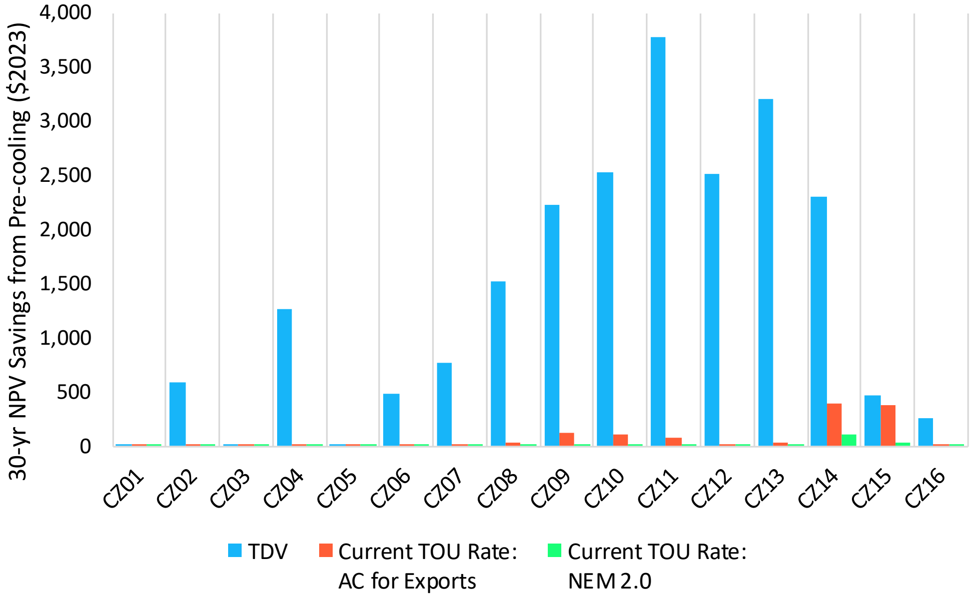

Figure 37 shows the net TDV cost saving from precooling is small unless more time differentiated utility rate structures are in place such as TDV-based hourly rates.

Source: Lawrence Berkeley National Laboratory

An important benefit of these precooling schedules is that they will actually increase customers' comfort levels compared to Basic setpoint schedules: under precooling, homes are already cool when customers arrive home.

Three elements are needed to realize the savings from precooling in new residential construction.[22] First, the CEC should require or credit the installation of occupant controlled smart thermostats in new construction. This technology is required to enable future control of cooling loads by aggregators or utilities, if and when customers agree to provide this control. Second, the price signal to customers or to aggregators (such as Nest, Honeywell, Ecobee, and others) needs to be sufficiently time-differentiated to incent customers to pre-cool. This could be, for example, through greater differentials between TOU rate periods and a change in NEM policy. Third, customer education efforts are needed to communicate the financial and comfort benefits of precooling and reiterate customer control and opt-out options. These education efforts could be undertaken by the CEC, the CPUC, aggregators, and/or utilities. The research team expects that with these three elements in place, customers are likely to take up precooling as a means to increase their comfort while lowering their electric bills.

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[22] While the BEopt building prototypes used in this analysis were not selected to optimize for precooling, their efficient shells store cool air well enough to benefit from precooling. Older vintages or other building designs may interact differently with precooling setpoint schedules.

Renewable Natural Gas

Forecasted Renewable Natural Gas Supply and Production Costs

The delivered cost of RNG includes several components: feedstock costs, conversion costs, upgrading/injection, and pipeline connection (see Appendix B for a detailed description of these costs).

The cost to produce RNG may remain high since many biomass producers are small operations that do not have RNG collection and delivery as their primary objective. Thus, RNG plants may not be able to achieve sufficient production levels necessary to reach economies of scale that can bring down costs. Engagement with potential RNG providers can also be challenging since prospective RNG providers may require significant financial incentives to change their processes, staffing, and, technologies since they do not consider RNG production part of their primary business. Financing of new equipment can also represent a significant challenge and cost.

E3 used its PATHWAYS model,[23] with data from Jaffe (Jaffe, et al., 2016) and the U.S. DOE's Billion-Ton Report (Langholtz, Stokes, & Eaton, 2016) to create forecasted RNG supply curves for California in 2030. The year 2030 represents a milestone in evaluating the state's policy targets and a useful timeframe for consideration of the initial effects of 2023 building code changes. The curves in Figure 38 estimate the annual quantity of RNG that suppliers may be willing to provide at each all-in production and transportation cost, which includes all the cost components described in the preceding text. Note that these supply curves do not include advanced biofuels from purpose-grown crops (since purpose-grown crops can have ill effects on land use and other resource cycles, and the forecasted supply of purpose-grown crops is highly uncertain). They do, however, include non-purpose-grown woody biomass and crop residual-derived RNG (under the assumption that RNG development from these sources increases in the next decade). These curves also do not account for the retail markup added by sellers of RNG.

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[23] For more details on E3's PATHWAYS model, see https://www.arb.ca.gov/cc/scopingplan/california_pathways_model_framework_jan2017.pdf

Figure 38: California Renewable Natural Gas Supply Curves Under Two Scenarios, 2030

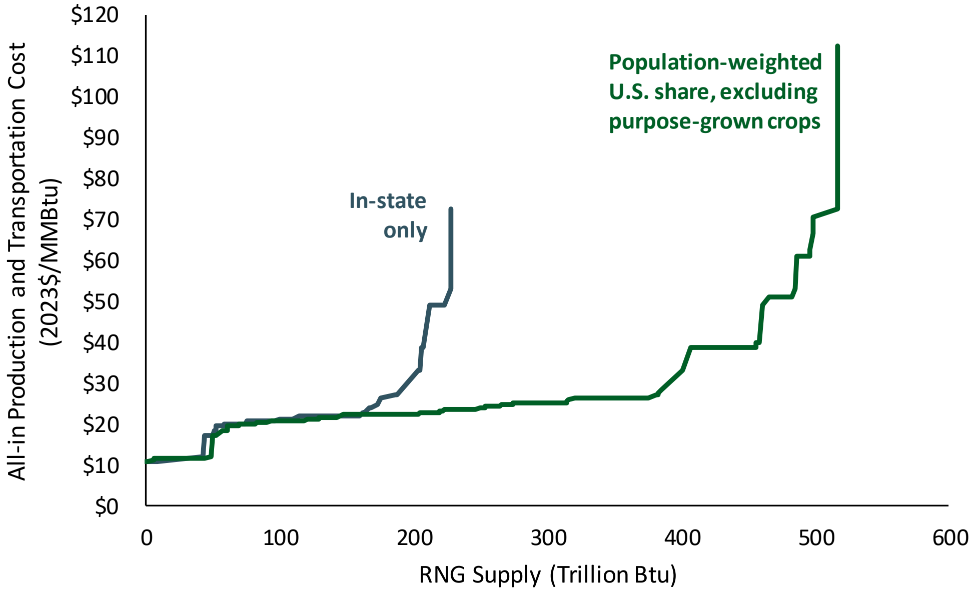

Figure 38 shows supply curve scenarios for renewable natural gas in 2030.

Source: E3 PATHWAYS analysis (Mahone, et al., 2018)

The left-hand curve in Figure 38 depicts a baseline RNG supply curve that includes in-state California biomass feedstocks projected by the U.S. DOE's Billion Ton Study supplemented by the better resolution in Jaffe et al. (2016) on waste biogas sources. This supply curve includes landfill, MSW, dairies, and woody biomass, and excludes any assumed purpose-grown crops. The right-hand curve shows an RNG supply curve that assumes California also has access to the state's population-weighted share of total U.S. biomass feedstocks, and assumes all available, non-cellulosic feedstock is converted to RNG.

The lowest-cost portion of both supply curves is composed of RNG from large landfill facilities that are also located near existing natural gas pipelines. These are followed by a mix of wastewater treatment plants, MSW, more expensive landfill sources and cellulosic feedstocks. Dairies generally produce the most expensive RNG, and the supply curves begin to climb steeply as existing and more economic resources are exhausted. The far-right portions of the supply curve are due to smaller or more difficult-to-access and expensive sources of RNG from all the supply categories.

These supply curves suggest that RNG is likely to be an energy resource with limited supply in California. In addition, the cost of RNG is expected to increase rapidly as cheaper sources of biogas close to existing pipeline infrastructure are exhausted. The curves also illustrate the significant uncertainty surrounding the future cost of RNG to an individual homeowner. Depending on the demand for this resource in the future, individual homeowners could see a very wide range of costs.

Forecasted Demand for Renewable Natural Gas

The research team combined two sources to estimate the potential demand for RNG from new residential construction were it to be required for ZNE compliance in mixed fuel homes. Table

B-9 in Appendix B provides the resulting annual estimate of natural gas demand, 10 trillion British thermal units (TBtu), from new residential construction for 2017.

There is likely to be significant future demand for RNG from sources other than new residential construction. New construction is only a tiny share of the total residential building stock — which also needs to decarbonize to meet the state's climate goals — and residential buildings represent only about 19 percent of total gas consumption in the state. The commercial sector currently uses gas to heat spaces, and the transportation sector uses natural gas for vehicle fuel (Table B-10 in Appendix B).

As California's climate goals ramp up over the next few decades, the state will require low-carbon alternatives to serve these gas end uses. In many cases, this will involve moving to electrified technologies powered by low-carbon electricity. However, some end uses, such as chemical manufacturing, process heating in glass, cement, and other materials fabrication have thus far proved difficult or prohibitively expensive to electrify.

E3 has estimated RNG demand curves as part of its prior PATHWAYS analyses for California, to assess how much of the resource may be needed to meet the state's climate goals. Figure 39 depicts the same RNG supply curves E3 used in its PATHWAYS model, with data from Jaffe (Jaffe, et al., 2016) and the U.S. DOE's Billion-Ton Report (Langholtz, Stokes, & Eaton, 2016) to create forecasted RNG supply curves for California in 2030. The year 2030 represents a milestone in evaluating the state's policy targets and a useful timeframe for consideration of the initial effects of 2023 building code changes. The curves in Figure 38 estimate the annual quantity of RNG that suppliers may be willing to provide at each all-in production and transportation cost, which includes all the cost components described in the preceding text. Note that these supply curves do not include advanced biofuels from purpose-grown crops (since purpose-grown crops can have ill effects on land use and other resource cycles, and the forecasted supply of purpose-grown crops is highly uncertain). They do, however, include non-purpose-grown woody biomass and crop residual-derived RNG (under the assumption that RNG development from these sources increases in the next decade). These curves also do not account for the retail markup added by sellers of RNG.

Figure 39 shows forecasted economywide RNG demand for 2030, assuming no building electrification. This includes demand from residential, commercial, transportation and industrial sectors, but excludes gas demand from electric generators. The figure also shows 2015 demand for reference.

Natural gas demand (excluding electricity generation) is projected to decrease over time: the 2030 demand scenario assumes (1) improvements in residential and commercial energy efficiency as the building stock turns over, (2) implementation of California's climate policy drives a 30 percent improvement in natural gas use efficiency for industrial end uses, and (3) reduced demand from petroleum industries as petroleum use from vehicles declines to meet California's climate goals. However, even with these reductions in gas demand, a large gap still exists between RNG supply and the gas demand under this scenario that meets California's climate goals: 2015 and 2030 gas demand of approximately 1,600 and 1,300 TBtu, respectively, greatly exceed the largest potential supply of 520 TBtu shown.

Figure 39: Forecasted 2030 Renewable Natural Gas Supply and Gas Demand

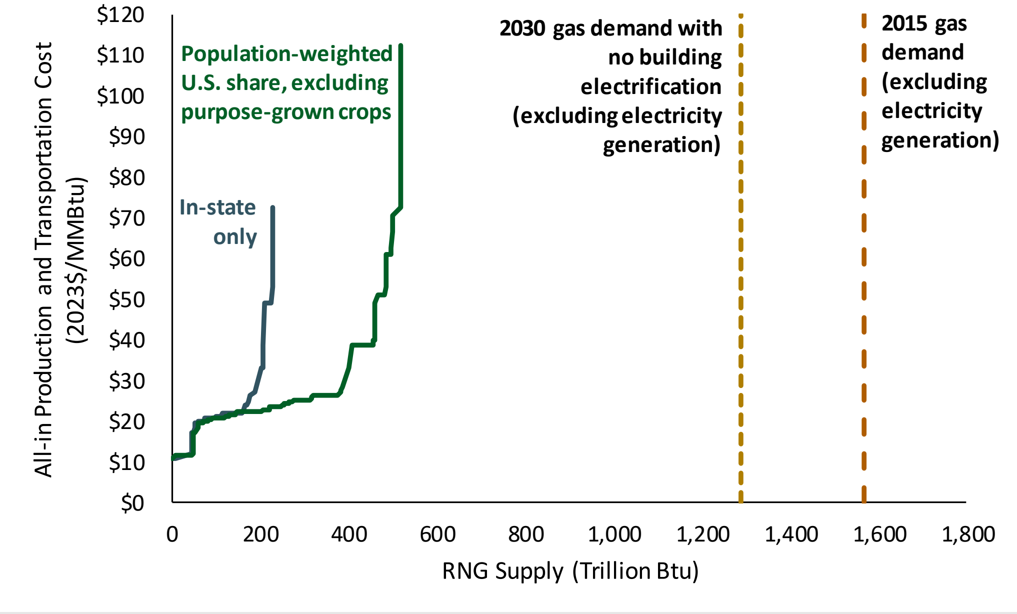

Figure 39 shows that in-state and California's share of U.S. renewable natural gas is much lower than estimated gas demand in 2030 (excluding gas demand for electricity generation).

Source: Lawrence Berkeley National Laboratory

Thus, even with projected technology and infrastructure improvements, it is evident that RNG will likely be a scarce resource. If RNG is used as a ZNE compliance option, homeowners and home developers will likely be competing with other end uses for RNG and biomass feedstocks. These competing demands will include existing residential and commercial buildings, industrial end uses that have fewer alternatives to continued gas consumption, as well as transportation subsectors. Current state policy tends to push available and low-cost RNG supplies into electricity generation or transportation. Onsite production of RNG at many landfills, dairies or MSW facilities is co-located with onsite electricity generation. For RNG use as transportation fuels, climate externalities are taken into consideration through existing policies (the Low Carbon Fuel Standard [LCFS] and the United States Renewable Fuels Standard [RFS]. These credits allow RNG produced for transportation fuel to receive both the market price for RNG and the additional LCFS and RFS credits, resulting in more cost-effective RNG for transportation. Homeowners may, therefore, see high and uncertain prices for RNG.

Different end uses also have varying options for alternative energy supply and ease of electrification. For instance, even within the residential and commercial building sector, which faces fewer challenges to electrification compared to industrial end uses, it is more difficult to electrify existing buildings than new construction. Given the limited trajectories across all industries that enable California to meet its 2050 carbon reduction goals, policymakers may wish to direct the state's limited RNG supply to end uses with fewer, or less cost-effective, greenhouse gas mitigation alternatives.

Cost-Effectiveness of Renewable Natural Gas Home Compared to the Prescriptive Home

RNG mixed-fuel ZNE homes are not cost-effective by the current standard of comparison, that is, using TDV values to compare to the CEC's reference mixed-fuel, 2019 Title 24 code-compliant home. Mixed-fuel RNG ZNE homes are forecast to be more expensive than the reference fossil mixed-fuel home due to the cost premium of RNG over fossil-based natural gas. The RNG on the *very lowest* end of the supply curves shown previously is forecast to have a delivered price of approximately $27 per million British thermal units (MMBtu) in 2020. Assuming a delivered fossil natural gas price of $17/MMBtu, this represents a $6/MMBtu cost premium for RNG. As shown in Figure 40Figure 40:, this equates to $4,000 TDV-weighted over the assumed 30-year life of the building in 2023. In reality, there is likely to be a very limited quantity at this lowest supply cost, which is sourced from landfill resources that have low upgrading and pipeline costs. The premium that homeowners would pay for RNG is expected to increase as total RNG demand increases and the lowest-priced RNG sources are no longer the marginal resource.

Figure 40: Time Dependent Valuation Cost-Effectiveness Comparison — Renewable Natural Gas Mixed-Fuel vs. 2019 Code-Compliant Mixed-Fuel Prescriptive Home

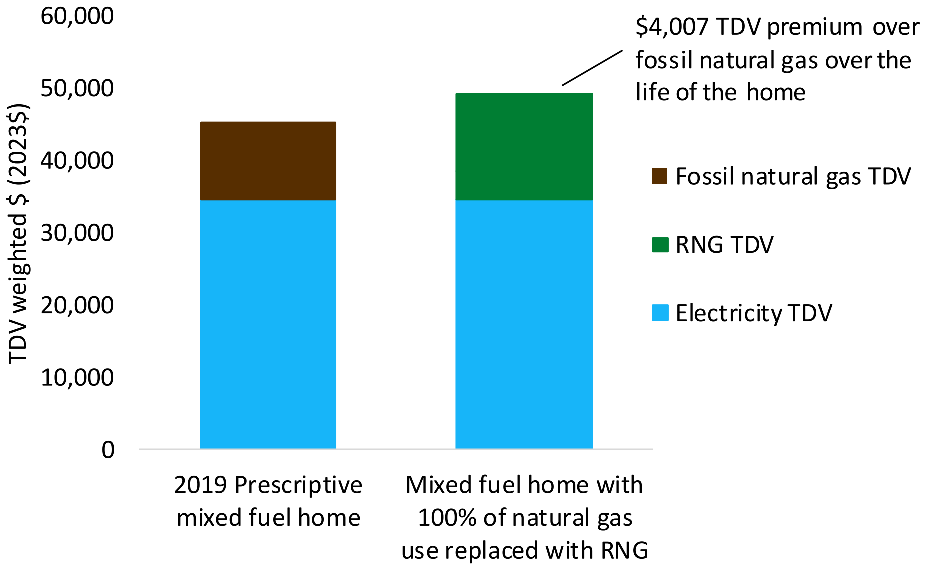

Figure 40 shows that sourcing a mixed-fuel home with renewable natural gas instead of fossil natural gas would incur $4,007 additional cost (TDV premium over life of home).

Source: Lawrence Berkeley National Laboratory

Further, unlike the ZNE compliance option of rooftop solar (for which a new homeowner can pay an upfront cost for compliance), the use of RNG requires the continual purchase of fuel at future market prices. This makes cost-effectiveness over the lifetime of the home difficult to ensure. A long-term contract for RNG could address this concern, but since RNG prices are subject to high levels of price uncertainty, suppliers and homeowners may not wish to commit to long-range future contracts for this fuel.

This analysis suggests that the RNG mixed-fuel home will not pass the CEC's cost-effectiveness standard in the 2022 cycle. It could, however, be offered as a compliance option. This option could potentially include a blended RNG and fossil-based natural gas mix to reduce costs to the homeowner, though this would mean that homes would not exclusively use energy sources that are defined by state agencies as carbon neutral.

Assuming that the ultimate goal of ZNE is for homes to use only energy sources that are classified as carbon neutral, it is useful to compare the cost-effectiveness of new all-electric versus new mixed-fuel-with-RNG homes as shown in Figure 41. Note that this comparison only considers the cost of fuel and does not analyze the capital cost differences of each type of residential construction. Again, the parity price for RNG is $27.36/MMBtu (retail), which is at the low end of the forecasted RNG supply curve in 2020. Any higher price would make the new mixed-fuel-with-RNG home more expensive than the new all-electric home.

Figure 41: California Energy Commission 2019 Code-Compliant Mixed-Fuel Home versus Fossil Natural Gas Replaced by 100 Percent Renewable Natural Gas

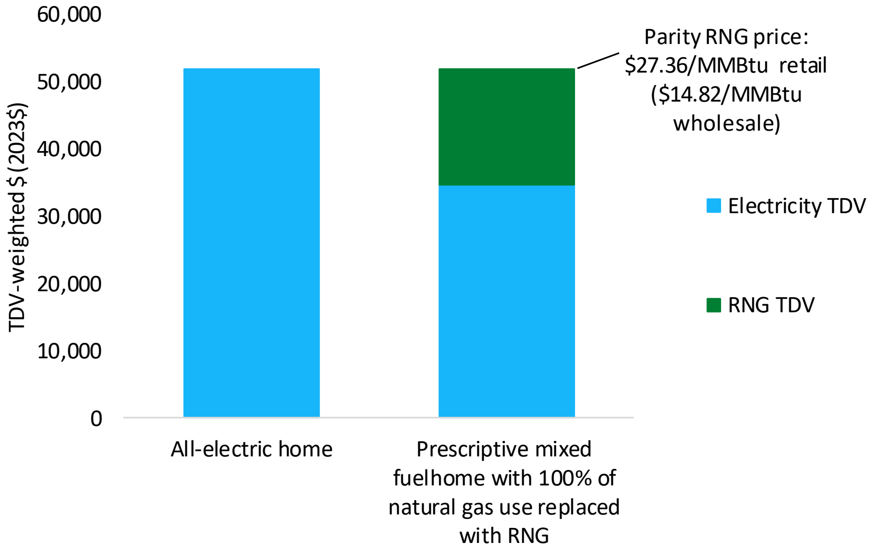

Figure 41 shows that to achieve equivalent annual energy cost on a TDV-weighted basis, a 2019 code compliant mixed-fuel home would need RNG at a retail price of $21.36/MMBtu.

Source: Lawrence Berkeley National Laboratory

Implementation Challenges for Renewable Natural Gas

There are some key challenges around ensuring ZNE compliance that would need to be addressed to offer RNG as a ZNE compliance option. Unlike the ZNE compliance options of rooftop solar, in which a new homeowner can pay an upfront cost for compliance, use of RNG requires the continual purchase of fuel at future market prices. Policy administrators would need to ensure that homeowners continue to purchase RNG instead of fossil-based natural gas. This could be achieved through:

- Long-term contracts for RNG
- An upfront, lump-sum payment for building lifetime RNG use
- A credit system, like renewable energy credits, under which the carbon-neutral attribute of the RNG is tracked.

Each of these solutions faces barriers. Because RNG prices are subject to high levels of price uncertainty, suppliers and utilities may not wish to commit to long-range future contracts or upfront lump-sum payments for this fuel. This would also have the impact of creating two customer classes for natural gas that see very different prices, with a higher gas rate for homeowners in new homes and a lower gas rate for homeowners in existing homes. This could be viewed by customers as unfair. A credit system is certainly feasible, but has not yet been established, and would require significant coordination among the CEC, CPUC, and gas companies.

Community Solar

The dominant source of generation for new ZNE homes is expected to be rooftop solar participating in the NEM program. However, community renewables provide many potential advantages relative to rooftop solar, including (1) providing ZNE compliance at a lower cost, (2) providing a potential option for ZNE compliance where rooftop solar is infeasible, and (3) reducing the costs to ratepayers who do not install solar.

Providing Zero Net Energy Compliance at Lower Cost

Installing solar in larger installations, as in community solar projects, can take advantage of economies of scale that are not available to rooftop solar at the level of a single home. This decreases the installed cost on a dollar per watt ($/Watt) basis. NREL estimates that as of the first quarter of 2016, larger-scale solar (200kW) costs almost 40 percent less than residential rooftop solar, due largely to reductions in soft costs on a per-watt basis (see Figure B-5 in Appendix B).

The kWh production can also be higher for community solar systems than for rooftop. Rooftop solar is constrained by the limitations of the roof on which it is being installed. Community solar can be installed on sites that do not face these constraints, so that the tilt and azimuth of the panels can be configured to maximize solar production over the course of the year. Additionally, community solar panels can be installed in areas that are free from tree and building shade, which can limit the production of some rooftop systems in the morning or evening.

The cost benefits of community solar apply whether the installation is close to the home load receiving ZNE compliance credit, such as within the same municipality, or further from the load, such as within the same utility service territory.

This combination of lower installed cost on a $/Watt basis and higher output suggest that community solar could meet ZNE goals at a lower total cost to California than mandated residential solar. For example, a 2016 study of the levelized cost in dollars per megawatt-hour ($/MWh) of solar PV at varying scales estimated that community solar systems cost approximately 40 percent less than residential rooftop solar (see Figure B-6 in Appendix B).

Distributed solar today is increasingly being installed in conjunction with energy storage and smart inverter devices, a trend that many expect to increase in the coming years. Smart inverters can control the output of the rooftop solar system in response to the needs of the broader electric system, specifically through voltage control and volt/volt-ampere reactive (VAR) or reactive power optimization. This responsive control can increase the value of the output of the solar system to the utility. Energy storage can increase the value of solar to the grid, by storing excess solar production and discharging in hours when system costs are highest (for example, when natural gas peaking units are running or there is a general system capacity shortage). Just as these smart inverters and energy storage systems can be installed with rooftop solar systems, they can also be installed in conjunction with community solar projects. Thus, the existence of these technologies does not lessen the relative cost advantages of community solar outlined above.

Feasibility

While some new homes can feasibly install rooftop solar, for many new homes it is not feasible. New homes that are built near trees or other tall buildings often experience significant shading that makes the installation of solar panels impractical. Similarly, the orientation, size or roof design of some homes may make it infeasible to install solar arrays that produce enough electricity to offset annual use. For example, in the northern hemisphere solar panels oriented toward the south produce significantly more output than solar panels oriented toward the north. This optimal orientation may not be available for all homes. For some homes, the available roof area may be inadequate for the quantity of solar panels needed, regardless of orientation. Finally, even if a home can feasibly install a rooftop system that is optimally oriented and free from substantial shading, there is the potential that it may not be able to interconnect to the local distribution system, due to constraints such as distribution system overloading or other engineering requirements (California Public Utilities Commission, 2019). The possibility of a rejected interconnection request will increase as penetrations of distributed solar on California's grid continue to increase. For these homes where rooftop solar is infeasible or impractical, community solar is the only viable ZNE compliance option.

Nonparticipant Impacts

Rooftop solar is cost-effective to participants (that is, those customers who install rooftop solar) under a variety of configurations, climate zones, and potential NEM tariff reforms. However, NEM does increase rates for *non-participating* customers through a cost-shift (California Public Utilities Commission, 2013). Under NEM, the utility purchases renewable energy from participating customers at a price equivalent to the full retail rate, which is expected to average $0.20/kWh in California by 2020. (E3; NORESCO, 2017). The difference between this $0.20/kWh and the value of the solar energy, which is approximately $0.10/kWh,[24] is a cost borne by all other non-participating ratepayers. The $0.10/kWh residual cost-shift, when multiplied by the number of expected new homes, creates a cost impact to non-participating ratepayers of approximately $80 million per year in 2020 and rising to $240 million per year by 2022.[25] These costs increase rates to non-participating customers. In contrast, if the utility were able to construct community renewables for a levelized price lower than this retail rate ($0.20/kWh), the impacts on non-participating customers would be reduced. Based on the forecasted prices of large-scale community solar listed described previously, these systems can be constructed for 40 percent to 60 percent less than the full retail rate of $0.20/kWh.[26] This suggests that there are cost reduction opportunities for the utilities to pursue on behalf of their non-NEM customers that could mitigate rate impacts.

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[24] 2019 CEC TDV model (average of all TDV components except for Retail Rate Adder).

[25] $0.10/kWh cost-shift multiplied by 8000 kWh/yr per new home, multiplied by approximately 100,000 new home starts per year.

[26] $2.13/W and $1.42/W equates to $0.12/kWh and $0.08/kWh, which is 42 percent and 61 percent less than the $0.20/kWh retail rate, respectively. Assumptions: 18 percent capacity factor, 7 percent nominal discount rate, 25-year PV system life.

Potential Community Renewables Solutions

There are solutions that the CEC, CPUC, and investor-owned utilities could collectively pursue as a workable and attractive new community renewables program for ZNE compliance. The research team presents two hypothetical community renewables programs. The treatment here is not meant to be comprehensive or exhaustive, however, nor to address all the challenges and barriers associated with community renewables such as ownership structures, capital sources, cash flow issues, incentive options, and past examples from other states.

Ratepayer-Funded Green Tariff

A ratepayer-funded green tariff could be designed to meet the three criteria described previously: (1) providing ZNE compliance at lower cost, (2) providing a potential option for ZNE compliance where rooftop solar is infeasible, and (3) reducing the costs to ratepayers who do not install solar. In this hypothetical program, the load-serving entity (LSE) would commit to procuring renewable energy for a new home. The incremental cost of this renewable energy would be recovered from all ratepayers, to make the program cost-effective for the participant. At an estimated community renewable cost premium of $0.02/kWh, this program would create a cost to non-participants of approximately $16 million in 2020,[27] which is substantially less than the $80 million 2020 non-participant cost impact that is predicted from rooftop solar participating in NEM as it is currently defined. Because the LSE would administer this program, it could provide a streamlined verification process to building departments to ensure that the community renewables meet all necessary ZNE compliance criteria. In particular, the fact that this solution is cost-effective to the participant should reduce concerns of subscriber attrition.

Upfront Green Tariff

Another option is an upfront green tariff. In this case, the owner or builder of a new home would have the option to purchase a 30-year supply of community renewable electricity to be attributed to the home as a ZNE compliance measure in lieu of installing rooftop solar. The cost of this option would be set as the net present value of the cost premium of community renewable solar power over standard electric power. This amount would vary for each home, but under today's prices would total approximately $2,000 per home.[28] This payment would fund LSE investments in community solar assets that would be used to serve to the home. Once the new homeowner had paid the upfront charge, he or she would receive full electric service from the LSE at standard electric service rates.

Since the participant bears the cost premium of community renewable energy in this case, there is no cost impact to other ratepayers. However, because this option imparts a significant additional cost to the homeowner, it is not cost-effective to the participant. It therefore cannot be mandated by the CEC for ZNE compliance but may be offered as a compliance *option*. Since it is not cost-effective to the participant, it is not clear that this option would encourage community renewables as a ZNE compliance mechanism at scale. Most homeowners are likely

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[27] Assumes 8,000 kWh/yr per new home, $0.02/kWh community renewables premium, 100,000 new home starts in 2020. Nominal dollars.

[28] 8000 kWh/yr, $0.02/kWh community renewable premium, 30-yr life, 7 percent discount rate.

to prefer rooftop solar with NEM. However, this option would provide homes with an alternative compliance option where rooftop is infeasible or otherwise unwanted by the homeowner. It also may be more popular with home builders and developers, who are sensitive to home listing prices and may prefer to add the $2,000 upfront cost of this program rather than the full upfront cost of a rooftop solar system.

Expert Elicitation Key Findings

Results from the expert elicitation process were used to determine overall important cost considerations from a range of California builders and to ground-truth important cost estimates and cost deltas for important ZNE measure costs such as air source heat pumps, advanced framing, gas infrastructure costs, and battery storage costs. In many cases, it was difficult to elicit expert opinion on the exact same measures with the same units that were used as inputs to the BEopt modeling tool since builders may operate with different sets of units and often associate aggregated costs with packages of measures. For these cases, the expert elicitation process provided valuable qualitative information, but their inputs were not directly usable to inform BEopt cost inputs.

A summary of key findings from the expert elicitation task is provided here with a fuller discussion of expert inputs on ZNE construction costs in Appendix C.

Current and Future Costs

- Several builders think there is lower cost for all-electric homes vs. mixed-fuel homes since the savings from avoided gas infrastructure outweighs the cost increases from electric HVAC and water heating systems.
- Future costs are highly uncertain, but builders noted that heat pump HVAC system costs could drop 5 percent to 20 percent between now and 2026 and that solar PV system costs could decline by another 5 percent to 10 percent between now and 2026.
- Many builders expressed the following: the sooner that full ZNE compliance is required, the sooner that cost reductions associated with building ZNE homes will occur.

Status and Outlook for All-Electric Homes

- All-electric homes have air quality advantages in that gas-fired appliances may create indoor air quality issues in increasingly airtight homes.
- All-electric may be the end goal, but the market may not be ready for a wholesale shift.
- Eliminating gas could be wasteful since gas is cheap and large-scale infrastructure exists. Remaining gas customers would bear the operational and maintenance expenses for the existing gas infrastructure.
- As there is a consistent demand for gas cooktops, gas dryers, and gas furnaces, some production home builders still plan to have a full gas infrastructure in place so they can provide gas as an option for home buyers.

Community Renewables and Storage/Demand Response

- Most experts hold a positive attitude toward community solar but also noted the regulatory challenges and complexity of making it workable in practice.

- Among interviewees, only a few custom home builders have installed energy storage in their ZNE homes, and none of them had implemented any demand response management system. Production home builders appear more hesitant to try these technologies mainly because of the costs, unless they receive funding opportunities to partner with utilities and research institutes

Market Awareness and Policies

- Builders mentioned a general lack of awareness and knowledge of ZNE homes among home buyers, and builders lack incentives to develop ZNE homes. Establishing an appraisal system to better capture the financial benefits and added value of ZNE homes becomes critical to overcome market barriers from lack of knowledge for both builders and home buyers.
- Care should be taken in the marketing and capabilities of ZNE home. For example, some experts have seen other builders become involved in lawsuits as a result of promoting ZNE homes as having a "zero energy bill" or marketing energy efficient home as ZNE homes.
- Having a clear policy target would facilitate greater ZNE adoption among home builders.

CHAPTER 4: Technology/Knowledge/Market Transfer Activities

The knowledge produced through this study is being transferred in several ways. First, this report discusses the methods and results in detail and will be made available to other research, standards and codes, and deployment teams. For example, the research team has shared data and methods for its precooling analysis with Frontier Energy in its work for the Statewide Utility Team to develop code change proposals for the 2020 California Building Energy Efficiency Standards (Title 24, Part 6). This sharing of data and method approaches will be helpful for the CASE report that will analyze whether the demand-flexibility credit for precooling should be changed. The Statewide Utility Team is comprised of PG&E, SCE, SDG&E, and Los Angeles Department of Water and Power (LADWP).

The team presented the project results in a panel at the 2018 ACEEE Summer Session, "Net Zero: Moving beyond 1% of Homes," held in Pacific Grove, California. This conference provided an opportunity for stakeholders to meet and discuss the effects of electrification on cost-effectiveness of ZNE homes, provide feedback on technical inputs of this work, and learn about best-practice implementations for all-electric, ZNE and ZNE-ready homes. LBNL will continue to present the project results in various stakeholder meetings, including the ASHRAE 2020 Building Performance Analysis Conference & SimBuild, both in August 2020. The team expects these conference presentations will help to stimulate further industry-wide discussions and thinking on ZNE home designs, all-electric ZNE home cost effectiveness, the role of battery storage, and opportunities for precooling for bill savings and/or peak demand reductions. As previously discussed, the research team will make available its data, methods, and results to other research teams or interested stakeholders to support other efforts in code and standards development and techno-economic analysis for ZNE homes.

Additionally, the technical advisory committee for this project included stakeholders from utilities, government agencies, and academia. Through their participation in this project they have helped in the development of assumptions and have reviewed the results as they were developed and in their final form. This will ensure that they understand the benefits of this work and that the results can be used to direct future programs and studies.

Finally, LBNL anticipates publishing the results of this analysis in a journal. The article is in preparation; publication is expected in 2021. This will make the data, methods, and results of this work broadly available to the research, development, and deployment (RD&D) communities on a national and international level. In addition to communicating and archiving the key findings of this work to a wider audience, this publication will also provide an opportunity to highlight to other RD&D stakeholders key areas and opportunities for further cost reductions and other important areas for follow up work (for example, passive homes, thermal storage integration, and greater characterization of the potential cost savings from pre-fabricated components).

This study has helped to prepare the CEC and E3 for the development of final 2022 TDV values, helped the CEC improve their production cost grid modeling (using the PLEXOS tool), and has informed E3’s work on non-residential solar policies.

CHAPTER 5: Conclusions

In conclusion, the research team finds the following key findings from this work:

Building Energy Modeling Key Findings

- New all-electric 2,100 ft^2 homes with cost-optimized designs have lower costs on a 30-year life-cycle cost basis than 2019 Title 24–compliant all-electric reference homes for all climate zones; similarly, cost-optimized designs for mixed-fuel new 2,100 ft^2 homes have lower life-cycle costs than 2019 Title 24–compliant mixed-fuel reference homes in all climate zones.
- New all-electric 2,100 ft^2 homes with cost-optimized designs are comparable to cost-optimized mixed fuel homes on a life-cycle cost basis across most climate zones and have significantly lower CO2 emissions (average of 38 percent, or 26 metric tons, lower).
- All-electric home costs can benefit from eliminating natural gas infrastructure costs.
- For all-electric homes, higher performance heat pump systems with greater energy efficiency (for example, SEER 22 and HSPF 10 heat pumps) are cost-effective for climate zones with high cooling energy demand.
- Greater energy efficiency in large appliances, plug-load management, hot water pipe insulation, and ducts in conditioned space are cost-effective measures across climate zones and building types.
- All-electric single-family homes with cost-optimized designs have an average solar PV system size 1 kW larger than mixed-fuel homes to offset increased electricity consumption.
- When 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 exports).
- PV system orientation facing southwest and west is advantageous compared to south when optimizing life-cycle cost due to coincidence with higher TDV values in the late afternoon.
- Full ZNE homes (TDV-ZNE[29]) can be achieved by oversizing solar PV systems (without storage) to offset the TDV of a building's total annual site energy usage with TDV from PV-generated electricity. However, this violates NEM policy that solar PV output not exceed site electricity consumption.

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[29] Full ZNE homes ("TDV-ZNE") refers to homes that meet the TDV-based ZNE definition described in the Introduction. Homes that are 2019 Title 24 compliant are not TDV-ZNE since they would require much larger PV systems and violate NEM policy.

Community Renewables: Community Solar and Renewable Natural Gas Key Findings

- Community solar — systems where electricity production is shared by more than one household — present an alternative ZNE pathway with the potential to provide the same environmental benefits at a lower cost to Californians compared to onsite rooftop solar PV.
- Existing community solar programs are not financially attractive to participants and do not adequately satisfy CEC-outlined ZNE compliance criteria. There is an important opportunity for the development of new community solar programs that are cost-effective for participants, improve non-participant impacts relative to the status quo, and satisfy CEC ZNE-compliance criteria.
- Using renewable natural gas (RNG) for ZNE compliance presents significant challenges in cost-effectiveness, competing demands in hard-to-decarbonize sectors (industry, trucking), and supply uncertainties. Given the importance of the limited RNG supply to the state's broader GHG goals and the available alternatives to achieve ZNE compliance in new residential construction, there may be more valuable uses for RNG in meeting the state's climate goals than in new residential construction.

Battery Storage Key Findings

- For residential storage to contribute to the state's ZNE goals and be cost-effective to the participant, storage control algorithms must consistently and reliably respond to price signals that are more closely aligned with TDV values than current TOU rates and with less favorable NEM compensation for grid exports 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, or aggregation services, and NEM policy that compensates exported electricity at avoided cost.
- If storage is dispatched a) according to current TOU periods, or b) to charge on solar PV net exports and discharge when load exceeds PV production ("Basic" dispatch), storage cannot achieve TDV-ZNE.[30] Conversely, battery storage that is assumed to respond to TDV price signals added to cost-optimized all-electric home designs can achieve TDV-ZNE.
- If compensated under current TOU rates and NEM2.0 policies, storage is not projected to be cost-effective to the participant even if storage costs reduce over time.[31]
- If storage systems are instead compensated according to TDV values and sized to maximize net TDV benefits,[32] potential benefits from storage depend upon future

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[30] That is, enable the building to consume and produce equal amounts of electricity TDV over each year.

[31] Assuming that 2023 and 2043 costs are 64 percent and 47 percent of 2018 costs, respectively, and based on a forthcoming journal paper by Amol Phadke, et al. of LBNL.

[32] TDV benefits for 2022 to 2052 minus storage costs.

storage cost trajectories. If storage costs decline from present average costs,[33] storage generally sees net TDV benefits, provided the storage is not simply used for backup power.

- Optimal battery size and associated net benefits vary greatly, depending on climate zone, dispatch algorithm, and building load.
- 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 the CEC as part of any market analysis performed to support the inclusion of battery storage in building codes.
- This analysis does not compare the cost-effectiveness of residential storage to distribution system-sited storage. Though residential storage is cost effective to the homeowner under some dispatch methods, battery cost trajectories, and in some climate zones, it may not be cost effective compared to larger scale storage sited at the distribution system (or compared to other potential forms of load management such as demand response from air conditioning or electric vehicles).

Precooling Key Findings

- The CEC's current tool for calculating new home energy consumption, CBECC-Res, currently models a cooling setpoint schedule that enables the home's temperature to rise above the 78°F (26°C) comfort threshold when the building is unoccupied (referred to in this report as the "Base Case" schedule). An optimized precooling schedule that instead dynamically chooses a setpoint schedule each day to minimize TDV costs (hourly net load multiplied by TDV values) often uses more kWh than the Base Case setpoint schedule.
- An optimized precooling schedule could save up to 26 percent of net TDV by shifting electricity consumption from high-cost evening peak periods to lower cost afternoon hours and reducing the amount of power that is exported to the grid at low avoided cost compensation.
- A fully optimized precooling control algorithm is impossible to implement, as it requires perfect foresight of TDV values and cooling needs. However, the research team finds that a single setpoint schedule for all days that is customized by climate zone could provide much of the precooling cost savings provided by an optimized schedule, while being simpler to implement and not requiring forecasting.
- An important benefit of these precooling schedules is that they will increase customers' comfort levels compared to Base Case setpoint schedules.

Policy Implications

- All-electric homes are attractive for their lower overall CO_2 emissions than mixed-fuel homes and are cost effective for all climate zones compared to all-electric 2019 Title 24 compliant homes.

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[33] Assuming that 2023 and 2043 costs are 64 percent and 47 percent of 2018 costs, respectively.

- With tighter building shells and energy-efficient lighting, energy-efficient large appliances (clothes dryers and washers, dishwashers, refrigerators, cooktop stoves, and ovens) are increasingly important for life-cycle energy costs.
- Similarly, plug loads (miscellaneous electric loads, or MELs,) represent a growing fraction of electricity usage, and plug load reduction measures in this study, such as advanced power strip and smart plugs, show promise as cost-effective energy measures.
- With the intent to provide more viable community solar ZNE compliance options, the research team provides two potential designs including a ratepayer-funded Green Tariff and an Upfront Green Tariff.
- Storage systems optimized to maximize net TDV benefits are often smaller than the current Title 24 minimum size of 5 kWh and common commercially available sizes like the 13.5 kWh Tesla Powerwall. Any market analysis performed to support the inclusion of battery storage in building codes should consider this fact.
- Three elements are needed to realize the savings from precooling in new residential construction.
    - The CEC should require or credit the installation of occupant controlled communicating smart thermostats in new construction. This technology is required to enable future control of cooling loads by aggregators or utilities if customers agree to provide this control.
    - The price signal to customers or to aggregators needs to be sufficiently time-differentiated to encourage customers to pre-cool.
    - Customer education efforts are needed to communicate the financial and comfort benefits of precooling and reiterate customer control and opt-out options. These education efforts could be undertaken by the CEC, the CPUC, aggregators, and/or utilities. The research team expects that with these three elements in place, customers are likely to take up precooling to increase their comfort while lowering their electric bills.

Future Work

This project did not consider some available options: passive homes, homes which rely on prefabricated components, high-rise apartment buildings, thermal storage, hydronic heating district heating, and CHP units. Each of these options has potential to some degree and are deserving of consideration for follow up.

The study also did not focus on lower income/affordable units although basic structural designs may be similar for affordable units compared to market-rate units. Nor did the study quantify grid interactions or grid support that can be provided by electrified end uses in the context of ZNE homes. Both are important topics that should continue to be modeled and quantified.

Combined heat and power units, or self-contained distributed energy systems that provide both onsite power and heating, are most cost-effective where there is sufficient year-round heating load. Waste heat from a power generation unit could be used for water heating throughout the year. However, CHP units are generally more cost effective for units that are sized larger than residential unit sizes, since the cost per kW is more attractive at larger system sizes — for example, greater than 50 to 100kW systems for commercial buildings (M. Wei et al. 2014). Also, the CO_2 savings and criteria emissions savings from CHP systems versus grid electricity and conventional natural-gas fired building heating is greater in locations where the supply of grid electricity has large fractions of coal-based power, which is not the case for California (Wei 2018 encyclopedia).

Energy efficiency from ZNE homes also offers intangible benefits from greater comfort and health from indoor/outdoor air quality and potentially greater productivity from ZNE building goals. This study did not quantify those benefits, although it would be an informative area for follow-up work.

Passive homes, thermal storage integration, and greater characterization of potential cost savings from prefabricated components are important areas for follow-up work. As noted above, modeling of mini-split heat pumps in single-family homes is needed. Additionally, modeling of ZNE home designs and subdivisions can be extended to include other sectors such as transportation (for example, optimal ZEV battery charging and discharging), water, and waste for more integrated system design. These types of systems are most readily designed and implemented for new developments.

Thus, new housing in California represents an opportunity to meet multiple policy objectives including ZNE goals, grid harmonization, greater resilience to climate change, affordability, and greater water and resource conservation.

CHAPTER 6:
Benefits to Ratepayers

This research is important to ratepayers because it provides approaches for cost-effective ZNE designs for all-electric and mixed-fuel homes and identifies the conditions under which battery storage and precooling options can be cost-effective. All-electric designs, if adopted by contractors, architects, building owners, residents, and property owners, can lower annual energy costs and realize an average of 38 percent annual CO_2 savings compared to mixed-fuel family homes. All-electric homes with onsite solar or community solar agreements could insulate consumers from future volatility in natural gas prices and increasing electricity prices from the grid.

Increasing the adoption of all-electric ZNE homes across California will improve the health and safety of ratepayers by reducing criteria pollutants from natural gas combustion. To the extent that natural gas consumption will be reduced with greater adoption of alternatives such as electrically powered heat pump-based water heating or space heating, consumer and neighborhood safety will be improved by reducing natural gas distribution, possible leakage, and combustion for onsite heat generation.

Transitioning to ZNE all-electric new single-family and multi-family homes by 2023 would result in more than 50 Mt CO_2 cumulative savings from 2023–2050 with about 0.62 billion therms of natural gas savings in 2050, resulting in 3.3 million metric tons net CO_2 savings in 2050.[34] (Note that this represents savings from shifting from a baseline of gas and electric ZNE new homes to all-electric ZNE homes starting in 2023). The criteria emissions avoided from natural gas combustion in 2050 are estimated to be 1,080 tons of nitrogen oxides (NOx), 1,290 tons of carbon monoxide (CO), and 180 tons of volatile organic compounds (VOC).

With all-electric homes with onsite solar PV coupled with electricity storage, there is the potential for greater resilience in buildings, fewer power outages, and reduced potential hazards associated with power outages. Onsite PV/heat pump heating with storage or solar thermal water heating systems will provide greater reliability of water and space heating service in times of natural disaster, blackouts, or earthquakes. As "distributed heating" technologies such as this become more prevalent, consumers would be less reliant on the natural gas system and the electricity grid. Similarly, onsite PV with storage can provide air conditioning service during a power outage and improve the health and safety of the most vulnerable populations in intense heat waves. Precooling can also improve residential comfort by providing a cooler home when residents come home in the late afternoon.

This work provides intangible ratepayer benefits by providing a detailed modeling framework for ZNE single-family and multi-family homes. An aggressive ZNE building path may provide intangible benefits for the state as a technological and/or industrial leader in various energy

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[34] This assumes 4.9 million new all-electric ZNE homes from 2023 to 2050, or about 175,000 homes per year, and corresponds to about 127 therms per year of natural gas savings and about 0.67 metric tons of CO_2 savings per year per home.

technologies, energy systems, and energy deployments (for example, heat pump systems, demand response controls, electrical and thermal storage). There is also value provided to other regions and states by demonstrating that California is serious about tackling the long-term climate challenge, and studies such as this one can serve as both an example and a call for further action, both within and outside California.

This research also sets the groundwork for the future Title 24 building cycle with new time dependent valuations for 2022 and a “High Renewables” time dependent valuation case with a lower GHG target in 2030 of 30MMt CO_2e in the electricity sector, new zero net energy building designs, and new battery storage and precooling cases.

LIST OF ACRONYMS

Term	Definition
AB 3232	California Assembly Bill 3232, Friedman, Chapter 373, Statutes of 2018
ACE	avoided cost for export
ACH	air changes per hour
AFUE	annual fuel utilization efficiency
BEopt	Building Energy Optimization Tool
California ISO	California Independent System Operator
California ARB	California Air Resources Board
CEE	Consortium for Energy Efficiency
CEF	combined energy factor
CH_4	methane gas
CHP	combined heat and power
CO_2	carbon dioxide
Community solar	community solar, or shared solar, refers to a nearby site separate from the site of the home, with a solar PV installation, a portion of whose output is associated with one residential home.
CPUC	California Public Utilities Commission
CZ	climate zone
DC	direct current
Demand shifting	A type of demand response in which a given electricity load is shifted to a different time of the day, usually to better align with a more favorable electricity rate.
$/kWh	dollars per kilowatt-hour
$/Watt	dollars per Watt
EF	energy factor
E3	Energy and Environmental Economics, Inc.
EIA	United States Energy Information Administration
EPIC	Electric Program Investment Charge. Created by the California Public Utilities Commission in December 2011, supports investments in clean energy technologies that benefit electricity ratepayers of Pacific Gas and Electric Company, Southern California Edison Company, and San Diego Gas & Electric Company.
ft^2	square feet of area
GHG	greenhouse gas, including CO_2, CH_4, N_2O, and many common refrigerant gases

Term	Definition
Grid harmonization	Grid harmonization refers to the concept of adding electricity generation or load in such a way that the grid is not impacted negatively. For example, adding large amounts of solar PV to the grid can result in over generation during certain times of the year; and introducing electricity storage or demand shifting with large amounts of solar PV can provide better grid harmonization.
HPHW	heat pump water heater
HVAC	heating, ventilating, and air conditioning
IEPR	Integrated Energy Policy Report
IRP	integrated resource plan
kW	kilowatts
kWh	kilowatt-hours
LBNL	Lawrence Berkeley National Laboratory
LCFS	Low Carbon Fuel Standard
LSE	load-serving entity
MEL	miscellaneous electric loads
MMBtu	million British thermal units
MMcf	million cubic feet
MMT	million metric tons
MSW	municipal solid waste
NEM, NEM 2.0	Net energy metering. Allows customers who generate their own energy ("customer-generators") to serve their energy needs directly onsite and to receive a financial credit on their electric bills for any surplus energy fed back to their utility.35 NEM 2.0 refers to the current NEM policy for rooftop PV in California.
NPV	net present value
NREL	National Renewable Energy Laboratory
OC	occupancy sensor
Precooling	Precooling is a type of demand shifting where a building is pre-cooled to better coincide with the profile output of solar PV or to coincide with periods of low utility rates.
PV	photovoltaic
RFS	Renewable Fuel Standard
RNG	renewable natural gas. Usually refers to methane which is derived from renewable sources such as biogas from landfills, municipal solid waste, wastewater plants, and dairies.

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[35] http://www.cpuc.ca.gov/general.aspx?id=3800, accessed April 26, 2019

Term	**Definition**
SB 1477	California Senate Bill 1477, Stern, Chapter 378, Statutes of 2018
SB 32	California Senate Bill 32, Pavley, Chapter 249, Statutes of 2016
SB 100	California Senate Bill 100, De León, Chapter 312, Statutes of 2018
SB 1383	California Senate Bill 1383, Lara, Chapter 395, Statutes of 2016
SEER	seasonal energy efficiency ratio
SGIP	Self-Generation Incentive Program
Smart grid	Smart grid is the thoughtful integration of intelligent technologies and innovative services that produce a more efficient, sustainable, economic, and secure electrical supply for California communities.
SNG	synthetic natural gas
TBtu	trillion British thermal units
TDV	Time dependent valuation used in the cost-effectiveness calculations for Title 24. The concept behind TDV is that energy efficiency measure savings should be valued differently depending on which hours of the year the savings occur, to better reflect the actual costs of energy to consumers, to the utility system, and to society. At its root the concept of TDV is quite simple: it holds the total cost of energy constant at forecasted retail price levels but gives more weight to on-peak hours and less weight to off-peak hours. TDV is based on a series of annual hourly values for electricity cost (and monthly costs for natural gas) in a given weather year.
TOU	time-of-use
ZNE	Zero net energy. In buildings, there are different definitions for ZNE depending on source or site energy. In California, the definition for ZNE is based on TDV: "Based on the unit of a single project, a ZNE building is one where the value of the energy produced by onsite renewable energy resources is equal to the value of the energy consumed annually by the building measured using the Time Dependent Valuation metric."
Title 24 Building Code	Building code for California including energy efficiency measures; revised every three years.
Time of use rates (TOU)	TOU rates refer to customer utility rates that vary as a function of time.
U.S. DOE	United States Department of Energy

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APPENDIX A: Previous Work and Additional Information on Modeling Approach

Previous Work

A study by Navigant (2015) examined costs of TDV-ZNE homes in Southern California starting from 2016 Title 24 building codes and considering mixed-fuel and all-electric fuel configurations. Since this study adhered to the TDV-ZNE requirement that ZNE homes must offset 100 percent of their TDV consumption, resultant mixed fuel homes have large PV sizes that can overproduce electricity during certain periods of the year (i.e., these designs are not "grid harmonized"). The study focuses on single-family homes, does not provide as much characterization for multi-family homes, and focuses on current costs but also includes some limited modeling of homes with future anticipated costs.

Deason et al. 2018 describe benefits, barriers, and supporting policies to all-electric homes from a national perspective. This study finds that electrification of end uses in buildings is most cost-effective electrification is most cost-effective in new residential buildings, where a single heat pump can provide heating and cooling, where gas infrastructure costs can be avoided (e.g., in new all-electric buildings or communities), and where winters are mild. The study authors find 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 reduction of total electricity usage. The study highlights that key potential policy enablers include time-varying rates, ZNE building codes (electricity usage being readily offset by onsite generation), demand response programs, and payments for flexible loads

DEG et al. 2017 present all-electric cost-effectiveness for all-electric designs that exceed the requirements of the 2016 Title 24 building code. A key difference from the current study is that their analysis uses a customer-based lifecycle cost (LCC) approach to evaluating cost effectiveness based on investor-owned utility rates with NEM2.0 rooftop solar compensation policy, whereas the CEC LCC methodology (and the current study) uses Time Dependent Valuation (TDV) as the primary metric for energy savings. PV systems are sized in two ways: PV systems sizing to offset approximately 80 percent of estimated annual electricity consumption in a gas/electric home; or sized to offset 100 percent of estimated building site electricity use (total kWh). In all cases for single-family 2450 ft^2 and 8-unit multifamily, all-electric homes are found to have a lifecycle benefit ratio of greater than 1.0.

A recent study by(Mahone et al., 2018), assesses the energy savings, greenhouse gas savings, impacts to the electric grid and overall economics of residential building electrification for customers across several regions of California. E3 modeled the performance and costs of both all-electric new construction homes and existing homes retrofitted with heat pump HVAC systems and heat pump water heaters. These were compared to mixed-fuel homes that use natural gas and electricity. The study finds that all-electric new construction results in savings of $130-$540 per year relative to a gas-fueled home over the life of the equipment. There are cost savings to developers from elimination of costs to lay down gas lines as well as to homeowners, who will see lower bills.

In support of the state's policy goals for ZNE buildings, the CEC has also supported projects to facilitate the modeling of ZNE homes. Milne et al 2017 have developed new software tools to evaluate building envelope performance and a quick-sketch design tool to help Californians create non-residential buildings that exceed the 2013 Title 24 Energy Efficiency Standard and even to approach ZNE.

A recent study has examined the impacts of ZNE communities on the distribution grid. Narayanamurthy et al. 2017 details the design, deployment, construction, selling, and occupying of 20 homes built to California Title 24 ZNE standard with electrified heating. The goal of this study was to understand if the transformers, laterals, load blocks and feeders had sufficient capacity using today's planning methods. To alleviate distribution impact, these homes were set up with controllable loads and with behind-the-meter energy storage. Two important take-aways from the project 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.

Time Dependent Valuation Methodology

Table A-1: Description and Underlying Methodology of Time Dependent Valuation Components

	Component	**Description**	**Basis of Annual Forecast**	**Basis of Hourly Shape**
Marginal Energy Avoided Costs	Generation Energy	Estimate of hourly marginal wholesale value of energy adjusted for losses between the point of the wholesale transaction and the point of delivery	Modified IEPR Production Simulation Results for 2023-2030, escalated based on gas price forecasts thereafter	Modified IEPR Production Simulation Results

	Component	**Description**	**Basis of Annual Forecast**	**Basis of Hourly Shape**
Marginal Energy Avoided Costs	System Capacity	The marginal cost of procuring Resource Adequacy resources in the near term. In the longer term, the additional payments (above energy and ancillary service market revenues) that a generation owner would require to build new generation capacity to meet system peak loads	Fixed costs of a new simple-cycle combustion turbine, less net revenue from energy and AS markets	Effective Load Carrying Capacity track
Marginal Energy Avoided Costs	Ancillary Services	The marginal cost of providing system operations and reserves for electricity grid reliability	Scales with the value of energy	Directly linked with energy shape
Marginal Energy Avoided Costs	System Losses	The costs associated with additional electricity generation to cover system losses	Utility loss factors by season and peak period applied to energy value	Directly linked with energy shape
Marginal Energy Avoided Costs	Transmission and Distribution Capacity	The costs of expanding transmission and distribution capacity to meet customer peak loads	Survey of investor owned utility transmission and distribution deferral values from recent general rate cases	Hourly allocation factors calculated using a regression hourly temperature data and distribution feeder load data

	Component	Description	Basis of Annual Forecast	Basis of Hourly Shape
Marginal Energy Avoided Costs	CO_2 Emissions	The cost of carbon dioxide emissions (CO2) associated with the marginal generating resource	2017 IEPR	Directly linked with energy shape based on implied heat rate of marginal generation, with bounds on the maximum and minimum hourly value
Marginal Energy Avoided Costs	Avoided RPS	The cost reductions from being able to procure a lesser amount of renewable resources while meeting the Renewable Portfolio Standard (percentage of retail electricity usage).	Premium for renewable generation calculated using levelized renewable costs from CPUC RPS Calculator	Constant allocation factor, does not vary by hour
Retail Rate Adder		The components above are scaled to match the average retail rate through the retail rate adder.	2017 IEPR retail rate forecast	Constant allocation factor, does not vary by hour

Source: Lawrence Berkeley National Laboratory

Base Case Time Dependent Valuation DV Values

Table A-2 provides detail on the updated assumptions that the research team made for the Base Case TDV values for 2023–2052. All changes are described relative to the inputs used for the 2019 TDV values.

Table A-2: Updates to Base Case TDV Values for 2023–2052, Relative to Values Used for 2019 TDV Values

Element	Description of update
Generation Energy	We used CEC's PLEXOS model updated for the CEC's 2017 Integrated Energy Policy Report Update (IEPR). The results are shown in Figure 2. This update included changes to: • Generator fuel prices. Most notably, natural gas prices declined 33 percent. This lower generation cost is expected to lead to cheaper, more flexible resources, putting downward pressure on prices • Carbon prices, which increased 36 percent compared, putting upward pressure on energy prices • The modeling of electricity exchange between California and out-of-state entities. Previously, the CEC's PLEXOS cases did not include significant constraints on the export of energy from California, instead assuming that other states would absorb any renewable overgeneration. The updated PLEXOS case used for this report models all WECC entities and transmission constraints. • Generation resources, including a) the resources needed to meet the 50 percent RPS by 2030 required by SB350 (50 percent RPS assumed for all years post 2030), and b) announced and anticipated plant retirements The research team made the following changes to the CEC's PLEXOS model: • Repaired parametric characteristics of several hydro generators, which had offsetting impacts on increasing and reducing the flexibility of generation in the model • Enforced curtailment penalties on solar and wind plants in the model to eliminate no-cost curtailment of renewable energy.
System Capacity	Higher renewable penetration displaces generation from gas combustion turbines (CTs), which decreases their capacity factors. Lower capacity factors for CTs translates to a reduction in their energy revenue, so they require more compensation through the capacity market. Because CTs are the marginal capacity resource, capacity value increases.
CO_2 Emissions	A 36 percent increase in monetized carbon price increased the average emissions value. Higher penetration of solar in the updated generation fleet reduced the emissions value during the middle of the day.

Element	Description of update
Retail Rates	Statewide average electric retail rates in IEPR 2017’s forecast are 3 percent lower than those used for 2019 TDV values. In periods with low load and high renewable generation, renewable curtailment causes negative energy prices, which reduces the otherwise constant retail adder component of the TDV values. Because the retail adder component is applied as an adjustment to ensure the annual average TDV equals the average retail rate, the reduction of the retail adder in curtailment periods causes the retail adder to be higher in all other periods.

Source: Lawrence Berkeley National Laboratory

Higher Renewables Time Dependent Valuation Sensitivity Case

The research team created a second, sensitivity set of 2023–2052 TDV values that aimed to provide insight into the effects of a potential future with even higher renewable penetration than the Base Case.

For this case, the research team integrated results from the RESOLVE cases run by E3 for the California Public Utilities Commission (CPUC) Integrated Resource Planning process in 2017. Specifically, the team used the ‘IRP 30 Million Metric Tons (30MMT) case’, which models the least-cost approach to reaching statewide electric sector emissions of 30 MMT in 2030.This case results in a CAISO generation portfolio corresponding to a nearly 70 percent RPS in 2030 versus the SB350-required 50 percent by 2030 that is represented in the Base 2022 TDV values.[36]

The additional generation resources in the 30MMT case consist largely of solar, plus some wind, geothermal, and grid-level battery and pumped storage.

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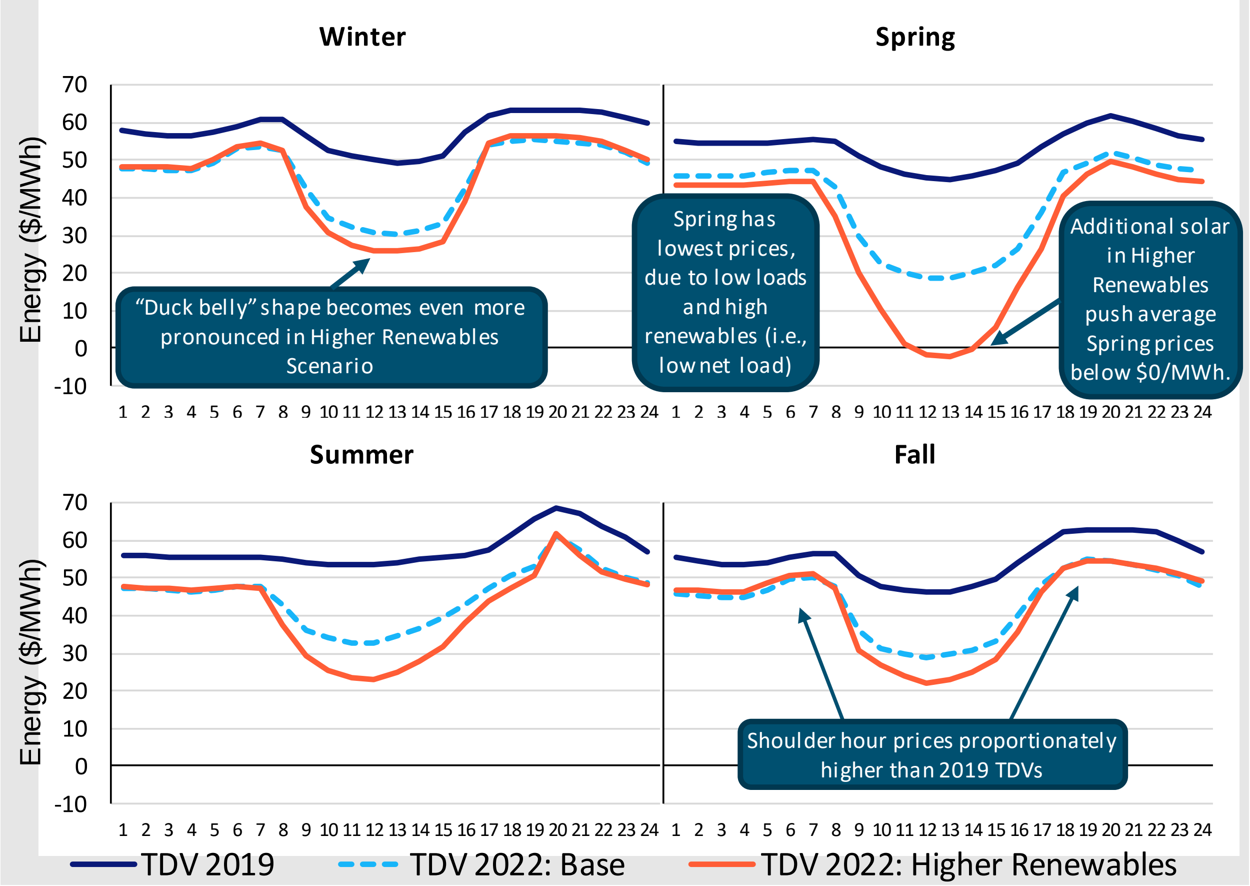
[36] In September 2018, SB 100 was approved which increased the 2030 RPS target to 60 percent from the 50 percent target in SB350. This increase in RPS target was passed after E3 computed their updated TDV values. The SB 100 TDV values for electricity are thus in between those for the ‘Base’ case and the ‘Higher Renewables’ case.

Table A-3: Modified Assumptions in Higher Renewables Time Dependent Valuation Sensitivity Case, Relative to Base Case

Element	Description of update
Generation Energy	The RESOLVE generation resources that are incremental to those in the Base Case PLEXOS runs were mapped to California and out-of-state zones in PLEXOS Changes in energy price shapes from 2019 TDV to Base 2022 TDV continue directionally in the Higher Renewables case (see Figure 2). • A lower "duck belly" as additional solar penetration depresses average energy prices during the middle of the day • Curtailment of renewables in the low load, high solar and hydro spring months becomes so prevalent that the average day has negative energy prices • An assumed 6,300 MW (vs. 1,300 MW in the Base Case) of grid-level battery and pumped storage does reduce some of the hourly variability and renewable curtailment
System Capacity	The higher renewable penetration referenced in the cell above displaces generation from gas combustion turbines (CTs), which decreases their capacity factors. Lower capacity factors for CTs translates to a reduction in their energy revenue, so they require more compensation through the capacity market. Because CTs are the marginal capacity resource, capacity value increases.
CO_2 Emissions	Higher solar penetration continues to reduce the average emissions value during the middle of the day
Retail Rates	Annual average retail rates of electricity from the 30MMT RESOLVE case were added to the TDV model. A higher average cost of renewable generation over conventional resources increases the average retail adder relative to the Base Case 2022 TDV values. With negative energy prices occurring more frequently than the Base Case 2022 TDV values, the retail adder is pushed more to hours without solar curtailment.

Source: Lawrence Berkeley National Laboratory

Figure A-1: Energy Price Impacts of Time Dependent Valuation Scenario Updates: Modeled 2026 Hourly Energy Prices for Seasonal Average Day in PG&E Valley



“Duck belly” shape becomes even more pronounced in Higher Renewables Scenario

Spring has lowest prices, due to low loads and high renewables (i.e., low net load)

Additional solar in Higher Renewables push average Spring prices below $0/MWh.

Shoulder hour prices proportionately higher than 2019 TDVs

Source: Lawrence Berkeley National Laboratory

Figure A-1 shows how the changes for each TDV scenario described above impact energy prices modeled in PLEXOS.

Source: Lawrence Berkeley National Laboratory

Storage Control Algorithms

1. Optimized Dispatch, which assumes that each battery is dispatched to maximize TDV values in each hour of each 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. This dispatch approach is designed to reflect a situation in which homeowners are provided with hourly TDV signals but face some forecast error rather than having perfect foresight.
3. Time of Use (TOU) Dispatch, under which batteries are assumed to dispatch in response to on-peak and off-peak TOU periods. The research team implemented this approach by averaging TDV values across on-peak and off-peak TOU periods for existing 4-9pm TOU rates of the investor-owned utility that corresponds to each CZ[37]
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.[38] Because the value of backup power is based on specific events, no dispatch was modeled for this system. The value shown for these systems in each use case is simply the cost of a battery sized to maximize net benefits under Basic dispatch, which is much smaller than capacities typical of backup batteries.

2019 Title 24 Prescriptive Requirements

Table A-4: Relevant Updates to 2019 Title 24 Envelope Prescriptive Requirements

Component	2016 Code	2019 Code Update
Exterior Walls	2x6 R-21 + 1" R-4: 0.051 U-factor (CZ 1-5, 8-16) 2x4 R-15 + 1" R-4: 0.065 U-factor (CZ 6-7)	SINGLE-FAMILY: 2x6 R-21 + 1" R-5: 0.048 U-factor (CZ 1-5, 8-16) No change (CZ 6-7) MULTIFAMILY: No change (CZ 1-16)
Wall to Garage / Kneewall	2x6 R-21 (CZ 1-5, 8-16) 2x4 R-15 (CZ 6-7)	No change (CZ 1-16)

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[37] PG&E E-TOU-B for CZs 1-5, 11-13; SCE TOU-D-4-9PM for CZs 6, 8-10, 15, 16; SDG&E TOU-DR-SES for CZs 7, 14

[38] See "Self Generation Incentive Program Reports," http://www.cpuc.ca.gov/general.aspx?id=7890

Component	2016 Code	2019 Code Update
Foundation Type & Insulation	Uninsulated slab (CZ 1-15) R-7 slab perimeter insulation (CZ 16)	No change (CZ 1-16)
Floor (Above Garage / Cantilever)	R-19 between framing	No change (CZ 1-16)
Roof/Ceiling Insulation & Attic Type	Vented w/ R-38 at ceiling, R-13 under roof deck (tile roof); R-18 under deck (asphalt) (CZ 4, 8-16) Vented w/ R-38 at ceiling only (CZ 1-2) Vented w/ R-30 at ceiling only (CZ 3, 5-7)	SINGLE-FAMILY: Vented w/ R-38 at ceiling, R-19 under roof deck (tile roof) (CZ 4, 8-16) No change (CZ 1-3, 5-7) MULTIFAMILY: Vented w/ R-38 at ceiling, R-19 under roof deck (tile roof) (CZ 4, 8, 9, 11-15) No change (CZ 1-3, 5-7, 10, 16)
Roofing Material & Color	Cool roof: ≥0.20 solar reflectance, ≥0.75 thermal emittance (CZ 10-15)	No change (CZ 1-16)
Radiant Barrier	Yes (CZ 2-3, 5-7)	No change (CZ 1-16)
Window Properties: U-Value / SHGC	Vinyl Low-E: 0.32 / 0.25 (CZ 1-16) 0.50 SHGC (CZ 1, 3, 5)	Vinyl Low-E: 0.30 / 0.23 (CZ 1-16) 0.35 SHGC (CZ 1, 3, 5, 16)
Opaque Doors	No requirement (default assumption of 0.50 U-value) (CZ 1-16)	Insulated, ≤0.20 U-value (CZ 1-16)
Quality Installation	No	Yes (full R-value)
House Infiltration	5 ACH50 assumed (7 ACH50 for multifamily) (CZ 1-16)	No change (CZ 1-16)

Source: Lawrence Berkeley National Laboratory

Table A-5: Relevant Updates to 2019 Title 24 HVAC Prescriptive Requirements

Component	2016 Code	2019 Code Update
System Type & Description	Ducted gas furnace & A/C Heat pump (if proposed is electric heating)	No change
Heating Efficiency (AFUE, COP or HSPF)	78 AFUE 8.2 HSPF (if proposed is electric heating)	No change
Cooling Efficiency (SEER/EER)	14 SEER, 12.2 EER	14 SEER, 11.7 EER

Component	2016 Code	2019 Code Update
Duct Location & Insulation	Attic, R-8 insulation (CZ 1-2, 4, 8-16) R-6 (CZ 3,5-7) Multifamily: ducts in conditioned space	No change
Mechanical Ventilation	Exhaust, 2010 ASHRAE 62.2	Exhaust, 2016 ASHRAE 62.2
Nighttime Ventilation Cooling	Whole house fan, 1.5 cfm/ft^2 (CZ 8-14) Multifamily: none	No change
Duct Leakage	Tested, 5 percent	No change
Verified Fan Watt Draw	0.58 W/cfm	0.45 W/cfm

Source: Lawrence Berkeley National Laboratory

Table A-6: Relevant Updates to 2019 Title 24 Water Heating Prescriptive Requirements

Component	2016 Code	2019 Code Update
System Type & Description	Tankless gas Central large gas water heater for multifamily if proposed is central	SINGLE-FAMILY: Tankless gas Heat pump (if proposed is electric water heating) located in the garage if one exists & conditioned space if not. MULTIFAMILY: Central large gas water heater (if proposed is central) Individual gas water heaters (if proposed is individual)
Water Heater Efficiency	0.82 EF (tankless) 80 percent thermal efficiency (central)	0.82 EF (tankless) 2.0 UEF (HPWH) 80 percent thermal efficiency (central)
Solar DHW: System Description + Solar Fraction	SINGLE-FAMILY: No requirement MULTIFAMILY: 20 percent solar fraction (CZ 1-9), 35 percent solar fraction (CZ 10-16)	No change
Distribution Type	All pipes insulated	All pipes insulated Compact distribution (if proposed is electric water heating)

Component	2016 Code	2019 Code Update
Drain Water Heat Recovery	No requirement	Serving showers only, 70 percent efficiency (if proposed is electric water heating)
Hot Water Fixtures	2 gpm showerhead, 1.2 gpm bath faucets, 1.8 gpm kitchen faucets, 1.28 gal/flush toilet	No change

Source: Lawrence Berkeley National Laboratory

Table A-7: Relevant Updates to 2019 Title 24 Prescriptive Requirements for Other Features

Component	2016 Code	2019 Code Update
Lighting Type	100 percent high-efficacy	No change
Lighting Controls	Vacancy sensors	No change
Refrigerator	Meet federal minimum standards	No change
Dishwasher	Meet federal minimum standards	No change
Cooking	No requirement	No change
Clothes Washer	Meet federal minimum standards	No change
Clothes Dryer	Meet federal minimum standards	No change
Home Energy Management System	No requirement	No change
Solar PV	No requirement	Meet EDR target to be set by CEC, ~100 percent electricity use of mixed fuel home
Storage	No requirement	No change
Demand Response	No requirement	No change

Source: Lawrence Berkeley National Laboratory

Table A-8: Envelope Options for Zero Net Energy Homes

Component	Option	Incremental Cost vs 2019 Title 24*	Cost Data Source
Wood Stud	R-23 fiberglass batt, Grade 1, 2x6, 24 inch o.c., framing factor=0.17	$0.28/ft^2 (CZ 1-5, 8-16) $0.50/ft^2 (CZ 6-7)	BEopt
Wall Sheathing	1" XPS, R-5	SINGLE-FAMILY: $0.00/ft^2 (CZ 1-5, 8-16) $0.18/ft^2 (CZ 6-7) MULTIFAMILY: $0.18/ft^2 (CZ 1-16)	BEopt
Wall Sheathing	2" XPS, R-10	SINGLE-FAMILY: $0.67/ft^2 (CZ 1-5, 8-16) $0.85/ft^2 (CZ 6-7) MULTIFAMILY: $0.85/ft^2 (CZ 1-16)	(German, 2017)
Wall Sheathing	2" polyiso, R-12	SINGLE-FAMILY: $1.08/ft^2 (CZ 1-5, 8-16) $1.26/ft^2 (CZ 6-7) MULTIFAMILY: $1.26/ft^2 (CZ 1-16)	(German, 2017)
Unfinished Attic	Roof R-38 Open Cell Spray Foam, Unvented	SINGLE-FAMILY: Ceiling -$1.61/ft^2 / Roof: $4.74/ft^2 (CZ 1-2) Ceiling -$1.29/ft^2 / Roof: $4.74/ft^2 (CZ 3, 5-7) Ceiling -$1.61/ft^2 / Roof: $4.02/ft^2 (CZ 4, 8-16) MULTIFAMILY: Ceiling -$1.61/ft^2 / Roof: $4.74/ft^2 (CZ 1-2) Ceiling -$1.29/ft^2 / Roof: $4.74/ft^2 (CZ 3, 5-7) Ceiling -$1.61/ft^2 / Roof: $4.02/ft^2 (CZ 4, 8, 9, 11-15) Ceiling: -$1.61/ft^2 / Roof: $4.16/ft^2 (CZ 10, 16)	BEopt

Component	**Option**	**Incremental Cost vs 2019 Title 24***	**Cost Data Source**
Unfinished Attic	Roof R-49 Open Cell Spray Foam, Unvented	SINGLE-FAMILY: Ceiling -\$1.61/ft^2 / Roof: \$5.92/ft^2 (CZ 1-2) Ceiling -\$1.29/ft^2 / Roof: \$5.92/ft^2 (CZ 3, 5-7) Ceiling -\$1.61/ft^2 / Roof: \$5.20/ft^2 (CZ 4, 8-16) MULTIFAMILY: Ceiling -\$1.61/ft^2 / Roof: \$5.92/ft^2 (CZ 1-2) Ceiling -\$1.29/ft^2 / Roof: \$5.92/ft^2 (CZ 3, 5-7) Ceiling -\$1.61/ft^2 / Roof: \$5.20/ft^2 (CZ 4, 8, 9, 11-15) Ceiling: -\$1.61/ft^2 / Roof: \$5.34/ft^2 (CZ 10, 16)	BEopt
Unfinished Attic	Ceiling R-49 Grade-1 Cellulose, Vented	SINGLE-FAMILY: \$0.44/ft^2 (CZ 1-2) \$0.76/ft^2 (CZ 3, 5-7) Ceiling: \$0.44/ft^2 / Roof: -\$0.72/ft^2 (CZ 4, 8-16) MULTIFAMILY: \$0.44/ft^2 (CZ 1-2) \$0.76/ft^2 (CZ 3, 5-7) Ceiling: \$0.44/ft^2 / Roof: -\$0.72/ft^2 (CZ 4, 8, 9, 11-15) Ceiling: \$0.44/ft^2 / Roof: -\$0.58/ft^2 (CZ 10, 16)	BEopt
Unfinished Attic	Ceiling R-60 Gr-1 Cellulose, Vented	SINGLE-FAMILY: \$0.88/ft^2 (CZ 1-2) \$1.20/ft^2 (CZ 3, 5-7) Ceiling: \$0.88/ft^2 / Roof: -\$0.72/ft^2 (CZ 4, 8-16) MULTIFAMILY: \$0.88/ft^2 (CZ 1-2) \$1.20/ft^2 (CZ 3, 5-7) Ceiling: \$0.88/ft^2 / Roof: -\$0.72/ft^2 (CZ 4, 8, 9, 11-15) Ceiling: \$0.88/ft^2 / Roof: -\$0.58/ft^2 (CZ 10, 16)	BEopt

Component	Option	Incremental Cost vs 2019 Title 24*	Cost Data Source
Roof Material	Cool Roof medium color asphalt, 0.25 reflectance 0.85 emittance	\$0.06/ft^2	(California Statewide Utility Codes and Standards Program, 2011)
Roof Material	Cool Roof light color asphalt, 0.40 reflectance 0.85 emittance	\$0.50/ft^2	(Levinson et al., 2016)
Radiant Barrier	Yes (attic insulation cases w/ no below roof deck insulation)	\$0.12/ft^2 (CZ 1, 4, 8-16) \$0.00/ft^2 (CZ 2-3, 5-7)	(J. Wei, Pande, Chappell, Christie, & Dawe, 2016)
Windows	Low-E, double-pane, non-metal, argon-filled, low SHGC (U 0.25, SHGC 0.23)	\$4.23/ft^2	(Hendron & Hoeschele, 2018)
Windows	Low-E, triple-pane, nonmetal, air-filled, high SHGC: (U 0.22, SHGC 0.44)	\$7.00/ft^2	(Hendron & Hoeschele, 2018)
Air Leakage	5 ACH50	SINGLE-FAMILY: \$0.00/ft^2 MULTIFAMILY: \$0.02/ft^2	BEopt
Air Leakage	4 ACH50	SINGLE-FAMILY: \$0.02/ft^2 MULTIFAMILY: \$0.04/ft^2	BEopt
Air Leakage	3 ACH50	SINGLE-FAMILY: \$0.06/ft^2 MULTIFAMILY: \$0.08/ft^2	BEopt
Air Leakage	2 ACH50	SINGLE-FAMILY: \$0.17/ft^2 MULTIFAMILY: \$0.19/ft^2	BEopt

*** A-8 ft^2 of exterior wall area for wall insulation measures, ceiling area for attic floor insulation, roof area for roof deck insulation and radiant barriers, window area for advanced windows, and conditioned floor area for air leakage.**

Source: Lawrence Berkeley National Laboratory

Table A-9: Heating, Ventilation, and Air Conditioning Options for Zero Net Energy Homes

Component	Option	Incremental Cost vs 2019 Title 24	Cost Data Source
Mechanical Ventilation	Balanced HRV system, 2016 ASHRAE 62.2, 70 percent efficiency, 0.3 W/cfm	$669.34	BEopt
Central Air Conditioner	15 SEER, 13 EER	SINGLE-FAMILY: $123.00 for 3 tons MULTIFAMILY: $61.50 for 1.5 tons	BEopt
Central Air Conditioner	16 SEER, 13 EER, 2-speed	SINGLE-FAMILY: $247.00 for 3 tons MULTIFAMILY: $123.50 for 1.5 tons	BEopt
Furnace	92.5 AFUE gas furnace	$452 for 60 kBtuh	BEopt
Air Source Heat pump	SEER 15, 8.5 HSPF	$217.50	BEopt+50 percent based on previous projects
Air Source Heat pump	SEER 16, 8.6 HSPF	$435.00	BEopt+50 percent based on previous projects
Air Source Heat pump	SEER 18, 9.3 HSPF	$871.50	BEopt+50 percent based on previous projects
Air Source Heat pump	SEER 22, 10 HSPF	$1743.00	BEopt+50 percent based on previous projects
Mini-Split Heat Pump for Multifamily Building (15kBtu/hr)	SEER 20, 10.3 HSPF	$295.50	BEopt+50 percent based on previous projects
Mini-Split Heat Pump Multifamily Building (15kBtu/hr)	SEER 25.3, 10.3 HSPF	$510.50	BEopt+50 percent based on previous projects
Ducts	In Finished Space	$2.55/ft^2 (CZ 1-2, 4, 8-16) $2.63/ft^2 (CZ 3, 5-7)	BEopt

Source: Lawrence Berkeley National Laboratory

Table A-10: Hot Water Options for ZNE Homes

Component	Option	Incremental Cost vs 2019 Title 24	Cost Data Source
Water Heater	Gas Condensing Tankless, 0.92 EF	$429	(Davis Energy Group, Misti Bruceri & Associates LLC, & Enercomp Inc, 2017)
Water Heater	HPWH, 50 gal, 3.7 UEF	$422	(Davis Energy Group et al., 2017)
Distribution	R-5, PEX, Demand	$0.48/ft pipe + $300 pump	BEopt
Solar Water Heating	20 ft^2/unit	$6859	BEopt scaled based on collector area
Solar Water Heating	40 ft^2/unit	$7179	BEopt

Source: Lawrence Berkeley National Laboratory

Table A-11: Other Options for ZNE Homes

Component	Option	Incremental Cost vs 2019 Title 24	Cost Data Source
Refrigerator	Bottom freezer, EF=21.3	$458.81	BEopt
Cooking Range	Gas cooktop (Optimized Burner/ Grates)/Gas Self-Cleaning Oven -Free Standing (Baseline + Standby-SMPS + Electronic Spark Ignition + Forced Convection + Reduced Conduction Losses)	$43.84	Federal Energy Efficiency Standards and/or Compliance Certification Database[39]
Cooking Range	Electric Smooth Cooktops Standby - SMPS, Automatic power down, Induction/ Electric Self-Cleaning Oven - Free Standing (Baseline + Standby - SMPA+ Forced Convection + Oven Separator + Reduced Conduction Losses)	$327.31	Federal Energy Efficiency Standards and/or Compliance Certification Database[43]
Dishwasher	Dishwasher Gap Fill_1, 86 kWh/unit/yr	$74.00	Federal Energy Efficiency Standards and/or Compliance Certification Database[43]

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[39] https://www.regulations.doe.gov/certification-data/#q=Product_Group_s percent3A*

Component	Option	Incremental Cost vs 2019 Title 24	Cost Data Source
Dishwasher	Dishwasher Maximum Available, 69 kWh/unit/yr	$160.00	Federal Energy Efficiency Standards and/or Compliance Certification Database[43]
Clothes Washer	Standard Front-loading CEE Tier 2	$334.10	Federal Energy Efficiency Standards and/or Compliance Certification Database[43]
Clothes Dryer	Vented Gas Standard: Modulating Heat EF 4.7	$57.80	Federal Energy Efficiency Standards and/or Compliance Certification Database[43]
Clothes Dryer	Vented Gas Standard: Max-Tech EF 5.0	$170.50	Federal Energy Efficiency Standards and/or Compliance Certification Database[43]
Clothes Dryer	Vented Elec Standard: Energy Star EF 3.93	$35.30	Federal Energy Efficiency Standards and/or Compliance Certification Database[43]
Clothes Dryer	Vent-less Elec Standard: Heat Pump Dryer (Max-Tech) EF 4.5	$755.60	Federal Energy Efficiency Standards and/or Compliance Certification Database[43]
PV System	0.1 kW incremental for single-family, 0.5 kW incremental for multi-family	$3.00/W	BEopt

Source: Lawrence Berkeley National Laboratory

Options not included in the final BEopt analysis:

- **Mini-Split heat pumps in single-family homes:** Several questions about the installed performance of mini-split heat pumps compared to the seasonal performance suggested by SEER/HSPF ratings remain unresolved. AHRI 210/240-2008 does not test variable capacity systems under a realistic range of operating conditions, including under low-load and extreme temperature conditions. As a result, HSPF and SEER ratings often imply greater savings compared to single-speed heat pumps than observed in laboratory and field tests. A new standard for variable speed heat pumps is currently under development by the Canadian Standards Association with support from U.S. partners including PG&E, but there is insufficient data on real equipment tested using this procedure to justify a particular methodology for adjusting performance characteristics in BEopt. The 2019 update to the Title 24 Alternative Calculation Method (ACM) includes new rules for modeling mini-split heat pumps, but the updated ACM was not yet available when the optimization analysis was performed for this project. Additionally, there was a fair amount of discontent expressed by manufacturers during the ACM Public Workshop at CEC. The sizing of mini-splits for single-family homes in BEopt was also an issue with undersized units being deployed for large homes. For this study, mini-split heat pumps were applied to the multifamily prototype model with all-electric apartment units. The cooling capacity for each apartment unit is less than 1 ton, thus 1.25 ton (15 kBtu/hr) mini-split heat pump systems are used for multifamily all-electric scenario analysis.

- **Slab insulation:** The preliminary modeling results for slab insulation measures indicated excellent cost-effectiveness, but upon closer examination the energy savings calculations appeared unrealistic from a building science standpoint. By comparing results from the latest version of BEopt (2.8) to the previous version (2.7), the team was able to determine that one of the updates included a new ground heat transfer model[40] that predicted smaller cooling and heating loads when slab insulation is used, instead of higher cooling loads as predicted by the earlier version of the software. Given that NREL is no longer able to provide technical support for BEopt and explain the difference, the team decided that the modeling results were suspect and removed slab insulation from the optimization.
- **Central heat pump water heaters (HPWH) and solar hot water for multifamily buildings:** Although central hot water systems can be modeled in BEopt, there is no ability to model a central heat pump water heater with high accuracy. In addition, an extensive search for reliable cost data did not result in a cost equation in which the research team had enough confidence to include central HPWHs in the optimization. Instead, individual heat pump water heaters were modeled, recognizing this measure would not be as cost-effective as a central system for larger multi-family buildings. A similar situation arose with solar hot water, where BEopt performs the analysis on a per-unit basis for multi-family buildings. A central solar system would likely be much more cost-effective, but BEopt does not currently have the ability to model the energy savings accurately.

MELs reduction measures savings estimates

1. Tier 2 advanced power strips with infrared (IR) and occupancy sensor. The occupancy sensor helps prevent false positives and increases occupant satisfaction but results in missed opportunities for savings. In one California field study, the occupancy sensor reduced energy savings from 29 percent to 25 percent of connected loads, but increased persistence of savings from 83 percent to 87 percent. There was also a large implied takeback effect of about 43 percent, indicating that occupants may have been less conscientious about turning off devices knowing that the controls will do it

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[40] BEopt version changelog: https://beopt.nrel.gov/sites/default/files/exes/Changelog.txt

automatically (Valmiki & Corradini, 2016). The measure assumes two power strips are installed, both on audio visual systems. There may also be energy savings potential for computers and peripherals, but insufficient data for residential applications are available to estimate savings accurately. A 1-watt continuous power draw is assumed for each APS.

2. Optimal occupant behavior, smart plugs with smartphone. This measure assumes smart sockets are installed on 10 outlets in each house and enable optimal energy conserving behavior by occupants, reducing total standby and active loads by 16 percent. Savings is assumed to be higher than the APS measure because the takeback effect would be eliminated, but the research team has not identified any field studies that demonstrate whether occupants fully utilize this technology.

Table A-12: Summary of BEopt Inputs for MELs Options Considered for ZNE Homes

Option Name	Annual Electricity Use (kWh/unit/yr)	Multiplier (frac)	DR Automatic Control	Material Costs	Lifetime	Labor Costs
Optimal occupant behavior, smart plugs w/smartphone	(calculated by BEopt)	71.4 percent	FALSE	$420	10	$0
Tier 2 Advanced Power Strips (2) with IR and occupancy sensor	(calculated by BEopt)	79.9 percent	FALSE	$126	10	$0

Source: Lawrence Berkeley National Laboratory

The multiplier column in Table A-12 includes several components:

- An adjustment factor (85 percent) to align the BEopt default MELs energy use with the Title 24 assumption
- The expected energy savings for connected MELs
- A small 1-watt continuous power draw for the APS
- An unknown takeback effect for the APS measure, which is reflected in the savings because it is based on field testing with real occupants. An earlier study indicated 43 percent without occupancy sensors, and the team expects the effect to be much lower. The smart plugs measure specifically excludes takeback effects because it is designed to optimize behavior.

Expert Elicitation Background and Approach

In recent years, expert elicitation has been widely used to support decision-making in energy technology studies. Green Growth Knowledge Platform (GGKP) Research Committee examined all the expert elicitation studies performed on energy technologies since 2007 and summarized the differences in key characteristics by technology type (GGKP 2016). Many of these studies focus on eliciting experts' views on cost evolution conditional on RD&D levels and providing evidence to support public research and development investments. For instance, Anadon et al. (2011) conducted an expert elicitation study to seek recommendations on the level of federal

RD&D funding needed to simulate innovation in a range of energy technology areas and to assess the impact of RD&D investment on their future cost and performance under different funding scenarios. In some other studies, no explicit RD&D assumption is made in the elicitation questions. A more recent study published by (Wiser et al., 2016) relied on an online expert elicitation survey with more than 100 global wind experts to gain a better understanding of the magnitude of future wind energy cost reductions and to identify the opportunities of those potential cost reductions without specifying any R&D funding assumption.

Here, the main body of the survey elicits experts' informed judgement on current and future cost estimates for building ZNE homes in California. As building costs can vary vastly depending on the size of the home, the research team encouraged experts to refer to either the single-family or multi-family prototype models used in the research team's building energy modeling work to calibrate their cost estimates. To properly represent the level of uncertainty in experts' cost estimates, the elicitation was structured to ask experts to provide the 5th percentile value first, then the 95th percentile value, and lastly their best estimate inside the 5th to 95th percentile range. The team also encouraged experts to re-evaluate their lower- and upper-bound estimates before providing their best estimate in order to minimize the over-confidence and cognitive heuristic biases commonly observed in expert elicitations(Curtright, Morgan, & Keith, 2008). When answering future cost estimates for two points in time, 2021 and 2026, two policy adoption scenarios reflecting different hypothetical ZNE adoption rates in California were presented for experts to consider explicitly. The first is a "Business as Usual" scenario, which assumes that policies will remain the same as they are currently, and that new housing starts will gradually reach full ZNE by 2026. The second is a "Full ZNE Compliance" scenario, which represents a very aggressive ZNE adoption scenario that will require that all new residential buildings in California achieve ZNE by 2021. The goal was to see whether different policy adoption scenarios would impact the cost projection of ZNE homes in California and, if so, by how much.

APPENDIX B:
Building Modeling Results

Table B-1: Single-family 2,100 ft^2 all-electric and mixed-fuel homes lifecycle cost savings and increased initial construction cost

Bldg/ Fuel Type	CZ	Lifecycle cost ($)			Initial cost ($)		
		Baseline	Cost-min.	Savings	Baseline	Cost-min.	Inc. Cost
SF2100, All-Electric	CZ01	$91,072	$82,904	$8,168	$73,747	$78,997	$5,250
	CZ02	$82,394	$76,524	$5,871	$72,520	$81,980	$9,460
	CZ03	$78,703	$74,441	$4,262	$71,242	$78,862	$7,620
	CZ04	$80,125	$74,701	$5,424	$73,585	$81,363	$7,778
	CZ05	$79,649	$74,541	$5,109	$71,194	$78,623	$7,429
	CZ06	$74,862	$70,448	$4,414	$71,214	$77,963	$6,749
	CZ07	$72,531	$68,209	$4,322	$70,362	$76,041	$5,679
	CZ08	$74,962	$71,264	$3,697	$73,633	$79,428	$5,795
	CZ09	$79,618	$74,446	$5,172	$74,185	$80,028	$5,843
	CZ10	$81,977	$76,339	$5,638	$74,485	$81,245	$6,760
	CZ11	$89,395	$80,538	$8,857	$75,685	$83,190	$7,505
	CZ12	$84,797	$77,347	$7,450	$74,485	$82,671	$8,186
	CZ13	$90,382	$81,948	$8,434	$76,285	$83,297	$7,012
	CZ14	$84,825	$77,162	$7,663	$74,737	$81,354	$6,617
	CZ15	$94,972	$84,175	$10,797	$80,785	$83,020	$2,235
	CZ16	$96,567	$85,781	$10,786	$73,837	$83,918	$10,081
SF2100, Mixed-Fuel	CZ01	$84,186	$79,255	$4,931	$75,680	$79,628	$3,948
	CZ02	$78,089	$75,109	$2,980	$74,957	$78,894	$3,937
	CZ03	$73,482	$71,833	$1,649	$73,945	$78,342	$4,397
	CZ04	$75,773	$73,668	$2,105	$75,770	$78,839	$3,069
	CZ05	$73,834	$71,737	$2,096	$73,379	$77,137	$3,758
	CZ06	$71,646	$69,790	$1,856	$73,651	$76,278	$2,627
	CZ07	$68,567	$67,416	$1,151	$72,786	$74,943	$2,157
	CZ08	$72,222	$70,638	$1,584	$76,057	$78,651	$2,594

Bldg/ Fuel Type	CZ	Lifecycle cost ($)			Initial cost ($)		
		Baseline	Cost-min.	Savings	Baseline	Cost-min.	Inc. Cost
	CZ09	$77,017	$73,828	$3,189	$76,609	$78,951	$2,342
	CZ10	$79,429	$75,830	$3,598	$76,922	$79,360	$2,438
	CZ11	$86,242	$80,324	$5,918	$78,122	$81,234	$3,112
	CZ12	$81,237	$77,113	$4,124	$76,922	$79,720	$2,798
	CZ13	$87,477	$82,120	$5,356	$78,722	$81,520	$2,798
	CZ14	$82,133	$77,156	$4,977	$76,949	$80,053	$3,104
	CZ15	$94,406	$85,264	$9,142	$83,222	$85,109	$1,887
	CZ16	$85,012	$78,957	$6,055	$75,784	$78,190	$2,406

Single-family all-electric and mixed-fuel homes lifecycle cost savings and increased initial construction cost for cost-minimum design compared to Title 24 2019 baseline, using 2022 TDV values and avoided cost for solar PV exports.

Source: Lawrence Berkeley National Laboratory

Table B-2: Multi-family 8unit all-electric and mixed-fuel building lifecycle cost savings per unit and increased initial construction cost per unit for cost-minimum design compared to Title 24 2019 baseline, using 2022 TDV values and avoided cost for solar PV exports

Building Type	Fuel Type	CZ	Life-cycle cost ($) per Unit			Initial cost ($) per Unit		
			Baseline	Cost-minimum	Savings	Baseline	Cost-minimum	Increased Cost
MF8unit	All-Electric	CZ03	$51,305	$48,149	$3,156	$29,393	$31,238	$1,844
		CZ10	$53,236	$49,342	$3,894	$30,238	$32,930	$2,692
		CZ13	$57,812	$52,467	$5,346	$30,948	$33,268	$2,320
	Mixed-Fuel	CZ03	$46,316	$45,353	$963	$33,269	$34,878	$1,609
		CZ10	$48,924	$47,459	$1,465	$34,051	$35,440	$1,390
		CZ13	$52,447	$50,560	$1,887	$34,739	$36,693	$1,954

Source: Lawrence Berkeley National Laboratory

Table B-3: Measure package for the most cost-effective single-family 2100 ft2 all-electric homes

Building Type	CZ	Fuel Type	Measures
SF2100	CZ01	All-Electric	Air Source Heat Pump: SEER 22, 10 HSPF; Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Clothes Washer: Standard Front-loading CEE Tier 2; Clothes Dryer: Vented Elec CEF 3.93; Plug Loads: Optimal occupant behavior with smart control; PV System: 3.1 kW;
SF2100	CZ02	All-Electric	Air Source Heat Pump: SEER 22, 10 HSPF; Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Refrigerator: Bottom freezer EF 21.3; Dishwasher: Energy Star; Clothes Washer: Standard Front-loading CEE Tier 2; Clothes Dryer: Vented Elec CEF 3.93; Plug Loads: Optimal occupant behavior with smart control; PV System: 4.1 kW;
SF2100	CZ03	All-Electric	Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Dishwasher: Energy Star; Clothes Washer: Standard Front-loading CEE Tier 2; Clothes Dryer: Vented Elec CEF 3.93; Plug Loads: Optimal occupant behavior with smart control; PV System: 4.1 kW;
SF2100	CZ04	All-Electric	Air Source Heat Pump: SEER 16, 8.6 HSPF; Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Refrigerator: Bottom freezer EF 21.3; Clothes Washer: Standard Front-loading CEE Tier 2; Clothes Dryer: Vented Elec CEF 3.93; Plug Loads: Optimal occupant behavior with smart control; PV System: 3.9 kW;

Building Type	CZ	Fuel Type	Measures
SF2100	CZ05	All-Electric	Air Source Heat Pump: SEER 16, 8.6 HSPF; Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Clothes Washer: Standard Front-loading CEE Tier 2; Clothes Dryer: Vented Elec CEF 3.93; Plug Loads: Optimal occupant behavior with smart control; PV System: 3.9 kW;
SF2100	CZ06	All-Electric	Wood Stud: R-23 Fiberglass Batt, Gr-1, 2x6, 16 in o.c.; Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Refrigerator: Bottom freezer EF 21.3; Dishwasher: Energy Star; Clothes Washer: Standard Front-loading CEE Tier 2; Clothes Dryer: Vented Elec CEF 3.93; Plug Loads: Optimal occupant behavior with smart control; PV System: 3.6 kW;
SF2100	CZ07	All-Electric	Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Refrigerator: Bottom freezer EF 21.3; Dishwasher: Energy Star; Clothes Washer: Standard Front-loading CEE Tier 2; Clothes Dryer: Vented Elec CEF 3.93; Plug Loads: Optimal occupant behavior with smart control; PV System: 3.2 kW;
SF2100	CZ08	All-Electric	Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Refrigerator: Bottom freezer EF 21.3; Clothes Washer: Standard Front-loading CEE Tier 2; Clothes Dryer: Vented Elec CEF 3.93; Plug Loads: Optimal occupant behavior with smart control; PV System: 3.4 kW;
SF2100	CZ09	All-Electric	Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Refrigerator: Bottom freezer EF 21.3; Clothes Washer: Standard Front-loading CEE Tier 2; Clothes Dryer: Vented Elec CEF 3.93; Plug Loads: Optimal occupant behavior with smart control; PV System: 3.6 kW;
SF2100	CZ10	All-Electric	Air Source Heat Pump: SEER 22, 10 HSPF; Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Refrigerator: Bottom freezer EF 21.3; Dishwasher: Energy Star; Clothes Washer: Standard Front-loading CEE Tier 2; Clothes Dryer: Vented Elec CEF 3.93; Plug Loads: Optimal occupant behavior with smart control; PV System: 3.4 kW;
SF2100	CZ11	All-Electric	Unfinished Attic: Ceiling R-60 Gr-1 Cellulose, Vented; Radiant Barrier: Yes; Air Source Heat Pump: SEER 18, 9.3 HSPF; Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Refrigerator: Bottom freezer EF 21.3; Clothes Washer: Standard Front-loading CEE Tier 2; Clothes Dryer: Vented Elec CEF 3.93; Plug Loads: Optimal occupant behavior with smart control; PV System: 4.2 kW;

Building Type	CZ	Fuel Type	Measures
SF2100	CZ12	All-Electric	Air Source Heat Pump: SEER 22, 10 HSPF; Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Refrigerator: Bottom freezer EF 21.3; Clothes Washer: Standard Front-loading CEE Tier 2; Clothes Dryer: Vented Elec CEF 3.93; Plug Loads: Optimal occupant behavior with smart control; PV System: 3.9 kW;
SF2100	CZ13	All-Electric	Air Source Heat Pump: SEER 22, 10 HSPF; Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Refrigerator: Bottom freezer EF 21.3; Dishwasher: Energy Star; Clothes Washer: Standard Front-loading CEE Tier 2; Clothes Dryer: Vented Elec CEF 3.93; Plug Loads: Optimal occupant behavior with smart control; PV System: 4.0 kW;
SF2100	CZ14	All-Electric	Unfinished Attic: Ceiling R-60 Gr-1 Cellulose, Vented; Air Leakage: 4 ACH50; Air Source Heat Pump: SEER 18, 9.3 HSPF; Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Clothes Washer: Standard Front-loading CEE Tier 2; Clothes Dryer: Vented Elec CEF 3.93; Plug Loads: Optimal occupant behavior with smart control; PV System: 3.8 kW;
SF2100	CZ15	All-Electric	Unfinished Attic: Ceiling R-49 Gr-1 Cellulose, Vented; Radiant Barrier: Yes; Air Leakage: 4 ACH50; Air Source Heat Pump: SEER 15, 8.5 HSPF; Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Clothes Dryer: Vented Elec CEF 3.93; Plug Loads: Optimal occupant behavior with smart control; PV System: 4.9 kW;
SF2100	CZ16	All-Electric	Unfinished Attic: Ceiling R-49 Gr-1 Cellulose, Vented; Air Source Heat Pump: SEER 18, 9.3 HSPF; Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Dishwasher: Energy Star; Clothes Washer: Standard Front-loading CEE Tier 2; Clothes Dryer: Vented Elec CEF 3.93; Plug Loads: Optimal occupant behavior with smart control; PV System: 4.8 kW;

Source: Lawrence Berkeley National Laboratory

Table B-4: Measure package for the most cost-effective single-family 2100 ft^2 mixed-fuel homes

Building Type	CZ	Fuel Type	Measures
SF2100	CZ01	Mixed-Fuel	Furnace: Gas, 92.5 percent AFUE; Ducts: In Finished Space; Water Heater: Gas Tankless, Condensing; Hot Water Pipe Insulation: R-5; Cooking Range: Gas Cooktop Max Tech; Clothes Dryer: Vented Gas CEF 3.48; PV System: 3.1 kW;

Building Type	CZ	Fuel Type	Measures
SF2100	CZ02	Mixed-Fuel	Unfinished Attic: Ceiling R-49 Gr-1 Cellulose, Vented; Furnace: Gas, 92.5 percent AFUE; Ducts: In Finished Space; Water Heater: Gas Tankless, Condensing; Hot Water Pipe Insulation: R-5; Cooking Range: Gas Cooktop Max Tech; Clothes Dryer: Vented Gas CEF 3.48; Plug Loads: Advanced Power Strips with IR and occupancy sensor; PV System: 2.6 kW;
SF2100	CZ03	Mixed-Fuel	Unfinished Attic: Ceiling R-49 Gr-1 Cellulose, Vented; Furnace: Gas, 92.5 percent AFUE; Ducts: In Finished Space; Water Heater: Gas Tankless, Condensing; Hot Water Pipe Insulation: R-5; Cooking Range: Gas Cooktop Max Tech; Clothes Dryer: Vented Gas CEF 3.48; Plug Loads: Advanced Power Strips with IR and occupancy sensor; PV System: 2.5 kW;
SF2100	CZ04	Mixed-Fuel	Central Air Conditioner: SEER 16 EER 13.5 2-speed; Furnace: Gas, 92.5 percent AFUE; Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Cooking Range: Gas Cooktop Max Tech; Clothes Dryer: Vented Gas CEF 3.48; Plug Loads: Advanced Power Strips with IR and occupancy sensor; PV System: 2.5 kW;
SF2100	CZ05	Mixed-Fuel	Furnace: Gas, 92.5 percent AFUE; Ducts: In Finished Space; Water Heater: Gas Tankless, Condensing; Hot Water Pipe Insulation: R-5; Cooking Range: Gas Cooktop Max Tech; Clothes Dryer: Vented Gas CEF 3.48; PV System: 2.4 kW;
SF2100	CZ06	Mixed-Fuel	Wood Stud: R-23 Fiberglass Batt, Gr-1, 2x6, 16 in o.c.; Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Cooking Range: Gas Cooktop Max Tech; Clothes Dryer: Vented Gas CEF 3.48; Plug Loads: Advanced Power Strips with IR and occupancy sensor; PV System: 2.6 kW;
SF2100	CZ07	Mixed-Fuel	Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Cooking Range: Gas Cooktop Max Tech; Clothes Dryer: Vented Gas CEF 3.48; Plug Loads: Advanced Power Strips with IR and occupancy sensor; PV System: 2.4 kW;
SF2100	CZ08	Mixed-Fuel	Central Air Conditioner: SEER 16 EER 13.5 2-speed; Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Cooking Range: Gas Cooktop Max Tech; Clothes Dryer: Vented Gas CEF 3.48; Plug Loads: Advanced Power Strips with IR and occupancy sensor; PV System: 2.6 kW;
SF2100	CZ09	Mixed-Fuel	Central Air Conditioner: SEER 16 EER 13.5 2-speed; Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Cooking Range: Gas Cooktop Max Tech; Clothes Dryer: Vented Gas CEF 3.48; Plug Loads: Advanced Power Strips with IR and occupancy sensor; PV System: 2.7 kW;

Building Type	CZ	Fuel Type	Measures
SF2100	CZ10	Mixed-Fuel	Air Leakage: 4 ACH50; Central Air Conditioner: SEER 16 EER 13.5 2-speed; Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Cooking Range: Gas Cooktop Max Tech; Clothes Dryer: Vented Gas CEF 3.48; Plug Loads: Advanced Power Strips with IR and occupancy sensor; PV System: 2.8 kW;
SF2100	CZ11	Mixed-Fuel	Unfinished Attic: Ceiling R-60 Gr-1 Cellulose, Vented; Air Leakage: 4 ACH50; Central Air Conditioner: SEER 16 EER 13.5 2-speed; Furnace: Gas, 92.5 percent AFUE; Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Cooking Range: Gas Cooktop Max Tech; Clothes Dryer: Vented Gas CEF 3.48; Plug Loads: Advanced Power Strips with IR and occupancy sensor; PV System: 3.2 kW;
SF2100	CZ12	Mixed-Fuel	Central Air Conditioner: SEER 16 EER 13.5 2-speed; Furnace: Gas, 92.5 percent AFUE; Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Cooking Range: Gas Cooktop Max Tech; Clothes Dryer: Vented Gas CEF 3.48; Plug Loads: Advanced Power Strips with IR and occupancy sensor; PV System: 2.8 kW;
SF2100	CZ13	Mixed-Fuel	Central Air Conditioner: SEER 16 EER 13.5 2-speed; Furnace: Gas, 92.5 percent AFUE; Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Cooking Range: Gas Cooktop Max Tech; Clothes Dryer: Vented Gas CEF 3.48; Plug Loads: Advanced Power Strips with IR and occupancy sensor; PV System: 3.4 kW;
SF2100	CZ14	Mixed-Fuel	Unfinished Attic: Ceiling R-60 Gr-1 Cellulose, Vented; Air Leakage: 4 ACH50; Central Air Conditioner: SEER 16 EER 13.5 2-speed; Furnace: Gas, 92.5 percent AFUE; Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Cooking Range: Gas Cooktop Max Tech; Clothes Dryer: Vented Gas CEF 3.48; Plug Loads: Advanced Power Strips with IR and occupancy sensor; PV System: 2.8 kW;
SF2100	CZ15	Mixed-Fuel	Unfinished Attic: Ceiling R-49 Gr-1 Cellulose, Vented; Radiant Barrier: Yes; Air Leakage: 4 ACH50; Central Air Conditioner: SEER 15 EER 13; Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Cooking Range: Gas Cooktop Max Tech; Clothes Dryer: Vented Gas CEF 3.48; Plug Loads: Advanced Power Strips with IR and occupancy sensor; PV System: 4.9 kW;

Building Type	CZ	Fuel Type	Measures
SF2100	CZ16	Mixed-Fuel	Unfinished Attic: Ceiling R-49 Gr-1 Cellulose, Vented; Central Air Conditioner: SEER 16 EER 13.5 2-speed; Furnace: Gas, 92.5 percent AFUE; Ducts: In Finished Space; Water Heater: Gas Tankless, Condensing; Hot Water Pipe Insulation: R-5; Cooking Range: Gas Cooktop Max Tech; Clothes Dryer: Vented Gas CEF 3.48; PV System: 2.5 kW;

Source: Lawrence Berkeley National Laboratory

Table B-5: Measure package for the most cost-effective single-family 2700 ft2 all-electric homes

Building Type	CZ	Fuel Type	Measures
SF2700	CZ03	All-Electric	Air Source Heat Pump: SEER 16, 8.6 HSPF; Ducts: In Finished Space; Water Heater: HPWH, 50 gal UEF3.7; Hot Water Pipe Insulation: R-5; Dishwasher: Energy Star; Clothes Washer: Standard Front-loading CEE Tier 2; Clothes Dryer: Vented Elec CEF 3.93; Plug Loads: Optimal occupant behavior with smart control; PV System: 4.5 kW;
SF2700	CZ10	All-Electric	Air Leakage: 4 ACH50; Air Source Heat Pump: SEER 22, 10 HSPF; Ducts: In Finished Space; Water Heater: HPWH, 50 gal UEF3.7; Hot Water Pipe Insulation: R-5; Refrigerator: Bottom freezer EF 21.3; Clothes Washer: Standard Front-loading CEE Tier 2; Clothes Dryer: Vented Elec CEF 3.93; Plug Loads: Optimal occupant behavior with smart control; PV System: 4.0 kW;
SF2700	CZ13	All-Electric	Wall Sheathing: R-10 XPS; Air Source Heat Pump: SEER 22, 10 HSPF; Ducts: In Finished Space; Water Heater: HPWH, 50 gal UEF3.7; Hot Water Pipe Insulation: R-5; Refrigerator: Bottom freezer EF 21.3; Clothes Washer: Standard Front-loading CEE Tier 2; Clothes Dryer: Vented Elec CEF 3.93; Plug Loads: Optimal occupant behavior with smart control; PV System: 4.8 kW;

Source: Lawrence Berkeley National Laboratory

Table B-6: Measure package for the most cost-effective single-family 2700 ft2 mixed-fuel homes

Building Type	CZ	Fuel Type	Measures
SF2700	CZ03	Mixed-Fuel	Air Leakage: 4 ACH50; Furnace: Gas, 92.5 percent AFUE; Ducts: In Finished Space; Water Heater: Gas Tankless, Condensing; Hot Water Pipe Insulation: R-5; Cooking Range: Gas Cooktop Max Tech; Clothes Dryer: Vented Gas CEF 3.48; Plug Loads: Advanced Power Strips with IR and occupancy sensor; PV System: 2.8 kW;

Building Type	CZ	Fuel Type	Measures
SF2700	CZ10	Mixed-Fuel	Unfinished Attic: Ceiling R-60 Gr-1 Cellulose, Vented; Air Leakage: 3 ACH50; Central Air Conditioner: SEER 15 EER 13; Ducts: In Finished Space; Water Heater: Gas Tankless, Condensing; Hot Water Pipe Insulation: R-5; Cooking Range: Gas Cooktop Max Tech; Clothes Dryer: Vented Gas CEF 3.48; Plug Loads: Advanced Power Strips with IR and occupancy sensor; PV System: 3.4 kW;
SF2700	CZ13	Mixed-Fuel	Unfinished Attic: Ceiling R-60 Gr-1 Cellulose, Vented; Air Leakage: 3 ACH50; Central Air Conditioner: SEER 15 EER 13; Furnace: Gas, 92.5 percent AFUE; Ducts: In Finished Space; Hot Water Pipe Insulation: R-5; Cooking Range: Gas Cooktop Max Tech; Clothes Dryer: Vented Gas CEF 3.48; Plug Loads: Advanced Power Strips with IR and occupancy sensor; PV System: 4.0 kW;

Source: Lawrence Berkeley National Laboratory

Table B-7: Measure package for the most cost-effective multi-family 8-unit all-electric building

Building Type	CZ	Fuel Type	Measures
MF8unit	CZ03	All-Electric	Air Leakage: 3 ACH50; Mini-Split Heat Pump: SEER 20, 10.3 HSPF; Hot Water Pipe Insulation: R-5; Refrigerator: Bottom freezer EF 19.8; Clothes Washer: Standard Front-loading CEE Tier 2; Clothes Dryer: Vented Elec CEF 3.93; Plug Loads: Optimal occupant behavior with smart control; PV System: 15.0 kW (3);
MF8unit	CZ10	All-Electric	Wall Sheathing: R-10 XPS; Air Leakage: 3 ACH50; Mini-Split Heat Pump: SEER 25.3, 13.4 HSPF; Hot Water Pipe Insulation: R-5; Refrigerator: Bottom freezer EF 19.8; Clothes Washer: Standard Front-loading CEE Tier 2; Clothes Dryer: Vented Elec CEF 3.93; Plug Loads: Optimal occupant behavior with smart control; PV System: 16.0 kW;
MF8unit	CZ13	All-Electric	Air Leakage: 2 ACH50; Mini-Split Heat Pump: SEER 25.3, 13.4 HSPF; Hot Water Pipe Insulation: R-5; Refrigerator: Bottom freezer EF 19.8; Clothes Washer: Standard Front-loading CEE Tier 2; Clothes Dryer: Vented Elec CEF 3.93; Plug Loads: Optimal occupant behavior with smart control; PV System: 17.5 kW;

Source: Lawrence Berkeley National Laboratory

Table B-8: Measure package for the most cost-effective multi-family 8-unit mixed-fuel building

Building Type	CZ	Fuel Type	Measures
MF8unit	CZ03	Mixed-Fuel	Unfinished Attic: Ceiling R-49 Gr-1 Cellulose, Vented; Air Leakage: 2 ACH50; Hot Water Pipe Insulation: R-5; Refrigerator: Bottom freezer EF 19.8; Cooking Range: Gas Cooktop Max Tech; Clothes Dryer: Vented Gas CEF 3.48; Plug Loads: Optimal occupant behavior with smart control; PV System: 15.0 kW;
MF8unit	CZ10	Mixed-Fuel	Unfinished Attic: Ceiling R-49 Gr-1 Cellulose, Vented; Radiant Barrier: Yes; Air Leakage: 2 ACH50; Central Air Conditioner: SEER 15 EER 13; Hot Water Pipe Insulation: R-5; Refrigerator: Bottom freezer EF 19.8; Cooking Range: Gas Cooktop Max Tech; Clothes Dryer: Vented Gas CEF 3.48; Plug Loads: Optimal occupant behavior with smart control; PV System: 16.0 kW;
MF8unit	CZ13	Mixed-Fuel	Wall Sheathing: R-10 XPS; Unfinished Attic: Ceiling R-60 Gr-1 Cellulose, Vented; Radiant Barrier: Yes; Air Leakage: 2 ACH50; Central Air Conditioner: SEER 15 EER 13; Hot Water Pipe Insulation: R-5; Refrigerator: Bottom freezer EF 19.8; Cooking Range: Gas Cooktop Max Tech; Clothes Dryer: Vented Gas CEF 3.48; Plug Loads: Optimal occupant behavior with smart control; PV System: 17.5 kW;

Source: Lawrence Berkeley National Laboratory

Figure B-1: Optimal Sizing of 2hr Battery (Minimum 2kWh): Average Cost-Reducing over Time, 2100 ft² All-electric Home, Base 2022 TDV

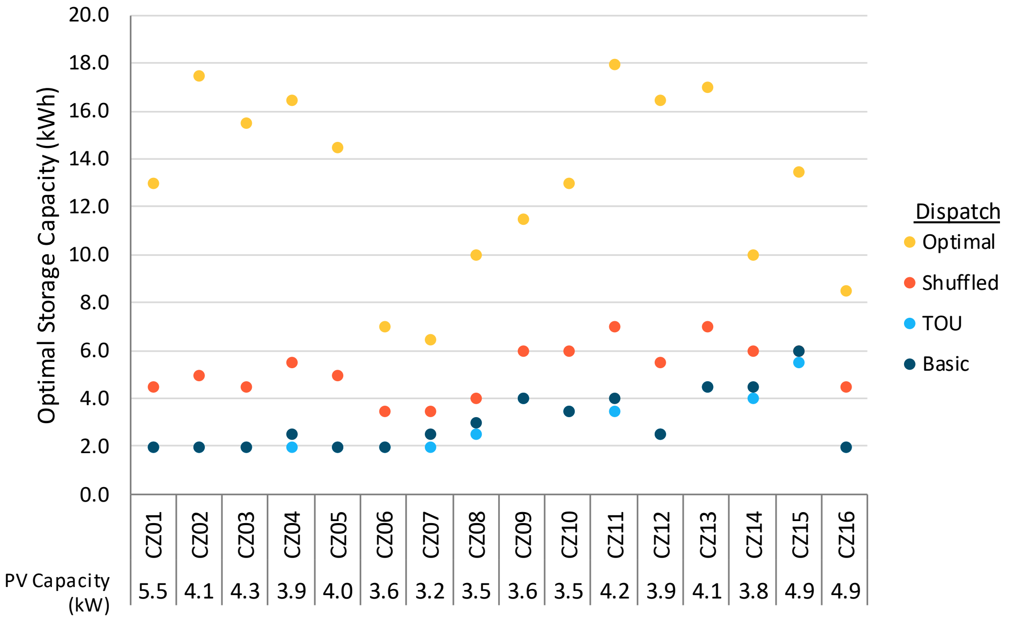

Figure B-1 shows that the optimal sizing of 2hr battery for the Average Cost-reducing over Time battery cost case for a single family all-electric home is very high for the optimal dispatch case and about 2-7kW for other dispatch cases.

Source: Lawrence Berkeley National Laboratory

Figure B-2: TDV Net Benefits Less Battery Costs (30-year NPV): Average Cost-Reducing over Time, 2100 ft² All-electric Home, Base 2022 TDV

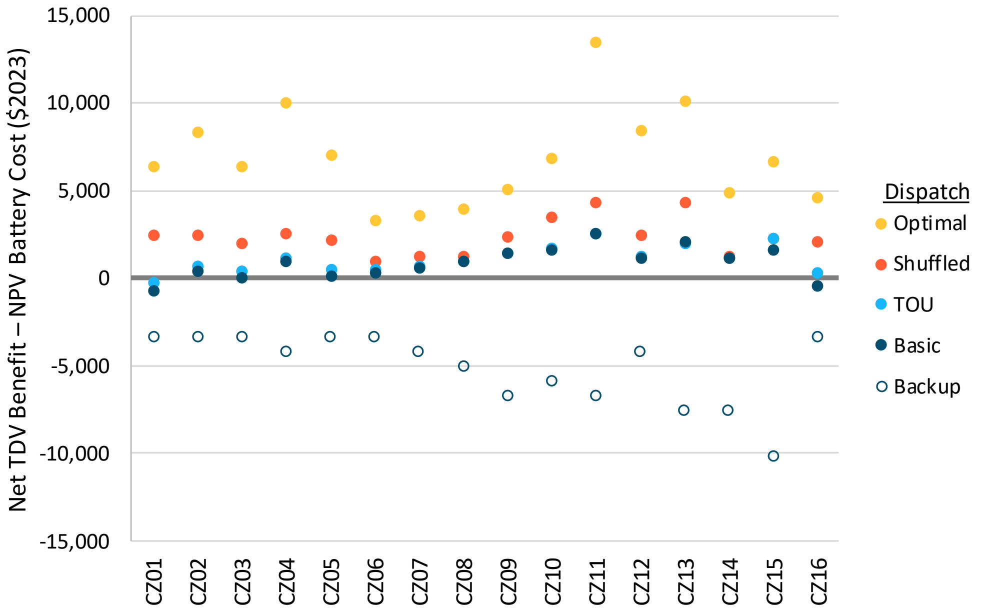

Figure B-2 shows the net benefits less battery costs for all-electric single family homes for the Average Cost-Reducing over Time battery cost case is mostly above zero except for the backup dispatch case.

Source: Lawrence Berkeley National Laboratory

Storage Sensitivity with Optimistic Battery Storage Costs

Storage case with optimistic case on battery storage costs, by starting with today's lowest (rather than industry average) battery storage costs and assuming that these costs will decline in the future[41]. As expected, this lower battery storage cost case suggests larger batteries and higher net benefits than the cases previously shown.

Figure B-3: Optimal Sizing of 2hr Battery (Minimum 2kWh): Low Cost-Reducing over Time, 2100 ft^2 Mixed Fuel Home, Base 2022 TDV

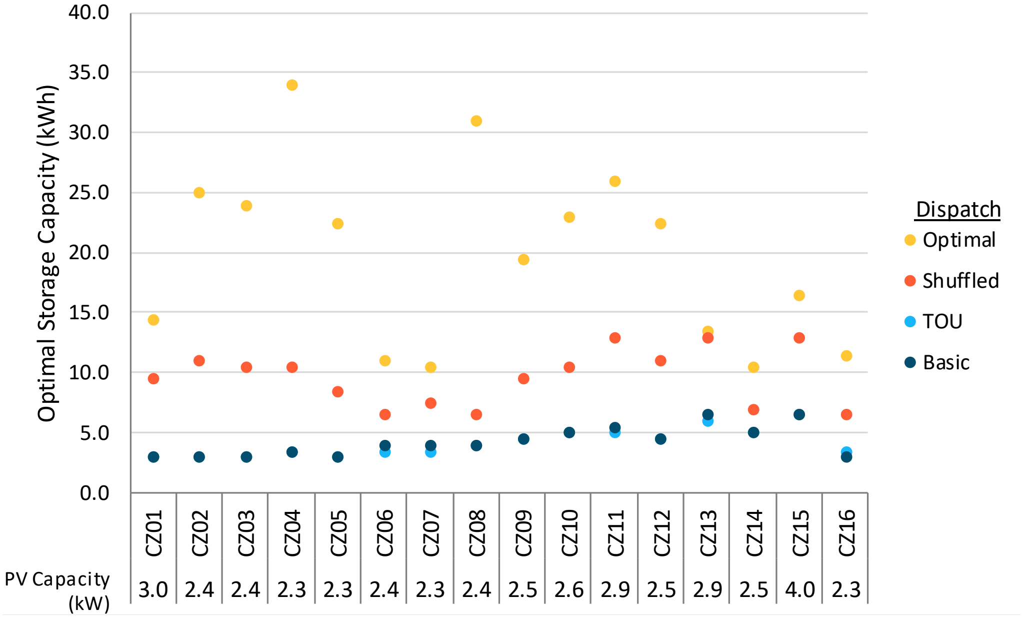

Figure B-3 shows the optimal sizing for 2hr battery can be very large in with low-cost battery storage cost assumptions.

Source: Lawrence Berkeley National Laboratory

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[41] See description of 'Low Cost-Reducing Over Time' in Methodology chapter

Figure B-4: TDV Net Benefits Less Battery Costs (30-year NPV): Low Cost-Reducing over Time, 2100 ft^2 Mixed Fuel Home, Base 2022 TDV

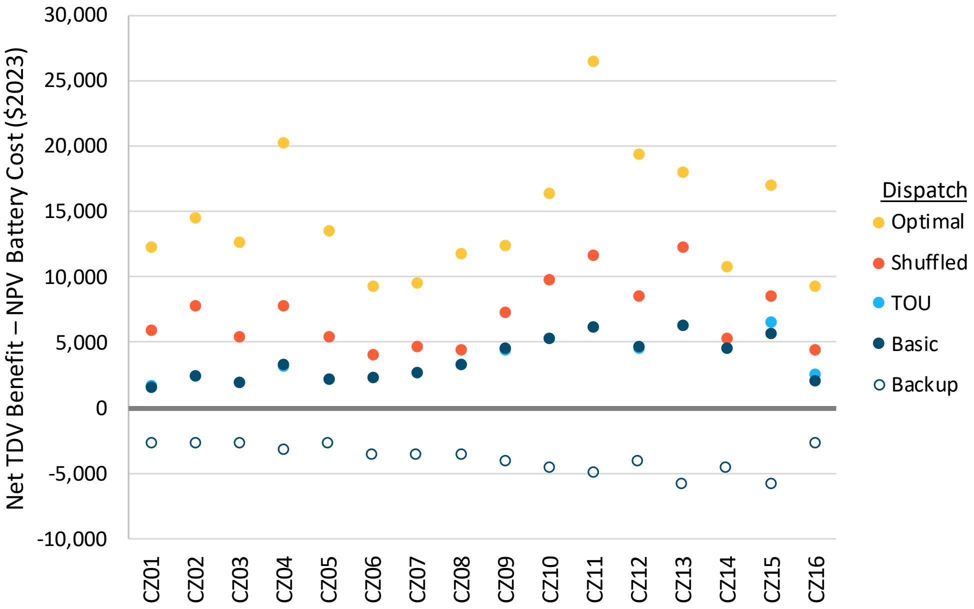

Figure B-4 shows that with low cost battery storage assumptions, battery storage can be cost effective for optimal, shuffled, and basic dispatch.

Source: Lawrence Berkeley National Laboratory

Renewable Natural Gas Cost Components

- Feedstock costs: Costs required to collect biogas, the raw input for RNG production, are described as feedstock costs. MSW has negative feedstock costs associated with it since the use of MSW to produce biogas reduces landfill tipping fees. These costs may be low or zero on a marginal basis if biogas is already collected (as is often required at landfills and wastewater treatment plants (WWTPs)). Dairies can face more significant feedstock costs from collecting manure for central processing, though these also may become lower over time on a marginal basis as the California Air Resources Board (CARB) works to address methane emissions from dairy as part of its Short-Lived Climate Pollutant Reduction Strategy.[42] Advanced biofuels are likely to face higher feedstock costs, as they require collecting residues that are currently not collected.
- Conversion costs: Costs associated with converting the feedstock into methane. These apply to dairy and MSW sources (e.g. the purchase and operation of bacteria digesters) as well as advanced biofuels (e.g. the purchase and operation of gasification equipment), but not to landfill gas or WWTPs.
- Upgrading/Injection: Specialized technology and infrastructure may be needed to process the biogas to meet commercial natural gas quality standards. Landfill, MSW, dairy and WWTP sources may need to upgrade equipment used to collect and process biogas into RNG.

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[42] See https://www.arb.ca.gov/cc/shortlived/shortlived.htm

- Pipeline connection: Costs are associated with the technology and infrastructure needed to deliver the RNG to distribution pipelines. Costs can vary widely depending on the distance from the biogas source to the pipeline and the volume of RNG being produced: per-unit costs are lower for larger-volume resources due to the fixed cost of connection being spread out over more RNG production. As an example, dairies may be located further from distribution pipelines, but are frequently clustered, which yields benefits in transportation costs.

Forecasted demand for Renewable Natural Gas

Estimates are based on the following:

1. **Annual gas consumption per new home.** Estimates of annual household site natural gas consumption for the single-family (SF), multi-family (MF) and mobile home (MH) types in the West region were taken from the U.S. Energy Information Administration (EIA) Residential Energy Consumption Survey (RECS) (Energy Information Administration, 2013); and
2. **The number of new homes**. Estimates of new homes of each type added annually were obtained from the CEC's 2015 IEPR report (CEC, 2015) mid-demand statewide housing forecast.

Table B-9: Estimated Gas Demand from New Residential Construction in California, 2017

Type	2017 demand (MMcf)
New single-family homes in 2017	128,975
Gas consumption per new single-family home (MMBtu)	59
New multi-family homes in 2017	81,484
Gas consumption per new multi-family home (MMBtu)	26
New mobile homes in 2017	3,034
Gas consumption per new mobile home (MMBtu)	49
Total new construction gas consumption (TBtu)	10

Table B-9 shows the estimated gas demand from residential new construction in California in 2017

Source: CEC 2015 mid demand statewide housing forecast by climate zone

Table B-10: Natural gas consumption in California, 2016 (MMcf)

Use	2016 demand (MMcf)
Lease Fuel Consumption	39,615
Plant Fuel Consumption	1,545
Pipeline and Distribution Use	22,460
Residential Consumption	411,828
Commercial Consumption	236,967
Industrial Consumption	774,504
Vehicle Fuel Consumption	19,395
Deliveries to Electric Power Consumers	671,152
Total Consumption	2,177,467

Table B-10 shows the 2016 consumption of natural gas in California, by end use.

Source: (Energy Information Administration, 2013)

Figure B-5: Cost Differences Between Residential, Commercial, and Utility-Scale Solar Photovoltaic

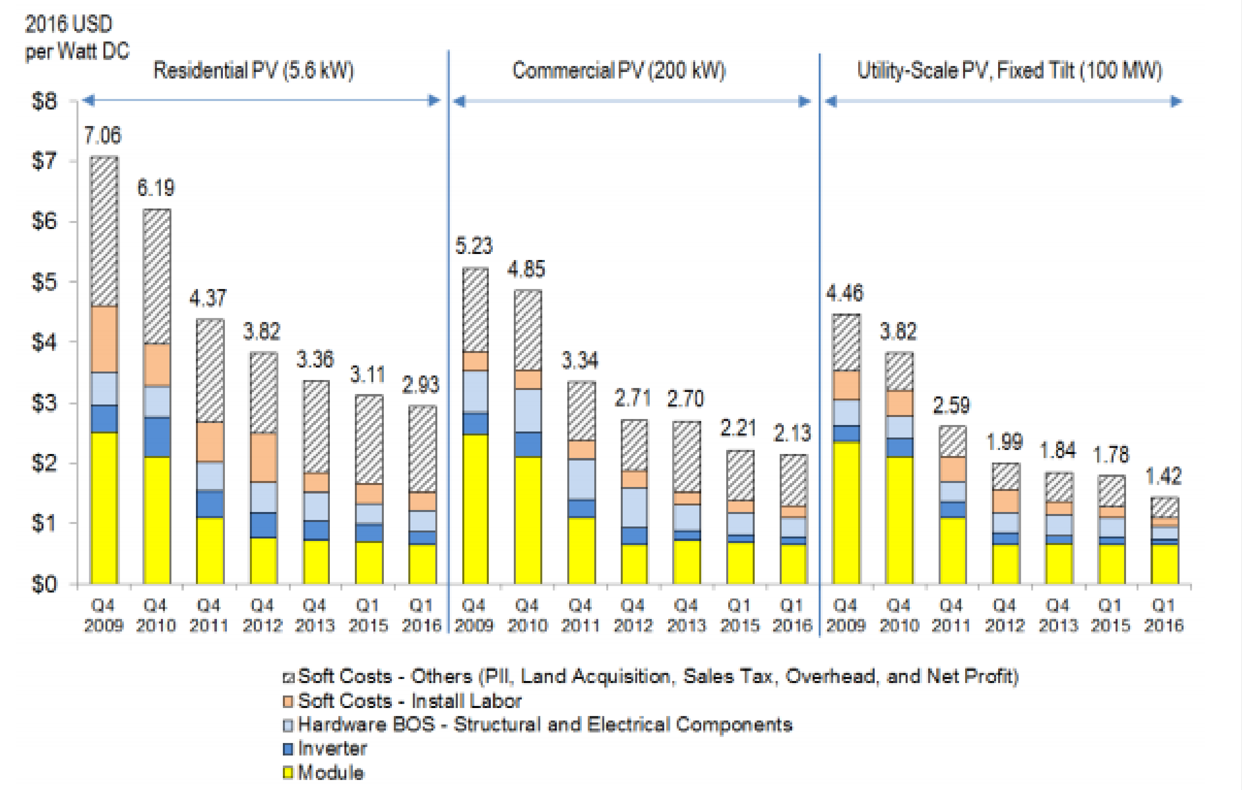

Figure B-5 shows the lower cost for solar PV with increasing project size.

Source: NREL, *U.S. Solar Photovoltaic System Cost Benchmark: Q1 2016*, September 2016, https://www.nrel.gov/docs/fy16osti/67142.pdf

Figure B-6: Unsubsidized Levelized Cost of Energy – Solar Photovoltaic Comparison (Lazard)

‡ Denotes distributed generation technology.

(b) Low end represents single-axis tracking system. High end represents fixed-tilt design. Assumes 30 MW system in a high insolation jurisdiction (e.g., Southwest U.S.). Does not account for differences in heat coefficients within technologies, balance-of-system costs or other potential factors which may differ across select solar technologies or more specific geographies.

(d) Illustrative "PV Plus Storage" unit. PV and battery system (and related mono-directional inverter, power control electronics, etc.) sized to compare with solar thermal with 10 hour storage on capacity factor basis (52%). Assumes storage nameplate "usable energy" capacity of ~400 MWh_{dc}, storage power rating of 110 MW_{ac} and ~200 MW_{ac} PV system. Implied output degradation of ~0.40%/year (assumes PV degradation of 0.5%/year and battery energy degradation of 1.5%/year, which includes calendar and cycling degradation). Battery round trip DC efficiency of 90% (including auxiliary losses). Storage opex of ~$10/kWh-year and PV O&M expense of ~$9.2/kW DC-year, with 20% discount applied to total opex as a result of synergies (e.g., fewer truck rolls, single team, etc.). Total capital costs of ~$3,900/kW include PV plus battery energy storage system and selected other development costs. Assumes 20 year useful life, although in practice the unit may perform longer. Illustrative system located in U.S. Southwest.

Figure B-6 shows the unsubsidized levelized cost of energy that compares solar PV systems.

Source: Lazard (2019)

APPENDIX C: Expert Elicitation Protocol and Summary Results

Survey Protocol

In choosing the elicitation mode, considering the great number of building measures included in the survey, the research team decided to carry out face-to-face elicitations to allow researchers to have more control over the pace of the elicitation and provide clarifications when necessary. The option of conducting elicitations through online video conference software was also offered in case face-to-face was unfeasible for researchers or experts. A diverse pool of expert candidates was selected from different sectors and industries. The list of experts was mostly drawn from pre-existing in-house building professional contacts and from *Department of Energy*[43] *and Zero Energy Project*[44] website. For this study, the research team initially identified around 30 home builders and policy analysts with expertise on the costs of ZNE homes in California and completed eight interviews during the period of November 2017 to June 2018.

The entire elicitation process proceeded in two phases. The first phase was the pilot study and the second was the formal elicitation. The pilot study helped researchers fine-tune the design of the survey, including improving the clarity of the questions, adjusting the length when necessary, and making sure the questions asked covered the objectives of the research project. Out of the eight interviews completed, three were conducted during the pilot study and the rest were conducted during the formal elicitation. Given that the interview protocol and questionnaire was not changed significantly between two phases, the team included responses from both phases in the analysis.

Once experts agreed to participate in the elicitation, they were provided a short online survey where they identified their area of expertise in terms of fuel type, housing type, and climate zone that they have the most experience with. The elicitation then focused on the areas of expertise they identified as most familiar to them. Prior to the elicitation the experts were provided with supplementary material relevant to their expertise, as well as the expert elicitation questions so they could familiarize themselves with the elicitation process in advance. To keep experts from being identifiable, only the aggregated and de-identified data are presented in this report.

All elicitations were performed by researchers who also took part in designing the survey. In most cases, researchers followed a standardized survey interviewing technique which only provided scripted information to respondents. However, researchers would sometimes engage in a conversational interviewing approach to clarify to respondents the meaning of questions

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[43] The Department of Energy Zero Energy Ready Home, more information is available at: https://www.energy.gov/eere/buildings/zero-energy-ready-home

[44] The Zero Energy Project is a non-profit educational organization focusing on helping the home construction industry to move towards zero net energy homes and near zero net energy homes. Website is available at: https://zeroenergyproject.org/

when required. In the formal elicitation stage, the completion time of each elicitation averaged around two and a half hours. During the entire elicitation period, participating experts were given full access to researchers via telephone or email for any additional concerns or question they might have.

Expert Elicitation Summary

This section summarizes inputs elicited from experts to address the following key research questions:

- What are the current and future cost estimates of building measures for residential ZNE construction? And what are the key cost reduction areas for TDV-ZNE implementation?
- What are the relative costs of all-electric versus mixed fuel homes?
- What is the potential for community renewables, storage, and demand response in ZNE implementation?
- What are the market barriers and key challenges for ZNE implementation?

Ranges of quantitative estimates are provided to support statements when available, otherwise most of the questions are addressed qualitatively. A detailed summary of experts' responses concerning current and future cost estimates can be found in this Appendix.

Key Takeaways Related to Current and Future Cost Estimates

Experts identified a few areas that they consider as the more impactful cost contributors to building ZNE homes in California. Among all the building measures, having better quality insulation and air sealing in the building envelope is the key to achieving ZNE, and having a well-insulated home will help reduce the need of HVAC capacity. It is estimated to cost an additional $4,000 for advanced framing in walls and attics in a standard-sized production home, the biggest cost increment by shifting from code compliant to ZNE homes. However, this cost increase associated with building a higher performance envelope has less to do with any material or technology innovation, instead it has more to do with the design change, namely the integrated design process. Most experts agreed that initially there must be a steeper learning curve in adopting this new design approach; however, as builders get more experienced, the cost is expected to go down by 25 percent in the coming years under the current CEC policy guideline. If the full ZNE compliance took place sooner, then it would help drive down the cost even faster. The second largest cost contributor is the HVAC system, estimated to be between $2,000 and $2,500 more in ZNE homes than code compliant homes. In ZNE homes, both production and custom home builders chose the use of heat pump systems rather than gas furnaces paired with split system air conditioners commonly seen in mixed-fuel conventional homes. Typically, a ZNE home does not have as much heating and cooling needs because of its well-insulated envelope, and heat pump capacity can be sized down which helps reduce the cost difference. Most experts think that HVAC equipment is not a particularly innovative industry, and they have not seen any huge breakthroughs that will change the cost drastically. However, they expect that heat pump HVAC system cost would naturally come down by 5 percent to 20 percent between now and 2026 as technology ramps up and gains higher market saturation.

Another prominent cost contributor could be windows when builders start installing triple-pane windows. As of today, triple-pane windows are a hot topic in the construction industry; however, their high price tag and heavy weight are perceived as immense barriers for builders, especially production home builders. Among all the experts that the research team spoke with, only a few custom home builders had installed triple-pane windows in ZNE homes, and most of those products were manufactured in Europe. There is still an unsettled debate over whether it is really worth spending tens of thousands of dollars for triple-pane windows per home. Some manufactures are working on developing technologies that can make triple-pane windows lighter and more cost effective. One company is developing a super thin film triple-pane which has a middle pane that is like a hanging film in between a dual-pane frame. This design makes it lighter and easier for installation. Windows made of uPVC (unplasticized polyvinyl chloride) might help bring the cost down while providing great sound and thermal insulation. Mainstreaming good quality triple-pane windows and increasing U.S. manufacturing capability would definitely help make it a more attractive choice for builders; however, most experts think there is still a long way to go before the market is ready for them. Given the complexity and uncertainty in the window manufacturing industry, experts were not able to provide future cost estimates with confidence. Lastly, the PV system, when it is purchased, could make up to a significant portion of the cost premium related to ZNE homes. Depending on the policy mandate, the rate of price decline in PV technology could play a major role in impacting the course of future ZNE costs. Most experts predict that PV system costs could decline by another 5 percent to10 percent between now and 2026.

For non-building measures, almost all experts focused on the importance of having a good design when building ZNE homes and how implementing an integrated design process can significantly help lower the construction costs. Most custom home builders apply a design-build model where they have their own in-house team that does both the design and construction of a project. Their services would range from architectural design, structural engineering, and energy modeling to site construction. The total design cost for a small custom ZNE home is estimated to be around $30,000 to $35,000. For some production ZNE builders, the biggest cost difference related to design is centered around investing more time, about 30 hours in total per year, for team-wide review across departments for each plan than code compliant homes. This practice manifests the core of an integrated design process and ensures that different departments, such as drafting, contract, modeling, marketing, etc., are in sync with each other resulting in more effective collaboration. Undoubtedly there is going to be a learning curve at first, but team members gain experience and knowledge each time they build ZNE homes, so less time will be needed in the future. Besides incorporating an integrated design process, providing continuing education opportunities allows team members to acquire the skills and knowledge needed for effectively building ZNE homes, which could ultimately reduce future labor costs. Even though advanced performance envelopes do not necessarily require any innovative building material or ground-breaking technology, it does require a skilled worker who knows how to install it properly. Builders who are willing to make investments into providing ongoing training for their management and trades have more success in building ZNE homes. In some instances, even building material manufacturers are involved in designing and delivering staff training.

All-Electric versus Mixed Fuel Homes

Experts' views on whether there is a cost difference for the shift from mixed fuel homes to all-electric homes are split between building ZNE homes on land with existing gas infrastructure or not. For those who think there is a cost decrease associated with the shift, the main argument is that gas infrastructure is not needed in all-electric new construction; therefore, the savings from avoiding installing gas infrastructure could outweigh cost increases from more expensive electric HVAC and water heating system. It is worth noting that the cost saving from infrastructure can vary depending on the location of the property (rural versus urban) and the size of the community. Major utilities across California offer different amounts of gas main extension allowances per gas appliances.[45] Builders located in regions where higher allowances are provided bear less additional costs associated with gas infrastructure. The cost savings from avoiding gas infrastructure diminish on a per home basis in larger communities as well. The range of estimated cost savings from avoiding gas infrastructure can be very different, from $3,000-$5,000 to $10,000 per home depending on the size of home. However, in most cases where there is already existing gas infrastructure, and experts expect cost increases from fuel switching would mostly come from heat pump space heating and cooling, electric water heater, and induction cooktop. The total estimated cost premium related to fuel switching from gas to electric appliances in the Central Valley ranges from $3,500 to $3,800.

Experts hold different perspectives on the future of all-electric homes. Some custom builders think all-electric homes are necessary when you build airtight ZNE homes; otherwise using gas-fired appliances may create in-door air quality hazards. Some builders think all-electric is the end goal, but they do not believe the market is ready for the shift. On the other hand, some experts think since gas is still relatively cheap and the infrastructure already exists in many places, removing gas completely would be wasteful and create burden on a subset of communities, meaning that remaining gas customers would bear the operation and maintenance expenses for the existing gas infrastructure. As there is a consistent demand for certain gas-fired appliances from home buyers, such as: gas cooktops, gas dryers, and gas furnaces, many builders, especially production home builders, still plan to have full gas infrastructure in place so that they can provide gas as an option for home buyers.

Community Renewables, Storage and Demand Response

The discussion related to community renewables has mostly centered on the role of community solar in ZNE implementation. Most experts hold a positive attitude toward community solar but also note the complexity of making it actually feasible. There are three main challenges that community solar faces: (1) physical challenges, concerning the physical location of community solar and assessment of related insurance or liability hazard (2) regulatory challenges, related to ways in which program design interacts with existing policy and regulations, and (3) economic challenges, in terms of the ownership structure, subscription pricing, and bill credit calculation. In order to remove these barriers, state-level

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[45] Gas main extension allowance works as credit for gas usage from qualifying natural gas appliances. The type of gas appliances or equipment installed at home determine the amount of credit that may reduce the construction costs of gas main extensions.

policymakers and regulators will have to work with utilities to create a supportive regulatory environment to expand the distributed solar market. They will also have to think through issues related to load management resulting from rising solar penetration.

One phenomenon that many energy policy researchers observe when increasing levels of variable generation resources (i.e., solar PV and wind) are added to the electric grid system is the unique change in the electric load shape, known as the "duck curve" (California ISO, 2016). The duck curve is observed when there is a sizeable imbalance between peak demand and solar generation which imposes grid operation challenges for system operators. Maintaining reliability in the grid system requires balancing both variable demand and variable supply and having controllable resources with ramping flexibility and the ability to react quickly depending on grid conditions. Many policy makers are considering integrating companion measures, such as energy storage and demand response in community solar program design to alleviate the duck curve and mitigate variability from growing penetration of solar PV. However, when the research team spoke to the experts, only a few custom home builders had installed energy storage in their ZNE homes and none of them had implemented any demand response management system. Production home builders are more hesitant to try these technologies mainly because of the costs, unless they receive funding opportunities to partner with utilities and research institutes. Besides the high cost, there are still some critical issues that need to be resolved (first and foremost is the proper sizing of the storage under different scenarios), and these issues are addressed in more detail in Chapter 3 of this report.

Market Barriers and Key Challenges

As stressed by experts from both custom and production home construction, many building technologies required in ZNE homes already exist, what matters the most is incorporating an integrated design process which requires all building development team members to work collaboratively throughout the entire building process starting from the design stage. This approach would require thinking about every aspect of the building process ahead of time including HVAC, plumbing, lighting and wiring, site planning, framing, etc., and sometimes the floor plan may need to be redesigned to take into account high performance attics and advanced framing walls. For instance, building 2x6 walls would mean having thicker walls, so builders would have to either build in or out to accommodate the thicker walls. If builders did not integrate the 2x6 wall insulation into their design process as early as land acquisition, they would very likely have to build in resulting in the home having less square footage, which would trigger downstream impacts on the layout of stairways, cabinets, bathroom, etc. Even though integrated design process may seem time-consuming at first, having everyone working as a team results in a much smoother building process and avoids the need for design revision which will lead to project delay and budget increases.

Many of the builders who have implemented the integrated a design process approach in building ZNE homes, stressed that the cost difference between a ZNE home and a Title 24 compliance home in equivalent size and climate zone is not as substantial as some builders might think. The problem is that there are only very few ZNE examples in the market to demonstrate how to get it done properly and cost effectively, so the majority of builders are still hesitant to begin building ZNE homes and adopting an integrated design process. This common cost myth toward ZNE homes further contributes to builders' unwillingness to strive for better home efficiency performance. In particular, builders located in milder climate zones might have limited energy saving potential and therefore, installing high efficiency measures is often not their top priority.

In addition, most home listing services do not show a differentiation in home value based on the energy savings and energy features. This coupled with home buyers having a lack of awareness and knowledge, while builders face a lack of incentives creates a challenge for ZNE homes to gain traction in the market. Establishing an appraisal system to accurately evaluate the added value of ZNE homes becomes critical to fill this lack of knowledge for both builders and home buyers.

The construction industry is extremely litigious, especially in California; therefore, fear of litigation is universal among builders, and any potential legal issues related to building ZNE homes may prevent them from adopting full ZNE designs. ZNE homes are still a relatively novel concept in the building industry, not only do builders struggle with what ZNE homes actually mean and what the benefits are, but so do homebuyers. Most legal issues arise when builders do not fully understand the nuances between full ZNE homes (TDV-based) and simply zero energy homes (kWh-based) and when there is miscommunication between the marketing team and homebuyers in terms of the promised energy savings. Different interpretations of ZNE homes could directly impact the solar capacity needed to install on homes. If the delivered energy savings did not align with the homebuyers' expectation, builders may face legal challenges. Some experts have seen other builders become involved in lawsuits as a result of promoting ZNE homes as having a "zero energy bill" or marketing energy efficient home as ZNE homes. These kinds of lawsuits happen more often to highly segmented builders who outsource their marketing team, sales agent, and energy consultants so that the nuances do not get communicated well across entities and disconnection may occur.

Expert Elicitation Conclusions

Results from the expert elicitation study show that ZNE residential new construction in California is feasible; however, it is not yet mainstream. With very few ZNE examples in the market to demonstrate how to properly and cost effectively achieve ZNE, builders are still hesitant to commit to building ZNE homes. Even though (Hoen et al., 2017) showed that new homes with purchased PV system have higher premium at about $3.58/watt, most builders are discouraged by the fact that some other energy efficiency features are not being accurately reflected in the current appraisal system. Similarly, experts emphasized builders being discouraged by a fear of litigation given that the construction industry is extremely litigious. With ZNE construction being a novel field, and there being a lack of clarity on definitions and metrics, builders fear increases in susceptibility to litigation.

Experts noted that successful ZNE residential new construction projects signify that the necessary technologies exist and are available, it is a matter of understanding what changes need to be made to the design plan and how to properly and effectively implement it. According to experts' responses, the most impactful building measures for meeting ZNE requirements relate to improving insulation and air sealing in building envelopes, they also noted that the cost premium associated with ZNE homes mainly comes from higher performance envelopes and the installation of heat pump systems. At first builders will experience a steeper learning curve, but as they gain more experiences and create greater demand for those building materials, the building envelope cost is expected to decrease by around 25 percent in the coming years, and potentially a greater price decline would occur if the full ZNE compliance took place sooner. Experts also anticipate a natural cost reduction in heat pump systems as the technology gains traction in the HVAC market. Experts also note that technology advancements in windows, PV, storage, and demand response could take place, however there are many uncertainties associated with these developments making it hard for experts to predict their future costs and potential for impacting overall costs associated with ZNE construction.

As California has put "decarbonization" on the center stage of its state-wide environmental policy strategy to combat the immense threat caused by climate change, this study attempts to explore how that policy shift would impact the future of ZNE in California, specifically on the topic of electrification in residential new construction. In this expert elicitation, the research team explicitly asked experts about their views on a shift from mixed fuel homes to all-electric homes and the associated cost implication. The responses are split between two scenarios, one is building ZNE homes on land with existing gas infrastructure and the other is building ZNE homes on land without existing gas infrastructure. In the first scenario, experts would expect a cost increase between $3,500 and $3,800 related to fuel switching the HVAC system, water heating system, and cooking product. In the second scenario, experts would expect cost savings from not having to install the gas infrastructure in all-electric new construction. In terms of the future perspectives of all-electric homes in California, the team received mixed reviews from experts. Some experts think all-electric homes are necessary for healthy indoor air quality when the envelope is airtight. Some experts also think all-electric homes are the end goal but that the market is not ready for the shift yet. On the other hand, some experts see removing gas completely from residential homes wasteful because gas is still relatively cheap, and the infrastructure already exists in many places. For the production home market, there is still a consistent demand for certain gas-fired appliances from home buyers; hence, most production home builders will plan to include gas-fired appliances as options in their community.

Despite all the cost increments related to ZNE construction and market barriers faced by builders, there are areas that builders can focus on to alleviate some of those cost premiums. Most notably, experts from both custom and production home construction repeatedly stressed the significant benefits of incorporating an integrated design process and providing ongoing training to team members including building contractors, HVAC equipment contractors, electricians, etc. An integrated design approach to ZNE construction requires collaboration on all aspects of the building process starting at the design stage which results in a smoother process down the road. A second key area experts discussed was focusing resources on team training to enable all members of the team to continuously obtain new knowledge by attending courses and conferences focused on ZNE construction. Although experts have differing experiences with ZNE, it was noted that having a clear policy target and improved modeling tools that recognize all energy efficiency measures would get a long way in promoting ZNE among home builders. Lastly, if full ZNE compliance happens sooner it would greatly help to drive prices down probably faster for each measure than if it weren't to happen until later.

At last, even though the expert elicitation approach is being used in several energy research studies now, to the research team's knowledge this is the first time this approach has been used in the ZNE research area to acquire cost estimates on various building measures. The research team acknowledges that the study approach is not without limitations. In the survey design, building measures were broken down similarly to how they are broken down in Title 24 and experts were asked to assess each measure using the same metric provided in BEopt. This led to a total of 16 building measures for experts to consider, and in some cases, experts were only able to provide answers to some of the measures or sometimes experts were not used to thinking of costs in pre-defined metrics. Therefore, the sample size of the responses differs across measures and cost estimates are based on a few different units, which created a challenge in aggregating the results. Additionally, as experts came from both the for-profit and not-for-profit sector, their business practices can be very different and so can their views on the future of ZNE adoption. Experts were asked to only provide cost estimates based on their own experiences, so given the variety of backgrounds, their current costs and future cost projection can differ widely. Many researchers have studied which the best method is to aggregate elicitation results, but little agreement is reached (Clemen & Winkler, 1999; Cooke & Goossens, 2008; Hora, Fransen, Hawkins, & Susel, 2013). For the present study, the research team simply presents the range of expert distributions in the results section and notes the differences in each context underlying those distributions (Morgan, 2014). The tradeoff associated with this approach is that the elicitation results cannot be directly used in any numerical calculation. However, it is hoped that by providing the range of expert distributions, the team ground-truths the variation in costs of building ZNE homes in California and gains insights on the effectiveness of various building measures.

Expert Elicitation Responses: Building Measures

Note: Conventional building practices/measures and associated current cost estimates are based on a single-family reference home that is (1) using mixed fuel, (2) located in CZ12 (reference city: Stockton), and (3) sized around 1,700 ft^2.

Note: The response summary for each measure does not necessarily represent the view of all experts we spoke with. We did our best providing a range of different views on various measures; however, there are cases where only a small subset of experts provided answers to the questions, especially when related to the current and future cost estimates.

Building Envelope

Exterior Walls

Topic	Expert Elicitation Responses
Current Building Practices	Conventional homes: • Framing: 2x4 with 16 o.c. • Cavity insulation: R-15 fiberglass • Exterior sheathing: R-4 • Current cost estimate: ~$8,800 (material +labor)
	ZNE homes: • Framing: 2x6 with 24 o.c. • Cavity insulation: R-21 to R-30 blown-in fiberglass/cellulose • Exterior sheathing: R-8 plywood/OSB • Current cost estimate: Extra $1,000 to $2,000 on advanced framing, depending on the size of the home
Future Costs	*7 respondents considered this an impactful cost contributor Business as usual scenario: • There is going to be diminishing return. At first there is greater saving potential but overtime the savings will reduce. • The cost might go down by 25 percent in 2021, another 15 percent in 2026, eventually tapering off. Full ZNE scenario: • If full ZNE compliance happens sooner, it will probably help drive the price down faster. • The cost might go down by 50 percent in 2021, another 25 percent in 2026, then 10 percent, then 5 percent.
Emerging Technologies	• Reaching advanced framing in ZNE, has less to do with any breakthrough technology, and more to do with a willingness to learn how to construct walls using 2x6 with 24 o.c. • Alternative emerging technologies: o Prefab walls: currently not cost effective but prefabbing in a factory might mean a better quality product. It could become more important in 5 to 10 years. o AeroBarrier: a product for air sealing that allows easier installation. The cost is still high but could be more cost effective if savings in labor costs outweigh the additional cost. o Concrete walls: Use thermal mass as a passive energy storage; however, it will be a long time before this would become game changing

Topic	Expert Elicitation Responses
General Comments	• Experts specialized in custom home construction identified the importance of doing proper air sealing and weather stripping, at an additional cost of $1,400. • As compared to conventional framing, builders could save 10 percent to 20 percent of lumber from doing advanced framing. • Envelope insulation and air sealing are the most impactful cost contributors in ZNE home construction.

Slab Foundation Insulation

Topic	Expert Elicitation Responses
Current Building Practices	Conventional homes usually do not use slab foundation insulation. For production builders it is not cost effective, especially in the Central Valley.
	ZNE homes: • Custom builders typically do slab on grade with insulation below it.* • The insulation uses 3” to 4” EPS (expanded polystyrene) foam with 2-pound density, which is around R-12 to R-16 value. • Current cost estimate: ~$1.5 per ft^2 of a 3” EPS foam at 2-pound density (price varies constantly) *The measure of slab foundation insulation is removed from consideration in the modeling work because of an error in the software input on ground to floor heat transfer.
Future Costs	*0 respondent considered this an impactful cost contributor
Emerging Technologies	N/A
General Comments	N/A

Attic Insulation

Topic	Expert Elicitation Responses
Current Building Practices	Conventional homes: • Vented attic is more common: R-38 to R-49 fiberglass loose fill; R-20 in milder climates. • Radiant barriers, when used, are put at gable ends in vented attic. • Current cost estimate: around $2,550 total (no radiant barrier)
	ZNE homes: • Unvented attic with insulation under the roof deck is more common: R-28 fiberglass batts or Owens-Corning products. • Current cost estimates: Extra $2,000 to $2,600 for R-38 fiberglass batt and wiring; Extra $3,000 to $3,900 for R-38 Owens Corning system
Future Costs	*2 respondents considered this an impactful cost contributor No future cost estimate for attic insulation were provided.

Topic	Expert Elicitation Responses
Emerging Technologies	- There is not much technology innovation happening here. The key is training contractors on proper installation.
General Comments	- The choice between vented versus unvented attic is largely driven by design, construction, and budget. - The cost associated with building higher performance attics has less to do with the material and construction cost and more to do with the design change. This creates a high barrier to entry for most builders. - Envelope insulation and air sealing are the most impactful cost contributors in ZNE home construction.

Roof Insulation

Topic	Expert Elicitation Responses
Current Building Practices	Conventional homes: - Vented attics are more common: R-19 batt - Current cost estimate: around $1,600
	ZNE homes: - For unvented attics, some use a dense packed blown-in blanket approach to insulate the rafters, with 2” of rigid insulation on top of the roof sheathing - Current cost estimate: N/A
Future Costs	*4 respondents considered this an impactful cost contributor. Generally, in the short term, there might be greater initial savings, with cost reductions slowing down in the long term. Reductions are mainly from labor. Business as usual scenario: - There will be about a 3 percent to 5 percent reduction between now and 2021, then maybe 10 percent to 12 percent reduction between now and 2026. Full ZNE scenario: - There will be about a 5 percent to 8 percent reduction between now and 2021, then maybe a 10 percent to 12 percent reduction between now and 2026.
Emerging Technologies	- There isn’t much technology innovation here. - Prefabbing framing could become more important, but it still has a long way to go. For instance, structural insulated panels (SIPs) could probably get a better insulated envelope and roof.
General Comments	- Envelope insulation and air sealing are two of the most impactful cost contributors in ZNE home construction.

Roofing

Topic	Expert Elicitation Responses
Current Building Practices	Conventional homes: - Most builders use clay tiles and they normally do not have a cool roof rating. - Current cost estimate: N/A
	ZNE homes: - Custom builders use metal roofs for longevity reason; some production builders use concrete tiles. - Current cost estimates: around \$6 per ft^2.
Future Costs	*1 respondent considered this an impactful cost contributor No future cost estimate for roofing.
Emerging Technologies	N/A
General Comments	- The type of roofing used is highly driven by design. - Roofing material has less impact on achieving ZNE as compared to other features.

Windows

Topic	Expert Elicitation Responses
Current Building Practices	Conventional homes: - Windows area is about 14 percent to 16 percent of total floor area - U-value/SHGC: 0.31/0.22 - Current cost estimate: around \$5,000 (material + labor)
	ZNE homes: - Windows area is about 20 percent to 25 percent of total floor area - U-value/SHGC: 0.14/0.24 (triple-pane); 0.25/0.21 (double-pane) - Current cost estimate: \$40,000 to \$50,000 per home (including triple-pane windows and doors, both from European models)
Future Costs	*6 respondents considered this an impactful cost contributor. Mainstreaming good quality triple-pane windows and increasing U.S. manufacturing capability would bring the cost down. Costs may go up or down for future costs, but some experts think window costs will become a smaller part of total cost when more U.S. manufacturers take it on. Business as usual scenario: - Best estimate is that the cost stays flat in 2021. No future cost estimate provided for 2026 Full ZNE scenario: - No future cost estimate provided for 2021 and 2026

Topic	Expert Elicitation Responses
Emerging Technologies	• One company is working on a super thin film triple-pane where the middle pane is like a hanging film in between a dual-pane frame, which makes it lighter. • Windows made of uPVC (unplasticized polyvinyl chloride) might be becoming a cost-effective way to make triple-pane windows that provide great sound and thermal insulation.
General Comments	• For windows, daylighting drives window design; it is really about solar control and design for shading, an area where integrated design comes into play. • Most custom builders order triple-pane windows from Europe, many of them said it’s difficult to find them manufactured in the U.S. • There is an unsettled debate on whether it is really worth spending extra money on triple-pane windows in milder climate area. • Triple-pane windows are hot in the construction industry now, but there are still some perceived barriers to wider adoption: its size and weight and its high costs.

HVAC Equipment

Heating/Cooling System

Topic	Expert Elicitation Responses
Current Building Practices	Conventional homes (mixed fuel): • Split system AC with 14-16 SEER and 2-3 ton capacity • Gas furnace with 92 percent to 95 percent AFUE • Current cost estimate: around $6,000 (material and labor)
	ZNE homes (all-electric): • Heat pump split system with 9.5-13 HSPF, 16-21 SEER and 3-ton capacity • Current cost estimate: Around $8,000 total (material + labor); around $5,000 for equipment only
Future Costs	*3 respondents considered this an impactful cost contributor HVAC system cost would naturally come down as technology ramps up on higher end systems. Experts do not think there will be any real difference between the two scenarios. Business as usual scenario: • The cost may come down by 5 percent to 10 percent between now and 2021 and by no more than 15 percent to 20 percent between now and 2026. Full ZNE scenario: • The cost may come down by 5 percent to 10 percent between now and 2021 and by no more than 15 percent to 20 percent between now and 2026.

Topic	Expert Elicitation Responses
Emerging Technologies	• As noted by many experts, HVAC is slow moving/slowly innovating industry, and they haven't seen any huge breakthrough that will really change costs. • Geothermal heat pumps or ground source heat pumps could be an alternative HVAC system to air source heat pumps and achieve higher efficiency in certain climate zones. However, the setup costs are generally higher than air source heat pumps.
General Comments	• Heat pump system makes up one of the largest cost increases in the transition to ZNE. • Heat pump capacity can be sized down when the home is very insulated. • It's a choice that builders will need to make; if you build an airtight and well insulated home, then the HVAC equipment will be a very minor thing.

Distribution System

Topic	Expert Elicitation Responses
Current Building Practices	Conventional homes (mixed fuel): • R-4 in conditioned space (sealed attic)/ R-8 in unconditioned space (vented attic) • Current cost estimate: around $1,700 (material + labor)
	ZNE homes (all-electric): • No duct if using ductless mini split heat pump system which is usually installed in conditioned attic space. • Current cost estimate: N/A
Future Costs	*0 respondents considered this an impactful cost contributor.
Emerging Technologies	N/A
General Comments	N/A

Mechanical Ventilation

Topic	Expert Elicitation Responses
Current Building Practices	Conventional homes: • Most builders still use an exhaust fan • Current cost estimate: $450 (material + labor)
	ZNE homes: • Custom home builders: HRV (heat recovery ventilation), ERV (energy recovery ventilation), mostly manufactured in Europe • Production home builders: a balanced strategy consisting of a continuous exhaust fan and an electronically communicated motor. • Current cost estimate: $5,000 to $7,000 for an European-made HRV including labor
Future Costs	*1 respondent considered this an impactful cost contributor. No future cost estimate provided.

Topic	Expert Elicitation Responses
Emerging Technologies	N/A
General Comments	N/A

Ventilation Cooling

Topic	Expert Elicitation Responses
Current Building Practices	Conventional homes: • Whole house fan • Current cost estimate: around $800 (material + labor)
	ZNE homes: • No whole house fan because HRV is in use already • Current cost estimate: N/A
Future Costs	*1 respondent considered this an impactful cost contributor. No future cost estimate provided for ventilation cooling.
Emerging Technologies	N/A
General Comments	N/A

Water Heating Equipment

Water Heating System

Topic	Expert Elicitation Responses
Current ZNE Compared with Conventional building practices	Conventional homes (mixed fuel): • Tankless gas water heater (95 percent or 98 percent efficiency) • Current cost estimate: around $2,000 (material + labor)
	ZNE homes (all-electric): • Heat pump water heater at HSPF=5; EF=2.5-3.8; and 50-80 gallon storage tank. • Current cost estimate: o $3,000 to $7,000 with material and labor for single unit purchase (depending on the equipment used), typically around $5,500. o Production home builders could get it at a much lower price because of large volume commitment to the manufacturer.
Future Costs	*3 respondents considered this an impactful cost contributor. Similarly, to HVAC equipment, experts do not think there will be any real difference between the two scenarios. Business as usual scenario: • The cost may come down by 5 percent to 10 percent between now and 2021 and by no more than 15 percent to 20 percent between now and 2026. Full ZNE scenario: • The cost may come down by 5 percent to 10 percent between now and 2021 and by no more than 15 percent to 20 percent between now and 2026.

Topic	Expert Elicitation Responses
Emerging Technologies	• Given the high efficiency performance that heat pump water heaters can deliver, experts do not know of any better up-and-coming technology coming along.
General Comments	• The current cost of a heat pump water heater is still too high for production builders, so they would opt for tankless gas water heater, especially if there is gas available.

Solar Water Heating

Topic	Expert Elicitation Responses
Current Building Practices	None of the experts we spoke with have installed solar water heating in their ZNE homes.
Future Costs	*0 respondents considered this an impactful cost contributor.
Emerging Technologies	N/A
General Comments	• Some experts considered it before but all determined that it is still too expensive and not cost effective. The installation is too complicated and requires too much maintenance.

Appliances, Lighting and Plug Loads

Lighting Package

Topic	Expert Elicitation Responses
Current Building Practices	Conventional homes: • Normally a combination of LED and CFL • The control type is just meeting Title 24 standards • Current cost estimate: N/A
	ZNE homes: • Use all LED • Generally, the control type meets Title 24 standards, but sometimes will be upgraded to smart light switches (controlled by mobile devices) in custom home construction. • Current cost estimate: About an extra $300-$400 going from 60 percent to 80 percent LED to 100 percent LED
Future Costs	*2 respondents considered this an impactful cost contributor. Lighting cost has already come down pretty significantly, LEDs specifically. It is probably already starting to get to the diminishing return part of that cycle. Business as usual and full ZNE scenario: • About 3 percent to 5 percent reduction between now and 2021, then further reduction should be capped around 5 percent to 8 percent (basically until the cost drops to the same level as incandescent light bulbs) • No specific future cost estimate for controls
Emerging Technologies	N/A
General Comments	N/A

Home Energy Management System (HEMS)

Topic	Expert Elicitation Responses
Current Building practices	Conventional homes: - Do not use energy management system - Current cost estimate: N/A
	ZNE homes: - Several experts mentioned "SiteSage" and it can monitor at the circuit level - "Schneider Wiser" energy panel (including a main and a sub-panel) is another product used by experts. - Current cost estimate: around $1,400 for the "SiteSage" equipment plus a few hours of installation, in the end it's about $1,700 in total.
Future Costs	*0 respondents considered this an impactful cost contributor.
Emerging Technologies	N/A
General Comments	- Some experts pointed out that the main thing that is currently missing in the code is that the EDR scores for plug-loads and appliances are stagnant, so any savings from them are not appreciated in the code (in other words, no incentives for builders to install higher efficiency appliances) - HEMS could be the solution if there is ever any agreement on what the definition of HEMS is and some means for demonstrating that less energy is consumed by plug-loads and appliances through HEMS. - Some experts expressed that if they can get Title 24 credit for high efficiency appliances and HEMS, they will start doing that.

Renewable, Storage and Demand Response

Solar PV

Topic	Expert Elicitation Responses
Current Building Practices	Conventional homes: - Do not have solar PV system installed - Current cost estimate: N/A
	ZNE homes: - Builders are about 50/50 between purchased and leased system. - Current cost estimate for a purchased system: around $20,000* for a 6.5 kW system; around $17,000* for a 4 kW system - Current cost estimate for a leased system: about 20 cents per kWh the system is estimated to generate in the year. (Tesla's solar roof) *Price does not include rebate

Topic	Expert Elicitation Responses
Future Costs	*3 respondents considered this an impactful cost contributor. - It's hard to tell what the future cost of PV will be because it will probably depend on policy mandate. - One expert estimated that assuming there is a ZNE mandate, PV costs could go down by another 5 percent in 2021 and 10 percent in 2026.
Emerging Technologies	N/A
General Comments	- The key question to think about is how to handle load shifting and how to mitigate the duck curve. Energy storage and control mechanisms can be part of the solution, but not all. Something is going to have to come from the energy provider level (i.e., utility).

Energy Storage and Demand Response

Topic	Expert Elicitation Responses
Current Building Practices	Conventional homes: - Do not have energy storage in place - Current cost estimate: N/A
	ZNE homes: - Most experts use Tesla "Powerwall" with 14 kWh capacity - Current cost estimate: around $10,000 (after incentives).
Future Costs	- *1 respondent considered this an impactful cost contributor. - It is hard to tell what the future cost of energy storage and demand response will be. It partly depends on how much R&D money is going into those technologies. - Most experts think that energy storage could drop fairly dramatically in the next 5 years, but don't have an exact prediction.
Emerging Technologies	N/A
General Comments	- The key question to think about is how to handle load shifting and how to mitigate the duck curve. Energy storage and control mechanisms can be part of the solution, but not all. Something is going to have to come from the energy provider level (i.e., utility).

Non-Building Measures

Design Costs

Topic	**Expert Elicitation Responses**
Current Practices	• Design cost is estimated to be around $30,000 to $35,000 for a small custom home, using an in-house design-build model, including architectural services, structural engineering, energy modeling, etc.). • One expert indicated that building ZNE homes would add an additional 30 hours of team-wide review time across departments when compared with building conventional homes. Once more experienced in building more ZNE homes, there will be less extra time needed for future builds.
Future Costs	• There is a learning curve at first, but the more people do it, the less it costs over time. • No specific future cost estimate provided.
Innovative Approach	There is really nothing new or innovative that is going to bring the cost down other than improving existing general practices and willingness to learn an integrated design approach.
General Comments	• Having a good design is key for building ZNE homes. Implementing an integrated design process can help achieve ZNE more cost-effectively. • Builders who are far behind code will see significant increases in design costs at first, which becomes one of the biggest barriers for builders.

Soft Costs

Topic	**Expert Elicitation Responses**
Current Practices	Permitting: • The permitting cost depends on the size of the home. It could be between $20,000 and $25,000 or as high as $45,000. • Some experts noted that permitting and inspection expenses for ZNE homes are more or less the same as conventional homes. Market and Legal: • Experts specialized in production home construction tend to invest a substantial amount of time and money to craft the marketing language, advertising layouts, and fine print to avoid potential legal issues. • Experts specialized in custom home construction have a minimal marketing budget, so mostly market through word of mouth. •

Topic	Expert Elicitation Responses
Current Practices (cont'd)	Insurance and Liability: • These expenses are typically sales-based and dependent on the building type. Custom homes usually are perceived as higher risk than production homes or multi-family homes. • These expenses are mostly wrapped up in all aspects of the building costs, such as design costs, construction costs, etc.
Future Costs	• Permitting expenses will likely go up in the future as the code gets more complicated. • Insurance costs in California are expected to go up due to significant impacts of climate change.
Innovative Approach	There is really nothing new or innovative that is going to bring the cost down other than improving existing general practice.
General Comments	• Soft costs will change the way the market changes, but it is not specific to ZNE construction.

Construction Costs

Topic	Expert Elicitation Responses
Current Practices	• Experts specialized in building high performance homes said there is only minimal additional cost related to construction for ZNE compared with non-ZNE homes. The team may take an extra 20-30 hours per year to review ZNE design. • For small custom homes, construction cost is around \$250 to \$300 per ft2 including excavation.
Future Costs	• Management and trades training could drop time from 20 to 30 hours to 10 to 15 hours per year. Training should be an ongoing thing, important to educate the staff on a regular basis.
Innovative Approach	There is really nothing new or innovative that is going to bring the cost down other than improving existing general practice.
General Comments	• Continued management and trades training is key for building ZNE homes. However, additional money and time investment on training creates barriers for builders. • It goes a long way when the manufacturer of the product gets involved in designing and delivering staff training of proper installation.

Utility Infrastructure Cost

Topic	Expert Elicitation Responses
Current Practices	• Gas infrastructure cost estimate: around \$15,000 (gas infrastructure and plumbing contractors in a 3,000 ft^2 custom single-family home) • Electric power line installation cost estimate: the range can be as wide as \$10,000 to \$100,000 (typically \$20,000) in remote area.

Topic	Expert Elicitation Responses
Future Costs	*1 respondent considered this an impactful cost contributor.
Innovative Approach	N/A
General Comments	• Generally, there is cost savings from not having to put in gas infrastructure, but the amount of savings could depend on the location of the property and the size of the community. • Utilities in Northern California put more effort into incentivizing all-electric homes. • Most production home builders still provide a gas option for various appliances, such as cooktop, furnace, water heat, etc.

Whole Home Costs

In this section, we asked experts two sets of questions. The first set of questions asked about the cost difference between building a Title 24 code compliant home and a ZNE home as of in 2017. The second set of questions asked about the future cost of building a ZNE home in 2021 and 2026 as compared to the cost of building a ZNE home in 2017. Experts can express the cost difference in absolute dollar value or in percentage term. We realize that the responses we received were quite different from one expert to another, so found it more appropriate to interpret those values separately by individual experts along with its underlying context.

Cost Comparison[46]

Production Home Construction:

2016 Title 24 Home in 2017	ZNE Home in 2017	ZNE Home in 2021 & 2026
• $150,000 to $160,000 for a regular home that is a bit beyond code.*	• The construction cost is around $6,000 more to build a ZNE home when considering only what is technically needed (envelope insulation and HVAC). If including all possible upgrades (additional smart light switches, energy monitoring electrical panels, smart thermostats, etc.), the cost premium could be up to $9,000 to $10,000.	• The rate of change in ZNE basic cost premium depends on how cost of envelope insulation and HVAC equipment evolve over time. Given the future cost estimates provided previously, that $6,000 cost differential could drop by 18 percent in 2021 and by 26 percent in 2026. • If all possible updates are included. The $10,000 ZNE cost premium could drop by as much as 50 percent in next decade.

***For a just code compliant home, the cost would be a little bit lower.**

Custom Home Construction:

2016 Title 24 Home in 2017	ZNE Home in 2017	ZNE Home in 2021 & 2026
• For basic custom homes at 2,000 ft^2, the average cost for code compliant home is around $250/ft^2 • Some custom builders could build a non-energy efficient home with a much higher price tag by putting fancier finishes that are not related to efficiency.	• To build a ZNE custom home, the cost is around $300 per ft^2, or 20 percent more than code compliant home (with the exact same finishes and design, the only difference is to invest in higher efficiency measures).	• Most experts expect the cost of ZNE homes to be the same in 2021. Further down the road, it is expected that ZNE cost could go down as products are available at a lower cost. One of the biggest driving factors would be the future cost of PV system.

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[46] Total cost of building a home can vary widely depending on factors such as location, type of home, finishes and design style. To make the responses comparable, we summarized responses in a manner that total costs of homes built in similar climate zones and with similar styles are presented in the same row.

2016 Title 24 Home in 2017	ZNE Home in 2017	ZNE Home in 2021 & 2026
	• For custom builders who only build ZNE homes in higher income neighborhoods, the average cost is \$400 to \$500 per ft^2 • When comparing to other homes in the same area, the cost differential is somewhere between cost parity to 5 percent max (if not including PV system cost).	
• For a 3,000 ft^2 code compliant home in the Bay Area, the cost is about \$900,000.	• The incremental cost of doing ZNE home is \$15,000, and another \$18,000 for PV system.	