MODELING AND COST-EFFECTIVENESS ANALYSIS OF ZERO NET ENERGY HOMES IN CALIFORNIA

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ABSTRACT

This paper presents a modeling and cost-effectiveness analysis of zero net energy (ZNE) new homes in California, which offers insights for future California building energy efficiency standards (Title 24). The time-dependent valuation (TDV) methodology was used to evaluate the cost-effectiveness of the ZNE home, and TDV-based hourly utility rates were applied to estimate future energy costs for the 2022 Title 24 code cycle. The BEopt software, using EnergyPlus as the simulation engine, was utilized to provide the life-cycle cost optimization of the building designs for both the all-electric and the mixed-fuel single-family homes across 16 California climate zones. Technologies to achieve ZNE homes include various energy efficiency measures (EEM) covering envelope, HVAC, domestic hot water, appliances as well as rooftop photovoltaics. The optimization results show that optimally designed ZNE homes have lower customer life-cycle costs for both the all-electric and the mixed-fuel cases. All-electric homes are comparable in life-cycle costs to mixed-fuel homes in most climate zones as they can benefit from not having to build natural gas infrastructure to the home. PV helps the cost-effectiveness of ZNE homes. These findings provide guidance for the future revision of Title 24 standards as well as inform California's policies on electrification and the adoption of renewable energy for residential buildings.

INTRODUCTION

California State is a worldwide testbed for low-cost and low-Green House Gas (GHG) strategies for a future decarbonized economy. The state has extremely aggressive economy-wide GHG reduction goals for 2030 with a 40% economy-wide GHG reduction target (CA SB 32, 2016) from the 1990 level and an 80% reduction goal in 2050 by Executive Order S-3-05 (State of California, 2005). More recently, the state has set the target of 60% renewable portfolio standard (RPS) for the electricity sector in 2030, a zero GHG emissions goal in the electricity sector by 2045 (CA SB 100, 2018), and the state governor announced a goal of net-zero carbon emissions statewide by 2045 (Executive Order B-55-18) (State of California, 2018).

Title 24 is a collection of building energy efficiency standards designed to ensure new and existing buildings in California to achieve energy efficiency (CEC, 2019a). Title 24 incorporates 16 California climate zones (CEC, 2019b). Each climate zone has a unique climatic condition that helps quantify a minimum efficiency requirement for that specific climate zone. The California Energy Commission updates and adopts Title 24 every three years that are cost-effective for building owners over the 30-year lifespan of a building. The standards are updated to consider and incorporate new energy-efficient technologies and construction methods. The standards help improve building energy efficiency, increase electricity supply reliability, and increase indoor comfort. Title 24 building energy efficiency standards for California buildings have become successively more stringent over time. For new homes, the state has the policy goal of zero net energy (ZNE) new homes by 2020 (CEC and CPUC, 2015). Title 24 building energy efficiency standards provide a pathway to achieve ZNE homes.

Recently ZNE buildings have been a policy interest for new buildings. US DOE defines a ZNE building as: An energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy (U.S. DOE, 2015). The California definition for ZNE (“ZNE TDV”) is based on time-dependent valuation (TDV) factors. ZNE TDV is a CEC developed and promulgated definition for the "utility cost" value of energy whereby the energy consumed by the building over the course of a typical year is less than or equal to the utility cost value of the on-site renewable energy generated (State of California, 2016).

Title 24 building energy efficiency standards are based upon the cost-effectiveness of energy efficiency measures in new buildings. TDV has been used in the cost-effectiveness calculation for California's 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. TDV reflects 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. The units are TDV kBtu which represents the conversion factor from actual energy used to TDV expressed as kBtu/Energy. This is a similar concept to the units of heat rate for a power plant. The denominator "Energy" uses kWh for electricity and therm for natural gas and propane (UC Davis, 2019). TDV values for electricity can shift the value of onsite renewable energy such as rooftop solar PV. TDV values are expected to change as the mix of electricity supply changes over time.

This paper provides findings from the cost-effectiveness analysis of the future California ZNE homes. The paper discusses the cost-effectiveness of the all-electric homes and mixed-fuel homes, and benefits and costs impact of the rooftop solar PV panels.

COST-EFFECTIVENESS ZNE HOMES

TDV for 2022

Since the ZNE home analysis is targeted for the 2022 building code and energy efficiency standard guideline, TDV values for 2022 are derived and used for the cost-effectiveness analysis. We used CEC's PLEXOS model (Energy Exemplar, 2019) updated for the CEC's 2017 Integrated Energy Policy Report Update (IEPR). Two sets of TDV for the 2022 – 2052 period were derived.

1. A "Base Case" set, which approximates energy costs under currently adopted policies including 50% renewable portfolio standard (RPS) by 2030
2. A "Higher Renewables" set, which uses 70% RPS

Figure 1 and Figure 2 show hourly 2022 TDV values under the base and high renewables 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 (Energy and Environmental Economics Inc. (E3), 2016). The Higher Renewables case shows higher average TDV values in each hour, due primarily to higher renewable portfolio standard and capacity values (and despite lower energy costs in the middle of the day during higher solar production).

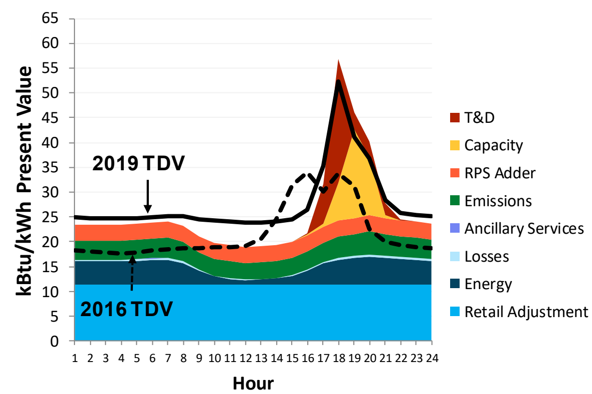

Figure 1 Base Case 2022 TDV Components across an Average day, California Climate Zone 12 (Total 2022 TDV value is the sum of all components in each hour)

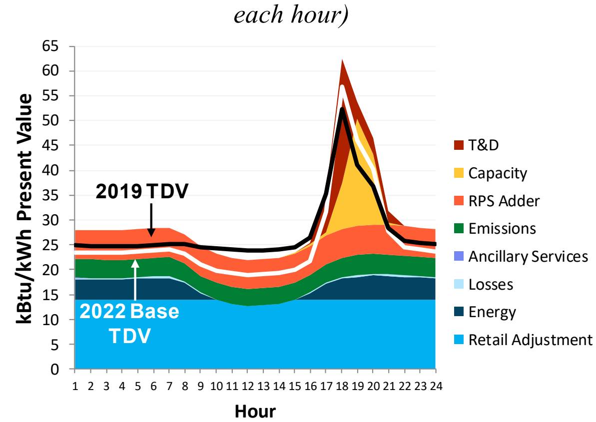

Figure 2 Higher Renewables 2022 TDV components across an average day, California Climate Zone 12

Modeling Assumptions

The cost-effectiveness analysis uses building energy modeling and simulation for cost optimization. Optimized building designs are determined from leveraging building energy modeling and energy performance simulation. Building energy modeling and simulation results are targeted for California's 2022 building energy code cycle. This work assumes lower compensation rates for exported electricity to the grid from solar PV (Avoided Cost for Exports) in anticipation of further evolution of the net energy metering (NEM) policy for rooftop solar. The cost-effectiveness uses the newly derived TDV values for 2022.

Building energy modeling is based upon the prototype residential building single-family home. The prototype home (Figure 3) is a single story with 3 bedrooms and 2100 ft^2 gross area. The prototype model was developed by the CEC for testing of the Alternative Calculation Method with the CBECC-Res compliance software (CEC, 2015), and the model was adopted in the residential building energy modeling and simulation tool: BEopt (Building Energy Optimization Tool) version 2.8 (NREL, 2018a) for the ZNE home energy performance evaluation and cost-effectiveness analysis. We validated that the baseline design for 2019 Title 24-compliant homes developed in BEopt comparing energy usage by end-use with output from CBECC-Res, and they were in good agreement.

Single Family 2,100 ft2
(CEC prototype)

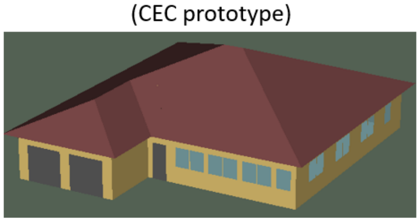

Figure 3 Prototype buildings for modeling in BEopt

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

BEopt calculates the annualized energy-related life-cycle-cost of the building design with efficiency measure packages. Key inputs for the analysis include the set of energy conservation measures, measure costs, rooftop PV capital costs, and utility cost as well as net PV compensation rates. Cost assumptions are a key aspect of the cost-effectiveness analysis for ZNE homes. Measure costs are primarily based on NREL's National Residential Efficiency Measures Database (NREL, 2018b) supplemented by additional sources, including expert elicitation inputs. For the study, utility rate inputs use TDV-based hourly electricity rates as a proxy for future utility rates. A fixed annual rate was used for natural gas rates taking the average TDV-based rate. The TDV-based hourly utility rate approach is aligned with the current codes and standards rulemaking process, although the CEC is evaluating cost-effectiveness options for the 2022 code cycle that may be more based on source-energy and/or provide more direct weighting to greenhouse gas (GHG) emissions reductions. The TDV-based 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 rates reflect the NEM policy evolution of less favorable rooftop PV compensation (CPUC, 2018).

The simulation finds optimal measure packages that minimize TDV-based life-cycle energy costs. The energy-related life-cycle costs include full annualized utility bills plus annualized capital cost values over 30 years for the improved cost case. Cash flows consist of equipment capital costs, installation costs, replacement costs, utility bill payments, and residual values. Underlying market economy assumptions include inflation 2.4%, discount rate 3%, energy rate escalation 0%, and no tax credit of capital cost for PV incentives.

Title 24 Baseline Model and ZNE Measures

The baseline home for the cost-effective analysis is based on the prescriptive requirements of the 2019 Title 24 with PV. Energy savings and cost impacts for ZNE measures were analyzed relative to this baseline. Promising efficiency measures for residential buildings were identified for each California climate zone, along with realistic estimates of the installed cost of each measure. A broad range of energy efficiency measures was included as options for achieving ZNE. The final 22 pre-screened measure categories with 46 measures options and costs were used as inputs to the BEopt models that predicted optimal pathways to ZNE in a variety of contexts. Details of the performance characteristics and incremental cost assumptions for the selected measures are documented in the CEC report (Note that the report is submitted to and under review for publication).

ZNE HOME SIMULATION RESULTS

All-electric vs. mixed-fuel homes cost-effectiveness

All-electric and mixed-fuel baseline models were used to evaluate the cost-effectiveness of ZNE home designs for future mixed-fuel and all-electric homes.

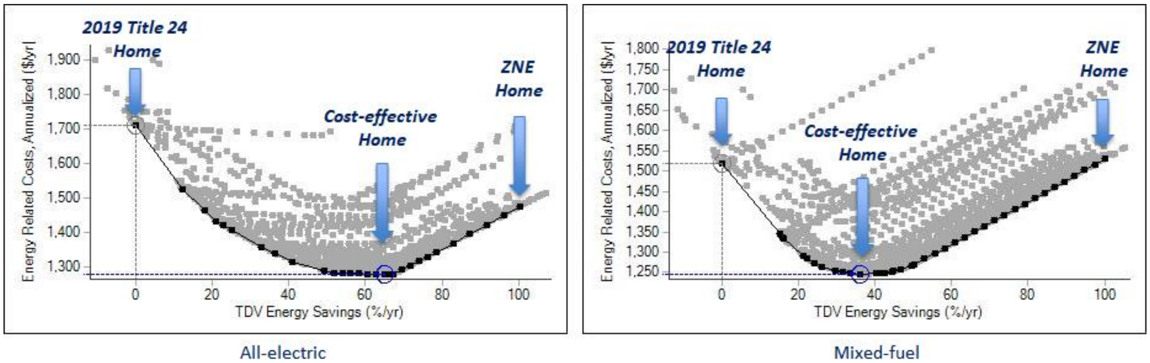

Figure 4 Cost-effectiveness optimization results for single-family 2100 ft2 climate zone 13 (left: all-electric home, right: mixed-fuel home)

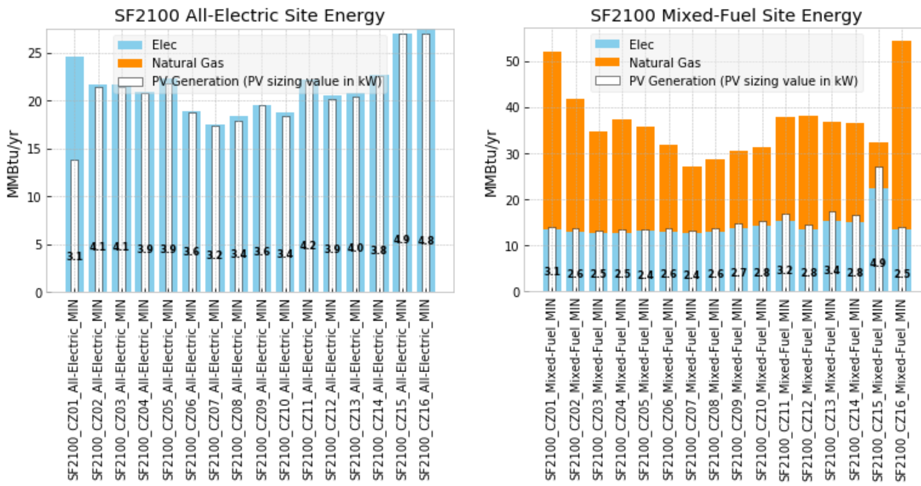

Figure 5 Cost-effective minimum points (single-family 2100 ft2): Electricity / natural gas consumption and PV electricity generation (left: all-electric home, right: mixed-fuel home)

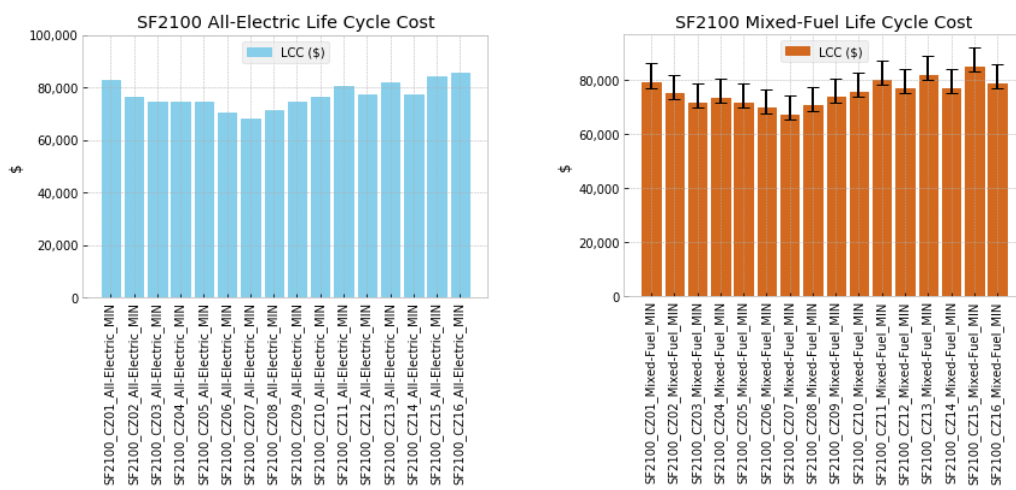

Figure 6 Life cycle cost of all-electric and mixed-fuel single family 2100 ft2 homes at cost-optimal design point for all California climate zones, using 2022 TDV values and avoided cost for solar PV exports.

Figure 4 shows building energy simulation results that illustrate the energy-related cost saving compared to the baseline homes for all-electric (left chart) and mixed-fuel (right chart) single family 2,100 ft^2 prototype homes in climate zone 13. The x-axis represents TDV savings compared to the reference point while the y-axis represents the annualized energy-related cost that integrates utility cost and added measure capital cost. Each curve is a Pareto front for thousands of building energy simulations performed during optimizations, which illustrates cost-effective designs compared to the baseline homes. 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 shows 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 impacts 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 mixed-fuel 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 4 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 5 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 6 shows the life-cycle cost of the minimum cost designs for all-electric (left) and mixed-fuel (right) prototype single-family 2100 ft^2 homes. These costs only include the subset of building measures that are included in BEopt and do not include every cost item associated with building construction (e.g., plumbing pipes), land costs, permitting, profit margin, etc. The average price of a new home sold in the US in May 2019 was \$377,200 (median price of \$308,000). For California, historical and current new home sales prices were not readily available, but the median price for existing homes in California was \$611,200 in May 2019 (YCHARTS, 20109; NewHomeSource, 2019; US Census Bureau, 2019). 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% discount rate, and 4% mortgage interest rate, and 28% marginal income tax rate used for annual tax deductions. Note that the mixed-fuel home heating and hot water fuel type is assumed to be conventional pipeline natural gas. A range of infrastructure costs is shown for mixed-fuel homes, as natural gas connection costs need to be considered when comparing to all-electric homes. These can vary depending on the degree of infrastructure required but typically vary from about \$1,000 to \$10,000 per home, centered at an assumed median point of \$3,000 per home infrastructure cost.

Measures for cost-effectiveness

For homes with mixed-fuel and all-electric, frequently selected individual efficiency measures for cost-optimal designs are large appliances, plug load reduction, duct, and hot water pipe insulation. A more efficienct air-source heat pump improves the cost-effectiveness for all-electric homes. Large Appliances include dishwashers, clothes dryers, clothes washers, and refrigerators. Figure 7 shows how individual measures can save electricity relative to the 2019 Title 24-compliant baseline home, for example, 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 appliances, clothes dryers show high energy savings followed by refrigerators.

PV orientation sensitivity

The baseline prototype models have PV systems with the South orientation. The South-facing orientation can generate the most electricity generation as shown in Figure 8 (top), for example for a single-family 2100ft^2 all-electric home at the cost-effective design point. PV module orientation to Southwest has the most beneficial to reduce the utility cost under the TDV 2022-based hourly pricing utility rate structure,

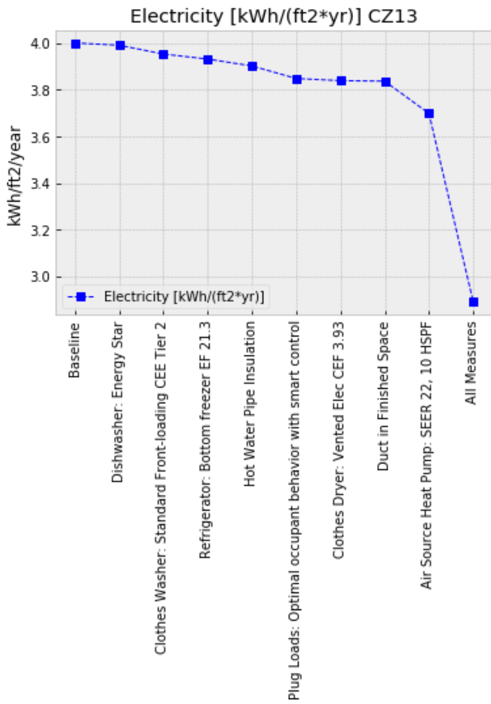

Figure 7 CZ13 measures for cost-effectiveness and its impact to electricity saving

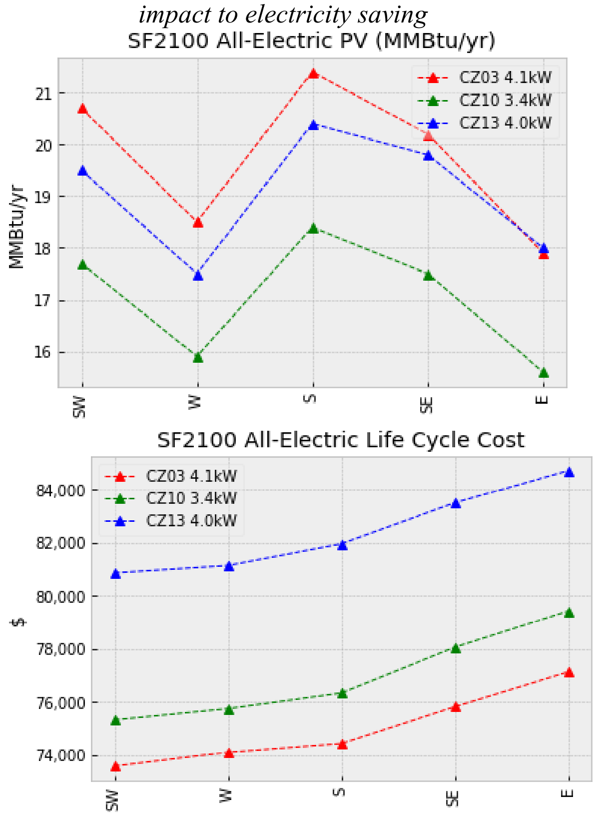

Figure 8 PV electricity generation by PV module orientation (top) and their impact to the life cycle cost (bottom)

followed by a West facing orientation. Figure 8 (bottom) shows the life cycle cost for different PV module orientations. Electricity generation in the late afternoon has a greater value for the life-cycle cost reduction with the TDV metric for Southwest and West facing PV modules.

DISCUSSION

Tighter building shells and energy-efficient large appliances (clothes dryers and washers, dishwashers, refrigerators, cooktop stoves, and ovens) are increasingly important for reducing life-cycle energy costs and represent cost-effective opportunities for life-cycle cost. Similarly, plug loads represent a growing fraction of electricity usage and plug load reduction measures, for example, advanced power strip and smart plugs, show promise as cost-effective energy measures.

Electrification has been found to be a key pathway to decarbonize the building sector (Mahone *et al.*, 2018; Wei *et al.*, 2019) and to meet long-term climate goals. All-electric homes can be more attractive for their lower overall CO_2 emissions than mixed-fuel homes. Requiring all-electric homes in a future code cycle would support California's objectives for much lower GHG in the building sector and would be a large policy lever to facilitate "market transformation". Due to the higher resulting volume of all-electric homes, this requirement would also motivate the development of greater industry expertise and a more extensive supply chain for equipment such as heat pump water heaters, air-source heat pumps, and mini-split heat pumps. The building industry would develop greater experience in construction and installation, and costs may decrease further due to greater supply chain competition and increased production volume for heat pump-based heating equipment. From historical examples of other energy technologies, appliance costs (Desroches *et al.*, 2013) and installation costs (Wei, Smith and Sohn, 2017) have both seen cost reductions with higher installed volumes and deployment programs such as higher energy efficiency standards. With further supportive policies for contractor training, general, plumbing, and HVAC contractors would traverse up the learning curve for construction and of all-electric homes and develop streamlined best practices.

California's TDV metric is unique for the evaluation of the cost-effectiveness of the ZNE homes. Full TDV-based ZNE homes can be achieved with oversizing PV systems that offset the TDV of a building's total annual site energy usage with TDV from PV generated electricity. However, this is not recommended as PV oversizing is not consistent with grid harmonization objectives. Rooftop PV annual output electricity that exceeds site electricity consumption violates the current NEM policy. PV system with the orientation to Southwest and West is advantageous compared to South when optimizing life-cycle cost with the TDV metric.

The cost-effectiveness analysis for new ZNE homes is based on the underlying assumptions including future building California code cycles using the updated TDV factors for 2022, less attractive compensation rates for rooftop solar power exported to the grid avoided cost for exports rather than the current NEM 2.0 compensation rate for exports.

CONCLUSIONS

This paper presented the cost-effectiveness analysis of ZNE new homes in California. Building envelope and energy-efficient large appliances, clothes dryers and washers, dishwashers, refrigerators, and plug loads are increasingly important EEMs for ZNE homes. The cost-optimized designs can reduce the life-cycle costs for all-electric and mixed-fuel homes compared to their all-electric and mixed-fuel 2019 Title 24 baseline cases for all climate zones. We find that all-electric homes are comparable in life-cycle costs to mixed-fuel homes for most California climate zones considering cost savings from avoided natural gas infrastructure. The cost-effectiveness of the all-electric ZNE homes can depend on the dynamics of capital costs of heat pumps and heat pump water heaters and the PV export compensation. These findings provide guidance for future updates of Title 24 standards as well as inform California's policies on electrification and the adoption of renewable energy for new residential buildings.

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