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Developing Single-Family Residential Prototype Models for California

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Abstract

Currently, different policy making agencies in California, including California Energy Commission (CEC) and the California Public Utilities Commission (CPUC), use different sets of prototype models for analyzing the impact of efficiency, renewable, electrification, and decarbonization measures. This effort is aimed at creating a unified set of prototype models to represent California's building stock and provide the agencies with a single set of prototypes for conducting their analysis.

This paper describes the prototype development performed for California's single-family buildings sector. The first step was to analyse the building stock and develop prototypes that were representative of single-family homes in the stock. The next step was to develop inputs for the representative prototypes. Data from several sources including the Residential Appliance Saturation Study (2019 Residential Appliance Saturation Study (RASS)), American Housing Survey (AHS, 2019) and ResStock (NREL, 2022) was used to develop the inputs. Lastly, the inputs were documented and used to develop prototype models in EnergyPlus. Four single-family models in five vintage bins and 16 climate zones were developed.

Background and Introduction

Prototype building models serve as representations of a region's building stock and, when coupled with construction data, facilitate the analysis of policy decisions on the building stock. The U.S. Department of Energy (DOE) employs commercial and residential prototype models, rooted in EnergyPlus™ (DOE, 2022) to evaluate energy savings from national energy codes, assess the efficacy of proposed changes to energy codes, conduct cost-effectiveness analyses, and evaluate emerging technologies. Additionally, these prototype building models play a crucial role in setting targets for beyond-code programs. In California, there are similar needs for prototype models, but there exists no single set of prototype models for these needs. Government agencies, private entities, consultants, and other stakeholders utilize accessible models, resulting in varying predicted outcomes and market uncertainty regarding the suitability of models for specific purposes.

The residential sector in the U.S. features additional prototype models, exemplified by ResStock (NREL, 2022)'s six models. Internationally, the EPISCOPE (Diefenbach, 2016) project in Europe has developed residential building models in various countries (i.e., Italy, Germany, Denmark, and Greece), and Chinese residential stock has been modeled using prototypes like MOHURD and CABR (An, 2023). These initiatives aim to represent the typical urban building characteristics, meteorological conditions, and construction years, contributing to the optimization of building energy conservation research by fostering innovations in energy-saving technologies, advanced controls, and new policies. Furthermore, they serve as valuable references for the development of building energy codes and standards (An, J., Wu, Y., Gui, C. et al. 2023).

This initiative to develop prototypes for California was funded by Southern California Edison (SCE) with the aim of creating a unified set of prototype building models representing California's diverse building stock. Such a unified approach would empower the CEC and the CPUC to employ a consistent set of assumptions about the building stock for various analyses, including the assessment of proposed changes to the energy code and the evaluation of deemed and custom measures for incentive programs. This paper focuses on the development of prototype models for the single-family building sector.

Methodology

This section describes the workflow used in developing unified prototype models for single-family homes in California. The development of prototype models was divided into four major tasks:

1. **Building stock assessment:** To develop models that represent the stock, buildings within the stock must

be characterized. Based on the stock assessment, a mix of prototype models was selected to represent key characteristics of the stock, such as floor area, number of bedrooms, number of stories, etc.

2. **Model inputs development:** Once the prototype models that represent the stock were identified, each was characterized further in terms of envelope, lighting, HVAC, water heating, plug and process loads, and other systems and characteristics. The inputs needed to define model characteristics were documented.
3. **Model construction:** Using the model inputs, models were constructed in DOE's EnergyPlus simulation engine. The intent is to host these EnergyPlus models as well as the underlying input assumptions in a publicly accessible workspace, so that all entities can share and use the same prototype models.
4. **Model Validation:** Prototype models were validated using stock energy consumption data from the 2019 Residential Appliance Saturation Survey (RASS) for single-family homes.

Model input documentation was a key feature of this study. The objective was to rigorously document the assumptions, host the models and documentation on a public platform, and provide a forum for future maintenance and development of California prototype models.

Building stock assessment

Nearly 74% of the residential buildings' floor area in California is occupied by single-family homes (Figure 1), which corresponds to approximately 60% of the total number of residential buildings in the state (Figure 2).

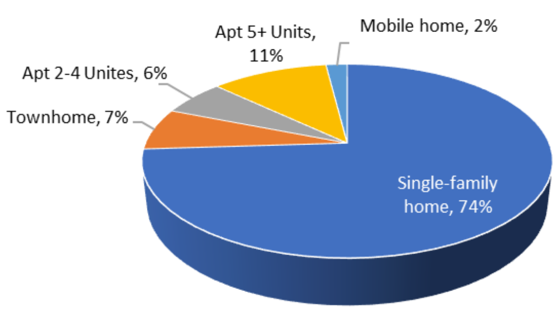

Figure 1 California residential building sector floor area distribution (Source: AHS 2019)

Single-family homes consume 83% of the total residential energy consumption in California (Figure 3).

In addition to single-family homes, RASS classifies the residential sector into apartments with 2-4 units, apartments with five or more units, townhomes, and mobile homes. "Apartments with 2-4 units" and "apartments with five or more units" were excluded from the single-family building type. Townhomes can be included in the single-family section because their characteristics are more aligned with single-family buildings than with multifamily buildings. However, because townhomes are a relatively small portion of the stock, they were excluded from the analysis.

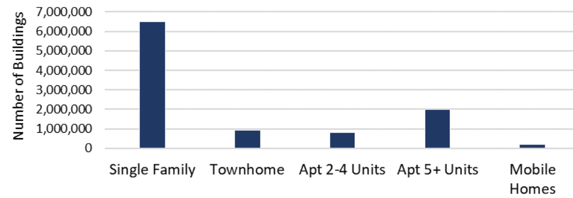

Figure 2 Number of buildings and units for various residential building types (Source: RASS 2019)

Similarly, mobile homes form a small portion of the residential building stock and were not included in this analysis.

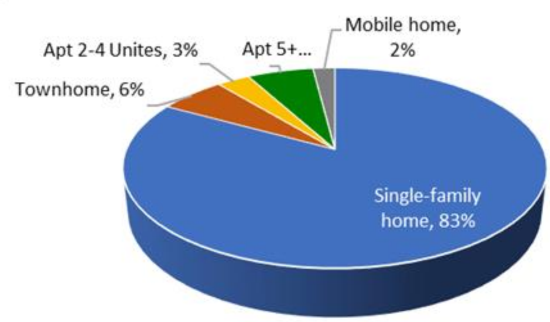

Figure 3 California residential building sector energy consumption distribution (kWh) (Source: AHS 2019)

The building stock assessment provided the defining characteristics of the building stock, including the floor area and number of bedrooms. While each home in the stock is different, the number of prototype models that can be used to represent the stock is limited by the usability of the model set. Having more models provides more granularity but also results in more run time, post-processing, and requires the ability to perform large-scale parametric simulations. This usability aspect was used to optimize the number and mix of prototypes that represent the stock. The prototypes mix was formulated based on the building stock assessment.

The California-specific Residential Appliance Saturation Study, known as RASS (CEC, 2019), and the American Housing Survey (AHS, 2019) were the building stock assessment primary data sources. RASS contains characteristic saturation, energy consumption patterns, and specific data about equipment energy use. AHS is a nationwide survey with information on houses and apartments constructed over the past few decades. The data is very detailed and is a near-complete picture of the residential building stock from the perspective of floor area, heating system type, and other key characteristics of residential buildings.

The main objective of the assessment is to determine the residential building distribution across floor area, vintage, and other defining features of single-family buildings, including number of bedrooms, number of stories, and other model features important for representing the stock.

Floor Area Distribution

Among the various characteristics of a single-family home, the conditioned floor area is the most important one. Figure 4 shows the distribution of the single-family home size in terms of the total floor area in the state. Single-family homes with floor area lower than 750 ft^2 cover a very small portion of the building stock. Those with an area in range of 1000-1500 ft^2 and 1,500-2,000 ft^2 occupy the most floor area. Overall, 81% of the single-family building stock has floor area in the range of 1,000 to 3000 ft^2.

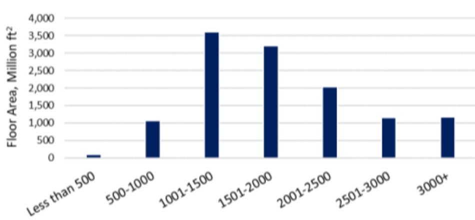

Figure 4 Single-family floor area distribution across floor area bins (Source: RASS 2019)

Distribution of the floor area across climate zones showed that the single-family building stock in California is dominated by construction in the Sacramento area, the Bay Area, and several counties in the coastal, southern part of the State (Figure 5). Climate influences building characteristics, such as wall and roof insulation.

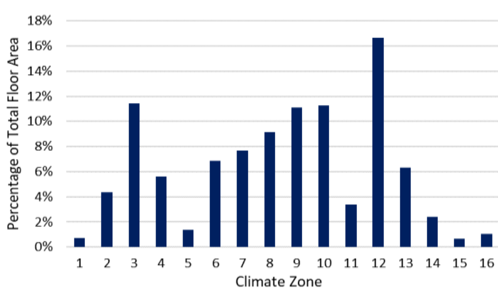

Figure 5 Single-family floor area distribution across California climate zones (Source: RASS 2019)

Number of Bedrooms

Plug and appliance loads are a key factor in determining the energy consumption of a single-family home. While envelope loads scale with floor area, plug and appliance loads, for example, from the kitchen appliances and domestic hot water, scale with the number of bedrooms. The number of bedrooms determines the home’s occupancy, which, in turn, affects the plug load intensity and the hot water usage.

Table 1 shows the floor area distribution by number of bedrooms for single-family buildings based on the data from AHS (2019). As can be seen, three- and four-bedroom homes occupy a large portion of the floor area and need to be incorporated in the prototype mix. However, given the prevalence of homes smaller than 1,500 ft^2 in the existing buildings stock, especially in the pre-1975 vintage bin, including a 2-bedroom prototype will better represent the stock.

Table 1 Floor area distribution by number of bedrooms (Source: AHS 2019)

Number of bedrooms	Floor Area Distribution
0-1	1%
2	14%
3	47%
4	29%
5+	9%
0-1	1%

Number of Stories

The number of stories directly influences the ratio of exposed envelope to conditioned floor area. For example, the impact of roof insulation may be lower in a two-story home than a single-story home. Table 2 shows the proportion of floor area by number of stories. One- and two-story homes are the dominant forms, and they need to be reflected in the prototypes mix.

Table 2 Floor area distribution by number of stories (Source: AHS 2019)

Number of stories	Floor Area Distribution
1	64%
2	32%
3	3%

Vintage

The age of single-family homes within the building stock is a key feature that influences energy consumption because of variation in opaque envelope insulation, fenestration performance, and air leakage with age. Lighting, HVAC, and hot water equipment is assumed to be replaced and does not correlate well with the age of the home. To develop a representation of the stock, homes constructed over a period of years were grouped into vintage bins. The amount of construction during a given time period and the approximate energy efficiency achieved during a range of construction years were factors considered when choosing vintage bins. Ultimately, a hybrid approach was used where the floor area distribution, amount of floor area in a given vintage range, and the energy efficiency of the stock within a vintage were optimized to provide a complete representation of the stock.

Figure 6 shows the floor area distribution by vintage and is based on data from RASS (CEC, 2019). The data from AHS is similar, and in fact, the sampled dataset used by RASS matches the distribution within AHS very closely. The vintage bins have been drawn from RASS and were based on a variety of parameters, including the Energy Commission's forecasting requirements and changes to code requirements.

A large portion of the existing single-family stock was constructed prior to 1975. The reason for starting with a pre-1975 bin was that the first California residential energy code was enacted in 1975, following the Warren Alquist Act (Cal. Pub. Resources Code sections 25000 et seq., 25402.1).

New editions of the energy code appeared approximately every three years after 1975. Most residential homes constructed prior to 1975 could be characterized by a lack of insulation in the walls, roofs, and around the slab edge, and single pane windows. While some of the homes would. For instance, only be retrofitted with double-pane windows, it is estimated that such replacements form an insignificant portion of the building stock. For instance, 75% of the single-family homes built in California before 1975 are still using their original single-pane windows (RECS 2020).

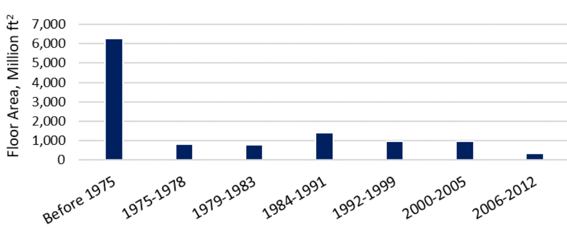

Figure 6 Single-family floor area distribution by vintage (Source: RASS 2019)

Figure 7 shows the floor area distribution by vintage and by floor area bins. The floor area bins smaller than 2,000 ft^2 occupy a larger portion of the stock for homes constructed prior to 2000. After the year 2000, the distribution skews slightly towards homes larger than 2,000 ft^2. This distribution is useful in understanding the characteristics of the existing building stock, in planning efficiency measures, and in developing the construction weighting that allow aggregating the impact to the state level.

Impact of Energy Codes

Past residential energy code editions in California regulated the energy efficiency of residential buildings.

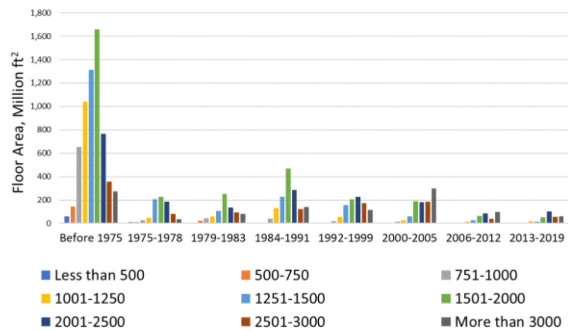

Figure 7 Single-family floor area distribution by vintage and by floor area bins (Source: RASS 2019)

Therefore, it might be logical to group vintage bins into year ranges where the stringency of the energy code was similar. Past energy codes were reviewed, and the findings of this review are summarized below:

- 1975-1982: These were the first generation of energy codes. These codes specified prescriptive residential requirements for all the major building components (envelope, HVAC, lighting, and water heating).
- 1984-1988: Beginning in 1984, the residential code sections switched from a prescriptive standard to a performance standard together with pre-calculated prescriptive packages. It is difficult to compare the efficiency level established by this set of standards relative to previous standards because of the differences in how performance is specified.
- 1992-1999: These set of codes revised the performance specification, and upon first review it appears that at least the water heating performance was less stringent than in previous codes. On the prescriptive side, fewer prescriptive packages were available for residential single-family buildings.
- Post-2000 codes: The prescriptive packages were further reduced, and the performance path used a differential approach, similar to the commercial performance compliance approach.

It was difficult to ascertain the stringency of past energy codes because the approaches change dramatically between some of the code editions. Absent a simulation-based investigation of the relative stringencies of each code edition, the suggested five vintage bins were used as a proxy for relative changes in stringency within the energy code – as presented in Table 3. The demarcation is approximate—there were many changes to the code in the intervening years of a time period—but the bins as arranged do follow the periods when the residential energy code underwent significant changes as a whole.

Table 3 Vintage bins for single-family prototypes

Building type	Vintage bin
Single-family	Pre 1975
	1975-1983
	1984-2005
	2006-2019
	New Construction

Floor-to-Ground Interface

The floor-to-ground interface plays a key role in heat transfer between the home and the exterior. Table 4 shows the proportion of floor area by foundation type. Most residential construction in California is primarily built with concrete slab followed by a significant number of homes with a crawl space.

Table 4 Floor area distribution by foundation type (Source: AHS 2019)

Foundation Type	Floor Area Distribution
Basement under all of house	2%
Basement under part of house	2%
Crawl space	30%
Concrete slab	66%

Sensitivity to Floor Condition

The prototypes mix could be defined to represent homes with both concrete slabs and crawlspaces. The question was whether a crawl space has significant energy impact compared to a concrete slab. A sensitivity analysis was performed using CBECC-Res (CEC, 2022) and the 2,100 ft^2 Title 24 CEC prototype in three climate zones: 12, 15, and 16 representing mild (CZ12), hot (CZ15), and cold (CZ16) climates in California.. Table 5 shows the results of the analysis. The maximum heating and cooling energy difference between the crawl space and slab configuration was found to be 13%. Although the impact on the heating and cooling end-uses is relatively small, given that crawl space represents 30% of the stock, it was decided to use a concrete slab for 66% of each prototype's floor area and a crawl space for the rest.

Table 5 Slab and crawl space sensitivity analysis

Climate Zone	Total space heating and cooling ($kBtu/ft^2$)		Percentage Change
	Slab	Crawl Space	
CZ12	8.02	7.02	13%
CZ15	6.75	7.53	-12%
CZ16	16.62	14.77	11%

Sensitivity to Floor Area

Figure 7 shows that homes smaller than 2,500 ft2 are the most dominant homes in California. They stand for over 80% of the single-family homes and this prompted the question of whether it would be appropriate to discard the larger prototypes (over 2,500 ft2) in lieu of prototypes smaller than 2,500 ft2 to represent new construction and existing building stock.

To answer this question, CEC single-family prototypes including a single-story 2,100 ft2 prototype and a two-story 2,700 ft2 prototype were selected. A sensitivity analysis was performed using CBECC-Res, to determine the heating and cooling annual energy consumption difference between the two prototypes. Table 6 outlines the results of the analysis. There is a decrease in the heating and cooling energy consumption when going to the larger prototype. This is because smaller homes have proportionally higher dependance on plug and process loads than larger homes and because the envelope-to-floor area ratio is proportionally higher in smaller homes. Considering the observed 12% difference in total heating demand in the cold climate zone (CZ16) and the need for uniformity, it was decided to develop an additional prototype model for homes larger than 2,500 ft2 in each climate zone.

Table 6 Sensitivity of energy consumption to prototype floor area

Climate zone	Total space heating and cooling (kBtu/sf)		Percentage Change
	2,100 ft2	2,700 ft2	
CZ12	8.02	7.43	7%
CZ15	6.75	6.55	3%
CZ16	16.62	14.65	12%

Single-family Prototypes Composition

Drawing from the building stock assessment, a set of prototypes and vintage bins were developed to accurately represent California's single-family housing stock. This was accomplished by utilizing four distinct prototype models, as shown in Table 7, and aligning them within five vintage bins, as specified in

More specifically, Table 7 encompasses the composition of single-family prototypes, delineating the floor area, number of stories, and number of bedrooms for each. A notable divergence among the prototypes is evident in their floor areas, exhibiting a 500 square foot (ft^2) variation, ranging from 1,250 ft^2 to 2,750 ft^2. The number of stories and bedrooms corresponds proportionally to the respective floor areas. Notably, the foundation type for all prototypes was uniformly designated as a concrete slab on grade for 66% of the floor area, while the remaining 34% utilized a crawlspace assembly, as detailed in Table 4. The approach presented here is intended to balance the various trends observed in the floor area, vintage, and other attributes with the needs of the agencies. With the four prototypes and their variation, and by applying weighting factors, it is possible to represent the California residential single-family building stock. While these represent the primary single-family prototype models, it is important to acknowledge the existence of additional variations discovered during the collection of input data. These alternative prototypes are elaborated upon in the following section.

Table 7 Single-family Prototypes Composition

Building Type	Prototype Name	Floor Area (ft2)	Number of stories	Number of bedrooms
Single-family	SF1250	1,250	1	2
	SF1750	1,750	1	3
	SF2250	2,250	2	4
	SF2750	2,750	2	4

Model Inputs Development

The next step in single-family prototype development was to collect model inputs for each prototype, vintage, and climate zone. These model inputs will define various features of the prototypes. For each input, data representing the building stock was given priority; otherwise, inputs were formulated from the prevailing energy code, or from other data sources, including ResStock, CEC and PNNL prototype models, and other literature. The primary data sources for developing model inputs were:

- Residential Appliance Saturation Study (RASS).
- U.S. Department of Energy Respiratory for Residential building energy analysis (ResStock).
- Building Standards for Residential and Nonresidential Buildings (Title 24).
- Appliance Efficiency Regulations (Title 20).
- California Energy Commission, 2015 (CEC).
- Building America House Simulation Protocols (NREL 2014).
- California's Building Energy Code Compliance Software – Residential, 2022 (CBECC-Res).
- PNNL Residential Prototype Buildings.
- Code of Federal Regulations. Title 10 CFR 430.

RASS was the primary source unless the required data was unavailable or limited, in which case, ResStock was used, if appropriate. For some cases such as R-values, particularly for "New Construction" or when RASS or ResStock lacked the required data, Title 24 (or other code) was referenced (if applicable). Other sources, such as a California single-family thermostat setpoint database, were consulted to develop certain model inputs. Table 8 lists the sources for various building characteristics used in the development of the single-family prototypes.

Table 8 Summary of the Data Sources

Tab	Characteristic	Source
Building Description	Aspect Ratio	PNNL Residential Prototype
	WWR	ResStock
	Floor Height	CEC Prototypes
	Framing	RASS
	Foundation	RASS
	U-factor/R-values	RASS/ResStock/Title 24
Envelope	Walls	ResStock
	Roof	RASS
	Slab	RASS
	Window U	RASS
	Window S	RASS
	Air Leakage	ResStock
Lighting	Interior	Building America
	Exterior	RESNET
	Lamp Type	RASS
Appliances	Design Level	Building America
	Consumption	RASS
	Saturation	RASS
People	Heat Gain	CEC Prototypes
HVAC	Heating Fuel	RASS/ResStock
	AC Present	RASS/ResStock
	Efficiency	CFR

Tab	Characteristic	Source
	Max Power	Title 24
Fan	Max Power	Title 24
Thermostat	Setpoints	ecobee
DHW	DHW Fuel	RASS/ResStock
	Efficiency	CFR
Schedules	Appliances	Building America
	DHW Fixtures	CEC Prototypes

HVAC System Selection: Space Heating

Distribution of the heating fuel type in single-family homes over vintage bins and climate zones (Figure 8). showed that there was more than one dominant fuel type in some climate zones. Although gas is the dominant fuel type in most vintage bins, other fuel types (i.e., electricity or propane) are dominant in a few climate zones. In order to enhance prototype representation of the single-family building stock, two sets of prototypes were proposed to be constructed:

- **SET1:** Uses natural gas as the source of space heating for all prototype models (within 16 California climate zones as well as four vintage bins) were modeled by gas as the primary source for space heating.
- **SET2:** Gas or electric space heating. This set of models includes either gas or a mixture of gas and electricity as the primary source of heating. Specifically, in a climate zone and vintage bin, if gas achieves at least 75% saturation, then the fuel type would be gas. If not, a second model with the other heating fuel would be modeled, which would be electric. Thus, we may have two models (gas and electricity as the heating fuel types) for those climate zones where gas does not meet the 75% threshold.

This approach allows model users to use the set of models that are appropriate for a given analysis. For example, a statewide analysis may use SET1 models, whereas an analysis looking into the impact of heating measures in a single climate zone may prefer the more detailed SET2 models. For the “New Construction” vintage bin, the 2022 Title 24 Building Standards were used to define whether the space heating should be gas furnace or heat pump.

HVAC System Selection: Space Cooling

Unlike heating systems, the presence of cooling systems in single-family homes varies, and in certain climate zones, single-family houses lack any form of cooling infrastructure. Using data for cooling from RASS (similar to Figure 8 for heating), the presence of cooling equipment was determined for each climate zone and vintage. The data showed that cooling is not present in single-family homes that lie in the northern coastal climate zones, particularly homes in the pre-1975 vintage bins.

HVAC Efficiency

The efficiency of HVAC systems varies across different vintage categories. Given that HVAC systems have a shorter lifespan compared to the buildings they serve, it is highly probable that a majority of homes have HVAC systems not older 20-25 years.

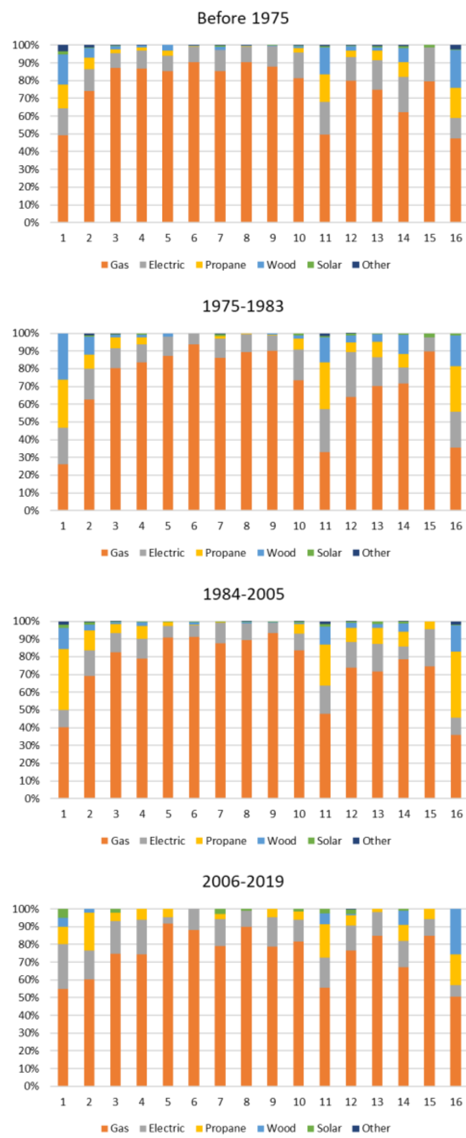

Figure 8 Distribution of the single-family heating fuel type (Source: RASS)

Data from RASS 2019 showed that the life of surveyed HVAC system was 15, 14, and 16 years, for the pre-

1975, 1975-1983, and 1984-2005 vintages, respectively. For those three vintages, heating efficiency (AFUE) was based on the minimum federally required efficiency in place at the time equipment was purchased. For the 2006-2019 vintage, heating efficiency was based on 2013 10 CFR, which is improved to AFUE 80. Finally, the new construction efficiency is set to 80% combustion efficiency, as required by Title 24, 2022. Table 9, presented below, summarizes the system efficiency for single-family prototype models.

Table 9 HVAC System efficiency for single-family prototype models

Vintage bin	Heating Efficiency	Cooling Efficiency
Before 1975	AFUE 78	SEER 13.0
1975-1983	AFUE 78	SEER 13.0
1984-2005	AFUE 78	SEER 13.0
2006-2019	AFUE 80	SEER 14.0,
New Const.	80% Ec	SEER2 14.3

DHW Selection

Similar to the space heating system, distribution of the DHW system for single-family homes was studied using data from RASS (

Figure 9 Distribution of the single-family DHW fuel type (Source: RASS 2019)

). The data showed that there was more than one dominant fuel type in some of the climate zones. As was done for the space heating fuel type, it was decided that two sets of models would be developed:

- **SET1:** Gas as the fuel type in all climate zones. All porotype models (within 16 California climate zones as well as four vintage bins) would be modeled with gas as the fuel type for water heating.
- **SET2:** Gas or electricity or a mix of the two as the fuel type. Within every climate zone and vintage bin, multiple models will be created representing the fuel type for the DHW system.

For the "New Construction" vintage bin, the 2022 Title 24 Building Energy Efficiency Standards (Energy Code) were used to define whether the water heater should be an instantaneous gas water heater or a heat pump water heater (HPWH).

DHW Schedules

A few approaches were evaluated to determine the optimum method for modeling DHW schedules. First, Building America average (BA) schedules were used for modeling purposes, which are simply hourly weekday and weekly schedules repeated throughout the year.

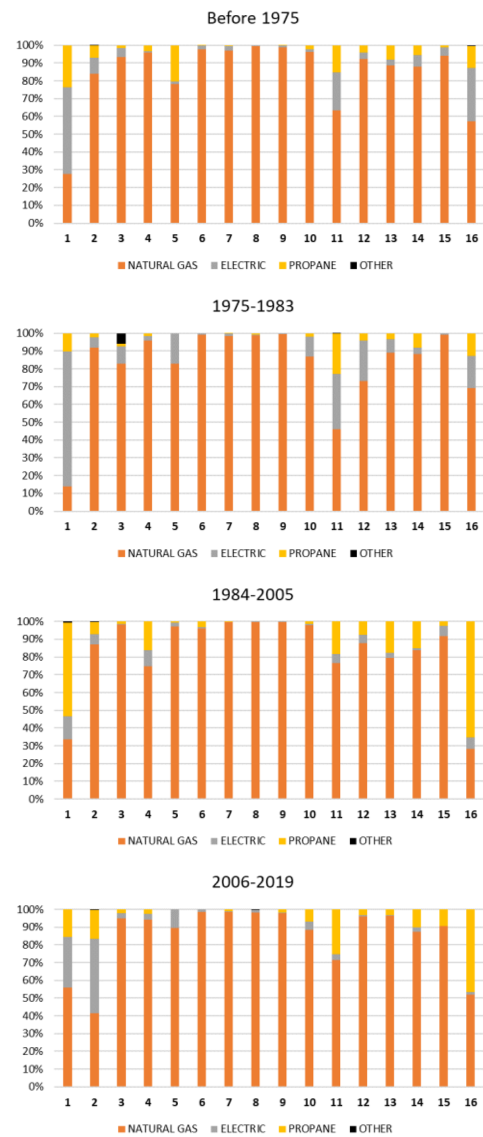

Figure 9 Distribution of the single-family DHW fuel type (Source: RASS 2019)

Then, the approach used in CEC single-family prototype models was tested, where the schedules were changed to hourly stochastic schedules currently being used in CBEC-Res models (Kruis, 2019). More specifically, 8760 hourly schedules were used to model DHW for each fixture. Those stochastic schedules were developed to reflect the actual cost of DHW energy to the consumers. The draw schedules would vary based on the number of bedrooms. For this approach, three setpoint temperatures must be defined: target temperature per fixture (T_{Target}), mains temperature (T_{cold}), and the tank temperature (T_{Tank}).

The schedules consist of 5 different fixture types (bathtub, clothes washer, dishwasher, faucet, shower) as well as 5 different schedules for each fixture (accounts for shuffling impacts to improve load diversity). Further, the schedules vary based on number of bedrooms. Thus, model SF1250 (with 2 bedrooms) has a different schedule compared to model SF1750 and SF2250 (with three bedrooms) as well as model SF2750 (with four bedrooms).

However, this stochastic approach requires using a CSV file an input to the model because each model would require 25*365 schedules. The additional benefit gain from the increased granularity is beneficial to heat pump water heaters (HPWH) whose performance is load dependent. For natural gas water heaters, the stochastic schedules were aggregated to one set of schedules per each of the five fixtures. This approach retains the annual hot water consumption load but dispenses with the complexity for gas water heaters. It should be noted that for HPWH, the minute-based stochastic schedules would be retained.

DHW Efficiency

To come up with DHW efficiency based on the age of the equipment, a Uniform Efficiency Factor (UEF) was derived for all models. These calculations were carried out using equations from the Water Heater Analysis Model (WHAM), including 10 CFR Parts 429, 430, and 431 (2015) and a procedure developed by the National Renewable Energy Laboratory. More specifically, we have used the following two equations to convert EF to UEF:

$$UA_{gas} = \frac{\frac{RE}{UEF} - 1}{(T_{set} - T_{amb})\frac{t_d}{Q_{load}} - \frac{T_{set} - T_{amb}}{P_{in} * UEF}} \quad (1)$$

$$UA_{elec} = \frac{Q_{load}\left(\frac{1}{UEF} - 1\right)}{t_d(T_{set} - T_{amb})\left(f_{high} + f_{low}\left(\frac{T_{inlet} - T_{amb}}{T_{set} - T_{amb}}\right.\right.} \quad (2)$$

These two equations were used to calculate the UEF using the following assumptions: burner thermal efficiency of 80% and 100% for gas and electric burners, respectively, a hot water setpoint temperature of 120 °F, and a recovery efficiency of 79%. A list of modeled UEF is presented in Table 10.

Table 10 HVAC System efficiency for single-family prototype models

Vintage	Pre-1975	1975-1983	1984-2005	2006-2019	New Const.
Gas (EF)	0.58	0.58	0.58	0.60	NA
Gas (UEF)	0.56	0.56	0.56	0.58	0.56
Electric (EF)	0.90	0.90	0.90	0.90	NA
Electric (UEF)	0.89	0.89	0.89	0.89	0.92
HPWH (UEF)	NA	NA	NA	NA	2.47-3.0

Infiltration

Several approaches were explored to modeling air leakage through envelopes and predicting the air infiltration rate in single-family buildings. The approaches include the Lawrence Berkeley Laboratory (LBL) model, the Alberta air Infiltration Model (AIM-2) (also called EMS approach), and the EnergyPlus Airflow Network (AFN). A summary of these approaches is presented in Table 11.

The ideal infiltration modeling approach would be easy to understand for the user, require minimal input, and would remain relatively fixed during modeling. For instance, AFN requires many inputs that could not be easily ascertained for this study. Data on Air Change per Hour at 50 pascal (ACH 50) was available through past studies of California homes. Therefore, the LBL simplified model (Sherman 1987), which relies on indicators for both house tightness (ACH50) as well as weather file, was chosen for infiltration modeling. In addition, an approach using CONTAM is being investigated as a potential improvement to the accuracy of the LBL approach. CONTAM is a physics-based simulation engine specifically used for modeling air leakage and duct leakage in buildings. In the CONTAM-based approach, preprocessed coefficients from CONTAM would be used to inform the simpler leakage model.

Table 11 Summary of various infiltration approaches

Aspect	LBL	AIM/EMS	AFN
Typical field-tested inputs inform the model, i.e., end-user-friendly	Yes	Yes*	No
Improved accuracy	No	Yes	Yes
Native deployment on multiple modeling engines/platforms	Yes	No*	Yes
Captures leakage effect in existing residential building scenarios	Yes	Yes	Yes
Captures leakage effect in new residential building scenarios	Yes	Yes	Yes
Captures envelope and HVAC duct leakage	No	Yes	Yes

Note: *Depends on pre-processor and user interface.

Occupancy/Activity Schedules

To model occupant sensible and latent heat gain an activity schedule was defined for all single-family prototypes (SF1250, SF1750, SF2250, SF270). The schedule was defined using the CBECC-Res activity schedule. To model the heat gain, the number of people in each prototype, which depends on the number of bedrooms, was calculated as shown based on equations below and presented in Table 12. The radiant fraction was set to 0.30 and the sensible heat fraction was set to 0.573.

$$People\ per\ unit\ = \frac{(1.75 * No.\ of\ Dwelling\ Units\ ) + (0.4 * No.\ of\ Bedrooms)}{No.\ of\ Dwelling\ Units} \quad (3)$$

$$Unit\ People\ Gai = \ People\ Per\ Unit\ * \left(\frac{3900}{0.573}\right) \quad (4)$$

Table 12 Number of bedroom and people distribution within single-family models

Model	SF1250	SF1750	SF2250	SF2750
Number of bedrooms	2	2	3	4
Number of people	2.55	2.55	2.95	3.35

Other Schedules

Schedules for appliances, lighting, and miscellaneous loads were sourced from Building America. Utility Energy Consumption (UEC) from RASS was combined with the Building America schedules to determine the design load for systems. A summary of the UEC numbers, saturation, and schedules are listed in Table 13. For interior lighting, 1.1 Watt/ft^2 was used as the lighting power density (LPD) based on ASHRAE 90.2-2018.

Table 13 Other schedules, consumption, and design loads within single-family models

Appliances	Annual Average Design Level, W	Annual Consumption, kWh	Saturation
Washer	28.5	94	94%
Dryer	141.2	552	35%
Dishwasher	44.3	93	74%
Refrigerator	164.6	1,209	100%
Cooking Range/Oven	166.0	404	43%
Microwave	64.5	157	90%
TV	169.4	483	66%
Miscellaneous (plug load, home office, PC)	414	2,450	100%
Lighting (Exterior)	88	251	76%

Model Construction

EnergyPlus was selected for energy modeling of the prototypes. It is a well-known open-source energy software with detailed calculation algorithms and capability of modeling a wide ranges of building features and technologies. It is also the modeling engine used by CPUC for measure analysis. The accompanying prototype documentation allows the same prototype models to be constructed in other simulation engines.

SketchUp Pro (with an OpenStudio plugin) was used to develop the geometry of the single-family prototype, and then the geometry was transferred to EnergyPlus to build out the rest of the model. Geometry includes all elements of the buildings' envelope, such as floor, walls, roof, windows, overhangs, and door(s).

Table 14 presents the characteristics of each geometry model, and Figure 10 displays the northeast view of the models. The only distinction between the appearance of the SF1250 and SF1750 prototype is the floor area. The SF2250 and SF2750 models are two story and are similar in appearance.

Table 14 Geometry characteristic of the single-family prototypes

Prototype	Aspect ratio	Floor-Ceiling Height (ft)	WWR (%)	No. of Thermal Zones
SF1250	2	9	12.7	2 (1 unit & 1 attic)
SF1750	2	9	12.7	2 (1 unit & 1 attic)
SF2250	2	9	12.7	3 (2 units & 1 attic)
SF2750	2	9	12.7	3 (2 units & 1 attic)

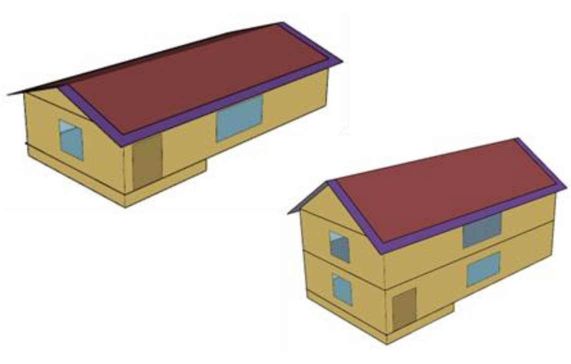

Figure 10 N-E view of the single-family protype models

For developing the prototype models, a seed model of a specific vintage and climate zone was started and then expanded to other vintages and climate zones. For example, for developing the SF1250 model, the pre-1975 model in climate zone 12 was developed first, and then it was expanded to other vintages and climate zones.

After developing this seed model, its end-uses were validated against RASS consumption data. Only after the model was validated was it expanded to other vintages and climate zone. The validation step is explained in greater detail below. Having the validated seed model, the next step was to expand the model to all climate zones and vintage bins using the input data. A large-scale simulation infrastructure was used to expand the seed model across vintages and climate zones. The model inputs, developed previously, were fed into a data structure, and scripts were used to replace portions of text input with appropriate inputs for a given vintage and climate zone. The entire model generation process was automated for speed and accuracy.

Validation

The last step in prototype development is model validation. The single-family prototype models were to be validated against the appliance consumption in RASS. RASS employs statistical techniques to develop climate-zone-weighted appliance consumption, representing the average consumption of an appliance within the sample. Considering the wide variability in consumption patterns across the building stock and the existence of four prototype models and four vintage bins in each climate zone, there exists the potential for the aggregated consumption (across four prototypes and four vintage bins) to deviate from the mean while still being deemed appropriate.

Given that consumption is specified at the climate zone level in RASS, prototype model consumption was aggregated across the four vintages and four prototypes for validation. The aggregated consumption at the climate zone level was calculated by utilizing floor area weighting factors by vintage, prototype, and climate zone. For end-uses that are not climate zone dependent, such as the dishwasher or washer/dryer consumption, validation was relatively straightforward. Once the seed models were validated for these weather-independent end-uses, the models could be safely expanded to other vintages and climate zones without further validation of those end-uses. Heating and cooling end-uses are weather dependent and therefore, these end-uses would need to be validated for the group of models representing a climate zone.

It was observed that without making any adjustments the predicted cooling and heating consumption were not within an acceptable range of the RASS cooling and heating consumption in most climate zones. The source of the differences between modeled and actual (from RASS) consumption is being investigated and that process has not concluded at the time of writing. There could be several reasons for the heating and cooling end-uses to deviate from what is expected, including model input transcription errors, unanticipated operation of appliances and equipment, such as turning off cooling during shoulder months, and differences in weather between the RASS sample and the TMY weather data used for simulation. Completion of the validation process will continue in 2024.

Summary and Future Work

The development of prototypes for California was undertaken in late 2022. This development has been carried out through 2023 and has resulted in the development of single-family prototype models. The model development was carried out in four steps, starting with a building stock assessment to determine the prototypes mix that represents the primary features of the single-family building stock. Once the prototypes mix was determined, the inputs to the prototype models were developed, mainly using data from RASS. Next, the inputs were used to develop the prototypes in EnergyPlus. The last step was to validate the models, and while the end-uses that are not weather-dependent have been validated, the heating and cooling end-use validation is underway.

A few tasks and updates have been slated for completion in 2024:

1. The development and validation of SET2 models. This step will allow stakeholders to perform climate-zone based analyses with greater accuracy. Generation of SET2 weighting factors that play a key role in the aggregation process.
2. Enhancement of infiltration modeling by adding CONTAM-based coefficient approach to the models. This action is expected to improve the accuracy of infiltration modeling.
3. Modeling of HPWH for the "New Construction" vintage bin using minute-based schedules. This item aims to increase the accuracy of models by capturing coincident draw events using the stochastic schedules for each fixture that varies on a minute- basis.

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