Opinion Dynamics

Grid Benefits of Passive Houses

Phase II

January 15, 2025

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1. Executive Summary

The California Public Utilities Commission (CPUC) Energy Division contracted with Opinion Dynamics to conduct a study that explores the potential grid benefits of incorporating Passive House (PH) design principles into California's Title 24 Building Energy Code ("the Study"). The 2019 California Title 24 Building Energy Code update introduced a combination of energy efficiency and photovoltaic (PV) requirements resulting in residential buildings that use 53% less energy compared to 2016 Code (CEC Efficiency Div. 2018). As a core concept, designing a Passive Home eliminates or minimizes the need for active space conditioning (heating and cooling) by leveraging the use and conservation of existing natural energy resources and take into consideration the location and local climate conditions.

The Study builds upon Opinion Dynamics' previous research a white paper on Passive Houses, which was completed for the CPUC in December 2019.[1] That paper reported findings regarding the opportunities for, and barriers to, incorporating Passive House standards into California's Building Energy Code. This Study extends that research to explore how widespread deployment of Passive Houses could offer benefits to the electric grid. To ensure an informed and thoughtful approach, we structured our research efforts in two phases:

- **Phase I: Establish Existing Knowledge Base** to develop an understanding of the current state of knowledge regarding potential grid benefits from the Passive House construction. Phase I research revealed that if California Building Energy Code were updated to include PH principles, we would expect to see several key benefits to the electric grid, including avoided grid investment and operating costs, and deferred grid equipment maintenance. Proponents of PH principles have identified these grid benefits but have provided only limited quantitative research on these impacts when deployed on the grid.
- **Phase II: Grid Benefit Assessment** to quantify potential Passive House electric grid impacts, Phase II quantifies the magnitude of PH grid benefits beyond single households. This effort involved developing theoretical load shapes for various Passive House construction options using energy modeling, as well as modeling the impacts of Passive House deployment on individual circuits.

1.1 Phase I Findings: State of Current Knowledge Regarding PH Grid Benefits

Passive House is a performance standard which relies on five core design principles: (1) continuous insulation, (2) no thermal bridging, (3) airtight construction, (4) high performance windows and doors, and (5) a dedicated mechanical ventilation system with heat recovery. Passive Houses are often all-electric and frequently feature heat pump technology to satisfy heating and cooling needs. Solar generation is not only a common part of Passive House new construction but is actively encouraged by the standard through tiered certification. Passive House design principles minimize the load that renewables are required to provide in electrified buildings or net zero buildings.[2]

According to the Passive House Institute US, "Passive building comprises a set of design principles used to attain a quantifiable and rigorous level of energy efficiency within a specific quantifiable comfort level" (PHIUS n.d.). Passive Houses are energy-efficient buildings with thermal mass properties that can store heat and cold and release it steadily and slowly. Passive Houses have long thermal time constants, meaning they do not react to daily temperature swings,

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[1] http://www.calmac.org/publications/Passive_Home_Whitepaper_1_22_2020_Final.pdf

[2] Norris, Neil. Five Principles of Passive House Design and Construction." Passive House Buildings. October 19, 2019. http://www.passivehousebuildings.com/books/phc-2019/five-principles-of-passive-house-design-and-construction/.

offer predictable and consistent performance, and can maintain comfortable indoor temperature for hours without operating heating or cooling equipment.

Our literature review, in-depth interviews, and analysis of electric data for two Passive Houses point to several important impacts of the Passive House performance standard on residential new construction building load, including reduced annual load, reduced summer and winter peak load, flatter load shape (including reduced ramp rates and higher load factor), more predictable load, and more flexible load. The degree of each of these benefits varies by climate zone, with Passive Houses in inland climate zones offering greater benefits than those in coastal climate zones. Furthermore, Passive House load benefits are particularly relevant for addressing winter load, which is projected to increase in light of broad electrification trends in California.[3]

Together, these load benefits can lead to several key benefits to the electric grid, including avoided grid investment costs for new housing developments, deferred maintenance on existing circuits, avoided use and new construction of flexible resources, avoided power quality issues on distribution lines, and lower costs to operate the grid. While these grid benefits have been widely hypothesized in the Passive House community, our literature review found that there is limited quantitative research confirming the impacts of Passive Houses on the grid. Further research is needed to quantify the impacts of Passive Houses on grid operations and maintenance more precisely. The Phase II Grid Assessment work described in this report is a first step in quantifying the impacts of PH on CA's grid operations.

1.2 Phase II: Exploring Passive Home Design Grid Benefits for CA

1.2.1 Scenario Development

The grid assessment work began with developing new construction scenarios to model. We developed nine scenarios by defining three housing types and identifying three California CZs that would demonstrate the benefits and challenges of PH designs. We selected housing types and regions to ensure representation of SF and MF low-rise (MFLR) residential dwellings, in regions where new construction is forecasted to be the highest over the next 10 years, and CZs from mild to extreme conditioning levels.

The nine scenarios for this study are summarized in Table 1. For each CZ there are three housing types: SF one-story (SF-1), SF two-story (SF-2) and Multi-Family Low-Rise (MFLR). Opinion Dynamics developed Building energy models (BEM) for these scenarios, which subsequently provided the energy use and demand load shapes to help determine the specific grid distribution feeders used to assess grid impacts. For each CZ, we worked with the IOUs to identify three grid distribution feeders, or circuits, for the grid benefits analysis. We selected feeders to capture a range of CZs, home types, and new construction growth.

Table 1. Scenario Criteria for the PH Grid Impacts Analysis

Scenario #	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Housing Type Code	Single-Family (1 Story)	Single-Family (2 Story)	Multi-Family Low-Rise	Single-Family (1 Story)	Single-Family (2 Story)	Multi-Family Low-Rise	Single-Family (1 Story)	Single-Family (2 Story)	Multi-Family Low-Rise
T24 Climate Zone	Climate Zone 4			Climate Zone 14			Climate Zone 7		
Representative Weather Station	San Jose			Palmdale			San Diego		
Conditioning Level	Moderate			Extreme			Low		

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[3] Memorandum to Rory Cox, Energy Division, California Public Utilities Commission from Opinion Dynamics. Scenario Development for Passive Houses Phase II Study: Grid Benefits. April 18. 2022.

1.2.2 Household Performance

Passive House Design Representation

In the U.S., Passive Houses are certified by two organizations, Passive House Institute[4] (PHI) and Passive House Institute US[5] (Phius). While both standards are based on the same building science principles, they differ in the performance targets required to certify a building. We reviewed these standards considering how to best represent PH design principles for our research on the grid benefits of PH versus T24 California Building Energy Code. Previous PH studies indicated that the 2019 T24 minimum requirements already approach current PHI requirements, requiring only minor adjustments in most climate zones. However, in mild climate zones there is a potential for a house to meet PHI passive house criteria but still be non-compliant with the current 2019 T24 code.[6] PHI also has some site-specific climate factors used to scale the typical or standard household demand profile.[7] This top-down approach approximates local climate impacts on heating, cooling, and a few other loads. It is focused on informing decarbonization with available local renewable energy supplies. Alternatively, Phius provides prescriptive construction and performance requirements comparable to the Title 24 approach, which are more specific than the universal PHI energy use target and is specifically adapted to the US market and range of climate zones. The more prescriptive form of Phius allows for a bottom-up engineering approach by letting the thermostat in the model determine the need for more or less heating and cooling based on solar gain, building shell prescriptions, and heat pump efficiency, Other significant differences include the use of a simple monthly bin analysis approach for PH calculators versus the higher-resolution hourly physics-based simulation approach for Title 24 and EnergyPlus, and PH principals require mechanical ventilation and energy recovery due to air tightness requirements which are not typical for T24 and is the primary driver for the PH discrepancy noted in mild climates.

It is imperative that we model these houses in the same software to eliminate questions about model differences driving differences in results. So, we adopted CBECC-Res prototype basic characteristics and leveraged existing T24 passive home CASE studies.[8] We then developed a representative framework using PH principles, as described in detail in Section 3.2.2. For parameters not defined in either PH code base, we assigned the T24 prescriptive value, which may not be as aggressive as expected in practice for PH construction. Ultimately, our PH Principles household is similar to a Phius household since that code base prescribes most of the parameters needed. EnergyPlus was used for our analysis to avoid the idiosyncrasies of compliance-based modeling tools, and to provide flexibility, configurability, and hourly end-use results needed for the multitude of analysis scenarios to inform our grid impact modeling.

As with any modeling exercise, simulating these household designs in another software package, such as the PHPP package for PHI, would require a different set of assumptions, produce different answers, and offer a different collection of outputs, that may or may not be slight. We have chosen to model T24 as accurately as possible with a proven software tool since this is the prevailing energy code compliance software in California. We model PH principles as closely as possible in the same package so there is no question about different models producing different results. A PH-specific software tool would likely have represented PH designs and performance better but would also not have

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[4] Passive House Institute (PHI) https://passivehouse.com/

[5] Passive House Institute US (Phius) https://www.phius.org/

[6] https://title24stakeholders.com/measures/looking-forward/passive-house-prescriptive-pathway/

[7] Primary Energy Renewable (PER) factors for electricity use that are location and application specific: https://passipedia.org/certification/passive_house_categories/per

[8] Codes and Standards Enhancement (CASE) initiative. Future Cycle Single Family Passive House Prescriptive Pathway. https://title24stakeholders.com/measures/looking-forward/passive-house-prescriptive-pathway/

exactly model T24 requirements or provided the 8760 hourly household load profiles, which were essential for the grid impact purpose of this study,

Reducing Annual Energy Consumption

PH design's ability to reduce overall household energy and benefit the grid comes down to how the design will affect household electricity used for HVAC loads, because all other household loads, such as lighting, appliances, and plug loads do not vary from the application of PH principles. With better insulation and lower infiltration, PH resembles a building shell energy efficiency measure, which reduces the need for HVAC. Our analysis shows that a PH can reduce annual household HVAC electricity usage by as much as 32% depending on CZ and house type, as highlighted in Table 2. As also shown, energy impacts vary significantly by climate zone and for single-family versus multi-family building types, with a PH multi-family home potentially resulting in a slight increase in energy use for CZ07, which is a temperate climate zone that rarely needs heating or cooling. In this case, the increased ventilation loads outweigh the reduced heating and cooling loads. However, we note that EnergyPlus modeling software does not adequately represent shading which may also drive this anomalous result.[9]

Table 2. Annual Whole-House Savings Comparison by Home Type

Home Type	CZ (Conditioning Level)	Energy Use per unit (kWh)		% Reduction	HVAC Energy Use (kWh and % of Total)				% Reduction
		T24	PH	PH	T24		PH		PH
Single-Family (1 Story)	CZ07 (Low)	5,774	5,692	1.4%	608	11%	525	9%	13.6%
Single-Family (2 Story)		7,608	7,389	2.9%	1,164	15%	945	13%	18.8%
Multi-Family Low-Rise		4,726	4,800	-1.6%	320	7%	394	8%	-23.2%
Single-Family (1 Story)	CZ04 (Moderate)	6,067	5,875	3.2%	899	15%	706	12%	21.4%
Single-Family (2 Story)		7,925	7,645	3.5%	1,478	19%	1,198	16%	18.9%
Multi-Family Low-Rise		4,812	4,804	0.2%	401	8%	394	8%	1.8%
Single-Family (1 Story)	CZ14 (Extreme)	7,401	6,802	8.1%	2,265	31%	1,666	24%	26.4%
Single-Family (2 Story)		10,471	9,174	12.4%	4,058	39%	2,760	30%	32.0%
Multi-Family Low-Rise		5,546	5,201	6.2%	1,174	21%	6,631	16%	29.4%

With better insulation and other improvements, the PH design versus T24 will almost always save energy when heating or cooling is needed. The one probable exception to this in Table 2 is for the large multi-family low-rise prototype in low/mild-conditioning climate zone CZ07. Because PH design has a tighter envelope, the mechanical ventilation system

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[9] Comments from Bronwyn Barry of PHN received on July 19, 2024

fans must run more often to maintain good ventilation in the building. In mild climates, PH will generally reduce heating and cooling energy use, but the increased runtime for the fan outweighs the savings gained from less heating and cooling. Energy and heat recovery to offset fan energy use may not be calibrated well in EnergyPlus, which could be driving this result.

Recall that our PH house is very similar to a Phius house, but not exactly the same. A PH-specific modeling package may show better performance for a PH design, and in practice, a PHI- or Phius-certified home will likely perform better than is demonstrated in this study. Achieving PH certification is an exercise in maximizing the performance of a single specific building which may lead architects and designers to choose better PH performance parameters (e.g., SHGC, slab insulation), which are choices, not necessarily requirements.

Reducing Demand Peaks in Summer and Winter

With PH principles, hourly HVAC summer peak loads can be reduced by up to 30% and winter loads by up to 50% from the T24 equivalent home. Figure 1 illustrates HVAC-only load use during a representative hot summer week at the end of June, where the temperature reaches 108°F. The PH house peaks are lower than the T24 peak, and the PH peak is also slightly delayed from the T24 curve due to a slower rise in indoor temperature from better insulation and other performance characteristics. This lower ramp rate may help the PH design shift the peak by an hour, but the primary impact is an overall reduction in load.

The PH concept is most beneficial for reducing winter heating loads and energy use. Figure 2 illustrates a cold week for CZ14 at the end of November and the beginning of December, where the nighttime temperature drops to 20°F. The better-insulated PH home reduces the heating load by over 50%. PH principles also significantly delay when the heating load begins, shifting all-electric heat pump (HP) heater loads entirely out of the evening peak window. This is increasingly important as portions of the grid shift to winter peaking rather than summer peaking.

Figure 1. Summer Peak Reduction for HVAC End Use

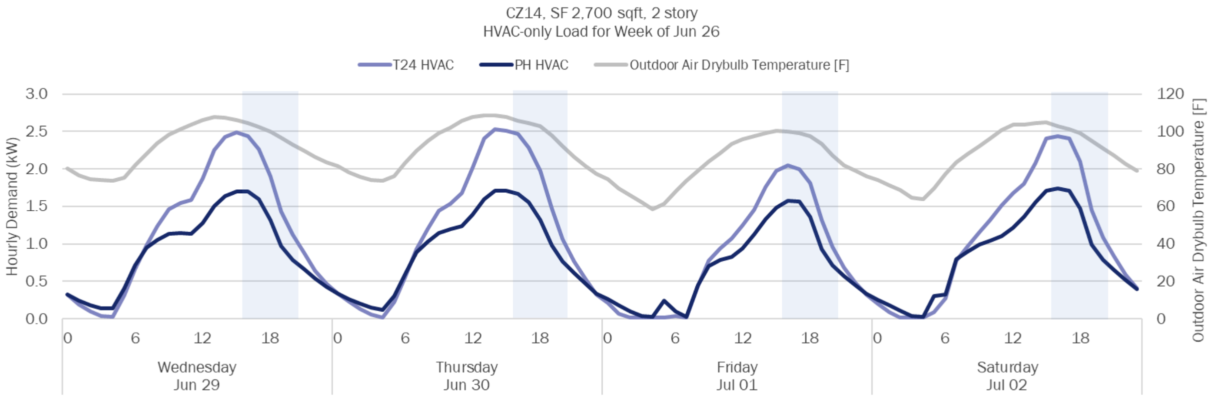
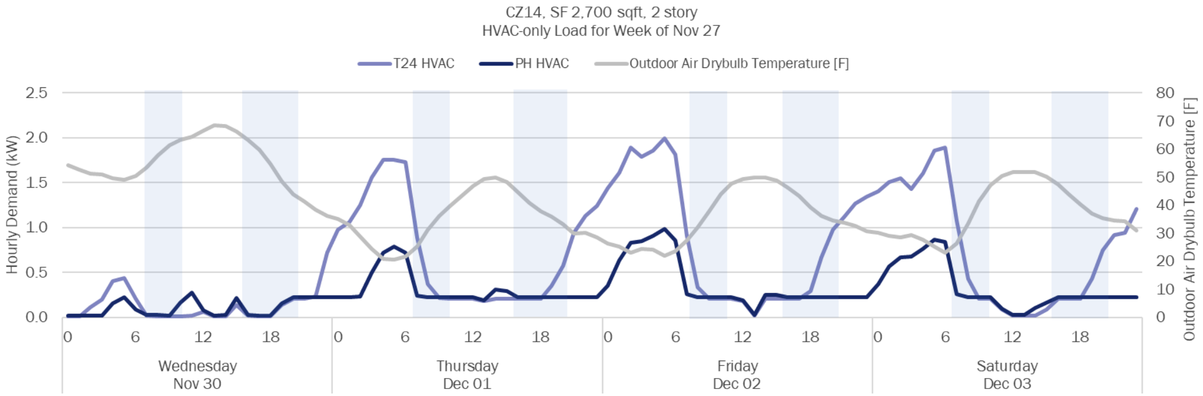


Figure 2. Winter Peak Reduction for HVAC End Use



In Section 5.4 we compare our load shapes to measured energy use in an existing PH residential household. Note that our modeled houses are not replicas of those measured but in similar CZs. The overall magnitudes are similar, but the average daily load shapes are a little different. These differences are driven primarily by assumptions about what electric appliances are installed and how and when they use energy throughout the day. While any model of a house will differ from measurements of actual houses, the differences and similarities are reasonable and reflect we have sufficiently modeled the overall energy use in PH. For our study, these assumptions are the same between our T24 and PH Principles houses, thus providing the necessary performance differences in hourly load to inform the grid impact purpose of this study.

Passive House as a Grid Resource

A portfolio of PH-designed homes participating in a smart thermostat program could exceed the benefits of independent households. This portfolio could flatten the aggregate load, reduce the ramp rate, and further reduce load during resource adequacy (RA) windows.

As described in detail in this report, we aggregated a theoretical neighborhood of PH homes and assigned each to one of five precooling periods during which the thermostat is set to 70°F. Each four-hour precooling period is followed immediately with a two-hour lockout where the air conditioner does not run at all.

Compared to the non-precooled PH home, the average precooled portfolio home has a slightly higher load in late morning from the additional HVAC demand needed for precooling a portion of the homes. The average load stabilizes throughout the afternoon, compared to the non-precooled house, which continues to rise in load. This more stable, flatter portfolio average profile also has a lower peak leading into the RA period.

1.2.3 Grid Benefits

To test the grid benefits of PH homes, we acquired grid topology models listed in Table 3, and simulated the impacts from the addition of new residential construction loads to the selected feeders. Inputs included the simulated BEM household load shapes, baseline (existing) loads on each feeder, new construction loads, peak hours, and solar backfeed hours for each feeder.[10] Outputs included element overload (% of rating), voltage (% of nominal), and the costs avoided by not doing grid upgrades to address overloaded elements.

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[10] The peak hour is defined as the hour with the most energy flowing from source (substation) to load (buildings and homes) and the backfeed hour is defined as the hour with the most energy flowing from load to source due to solar overproduction. Note that backfeed refers to the flow of electricity in the reverse of the normal direction. In this study, it refers to electricity flow to the grid rather than from the grid to the house.

Table 3. Grid Feeders for Distribution Grid Analysis Stage

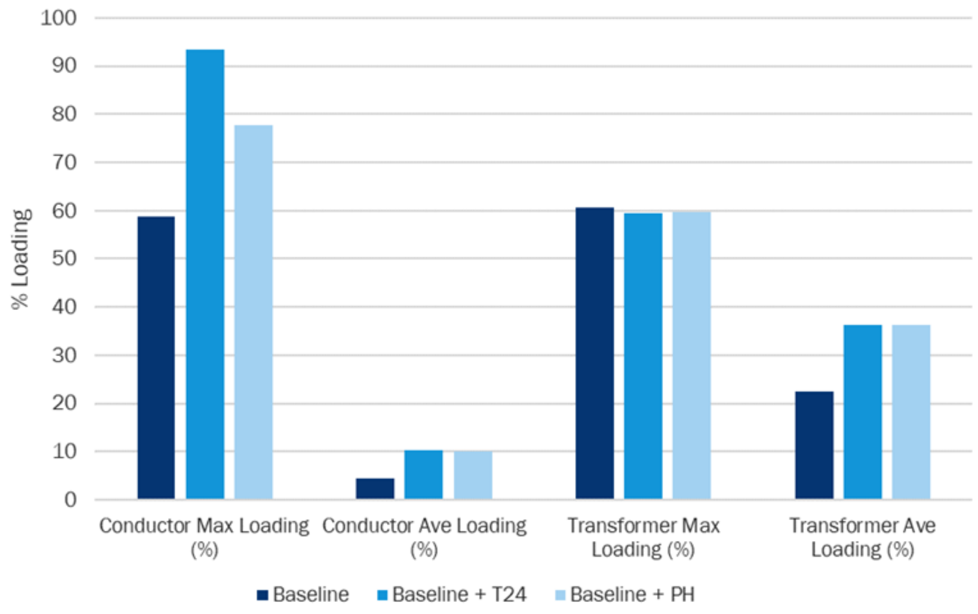
Geographic Description	**PG&E, between Coast and Inland**			**SCE, Inland**			**SDG&E, Coastal**		
Substation	Edenvale	McKee	Mountain View	Palmdale		Redman	San Ysidro	Telegraph Canyon	Melrose
Feeder Identifier	82951103	83531110	82031105	Paint	Mark	Alfalfa	460	1225	205
% Residential	90%	94%	52%	94%	83%	69%	87%	68%	52%

Each feeder is unique with different capacity, length, heterogenous loads, environmental conditions, and more. What may lead to a significant impact on one feeder, may be irrelevant to another. There are, however, some consistent results worth highlighting.

Grid Element Loading

When adding new homes to a feeder, care should be taken not to exceed the conductor or transformer design limits; however, we only encountered conductor limits in this study and no transformer limits when carrying out our exercise of adding homes to a feeder. A good example of exceeding conductor limits is illustrated in Figure 3 which summarizes the results from the SCE–Mark feeder, one of the feeders jointly identified by SCE and our team for this study. When adding the same number of new homes to the feeder, the T24 maximum conductor loading exceeded the 85% threshold. This additional conductor loading would trigger a reconductor upgrade with a cost of about $20,000. This is tallied along with all scenario-avoided costs below in Table 4.

Figure 3. SCE - Mark Feeder - Results Summary



If element loadings are not already at their limit, it is possible more PH homes could be built than T24 without any impact on distribution grid loading. We did not test this on all feeders, but for those cases where we did, we found about 20% more PH homes could be built than T24 homes without exceeding grid element loading limits.

SF and MF loads behaved similarly in this analysis. Feeders with more MF load are more likely to experience higher load growth concentrated in a smaller area due to the dense nature of multi-family housing. This is another example of the locational impact described above where PH Principles can beneficially defer grid investments.

Voltage

Increased load density, line length, load variations, power factor, cable size, transformer reactance, motor starting, circuit design, distributed generation like solar PV and EVs, and more can lead to voltage fluctuations. Operating within a narrow voltage range helps protect against issues like overheating, reduced lifespan, and malfunctioning of electrical devices due to inconsistent voltage levels.

In this study, the only difference in impact on voltage between housing types is from solar PV. While the two houses have different demand load shapes, they have the same solar PV capacity. The lower load from the PH homes allows for more solar backfeed, which produces a slightly higher minimum voltage on feeders when PH homes are added instead of T24 homes. A higher voltage helps meet voltage regulation requirements, but the difference is small with all cases within the +/- 5% threshold of nominal. However, as more real and diverse load shapes are applied to these case studies, the system peak hour could shift, and the voltage variation impact could be greater.

Cost Savings

Overall, PH new construction can have a significant impact on grid upgrades and construction costs. As usual with gird costs, the impact is highly locational and depends on factors like the loading, feeder topography, and the location of new growth on the feeder. In this study, we did not encounter any transformer limits, only conductor limits. Reconductoring a distribution line segment has a relatively predictable cost, and we use a recent PG&E non-Bay Area cost guide as the basis. Table 4 collects avoided reconductoring costs for our small number of cases, which ranges from $0 to $1.4M.

Table 4. Avoided/Deferred Interconnection Upgrade Costs (Reconductoring)

Feeder	Upgrade Planning Threshold %	+T24 ft. overloaded	+PH ft. overloaded	Approximate PH cost savings ($)
SCE – Mark	85%	75.6	0	$20,000
SCE - Mark + 275 of each home type	100%	727.5	49.9	$180,000
SCE - Paint (counterfactual)	85%	8,022.3	2,783.2	$1,400,000
SCE - Paint (utility-provided)	100%	2,783.1	2,782.9	$0
PG&E - McKee (counterfactual)	100%	12,631.8	11,417.8	$316,000
PG&E - McKee (utility-provided)	85%	1,773.6	1,773.6	$0
PG&E - Edenvale	100%	3,344.3	3,344.3	$0

Source: We modeled results and estimated approximately $260/linear foot reconductoring costs.[11]

We assessed the impacts of PH homes on a mere few out of about 10,000 feeders state-wide, but this small window indicates that adding PH homes rather than T24 homes to an existing circuit could reduce or delay significant upgrade costs statewide.

1.3 Conclusions and Recommendations

This study aimed to explore the potential grid benefits of all-electric homes built using PH principles versus T24 building code-compliant homes. Overall, adopting PH principles in California residential new construction would make all new homes potential grid assets while reducing the energy consumption and peak load below that of the current T24 code.

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[11] $260/ft underground non-Bay area costs, from PG&E Unit Cost Guide Updated April 2021. pge.com/pge_global/common/pdfs/for-our-business-partners/interconnection-renewables/Unit-Cost-Guide.pdf.

Leveraging these techniques to reduce average household energy usage will also lower operating costs for homeowners. The overall conclusions and recommendations from this study are:

- **The more extreme the climate zone, the higher the percentage of household energy attributed to HVAC, and the larger percentage is reduced through PH design**. The Single-Family PH models in this study outperformed T24 in all modeled CZs. The Multi-family Low-Rise PH model outperformed T24 in moderate and extreme HVAC regions but underperformed in mild climates (e.g., CZ07 of Coastal San Diego). The more efficient envelope from PH principles can only reduce energy consumption in a household by reducing HVAC usage. In the T24 SF homes, HVAC energy use ranges from 10-15% of the total in a mild CZ, 15-20% in moderate, and 30-40% in extreme. PH principles will reduce HVAC usage by about 15%, 20%, and 30% in mild, moderate, and extreme CZ, respectively.

- **These annual benefits of PH principles in residential new construction translate to significant peak load savings**. The PH principles can reduce annual household HVAC energy use over a T24 home. During a peak summer day, PH can also reduce the HVAC peak load by almost 30% is an extreme CZ. On a winter nighttime peak, the energy savings can be upwards of 50% of HVAC load. The PH design might shift the peak load by an hour and slightly reduce the ramp rate, but the overall peak reduction is the primary impact.

- **Building PH homes versus conventional T24 homes will reduce feeder loads per household and delay the need for feeder upgrades**. With lower energy use per PH household, adding PH homes to a feeder will use less energy and reduce the peak load compared to the same number of added T24 homes. Our SCE analysis showed that over 20% more PH homes than T24 homes could be added to our sample feeder without exceeding grid element loading limits. Each existing feeder has different capacity and loading benefits, but this could be one strategy for delaying substation upgrades or avoiding overloaded feeders.

- **The minimum voltage in the peak loading cases is slightly higher on feeders when PH homes are added instead of T24 homes**. This is a direct result of less load for PH homes resulting in more solar PV back feed. Having higher voltage helps meet voltage regulation requirements, but the difference is small with all cases within the +/- 5% threshold of nominal. However, as more diverse loads are applied, impacts on voltage variation could become an issue. We recommend the application of broader load shape diversity to test this theory,

- **Quantifying grid impacts requires more research building from the foundational analysis provided in this study.** Additional research and analysis is needed, including:
    - More exploration to assess dynamic and dispatchable flexible load possibilities beyond the brief precooling analysis involved in this study and should include solar-storage combinations.
    - More use of diversified homes should be explored in future studies as this study was limited to an initial exploration using identical homes with identical load shapes. We modeled PH and T24 homes in EnergyPlus, then replicated those homes as many times as needed to test the impacts on the given feeder. In reality, each home on a feeder is unique and will have different demand load shapes, which will have different impacts on peak demand, circuit hosting capacity, impacts to reliability and resiliency and more. .

Future research and analysis can build upon this study to fully understand the grid benefits of PH design in CA's energy code. This study demonstrates that there are many potential grid benefits worth further exploration. Suggestions for how future work can build upon this study are summarized below.

- **Deeper exploration of PHI, Phius, and T24 modeling differences:** The primary aim of this study was to explore the potential grid benefits from PH principles and to determine if deeper research and analysis should be considered. To enable the grid portion of this research, prescriptive parameters from the PHI and Phius code bases were aggregated to develop a more generic house based on these principles. This aggregation was necessary to meet this study's research objectives primarily due to differences and capability gaps between T24 and the respective PH modeling platforms. However, there are still differences in how each model represents their respective code bases (e.g., how energy and heat recovery mechanisms differ between the different models). A full review of these differences and comparisons of results would significantly inform the code and grid discussion in CA.

- **Expanded Model Responses:** More questions could be explored with these T24 and PH models. One extension could model the same houses in all California CZs. Before expanding the range, however, further exploration of household responses to additional controls (passive and active) should be undertaken. In this study, we briefly tested overhanging eaves, excessive thermal mass, and precooling conditions, but these were outside the scope of work. Our precooling exploration indicates a good alignment with active demand response programs and could open new program offerings.
- **Recommend Grid Reliability Modeling for PH:** In this study, we conducted a deterministic analysis to explore the impact of PH designs on the feeder-level infrastructure when the grid is at peak demand. However, PH homes may also provide significant reliability and resilience benefits when deployed at scale due to their long thermal time constants. Furthermore, with their reduced load compared to T24, the prevalent deployment of PH homes increases the hosting capacity of distribution feeders, which means existing feeders can host more electric load such as more homes and electric vehicles (EVs). We expand upon these concepts for further analysis in Chapter 8.

2. Introduction and Study Overview

2.1 Passive House Overview

As a core concept, designing a passive home eliminates or minimizes the need for active space conditioning (heating and cooling) by leveraging the use and conservation of existing natural energy resources and taking into consideration the home's location and local climate conditions. In its current evolution, a PH is a very well-insulated, virtually airtight building that is primarily heated by passive solar gains and internal heat gains from cooking, bathing, electrical equipment, and other end-use services. A PH standard is a building performance standard that aims to achieve specific minimum building performance criteria using the following five key principles:[12]

1. Continuous insulation
2. No thermal bridging
3. Airtight construction
4. High-performance windows and doors
5. Mechanical ventilation with heat recovery

This house can be thought of as an insulated thermos bottle with controlled ventilation and outdoor air infiltration that continuously delivers fresh air while also extracting heat from the exhaust air without directly mixing the airstreams together.

The PH concept and movement started in North America in the 1970s as a response to the oil embargo and energy crisis at the time. In the 1980s, German physicist Wolfgang Feist further developed PH design and founded the Passivhaus Institute (PHI). With a focus on how to deliver comfort, he found the peak heating target to be 10 Watts per square meter (W/m^2). This led to an annual heating and cooling energy design target of 15 kilowatt-hours (kWh) per square meter per year (kWh/m2) in mild climates, which could be adjusted for other climates. By the early 2000s, the PH concept returned to its US roots when the Passive House Institute US (Phius) was founded. The work of Katrin Klingenberg, a Phius co-founder and still active promoter, and others showed other performance metrics and methods to better account for the diverse North American climate. Their work resulted in the release of the first Phius+ standards in 2015, which incorporate more of a detailed, prescriptive design approach similar in concept and scope to California's Title 24 Building Standards.[13]

2.2 Passive House and California T24 Building Energy Efficiency Standards

As originally conceived for this study, we planned to use the international PHI standard for the assessment.[14] After reviewing previous California T24 passive home studies conducted by the Codes and Standards Enhancement (CASE) group,[15] performing preliminary simulation modeling investigations based on the PHI standard, and reviewing the Phius

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[12] Norris, Neil. Five Principles of Passive House Design and Construction." Passive House Buildings. October 19, 2019. http://www.passivehousebuildings.com/books/phc-2019/five-principles-of-passive-house-design-and-construction/.

[13] Environmental & Energy Study Institute. "The History of Passive House: A Global Movement with North American Roots." June 2, 2017. https://www.eesi.org/articles/view/the-history-of-passive-house-a-global-movement-with-north-american-roots

[14] Passive House Institute (PHI) https://passivehouse.com/

[15] Available at https://title24stakeholders.com/archived-case-reports/

standard,[16] we based our PH prototypes on Phius because it provides explicit prescriptive construction and performance requirements for the US market and climate zones.

For single-family homes, initial CASE study research showed that PH designs perform at least slightly better than T24 in almost all climate zones. In some mild climate zones, PH prescriptive pathway approach homes did not comply with T24 based on CBECC-Res analysis and results.[17] And while these issues were not insurmountable, as previously mentioned the PH compliance path was not pursued further due to added compliance complexity.

Our study is based on 2019 building standards since the 2022 T24 update which went into effect January 1, 2023 was still in development at the time we began this study. The primary changes made in the 2022 T24 residential update were to encourage heat pump technologies, require "electric-ready" capability for future electric devices when gas is used, expand PV and especially battery requirements and options, and update ventilation requirements especially when gas is used. These code changes would have little impact on the current study results since we use all-electric homes with HVAC HPs and heat pump water heaters, and we evaluate PV impacts separately.[18]

There are, however, several detailed and potentially significant code changes that could impact the approach and results for a future study:

- A solar/PV system is now required for new construction homes.
- The energy design rating scores produced by the performance compliance approach are being expanded to put more emphasis on the time value of hourly energy use, which may enhance the benefit of PH design.
- Updates were made to the efficiency rating approaches (from Seasonal Energy Efficiency Ratio/Energy Efficiency Ratio [SEER/EER] to Seasonal Energy Efficiency Ratio 2/Energy Efficiency Ratio 2 [SEER2/EER2]) and ventilation requirements for both SF and MF buildings. A change to ventilation requirements would likely have more impact on PH results than efficiency changes.
- MF low-rise is no longer part of the SF code section. Instead, all MF buildings are covered under a single code section which also includes MF common areas. There may be unknown or unintended consequences of this restructuring on the prototypes and modeling approaches.
- There were some minor changes made to prescriptive fenestration, and for MF prescriptive, the wall insulation requirements are more stringent for almost all climate zones.

2.3 Study Overview

California has long been a leader in using building codes to encourage energy-efficient new home construction. More recently, the 2019 California Building Energy Efficiency Standards, referred to as T24 in this report, updated the previous Title 24 standard by introducing a combination of energy efficiency and PV requirements that result in a home that uses 53% less energy than the 2016 Code.[19] For future code updates, CPUC Energy Division staff expressed interest in exploring the potential for the energy efficiency requirements of Title 24 to incorporate PH principles,

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[16] Passive House Institute US (Phius) https://www.phius.org/

[17] California Energy Codes and Standards. "Single Family Passive House Prescriptive Pathway." Accessed 2022. https://title24stakeholders.com/measures/looking-forward/passive-house-prescriptive-pathway/.

[18] Reference sources include "2022 Building Energy Efficiency Standards Summary" (https://bit.ly/CEC-2022-Summary), "Single-family Buildings: What's New in 2022?" Fact Sheet. https://energycodeace.com/download/66973/file_path/fieldList/FS.SF%20Bldgs.2022.pdf) and "Multifamily Buildings: What's New in 2022?" Fact Sheet (https://energycodeace.com/download/66025/file_path/fieldList/FS.MF%20Bldgs.WhatsNew.2022.pdf). Last accessed 11/30/2022.

[19] California Energy Commission Efficiency Division. 2019 Building Energy Efficiency Standards FAQ. March 2018. https://ww2.energy.ca.gov/title24/2019standards/documents/2018_Title_24_2019_Building_Standards_FAQ.pdf.

including the potential inclusion of a Compliance Pathway for PH. A T24 PH pathway was also explored extensively by the California Code and Standards Enhancement (CASE) group for the 2022 code cycle but was ultimately deferred to consideration for a future code cycle.[20] Some of the ideas and inspiration for this study were also illustrated in a presentation by the North American Passive House Network (NAPHN) at a CPUC meeting on resilience.[21]

This study builds off a previous Opinion Dynamics' white paper on PH, which was completed for the CPUC in December 2019.[22] That paper reported on opportunities for and barriers to incorporating PH standards into the California energy code. This work extends from that research to understand what benefits the widespread deployment of PH could offer to the electric grid. Following the white paper, Opinion Dynamics conducted this research study for the CPUC in two phases to help summarize current knowledge of PH design principles and potential grid benefits and add to that existing wealth of knowledge by analyzing the potential grid impacts of constructing new homes in specific regions in CA using PH design principles.

The objectives of Phase I research were to:

- Review the current understanding of potential grid benefits of Passive Houses;
- Identify whether Passive Houses have load shapes that might provide grid benefits;
- Identify which characteristics of circuits (e.g., location, customer mix, load shape, etc.) make them likely to benefit from Passive House construction; and
- Quantify the potential circuit-level grid benefits of widespread Passive House new construction in California.

The goal of Phase II was to expand on Phase I and begin to quantify potential electric grid benefits and avoided cost from new construction using PH principles compared to a conventional T24 baseline. A key element of this effort was identifying the areas in California where current and future residential new construction growth is highest, and where current or future grid-constraints are a potential concern. This involved developing theoretical load shapes for various home configuration options, as well as modeling the impacts of their deployment on individual grid circuits or feeders.[23] We compared each PH application to its T24 baseline house equivalent. The differences in hourly load between them allowed us to model the grid benefits from PH deployment.

We begin below with context starting with a brief background in PH design. We describe our approach and methodologies in Section 3. In Section 4, we discuss literature review findings. In Section 5, we discuss load shape analysis results. Next, we define additional grid impact activities in Section 6 and grid impact results in Section 7. Finally, we summarize our conclusions and recommendations in Section 8.

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[20] Codes and Standards Enhancement (CASE) initiative. Future Cycle Single Family Passive House Prescriptive Pathway. https://title24stakeholders.com/measures/looking-forward/passive-house-prescriptive-pathway/

[21] North American Passive House Network (naphn). "Stakeholder Workshop: Building Decarbonization Phase II Staff Proposal and Mobilehome Park Electrification and Tenant Protection Topics", slides 44-70. September 15, 2020. https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/building-decarb/bd-phase-ii_mhp-workshop_09152020.pdf

[22] Opinion Dynamics. Barriers to Incorporating Passive House Concepts in Residential New Construction. December 11, 2019. http://www.calmac.org/publications/Passive_Home_Whitepaper_1_22_2020_Final.pdf.

[23] Feeder and Circuit are synonymous and refer to the distribution line to each neighborhood. Which term is used in practice depends on the IOU. We use feeder in this report since the term 'circuit' is potentially ambiguous as it can refer to many levels of transmission and distribution applications.

3. Study Approach and Methodology

3.1 Phase I: Literature Review

We completed an extensive review of existing materials and literature. The following components were reviewed:

- Passive House performance standards and relevant energy modeling tools and techniques
- Studies and publications exploring Passive House design and construction principles
- Conference proceedings from North American Passive House Network Conference and Expo across multiple years
- Studies, protocols, and publications exploring how the Passive House standards interact with the California building energy code
- Studies and publications exploring the grid benefits of Passive House design

Due to the very limited research available on Passive Houses specifically, we also included literature on high-energy efficiency ZNE homes in our scope. In addition to the literature review, we completed a series of in-depth interviews with experts on topics of the Passive House and the grid, including Passive House consultants, certifiers, architects, and engineers with grid expertise. We completed eight interviews over the course of July and August 2021.

Finally, we obtained circuit-level electric energy consumption data for two Passive Houses and compared the results to the consumption data from a sample of six new construction ZNE homes to characterize the differences between ZNE and Passive Houses on a non-representative sample of actual building data (Allen et al. 2019; The authors collected the circuit-level electricity consumption data for the six ZNE homes). The six ZNE homes were built between 2018 and 2019 with new homeowners moving in between July and November 2019. There are several key distinctions between homes built to ZNE specifications versus homes built to 2019 Energy Code requirements. ZNE specifications go beyond the 2019 Energy Code requirements that further reduce the energy load of the home and ensure that on-site PV generation adequately covers the entire energy load. Specifically,

1. The 2019 Energy Code offers prescriptive and performance-based paths for compliance. Performance-based compliance relies on building energy simulation software to determine an energy budget for a home. This software allows builders to trade-off a variety of energy saving measures, so long as the design does not exceed that energy budget. ZNE homes are designed to “reduce before produce”, with modeled energy consumption typically 20-30% lower than the 2019 Code energy budget.
2. The 2019 Energy Code requires PV capacity, but only as it pertains to offsetting the electric use of the home, whereas ZNE specifications require PV capacity to offset ALL of a home’s energy use, including that from non-electric sources.

A complete list of literature review resources is provided in Appendix A. The primary studies and data sources leveraged for the Phase II grid assessment include:

- **“Passive House as a Grid Resource” ACEEE 2022 Summer Study paper (2022).** This conference paper discusses the potential grid benefits of passive homes assessed from extensive research, data analysis, and interviews with a broad range of PH and electric grid experts. It explores potential key benefits to the electric grid for new housing developments including avoided grid investment costs, deferred maintenance on existing feeders, avoided use and new construction of flexible resources, avoided power quality issues on distribution lines, and lower costs to operate the grid. The findings in this paper resulted from the Phase I assessment.
- **“Residential Zero Net Energy Building Integration Cost Analysis” grid impact study for CPUC (2017).** This study was one of the primary inspirations for the PH grid impact study. Conducted for the California Energy

Commission (CEC) and CPUC, the study analyzed the grid integration impacts and costs of customer-sited PV and new home zero net energy (ZNE) policy requirements for a 10-year period. The study notes that most new homes built in California are in new home tract developments. Given this, there is an expectation that additional implementation of ZNE homes and PV systems will be geographically concentrated. Grid loads can be severely impacted by the difference between residential loads and high-saturation, oversized PV systems. If left unmitigated, these effects could cause significant impact on specific areas of the distribution grid. We used a variety of scenarios to characterize the issues and potential solutions.

- **T24 Codes and Standards Enhancement (CASE) studies**. As part of the 2022 code cycle development, several single-family and multi-family studies were conducted to explore the development of an alternative prescriptive compliance path for PH-certified homes. These studies incorporated building simulation models and compared the passive house design home features and requirements to T24 requirements. The analysis used the California Building Energy Code Compliance - Residential (CBECC-Res) software and residential prototypes to examine energy impacts.[24] We did not use CBECC-Res nor directly use the building energy models from these studies for our study; however, the observations and findings helped inform the decision to use PH requirements, and to use EnergyPlus™ as the Standard-agnostic building energy modeling tool for this study.[25]
- **CEC New Construction Forecast data**. Phase I research pointed to differences in grid benefits depending on climate, specifically noting that PHs in inland climate zones have greater potential benefits than those in coastal climate zones with lower space cooling needs. PH load benefits are traditionally directed at reducing winter heating loads, however, which are projected to increase significantly due to electrification efforts. The Phase I research reported that five counties—Los Angeles, Riverside, Orange, Santa Clara, and San Diego—will account for 47% of new households by 2030, and that about 500,000 new units would need to be added to meet demand. For Phase II, we leveraged the latest CEC 2021–2035 Demand Forecast data for single-family and multi-family residential units to validate and revise the Phase I findings. A growth rate analysis of the data resulted in the selection of CEC forecast zones (FZ). The original data and our analysis are described in the Scenario Development Memorandum.[26]
- **2019 Residential Appliance Saturation Study (RASS)**.27 This CEC California Statewide study provides annual end-use electric and gas energy savings estimates for the residential sector. The RASS provides space heating and space cooling average per-home annual energy use (UEC=unit energy consumption) and estimates for a variety of HVAC systems and fuel types.

3.2 Phase II: Grid Assessment

The grid assessment involved modeling homes with PH principles on multiple feeders and required three primary activities:

1. **Scenario development:** We began developing PH scenarios by defining residential housing types and locations in California where the houses are to be digitally located. The geographic location dictates the CZ, which informs the design requirements for both PH and T24 houses, determines the weather inputs for modeling, and narrows down the possible distribution feeders to assess grid benefits.

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[24] California Energy Codes and Standards Enhancement website. "Future Cycle, Single Family Passive House Prescriptive Pathway". https://title24stakeholders.com/measures/looking-forward/passive-house-prescriptive-pathway/

[25] EnergyPlus (website). Last modified December 8, 2022. https://energyplus.net/.

[26] Memorandum to Rory Cox, Energy Division, California Public Utilities Commission from Opinion Dynamics. Scenario Development for Passive Houses Phase II Study: Grid Benefits. April 18. 2022.

[27] California Energy Commission. 2019 California Residential Appliance Saturation Study. 2020. Publication Number: CEC-200-2021-005-MTHLGY.

2. **BEM load shape development and analysis**: With housing types and CZs determined and approved, we created simulated homes for each housing type with their CZ-specific requirements. We then developed 8760 load shapes[28] for each housing type and location for both T24 and PH homes. The specific house types also informed the deployment to the feeders on which to model grid impacts.
3. **Distribution grid scenario design and analysis**: With the derived load shapes and specific distribution feeders defined, we performed grid impact analyses to evaluate the benefits of PH principles on grid operating conditions under the different scenarios and loads. This allowed us to quantify grid benefits from PH principles and inform grid resiliency implications.

3.2.1 Scenario Development

In accordance with the Phase II scope of work, we developed nine scenarios by defining three housing types and identifying three prospective regions or CZs that would demonstrate the anticipated benefits of PH principles.[29] The nine scenarios are summarized in Table 5, followed by a detailed discussion on how they were determined. These scenarios informed the BEM development, which provided the annual energy use and hourly demand load shapes and informed the specific distribution feeders used to assess the grid impacts.

Housing types and CZs were chosen to meet the following criteria:

- **Housing Types**: Ensure representation of SF and MF low-rise (MFLR) residential dwellings.
- **IOU Territories**: Locate homes in the service territories of each of the three electric Investor-owned Utilities (IOU) in California: Pacific Gas and Electric (PG&E), Southern California Edison (SCE), and San Diego Gas and Electric (SDG&E).
- **New Construction**: Focus on regions where new construction is forecast to be highest over the next 10 years.
- **Conditioning Level**: Cover a range of CZs from low to extreme conditioning levels.

We did not consider existing solar penetration when developing the scenarios; however, we included existing solar in our grid modeling for comparisons.

Table 5. Scenario Criteria for Assessing PH Grid-Impacts Analysis

Scenario #	1	2	3	4	5	6	7	8	9
Housing Type Code	**SF-1**	**SF-2**	**MFLR**	**SF-1**	**SF-2**	**MFLR**	**SF-1**	**SF-2**	**MFLR**
Housing Type Description	Single-Family One-Story	Single-Family Two-Story	Multi-family Low-Rise	Single-Family One-Story	Single-Family Two-Story	Multi-family Low-Rise	Single-Family One-Story	Single-Family Two-Story	Multi-family Low-Rise
Forecasted New Construction units between 2021–2035	128,233		147,586	153,660		119,096	70,464		59,147
Forecast Zone	FZ1			FZ7			FZ12		
T24 Climate Zone	CZ04			CZ14			CZ07		
Representative Weather Station	San Jose			Palmdale			San Diego		
Conditioning Level	Moderate			Extreme			Low		
Geographic Description	PG&E, between coast and Inland			SCE, Inland			SDG&E, Coastal		
County	Santa Clara			Riverside			San Diego		

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[28] An 8760 load shape is a profile of the hourly load (kW) for each of the 8,760 hours in a non-leap year.

[29] See footnote 15.

Defining Housing Types

We modeled three housing types in each of the chosen CZs: SF one-story (SF-1), SF two-story (SF-2), and MFLR, which is an eight-unit structure with no common area. This residential housing diversity represents different impacts to the grid due to occupant diversity and construction requirements, including the integration of solar.

Deviating from the anticipated scope, we revised our SF housing type options to assess SF-1 and SF-2 dwellings rather than SF attached and SF detached. We made this adjustment for three reasons: (1) the CEC building stock forecast (discussed below in Section 3.2.2) does not distinguish between SF housing types,[30] (2) SF detached homes are far more numerous than SF attached homes, and (3) we assume that the energy use and profile for SF attached home would likely be covered by the range of revised SF and MFLR prototypes. While the CEC forecast also does not distinguish between one- and two-story construction, the household energy demands are different between them and prove to be helpful guidance on performance characteristics of PH principles.

Identifying New Construction Regions and Climate Zones

Phase I research pointed to differences in grid benefits depending on climate, specifically noting that a PH in an inland CZ will have greater potential benefits than those in a coastal CZ with lower space cooling needs. However, PH load benefits were originally developed to address winter heating loads, which are projected to increase significantly due to electrification efforts in California. Based on current codes and standards evaluation work, PH principles are expected to have the greatest impact on new construction, rather than on the retrofit of existing homes, due primarily to the quantity of new homes forecast for new construction rather than the one-at-a-time, occupant-driven, retrofit growth.

The Phase I research reported that statewide, just five counties—Los Angeles, Riverside, Orange, Santa Clara, and San Diego—are expected to account for 47% of new households by 2030, and these counties will need to add about 500,000 new housing units to meet demand. The latest CEC Demand Forecast data shows new construction trends from 2021 through 2035 of SF and MF dwellings vary across the state.[31] A growth rate analysis based on CEC electricity forecast zones (FZ) is presented in Table 6 and the three selected for this study are in bold: FZ1, FZ7, and FZ12. The table shows the total population of households in 2021 and forecasted through 2035 in each FZ, the population difference between those years, the percent growth over that time frame, and the average annual growth rate for both SF and MF households. It also shows the percentage of total growth that each FZ represents relative to all zones.

The State and local jurisdictions have modified zoning ordinances to allow for MF homes in traditional SF locations and require all-electric homes for new construction, which will further exacerbate issues for constrained grid points.[32] The construction of accessory dwelling units (ADU) is another significant trend; however, ADUs are not explicitly accounted for in the CEC forecast nor our analysis. While ADUs could benefit immensely from PH design, their grid impact—even in total—is not likely to be as significant compared to a larger population of SF or MF buildings. An assessment of the impact of ADUs might be a useful additional study to conduct in the future.

The CEC data does not have the fidelity required for the present analysis since each CEC FZ may encompass multiple T24 CZs, as shown in Figure 4. However, the weather inputs and building parameters required for the simulation models are based on T24 CZs. The CEC forecast also does not distinguish between SF-1 and SF-2 homes, though this is

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[30] Correspondence with and files sent by Cary Garcia, CEC, March–April 2022, CED 2021 Household Forecast by Scenario and Zone 2021-2035.xlsx.

[31] California Energy Commission. CED 2021 Household Forecast by Scenario and Zone 2021–2035. 2021. https://www.energy.ca.gov/data-reports/reports/integrated-energy-policy-report/2021-integrated-energy-policy-report/2021-1.

[32] California Senate Bill 9 allows up to four units on many single-family lots. Signed into law September 16, 2021. https://focus.senate.ca.gov/sb9.

less critical to the analysis. The MFLR listed in Table 6 appropriately encompasses only low-rise construction, where the quantities are individual residential units.

To determine how to align CEC FZs and T24 CZs for this study, we leveraged our previous new construction research,[33] codes & standards work, and observations made by team study team located throughout California to establish the selected FZs and CZs. We also applied additional constraints on the selection, such as coverage of each of the electric IOU service territories, and inclusion of low, medium, and extreme conditioning levels.

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[33] Opinion Dynamics. PY2016-2018 Building Advocacy Program Evaluation, Volume II Final Report. April 20, 2023. https://pda.energydataweb.com/api/view/2809/C%26S-Report%20Del%2013A_Vol2_FINAL_04-20-23.pdf

Table 6. CEC Demand Forecast of Residential New Construction Growth Rates and Total Population Estimates for SF and MF Households

Mid-Household Forecast Scenario [A]				Single-Family Households						Multi-Family Households					
Planning Area		Forecast Zone (FZ) Number and Name		Population [B]			Growth to 2035			Population [B]			Growth to 2035		
				2021	2035	2021–2035	% Growth	CAGR [C]	% of Total [D]	2021	2035	2021–2035	% Growth	CAGR [C]	% of Total [D]
1	PG&E	**1**	**Greater Bay Area**	**1,308,242**	**1,436,475**	**128,233**	**9.8%**	**0.7%**	**12.3%**	**874,746**	**1,022,332**	**147,586**	**16.9%**	**1.1%**	**31.5%**
		2	North Coast	358,138	381,166	23,028	6.4%	0.4%	2.2%	91,125	99,163	8,038	8.8%	0.6%	1.7%
		3	North Valley	141,639	153,336	11,697	8.3%	0.6%	1.1%	29,370	29,257	(113)	-0.4%	0.0%	0.0%
		4	Central Valley	650,306	759,867	109,561	16.8%	1.1%	10.5%	143,210	150,082	6,872	4.8%	0.3%	1.5%
		5	Southern Valley	518,408	617,305	98,897	19.1%	1.3%	9.5%	136,609	140,030	3,421	2.5%	0.2%	0.7%
		6	Central Coast	329,413	359,116	29,703	9.0%	0.6%	2.8%	100,456	111,162	10,706	10.7%	0.7%	2.3%
2	SCE	**7**	**LA Metro**	**1,671,516**	**1,825,177**	**153,660**	**9.2%**	**0.6%**	**14.7%**	**1,159,084**	**1,278,180**	**119,096**	**10.3%**	**0.7%**	**25.4%**
		8	Big Creek West	261,260	280,291	19,031	7.3%	0.5%	1.8%	79,987	91,372	11,385	14.2%	1.0%	2.4%
		9	Big Creek East	168,008	197,173	29,166	17.4%	1.1%	2.8%	32,151	34,007	1,856	5.8%	0.4%	0.4%
		10	Northeast	511,451	585,662	74,211	14.5%	1.0%	7.1%	124,737	136,910	12,173	9.8%	0.7%	2.6%
		11	Eastern	533,065	651,205	118,140	22.2%	1.4%	11.3%	100,855	108,323	7,468	7.4%	0.5%	1.6%
3	SDG&E	**12**	**SDG&E**	**810,396**	**880,859**	**70,464**	**8.7%**	**0.6%**	**6.7%**	**473,130**	**532,277**	**59,147**	**12.5%**	**0.8%**	**12.6%**
4	NCNC	13	SMUD	389,700	453,017	63,317	16.2%	1.1%	6.1%	140,535	149,832	9,298	6.6%	0.5%	2.0%
		14	Turlock Irrigation Dist.	71,346	86,274	14,927	20.9%	1.4%	1.4%	14,169	15,457	1,288	9.1%	0.6%	0.3%
		15	Remainder of BANC	141,505	165,498	23,992	17.0%	1.1%	2.3%	27,748	28,334	586	2.1%	0.1%	0.1%
5	LADWP	16	LADWP Coastal	503,580	541,099	37,519	7.5%	0.5%	3.6%	392,129	435,309	43,180	11.0%	0.7%	9.2%
		17	LADWP Inland	215,416	231,033	15,617	7.2%	0.5%	1.5%	168,295	186,450	18,156	10.8%	0.7%	3.9%
6	BUGL	18	Burbank /Glendale	55,882	60,020	4,138	7.4%	0.5%	0.4%	43,658	48,438	4,780	10.9%	0.7%	1.0%
7	IID	19	Imperial Irrigation Dist.	98,359	118,449	20,090	20.4%	1.3%	1.9%	22,017	25,141	3,124	14.2%	1.0%	0.7%
8	VEA	20	Valley Electric	8	10	2	25.0%	1.6%	0.0%	8	9	1	9.9%	0.7%	0.0%
			Total	**8,737,637**	**9,783,030**	**1,045,394**	**12.0%**	**0.8%**	**100.0%**	**4,154,019**	**4,622,064**	**468,046**	**11.3%**	**0.8%**	**100.0%**

Figure 4. Overlay of Forecast Zones and T24 Building Climate Zones

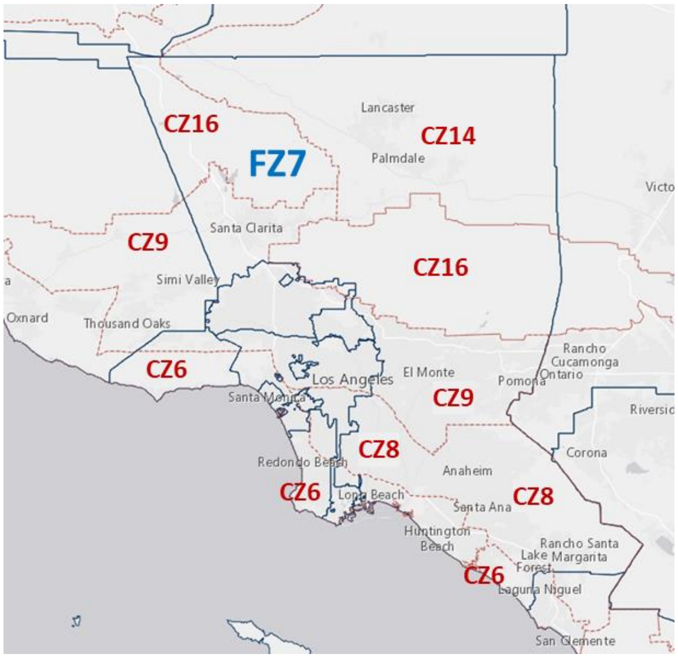
Note: Figure generated using the CEC GIS data hub at https://cecgis-caenergy.opendata.arcgis.com/

A description of the selected FZs and how we arrived at the CZs for this study is below:

SCE FZ7 LA Metro is illustrated in Figure 5.

- It accounts for the largest number of forecasted new SF and MF units in the state (153,660 and 119,096 units, respectively).
- It has modest SF and MF new construction growth rates (9.2% and 10.3%, respectively). The moderate growth is likely due to the already large existing population.
- It includes portions of T24 CZs 6, 8, 9, 14, and 16.
- Together, two of the covered CZ candidates, CZ9 and CZ14, are likely to have much of the forecasted residential new construction.
- We selected CZ14 due to the more extreme cooling and heating requirements, and because the other electric IOU service territories have some CZs with less extreme conditioning requirements to leverage.

Figure 5. SCE Forecast Zone 7 (FZ7) and T24 Climate Zones (CZs 6, 8, 9, 14, and 16)

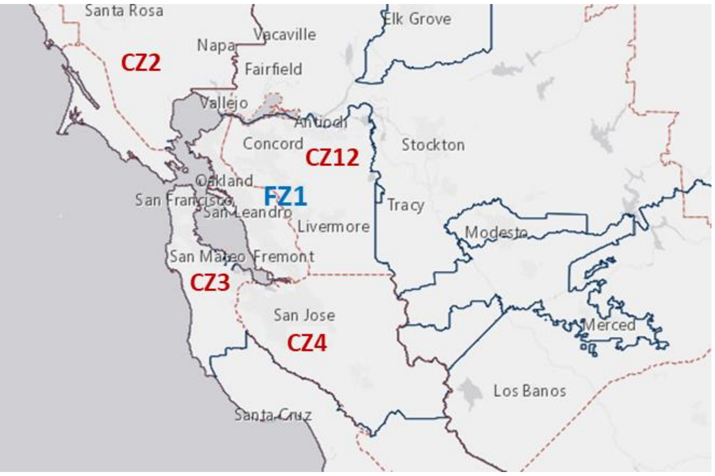


Note: Figure generated using the CEC GIS data hub at https://cecgis-caenergy.opendata.arcgis.com/

PG&E FZ1 Greater Bay Area is illustrated in Figure 6.

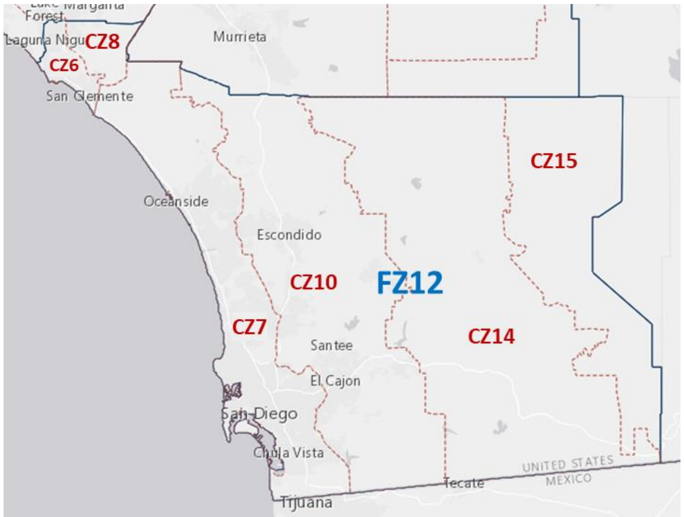
- It accounts for the second largest number of forecasted new SF and MF units in the state (128,233 and 147,586 units, respectively).
- It has modest to high SF and MF growth rates (9.8% and 16.9%, respectively).
- It includes portions of T24 CZs 3, 4, and 12.
- Together, two of the covered CZ candidates, CZ4 and CZ12, are likely to account for most of the residential new construction.
- We selected CZ4 due to the moderate cooling and heating requirements.

Figure 6. PG&E Forecast Zone 1 (FZ1) and T24 Climate Zones (CZs 3, 4, and 12)



Note: Figure generated using the CEC GIS data hub at https://cecgis-caenergy.opendata.arcgis.com/

Figure 7. SDG&E Forecast Zone 12 (FZ12) and T24 Climate Zones (CZs 6, 7, 8, 10, 14, and 15)



Note: Figure generated using the CEC GIS data hub at https://cecgis-caenergy.opendata.arcgis.com/

SDG&E FZ12 is illustrated in Figure 7.

- There is only a single FZ for all of SDG&E which represents the third largest number of forecasted new SF and MF units in the state (70,464 and 59,147 units, respectively)
- It has modest to high SF and MF growth rates (8.7% and 12.5%, respectively).
- It includes portions of T24 CZs 6, 7, 8, 10, 14, and 15.
- There are other SCE forecast zones with similar growth or total population; however, we want a location in each IOU territory.
- Most new construction is likely to occur in CZ7 and CZ10, and the distribution of housing types and growth are different in those areas. We assume, based on a visual review of the region, that CZ7 is currently more MF, while CZ10 is more SF or closer to evenly split.

- We selected CZ7 due to the mild cooling and heating requirements.

PV/Solar Penetration

We did not use solar penetration when we developed the scenarios. This parameter was not necessary to develop the BEMs and provide load shapes. Furthermore, feeder-level installed PV capacity was unavailable from the electric IOUs when we selected specific CZs and distribution feeders. We account for PV in the grid modeling by developing PV profiles based on T24 new construction criteria for sizing PV systems and using CEC solar assessment tools as required by the Standards.[34] We modeled the PV system separately so it can be added in as needed.

3.2.2 BEM and Load Shape Development

The building simulation models were created by our experienced passive house analysis partner SmithGroup. Opinion Dynamics facilitated review and knowledge sharing of the T24 CASE team PH studies. Opinion Dynamics and SmithGroup worked in close coordination and consultation to develop the prototypes and scenarios, to enhance the basic scenarios based on initial findings, and to understand and develop the results. In the following sections, we describe the prototype housing models and simulations used to generate 8760 load shapes for each analysis scenario, and the outputs that were subsequently used in the distribution grid analysis. We acknowledge the challenges and potential concerns of modeling two different Standards outside of their native platforms and that there are always tradeoffs and shortcomings that can impact the results, but modeling the two designs on the same platform was essential for this study, which is focused primarily on grid impacts.

Prototype Definition and Construction

We used EnergyPlus for our analysis to avoid the idiosyncrasies of Standards-based modeling tools designed primarily for compliance analysis, and to provide the flexibility, configurability, 8760 hourly end use results, and more automated processing capability needed to aggregate the multitude of BEM scenarios. However, the CASE study CBECC-Res passive home prototypes and simulation results were used as the basis for and in some cases calibration of our EnergyPlus-based prototype models. CBECC-Res is the CEC-developed T24 residential compliance tool and uses the California Simulation Engine (CSE), which is unique and specifically designed as the simulation engine for T24 residential compliance analysis.[35] But CBECC-Com, the commercial T24 compliance tool, uses EnergyPlus. We also considered the use of PHI or Phius certification modeling tools e.g., The Passive House Planning Package (PHPP) for PHI,[36] but could not use either of these tools due to the need for 8760 hourly results to identify peak load for grid impacts, and to assess PV hourly performance.

A recent Passive Home Network report discusses the differences between PH calculation tools and hourly building simulation tools such as EnergyPlus and T24 CBECC-Res.[37] The tools are described as "…fundamentally different programs…" and a few of the primary differences are summarized below:

- **Performance metrics versus prescriptive requirements:** Passive house design is based on a handful of primary, high-level performance metrics for heating/cooling and total energy use, air tightness, and thermal comfort that must be met by PH designs. This approach allows maximum flexibility in the construction characteristics used to

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[34] California Energy Commission. "Solar Assessment Tools." Building Energy Efficiency Standards – Title 24. Last modified October 5, 2022. https://www.energy.ca.gov/programs-and-topics/programs/building-energy-efficiency-standards/solar-assessment-tools.

[35] California Simulation Engine GitHub User's Manual: https://cse-sim.github.io/cse/cse-user-manual/index.html.

[36] https://passivehousecal.org/resources/passive-house-planning-package-phpp/.

[37] "Energy Standards Comparison Study: Comparing Passive House standards to baseline codes. Task 1: Methodology & Modeling Parameters". Passive House Network. November 2023. https://passivehousenetwork.org/wp-content/uploads/2023/10/PHN-RDH-Comparison-Study-Methodology-Report.pdf

design and build passive houses. For PHI, the energy and other performance metrics are single, universal values *regardless of climate or location*. For Phius, a similar set of performance metrics are used but they vary by climate zone, and Phius also includes an alternative prescriptive requirements compliance path for each climate zone, similar to the Title 24 option.

- **Calculation approach differences:** The software tools for both PHI (PHPP) and Phius (WUFI PH) use a simple, low-resolution, monthly, degree-day and bin method approach while EnergyPlus and T24 CBECC-Res use a physics-based hourly or even sub-hourly energy modeling approach. The physics-based energy simulation approach, and use of hourly operation schedules and weather data provides higher-resolution 8760 hourly results and operational insights for the building, PV, internal loads, and HVAC system performance.
- **Mechanical ventilation & heat recovery:** A primary difference between PH and T24 is PH principles require a significantly more airtight home and the use of mechanical ventilation including an energy/heat recovery ventilator (ERV) device to ensure fresh air is provided to the home. Typical Title 24 residential construction does not employ nor require mechanical ventilation.
- **Thermal Zoning:** Another critical difference between PH and hourly models is that PH tools only uses a single thermal zone for the entire building, whereas EnergyPlus and CBECC-Res can model multiple thermal zones. This is extremely important in California where about 50% of the single-family building stock is two -story homes, many with multiple HVAC units. Heating and cooling loads can be substantially different for the upper and lower HVAC units. For PH tools, a single zone makes sense for the lower resolution monthly degree-day approach.

The analysis presented in this report reinforced our use of EnergyPlus for this study, especially the need for higher-resolution 8760 hourly results that reflect the diversity of California climate zones.

We constructed each of the three building prototypes in EnergyPlus, adopting the CBECC-Res prototype basic characteristics and leveraging the T24 PH CASE studies mentioned previously. The three-dimensional (3D) model images for all three prototypes are illustrated in

Figure 8. The set of scenarios includes two SF homes and one MF low rise (MFLR) building. The two SF homes include a 2,100 square foot (sq. ft.), one-story house, and a 2,700 sq. ft., two-story house. The MFLR is a 7,040 sq. ft., eight-unit, two-story residence. The geometry was altered slightly from the CASE study to have windows distributed equally on all facades rather than running the building in all different orientations. The intention is to create an orientation-agnostic model to enable scalable deployment to the grid impact portion of this study.[38]

The orientation decision highlights the need for significant scalability in our household designs to better inform the grid impact goal of the study. When PHI code, for example, is executed, the modelers are typically focused on a single household in a specific parcel location and orientation, with an explicit set of characteristics about the house shape, solar exposure, number of bathrooms, occupants, and many more. This is an appropriate approach for assessing the energy use and code compliance for a single household. However, we need to scale the analysis across several climate zones and potentially add thousands of houses to each feeder in the study to assess the impacts of adding PH or T24 houses to the grid. It would be impossible to create thousands of orientation-specific households within the scope of this exploration study, rather than the nine orientation-agnostic houses we developed to enable this massive degree of necessary scale.

Figure 8. Building Simulation Model Prototype Images

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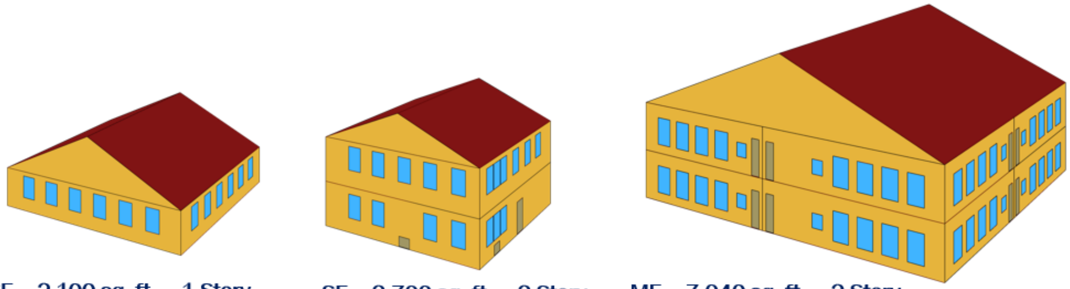
[38] For passive home design, the orientation of the building and window distribution are critical elements of the building's energy performance. However, the grid portion of this study considers new construction of whole neighborhoods. So as an alternative to modeling a whole fleet of building configurations and averaging those results, our orientation-agnostic approach serves as a conservative estimate of the benefits of applying PH principles.



SF – 2,100 sq. ft. – 1 Story SF – 2,700 sq. ft. – 2 Story MF – 7,040 sq. ft. – 2 Story

Housing Characteristics and Performance Parameters.

The primary characteristics, including floor area, window (glazing) area, and appliance specifications, are summarized in Table 7. These primary characteristics are maintained for all scenarios of the same housing type since they are not defined based on weather or CZ conditions and are primarily derived from the CBECC-Res prototype characteristics as noted in the CEC CASE research studies.

Table 7. Housing Type Characteristics

	SF – 1 Story	SF – 2 Story	MF – 2 Story
Conditioned Building Area	2,100 sq. ft.	2,700 sq. ft.	7,040 sq. ft. (4 × 780 sq. ft. 1Bed + 4 × 980 sq. ft. 2Bed)
Garage Area (Unconditioned)	440 sq. ft.	440 sq. ft.	-
Roof Pitch	5:12	5:12	5:12
Glazing per Façade (Uniformly Distributed)	96 sq. ft.	135 sq. ft. (60 sq. ft./Zone 1 + 75 sq. ft./Zone 2)	260 sq. ft. (65 sq. ft./Zone × 4 Zones/Orientation)
Shading	Not Included in Study	Not Included in Study	Not Included in Study
Zones	1	2	8
Stories	1	2	2
Heating & Cooling	Split Heat Pump	Split Heat Pump	Split Heat Pump
Hot Water	Heat Pump	Heat Pump	Heat Pump
Dishwasher, Clothes Washer, Dryer	Diversified – Matches IECC Prototype	Diversified – Matches IECC Prototype	Diversified – Matches IECC Prototype
Electrical Equipment	Calibrated – CBECC Example Models	Calibrated – CBECC Example Models	Calibrated – CBECC Example Models
Natural Ventilation	50% of Window Area per Orientation	50% of Window Area per Orientation	50% of Window Area per Orientation

Note: IECC is an abbreviation of the International Energy Conservation Code.

Key performance parameters vary between T24 and PH code standards. Parameter values for this study are summarized in Table 8 for all three CZs. The T24 prescriptive parameters defined the baseline set of performance parameters, such as insulation, glazing, and ventilation. The PH scenario uses prescriptive values from the Phius standard except as noted.

Table 8. Housing Type Performance Parameters

	T24	PH
CZ 04 – San Jose		
Wall Insulation	R21 + R5 – 2 × 6 Walls	R22 + R5 – 2 × 6 Walls
Roof Insulation	R30	R56
Slab Insulation	None	R21 Perimeter
Glazing U-Value	0.30	0.30[B]
Glazing SHGC[A]	0.23	0.23[B]
Ventilation	Exhaust Only	Energy Recovery Ventilator – 70% Eff
Infiltration	5 ACH50	0.6 ACH50
CZ 07 – San Diego		
Wall Insulation	R15 + R5 – 2 × 4 Walls	R20 + R5 – 2 × 6 Walls
Roof Insulation	R30	R53
Slab Insulation	None	R21 Perimeter
Glazing U-Value	0.30	0.30[B]
Glazing SHGC[A]	0.23	0.23[B]
Ventilation	Exhaust Only	Energy Recovery Ventilator – 70% Eff
Infiltration	5 ACH50	0.6 ACH50
CZ 14 – Palmdale		
Wall Insulation	R21 + R5 – 2 × 6 Walls	R25 + R5 – 2 × 6 Walls
Roof Insulation	R38	R60
Slab Insulation	None	R21 Perimeter
Glazing U-Value	0.30	0.24
Glazing SHGC[A]	0.23	0.23[B]
Ventilation	Exhaust Only	Energy Recovery Ventilator – 70% Eff
Infiltration	5 ACH50	0.6 ACH50

[A] SHGC is an abbreviation for solar heat gain coefficient.
[B] Set to the highest performance, which is the lower T24 value.

Weather Data

Each location chosen for this study is within a different CZ and requires a different representative hourly weather profile to drive the energy use in each house. All building simulations in this study used the latest California-specific CZ2022 typical year, normalized weather files maintained by the California Measurement Advisory Council (CALMAC) for the sixteen standard California climate zones illustrated in Figure 9.[39] The CZ2022 normal weather files are created from actual year weather data for a twenty-year time span from 1998 to 2017. These weather files are used for the 2022 T24 Standards, California energy-efficiency programs, and other studies.

The BEM simulation year for this study was set to start January 1 on a Saturday, which subsequently defines weekdays, weekends, and holidays for the model year. On a perpetual calendar, this corresponds to calendar years of 2011 or 2022. So, effectively all data described in this study represent typical weather drivers and responses for a 2022 calendar year.

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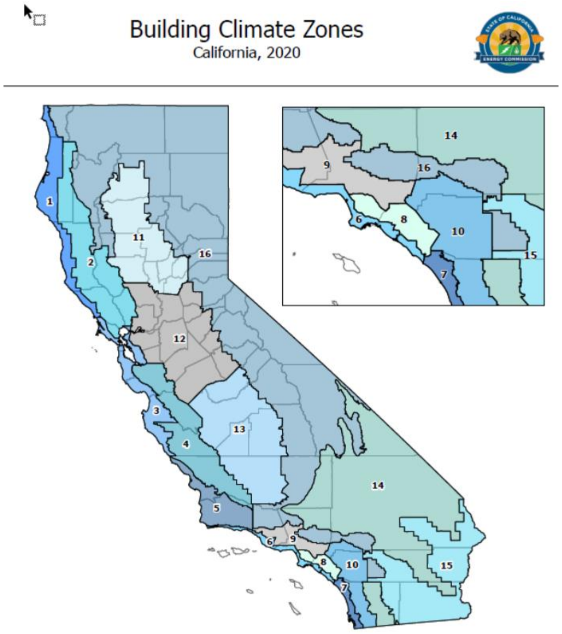
[39] CALMAC (website). "California Weather Files." Last modified December 9, 2022. https://www.calmac.org/weather.asp.

Figure 9. CEC T24 Building Standards CZs and Representative Weather Stations for 2019 RASS



Note: Adapted from Table 34, *2019 California Residential Appliance Saturation Study*. California Energy Commission. Publication Number: CEC-200-2021-005-MTHLGY.

Summer Peak Demand Investigation

We performed the following additional investigations to expand our comparative analysis and explore other PH features with potential grid benefits. The focus of our additional analysis was on cooling peak demand impacts, as the grid is currently most stressed during the summer in California, and the benefits of PH space heating impacts are already well known and the primary focus of PH design.

- **Precooling Scenarios.** We used a precooling approach to explore maximizing the inherent thermal storage aspect of a PH design. The approach included a four-hour precooling window from 78°F to a lower 70°F immediately followed by a two-hour HVAC system lock-out schedule that prevented the HVAC system from running. The lock-out period allowed the indoor temperature to increase naturally. We ran both T24 and PH models with this control approach to determine capability for peak shifting and lessening impact on the peak ramp. These model runs reflect a hypothetical precooling strategy rather than a realistic precooling and dynamic control demand response (DR) application and they allow for flexible load and load shaping assessments.
- **Shading/Overhangs and Thermal Mass.** We performed this additional analysis to explore the benefit of external window shading and the prevention of solar insolation from entering the home. Two distinguishing features of PH design are increased thermal mass and proper eaves, or overhangs, based on the exact location and orientation of the house. Neither of these provided the expected peak-shifting response from these modeled houses but notably, we explored them in a limited manner.
- **Rooftop Solar.** PV systems were sized based on T24 rules for every housing type. The current sizing rules are defined for new construction, so they are based on square footage of the home and location, not on energy use. For this reason, each household has the same PV design in each CZ, irrelevant of the code base. For example, for the SF one-story, 2100 sq. ft. home in CZ 4, the T24 and Phius PV systems are identical and produce the same solar profile. Since the PV system is independent of household energy usage, we can add the same solar profile to all SF one-story house types in the same CZ. This results in nine different PV profiles, one for each house type in each CZ.

BEM Run Summary

Table 9 captures the landscape of simulations that we ultimately modeled. We modeled houses with PH Principles and T24 code base in all three CZs, resulting in 18 individual runs. All are default thermostat-controlled with no DR or other advanced controls.

Five precooling conditions were run for each scenario, resulting in 90 additional model runs. We also included two shading runs on SF-1 in CZ04. For all the default thermostat-controlled, precooled, and shading runs, the energy use results are represented for the entire home and for all 13 end uses.

As noted above, there are nine separate solar profiles, one for each housing type by CZ.

Altogether, we have 18 default thermostat runs, 90 precooling runs, and two shading runs, all with 13 end-use breakdowns and whole-building profiles, resulting in 1,540 residential load shapes. The additional nine solar profiles bring the total load shape generation for this study to 1,549 load shapes.

Table 9. Building Energy Modeling Scenarios Completed

Housing Type	**SF 1-Story, 2100 sq. ft.**						**SF 2-Story, 2700 sq. ft.**						**MF 2-Story, 7040 sq. ft.**					
Code Base	**T24**			**PH**			**T24**			**PH**			**T24**			**PH**		
Climate Zone	CZ 04	CZ 07	CZ 14	CZ 04	CZ 07	CZ 14	CZ 04	CZ 07	CZ 14	CZ 04	CZ 07	CZ 14	CZ 04	CZ 07	CZ 14	CZ 04	CZ 07	CZ 14
Default Thermostat	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Precooling Scenarios	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Additional Shading	✓			✓														
By End Use	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Rooftop Solar PV	✓	✓	✓				✓	✓	✓				✓	✓	✓			

3.2.3 Grid Scenario Design and Assumptions

Sections 3.2 and 3.3 described the various permutations of home types and CZs that we used to inform the BEM, resulting in nine scenario combinations. Not all these combinations are considered for grid modeling due to time and budget limitations. Thus, the team designed a set of scenarios to capture a broad range of possibilities for consideration in the grid modeling exercise.

Representative Feeder Selection

Real world feeders are selected for this study to reflect realistic results based on actual existing conditions. However, existing feeders are generally heterogeneous with respect to building types on the feeder (i.e., are not homogeneous with respect to building types, such as SF or MF). This diversity of house type on the feeder, combined with the actual feeder infrastructure, is instrumental in producing real world (non-idealized) results more indicative of actual feeder impacts the IOUs might experience in their distribution feeder analyses and planning for interconnection of new homes with distributed energy resources (DER) including generation, at scale.

Table 10 lists the nine feeders, and the larger substations that serve them, initially considered for this study— three from each electric IOU territory. The criteria and methods for selecting them are defined below. As this work progressed, however, only six of these feeders were ultimately applicable to the study. The feeders shaded in grey in Table 10 (Mountain View/82031105, Redman/Alfalfa, and Melrose/205— one in each IOU territory), were eliminated during the grid modeling effort. These MF-dominant feeders have significant mobile and manufactured home populations which we could not identify until after the grid topology for these scenarios was obtained. Since PH does not have a specification for this housing type and adding MFLR to these feeders would not be consistent with the rest of the feeder, we eliminated these feeders from the study.

Table 10. Grid Feeders for Distribution Grid Analysis Stage

Geographic Description	**PG&E, between Coast and Inland**			**SCE, Inland**			**SDG&E, Coastal**		
Substation	Edenvale	McKee	Mountain View	Palmdale		Redman	San Ysidro	Telegraph Canyon	Melrose
Feeder Name/Identifier	82951103	83531110	82031105	Paint	Mark	Alfalfa	460	1225	205
% Residential	90%	94%	52%	94%	83%	69%	87%	68%	52%
% Single-Family	100%	50%	25%	99%	55%	18%	95%	50%	30%

We selected feeders to capture a range of CZs, home types, and new construction growth. Once each feeder was selected, the team collected data or made assumptions from maps about the new construction population (growth rate, types of homes being added, location of homes) on the feeder (discussed in Section 3.4.2). We used combinations of the variables to devise multiple scenarios for grid modeling (discussed in Section 3.4.4).

In Section 3.2.2, we described our selection of three desired CZs, one within each FZ. Because there might be hundreds of feeders in each CZ, we worked directly with each of the electric IOUs through several iterations to narrow down the feeder selections to support the study. The modeling of impacts would benefit from feeders that were predominantly residential loads. In addition, we wanted the selected suite of feeders to include one that is SF dominant, another that is MF dominant, and one with a blend of SF and MF.

Unfortunately, each utility provided inconsistent and varying levels of the criteria needed to make feeder selection decisions. As a result, the effort involved receiving some initial high-level information from the utility, such as a feeder identification list in the region we were interested in and the percentage of each that is residential. From this high-level information, we then interactively accessed all three IOU online transmission and distribution map portals to visually identify dominant residential feeders, assign a percent weighting for SF and MF, and determine if the feeders reside in the appropriate physical location. The steps we carried out to identify appropriate feeders for each IOU are summarized below:

- **SCE, FZ7 LA Metro, CZ14**: We leveraged an initial SCE data request response, which included peak load, percent load by sector, and total annual energy usage for SF and MF customers for each feeder. We visually confirmed the selections using SCE’s Distributed Resource Plan (DRP) portal, allowing us to calibrate this activity for the other IOUs where visual identification was necessary.[40]
- **PG&E, FZ1 Greater Bay Area, CZ04**: PG&E provided a list of relevant feeders disaggregated by residential and other sector loads, however PG&E staff could not identify usage or customers by SF and MF. To select the appropriate feeders for this study, PG&E’s web-based Integration Capacity Analysis Map allowed visual determination of the mix of residential types.[41] The share of SF results are estimates based on this visual assessment.
- **SDG&E, FZ12 Coastal, CZ07**: SDG&E was not able to provide any details about their feeders but could provide a list of regional feeders. To identify the appropriate feeders for this study, we used SDG&E’s web-based

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[40] SCE Distributed Resource Plan External Portal (website). https://drpep.sce.com/drpep/.

[41] PG&E Integration Capacity Analysis (ICA) Map. Access to map requires a login username and password obtains through PG&E. https://www.pge.com/b2b/distribution-resource-planning/integration-capacity-map.shtml.

Interconnection Map to extract load by sector for each feeder.42 This allowed us to determine the share of residential load, and visually determine the mix of residential types. The share of SF values are estimates based on this visual assessment.

Each selected feeder in Table 10 is characterized by residential statistics, and the shares of the load on the feeder that are SF residential with the remainder of residential load coming from MF buildings. The remainder of the load is a combination of commercial, industrial, and agricultural load. For example, SCE's substation Palmdale and feeder Mark is 83% residential by load; 55% of this is due to electricity consumption by SF homes, with the remaining 45% coming from MF housing.

Grid Models

Real-world grid models provided by the PG&E and SCE were used to test the impacts of our PH homes.[43] Grid models are used by utilities in their own grid planning efforts and exercises. Using these models allows power flow studies for hypothetical grid scenarios, determining the effects of different decisions on the distribution grid. Our team modeled the impacts of additional residential new construction home loads (both the baseline T24 and PH) and compared the results of the hypothetical scenarios which provide insight into the operational impact of adopting PH principles into the building code. Additional discussion of these grid models follows in the subsections below.

Existing utility grid models were provided for a sample of feeders (discussed earlier in Section 3.4.1) in the CYME software platform.

Grid Model Inputs

Meaningful simulations of the grid rely on a variety of inputs. Key input for this analysis includes:

- Simulated load shapes for T24 and PH homes in each CZ; these modeled load shapes are aggregated for analysis on the grid models
- Baseline (existing) loads on the feeder either provided by the utility or constructed by the project team (discussed further in Section 3.4.4)
- New construction development growth loads (additive load to the baseline load)
- Peak hours and backfeed hours for each feeder. The peak hour is defined as the hour with the most energy flowing from source (substation) to load (buildings and homes) and the backfeed hour is defined as the hour with the most energy flowing from load to source due to solar overproduction.

Energy storage and electric vehicle charging were not included in the grid analysis.

Grid Model Outputs

Grid models provide the following key metrics as outputs:

- Element overload (% of rating)
  - Overloaded elements require upgrade and replacement that often carries high cost. Avoiding grid upgrades to address overloaded elements is a large potential benefit from lower peak building codes like PH.
- Conductors and transformers are the two elements of focus in this analysis.

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[42] SDG&E Interconnection Map. Access to map requires a login username and password obtains through SDG&E. https://interconnectionmapsdge.extweb.sempra.com.

[43] SDG&E could not provide the full set of files we required to run grid models for the selected feeders.

    - Conductor rating is based on ampacity (A) and the current flowing through a conductor determines the percent loading for the element.
    - Transformer rating is based on apparent power (kVA) and the power required to move through the transformer.
- Voltage (% of nominal)
    - Overvoltage and undervoltage require mitigation projects, often at a high cost. Avoiding grid upgrade projects to address voltage issues is a large potential benefit from lower peak building codes like PH, but lower PH building loads is a concern for larger backfeed during peak solar generation.
    - Voltage is measured at each node in the feeder.
- Total annual energy (kWh)
- Total annual energy is used as a metric to measure energy efficiency savings.

Existing Load Allocation

To efficiently run the grid models, we require an industry standard process of load allocation. Load allocation takes the total feeder load and distributes it across each load element in the feeder. For SCE and PG&E feeders using CYME, load allocation assigns load based on the listed capacity of each load element.

Using load allocation allows for much more efficient model preparation and evaluation of scenarios, however it does not exactly reflect the number and type of homes at each node. This deviation from reality means that grid impacts at individual grid elements may not be accurate. However, the overall impacts to the feeder (the focus of the grid impact modeling) are still accurate. The added accuracy of assigning the real load to each element would add greater cost to this study with limited value to the key outputs.

3.2.4 Assumptions for Adding New Homes to Existing Populations

As described earlier, grid impact modeling could only occur after we developed scenarios for the locations and structures of the PH and T24 homes, completed building simulations, and obtained distribution feeders from the electric IOUs. As noted above, we relied on load shapes that represent T24 and PH principles. SF-1 story, SF-2 story, and MFLR model results with and without solar were included.

Types of Homes Added

The types of homes to add to each feeder are informed by the current home types at that feeder. The list below provides additional details for each feeder:

- Southern California Edison (SCE)
    - SCE – Paint: Only residential SF-two story modeled homes were added since SCE – Paint is an overwhelmingly SF feeder with relatively higher load per home.
    - SCE – Mark: New homes are split between residential SF-two story and MF since SCE – Mark is 55% SF and 45% MF, and the SF homes have relatively high load per home.
- Pacific Gas & Electric (PG&E)
    - PG&E – McKee: New homes are split between residential SF-one story and MF since PG&E – McKee is 50% SF and 50% MF, and the SF homes have relatively lower load per home.

  - PG&E – Edenvale: Only residential SF one story modeled homes were added since Edenvale is 100% SF, and the SF homes have relatively lower load per home.

No commercial buildings were added since the PH codes and modeled load shapes only apply to residential buildings. Additionally, both SCE feeders (Paint and Mark) are majority residential feeders (94% and 83% respectively) so no issues from omitting commercial growth were expected. Similarly, both PG&E feeders (McKee and Edenvale) are majority residential feeders (90% and 94% respectively).

Quantity of Homes Added

The quantity of homes added for each housing type is decided based on the current composition of SF and MF homes. For each feeder, 20% more SF homes are added as residential growth on the feeder. This value is reasonable for load growth and allowed us to explore loading and voltage issues.

Southern California Edison (SCE)

- SCE – Paint is 99% SF, so no MF homes were added and added SF homes were all SF-two story
- SCE – Mark is 55% SF and 45% MF. Given this, we added more MF homes to evaluate a scenario with high MF penetration. Added SF homes were all SF-two story. Due to lower loading, we explored additional scenarios with extra homes to push the limit of the feeder. This resulted in a maximum conductor loading near 105% of the nominal rating, the absolute maximum loading for the conductors.

Pacific Gas & Electric (PG&E)

- PG&E – McKee is 50% SF and 50% MF, so the growth was split evenly between the two types. Added SF homes were all SF-one story. Since PG&E did not provide customer counts, the provided residential load was split between SF and MF so the peak values were approximately equal. The number of homes was then chosen to match the load.
- PG&E – Since Edenvale is 100% SF, no MF homes were added. Added SF homes were all SF-one story.

Note that we used SF-two story homes for SCE and SF-one story homes for PG&E since the existing homes for SCE tended to have higher load per home. Existing homes for PG&E tended to have lower load per home.

Location of New Homes on Feeder

The location of the new homes has an impact on the outcome relative to planning metrics, depending on existing grid design and location of other loads. We determined the location for the new homes on the feeder based on lower density areas. In some cases, this results in new loads being located at the end of the feeder in a single location, and in other cases the new homes are split to either side of the feeders.

3.2.5 Grid Models – Impact Scenarios Summary

We used a counterfactual baseline model to maintain consistency across the analysis. This baseline uses the T24 home load shape without solar, along with the IOU provided quantities of SF and MF customers to construct an all T24 base model from which to work. This model used the T24 load shapes with no solar PV. We selected this model because it represents a peak load close to the reported utility values and is constructed from load shapes within the study. The solar PV was omitted from the T24 load shapes to bring the value closer to the utility-provided baseline and because, for consistency, it is more reasonable to assume no one has solar than to assume everyone has solar, for existing building stock. Commercial load on the feeders is accounted for using the commercial loading 8760 provided by the IOUs since no T24 or PH models are provided for commercial loads. SCE and PG&E’s provided residential loadings were incorporated into the additional "utility-provided baseline" scenarios but were not used in the counterfactual baseline for greater control of the feeder load. The commercial load was added onto the constructed residential counterfactual load to complete the total feeder load.

Core Growth Scenarios. From this baseline, we developed two core growth scenarios. These growth scenarios add homes using the method discussed in Section 3.4.2. In the first scenario, the new homes use the T24 load shape and have solar. In the second scenario, the new homes also have solar, but use the PH load shape. These two growth scenarios serve as the basis of this analysis, directly comparing growth using T24 to growth using PH.

Within the growth scenarios, both the peak load and maximum backfeed cases were evaluated to capture both operational extremes. The peak load has the most energy flowing from the substation to the loads and will reveal capacity overloads and undervoltage. The backfeed peak load has the most energy flowing from the solar PV DERs to the substation and will reveal capacity overloads and overvoltage.

The counterfactual baseline, and associated growth scenarios make up the core scenarios that we evaluated for every feeder.

Additional Alternative Scenarios. We added select additional scenarios to individual feeders. SCE – Paint was used to investigate an alternative baseline. In addition to the counterfactual baseline discussed above, the utility-provided 8760 load serves as the baseline for three additional scenarios: a base case and two growth scenarios using the same methodology as the counterfactual baseline growth scenarios. These cases are grouped as the utility-provided baseline scenarios. SCE – Mark was used to investigate maximum load growth. For this feeder, two additional growth scenarios with extra load are investigated. These scenarios load both the T24 and PH growth scenarios very close to the maximum conductor loading of 105% to evaluate how T24 vs. PH affects the amount of growth that could occur without reconductoring. These scenarios are grouped as extended load scenarios. PG&E – McKee was also used to investigate the utility-provided 8760 baseline load similar to SCE – Paint.

Table 11 summarizes all cases evaluated for the SCE feeders and Table 12 summarizes all cases evaluated for the PG&E feeders.

Table 11. Grid Impact Analysis Scenario Summary for SCE

Scenario Group	Scenario Title	Included for PG&E – McKee (Y/N)	Included for PG&E – Edenvale (Y/N)	New Load Model	Peak or Backfeed
Core Scenarios	Counterfactual baseline	Yes	Yes	-	Peak
	T24 growth with counterfactual baseline – peak	Yes	Yes	T24	Peak
	PH growth with counterfactual baseline – peak	Yes	Yes	PH	Peak
Utility-Provided Baseline Scenarios from 8760	Utility-provided baseline from 8760	Yes	No	-	Peak
	T24 growth with utility baseline from 8760	Yes	No	T24	Peak
	PH growth with utility baseline from 8760	Yes	No	PH	Peak

Table 12. Grid Impact Analysis Scenario Summary for PG&E

Scenario Group	Scenario Title	Included for SCE – Paint (Y/N)	Included for SCE – Mark (Y/N)	New Load Model	Peak or Backfeed
Core Scenarios	Counterfactual baseline	Yes	Yes	-	Peak
	T24 growth with counterfactual baseline – peak	Yes	Yes	T24	Peak
	T24 growth with counterfactual baseline – backfeed	Yes	Yes	T24	Backfeed
	PH growth with counterfactual baseline – peak	Yes	Yes	PH	Peak
	PH growth with counterfactual baseline – backfeed	Yes	Yes	PH	Backfeed
Utility-Provided Baseline Scenarios	Utility-provided baseline	Yes	No	-	Peak
	T24 growth with utility baseline	Yes	No	T24	Peak
	PH growth with utility baseline	Yes	No	PH	Peak
Extended Growth Scenarios	T24 extended growth	No	Yes	T24	Peak
	PH extended growth	No	Yes	PH	Peak

It is important to note that the core scenarios use a counterfactual baseline and modeled load shape. The core scenarios do not have a realistic residential load since they only use the modeled load shapes from BEM simulations. While the conclusions from this analysis are valuable for comparisons of T24 and PH homes, they do not represent the real-world loads as they do not reflect a realistic heterogeneity in household loads. The reason for this approach is to allow for control of variables of interest, such as the quantity of homes and presence or absence of solar PV. The utility-provided baseline group of scenarios relied on the real baseline load but uses the modeled load to represent new growth. Since all modeled homes of a given type (e.g., T24 SF single story) were identical, with an identical hourly load shape, this approach produced a 'worst case' planning scenario due to the lack of diversity in modeled hourly usage. Sensitivity of grid impacts to this effect is a topic for future study.

An additional consideration for the model is that only the extreme loading cases (hour of peak and hour of backfeed) were evaluated. The peak time for the existing feeder may be different than the peak time for the area of new load due to differences in building standards. This means the whole feeder peak and the local, new load peak may occur at different times. Therefore, the whole feeder peak analysis may be missing the highest loading conditions in the new area. This local to total difference may also be affected by using actual loads instead of the modeled loads. Conducting the study over multiple time periods is also a topic for future study.

4. Literature Review Findings

This section describes our research findings from Phase I of this study. The literature review findings from Phase I of this study help to summarize the current state of knowledge regarding potential grid benefits from Passive House construction prior to the grid assessment research (Phase II), conducted as part of this study and presented in subsequent chapters of this report.

We first discuss the key principles of Passive House construction that are relevant for our research questions alongside how those principles are applied in practice. We then discuss the impact of those principles on energy consumption and electric load. Finally, we translate those impacts into grid benefits.

4.1 Passive House Design Principles and Practices

A Passive House is a very well insulated, virtually airtight building that is primarily heated by passive solar gains and internal heat gains from cooking, bathing, electrical equipment, etc. The Passive House standard is a building performance standard that aims to achieve specific minimum building performance criteria using the following five key principles (Norris 2019).

- **Continuous insulation.** A Passive House has an uninterrupted and self-contained layer of insulation that minimizes the transfer of hot or cool air through the building shell.
- **No thermal bridging.** Thermal bridges are places where hot or cool air escapes through thermal breaks in assemblies such as exterior wall penetrations. A Passive Home’s advanced framing methods and low conductivity structural materials prevent thermal bridging.
- **Airtight construction.** A Passive House achieves low air infiltration rates by maintaining an uninterrupted air barrier.
- **High performance windows and doors.** The insulating and thermal properties of the high-performance windows and doors in a Passive House perform as a seamless extension of the building shell.
- **Mechanical ventilation with heat recovery.** A Passive House with airtight construction requires a dedicated ventilation system to deliver continuous fresh air and remove moisture. A Passive House ventilation system uses a heat recovery ventilator (HRV) to continuously remove stale or moist air and deliver fresh air. During this process, it extracts heat from the exhaust air and puts it into the incoming air without directly mixing the airstreams together. This way, all the heat in the exhaust air is not completely lost to the outside. For a Passive House HRV, at least 75% of that heat needs to be recovered.

There are two Passive House certification organizations in California: (1) Passive House Institute (PHI) and (2) Passive House Institute US (PHIUS). Each organization offers a standard which has a unique set of performance metrics and required energy modeling solutions (Table 13). As of September 2021, there are 4 PHI-certified new construction homes and 13 PHIUS-certified new construction homes in California. In addition, there are seven new construction homes listed in the PHI database that are not PHI-certified but have Passive House components.

Table 13. Passive House Standard Certification Criteria

Certification Component	PHI Standard	PHIUS Standard
	Passive House Institute	Passive House Institute US
Energy modeling tool	PHPP	WUFI Passive
Heating and cooling energy usage	Max of 15 kWh/m² (1.39 kWh/ft²) of treated floor area per year	Energy targets depend on occupant density and building size
Energy usage	Max of 60 kWh/m² (5.57 kWh/ft²) of treated floor area per year for Passive House Classic	Net source energy limits vary by occupant and unit density
Air leakage	0.6 air changes per hour at 50 Pascals (ACH50)	Max of 0.06 cfm/ft² envelope at 50 Pascals
Certification tiers	Classic: no renewable requirement	CORE: the net source energy demand limit depends on occupant and unit density
	Plus: max of 45 kWh/m² (4.18 kWh/ft²) per year; at least 60 kWh/m² (5.57 kWh/ft²) renewable energy generation per year	ZERO: max of zero kWh/person/year net source energy demand
	Premium: max of 30 kWh/m² (2.79 kWh/ft²) per year; at least 120 kWh/m² (11.15 kWh/ft²) renewable energy generation per year	

Source: PHI 2016; PHIUS 2021

At its core, Passive House is a performance standard, and as such, architects and designers can pursue a variety of pathways to achieve required performance. As part of the interviews with industry experts, we explored common building practices to achieve the Passive House standard. The following subsections highlight insights from the interviews:

Fuel Types

While the Passive House standard does not set specific requirements for fuel type, energy usage requirements set by the standard are hard to achieve with the use of fossil fuels. Most interviewees identified the standards as a driving factor behind the fact that, in practice, most Passive Houses are electric-only. Our exploration of new construction Passive Houses confirms that natural gas is rarely used for either space or water heating purposes in new construction certified passive houses.

> *It [Passive House Standard] does not disallow mixed fuel. But it basically creates an incentive structure that gas appliances are heavily penalized, and effectively makes it almost impossible to get certification with gas appliances.*

Heating and Cooling Equipment

Most new construction Passive Houses in California take advantage of heat pump technology, which is gaining popularity in California and across the country for heating and cooling. Water heating technologies used in new construction Passive Houses vary and primarily include heat pump water heaters and solar water heaters. Several interviewees mentioned that heating and cooling systems in Passive Houses are smaller than equivalent code-compliant homes, primarily because Passive House principles reduce demand for heating and cooling and, therefore, require smaller systems.

> *Passive House has already been pioneering heat pump technology for a long time, way before the whole electrification movement gained any momentum.”*

Integration of Renewables and Storage

While renewable generation is not a required component for achieving the Passive House standard, solar PV has been commonplace in Passive Houses since long before California Building Code began requiring solar readiness in residential new construction (CEC 2018). Multiple interviewees pointed to a long history of integrating solar PV in Passive House design. In fact, the PHI certification standard integrates solar as part of Tier 2 and 3 certifications by requiring at least 60 kWh/m^2 (5.57 kWh/ft^2) and 120 kWh/m^2 (11.15 kWh/ft^2) renewable energy generation, respectively. Although the PHIUS standard does not specify renewable energy generation requirements for the two certification tiers, it sets targets for net source energy demand, which is impacted by on-site renewable energy generation. Other renewable sources, such as wind, are not commonplace in California Passive Houses.

> “*The integration of solar in Passive Houses started to be credited in 2015. We always put solar on our projects.*”

Integration of storage is not required as part of the Passive House standard, and current practices vary. Some interviewees pointed to a natural proclivity of customers building Passive Houses to integrate storage to reduce their dependence on the grid. Others pointed to a growing trend of integration of storage into new construction across the state, with Passive Houses being no different. When probed on differences in storage specifications, one interviewee mentioned that people who are early adopters might be more likely to integrate storage into their homes, but integration of storage is not a common practice in the Passive House design and construction because of its costs and the fact that storage capacity might not necessarily meet household electric demand.

Appliances and Plug Load

At its core, the Passive House standard drives efficiency of cooling and heating loads. The standard does not impact the efficiency of appliances and plug load equipment. The load resulting from those technologies is driven by household characteristics and end user preferences. Several interviewees noted that customers looking to build Passive House-compliant homes are naturally inclined toward energy conservation and decarbonization. As such, they tend to select more efficient appliances and other energy using equipment to minimize their carbon footprint.

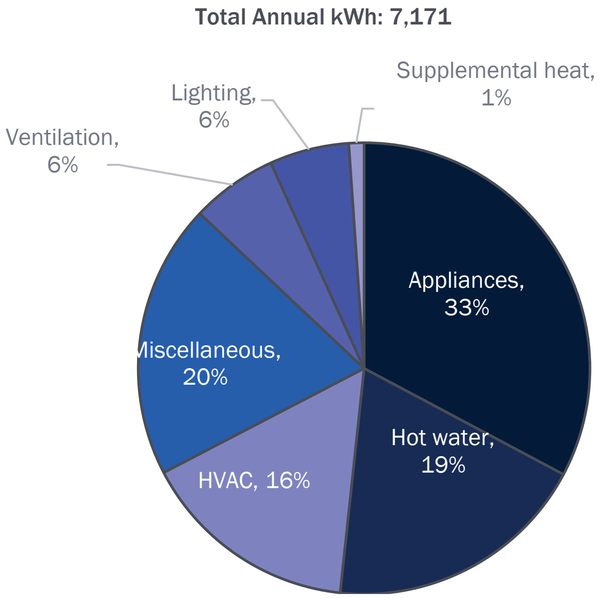
4.2 Impact of the Passive House Standard on Building Electric Load

Our literature review, in-depth interviews, and analysis of the consumption data for two Passive Houses point to several important impacts of the Passive House performance standard on building load shape compared to code-built homes. These include reduced heating and cooling load, reduced total annual load, reduced summer and winter peak load, flatter load shape, increased load predictability, and opportunities for load flexibility.

4.3 Heating and Cooling Load

While the exact amount of load reduction provided by Passive House construction depends on a number of factors, our literature review suggests that Passive Houses can have up to 75% less heating and cooling load than code-compliant new construction (CET 2020). Figure 10 shows disaggregated energy consumption for two Passive Houses in California (EIA 2009). Heating and cooling, including supplemental heating, represents 17% of whole home energy use, while lighting, appliances and miscellaneous uses represent 55% of energy use. In comparison, the Energy Information Administration (EIA) estimates that heating and cooling accounts for 31% of a home’s total energy use on average in California (EIA 2009). While this comparison is not perfect (the EIA data includes both existing and new construction across all of California), a Passive House has lower heating and cooling load in terms of its composition of total energy consumption.

Figure 10. Passive House Energy Consumption



4.4 Annual Load

The Passive House design principles described above significantly reduce heating and cooling load, thus driving reductions in energy consumption over the course of the year. White and Lindburg (2020) performed a case study in which they compared energy modeling for a Passive House and a code-compliant house[44], as shown in Figure 11. They showed that the Passive House had 45% lower annual load than the code-compliant house. Interviews also highlighted that there are regional variations in the amount of energy savings Passive House design can achieve. Heating and cooling loads in coastal areas, for example, are not as high as in inland or desert regions; thus, the impact of the Passive House standard on absolute energy savings is not as pronounced. That said, nearly all interviewees confirmed that the Passive House standard did reduce total energy consumption.

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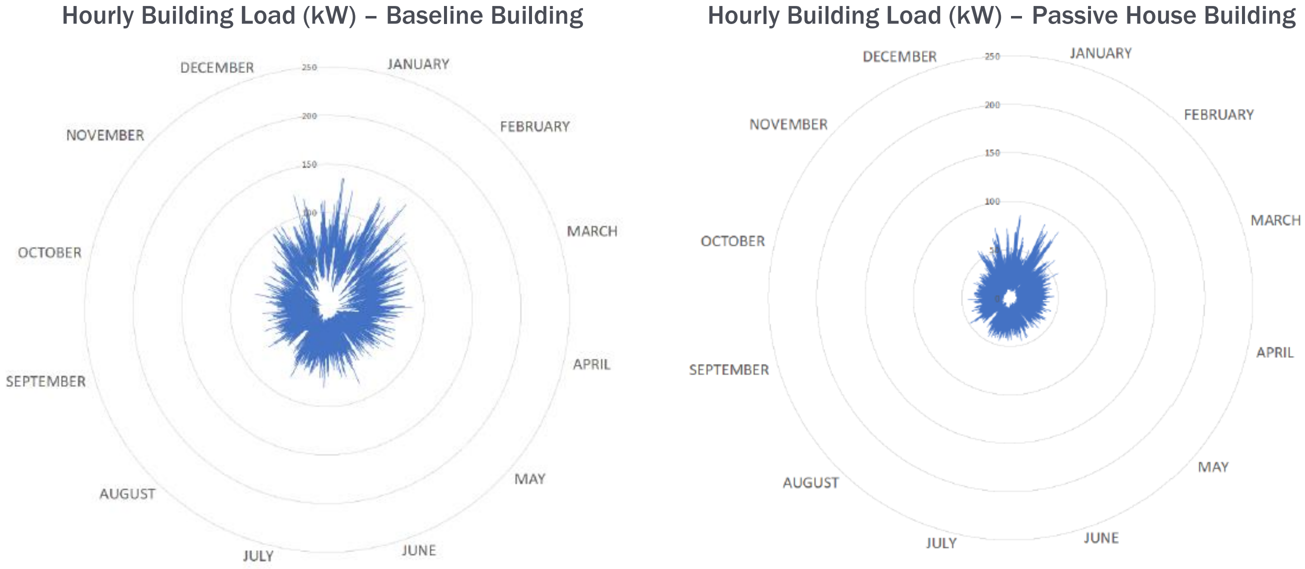
[44] Based on the code baseline Building America (BA) 2009 benchmark: https://www.nrel.gov/docs/fy10osti/47246.pdf

Figure 11. Passive House and Code-Compliant House Total Load Comparison



Hourly Building Load (kW) – Baseline Building

Hourly Building Load (kW) – Passive House Building

Source: White and Lindburg 2020

Another analysis (Gracik and Sanborn 2017) modeled both Passive Houses and otherwise identical code-compliant homes in three California climate zones (i.e., coastal, inland valley, and inland mountain). They found that the average Passive House used 10kWh/sq. ft of primary energy demand,[45] while the code-compliant home used about 15 kWh/sq. ft of primary energy, a savings of about 30%.

While Passive Houses have lower annual load than otherwise equivalent code-compliant homes, several of our interviewees mentioned that Passive House construction may result in overall increase in total electric load compared to conventional new construction due to electrification. We did not see this hypothesis borne out in the limited Passive House data we were able to examine, however. Furthermore, interviewees also mentioned the benefit of the Passive House design in light of increasing electrification trends as they relate to the winter load. As heat pump technologies gain momentum and beneficial electrification gains traction in California, winter demand for electricity is projected to increase.[46] With reduced solar production in the winter due to reduced hours of sunshine, meeting electric heating demand can become a challenge. The Passive House standard requires far less energy for heating, and, therefore, the increase in demand for electric heating load can be more easily met.

> “*Cause right now the big issue is like, well, how are we going to meet this heating load? If everyone switches to heat pumps, we're going to have to have all this new wintertime generation. If you actually designed it to the Passive House standard, you have almost no heating load, you've almost completely knocked out your heating load.*”

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[45] Primary energy demand is the amount of energy that must be generated at the source to meet the total energy demand of a building.

[46] California has some of the most comprehensive and ambitious clean energy policies in the world. Senate Bill 100 commits California to get 100 percent of its electricity from clean sources by 2045. California has made remarkable progress in growing clean energy's share of electricity generation, which exceeded the 2020 target of 33 percent coming from sources like wind and solar as set by the renewable portfolio standard and has set a goal of 100 percent carbon-free electricity by 2045. California has adopted aggressive greenhouse gas emission reduction targets, including returning to 40% below 1990 by 2030, and carbon neutrality by 2045.

Peak Load

In addition to reducing total annual load, our research shows that the Passive House standard can lead to significant reductions in peak load, thus reducing the stress on the grid in the times of peak demand. This observation was consistent in virtually every publication we reviewed, as well as across all interviews we conducted. Passive Houses have long "thermal time constants," which means they don't react to daily temperature swings. During winter, they can glide through cold nights without cooling down much, while in summer, they glide through hot days without warming up much. One case study we reviewed as part of our research showed 40% lower winter peak load for a Passive House building than for a baseline building defined as the Building America 2009 benchmark (White and Lindberg 2020).

> *So when you follow the Passive House standard, by default, you're getting a lower peak load across the board. You're reducing your heating peak load and your cooling peak load. And both of those things, have a tremendous benefit to the grid.*

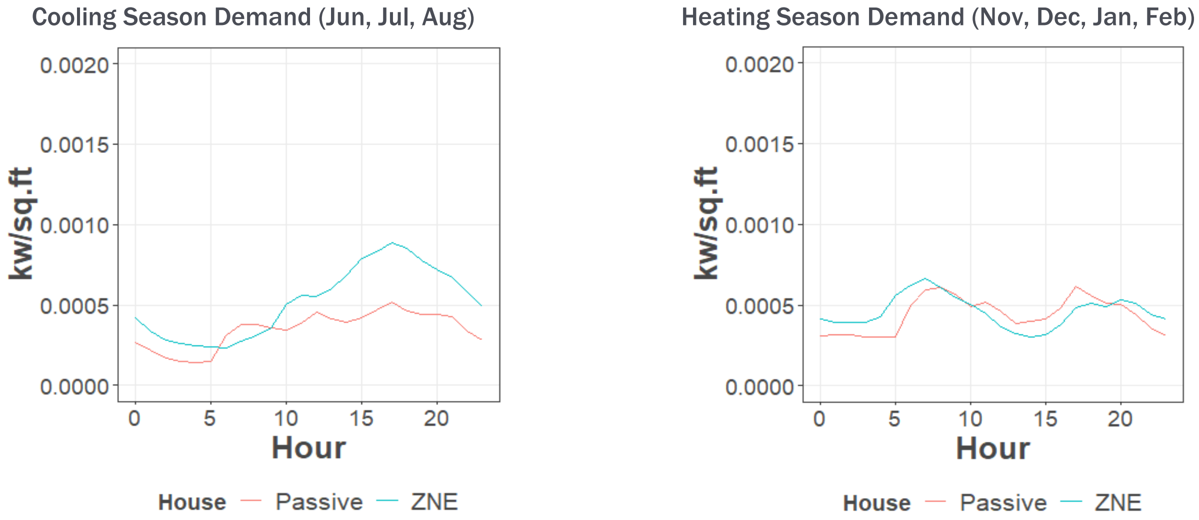
To further contextualize the impact of the Passive House design on peak load, we explored available consumption data for the two Passive Houses built in Sunnyvale and Alamo California (Barry 2021; The data in the figure represent average annual consumption across multiple years of data [07/01/2017–06/30/2019 for the Sunnyvale home and 07/01/2016–06/30/2019 for the Alamo home] across the two homes). We compared it to consumption data for similarly sized ZNE homes (Allen et al. 2020; The authors collected the circuit-level electricity consumption data for the six ZNE homes). While sample sizes are small and there is variation among homes' location, size, and year of construction, the comparisons offer insight into energy consumption patterns between the two sets of homes. Table 14 summarizes key details on the Passive and ZNE homes that were a part of our analysis.

Table 14. Passive Houses and ZNE Homes Detail

#	Home Type	Location	California Climate Zone	Square Footage	Number of Bedrooms	Solar Panel Size (KW)
1	ZNE	Clovis, CA	13	2,019	4	6.6
2	ZNE	Clovis, CA	13	2,019	4	6.6
3	ZNE	Clovis, CA	13	2,175	5	9.1
4	ZNE	Clovis, CA	13	2,019	4	6.6
5	ZNE	Clovis, CA	13	2,146	4	5.9
6	ZNE	Clovis, CA	13	2,544	5	6.6
7	Passive House	Sunnyvale, CA	4	1,540	3	7.7
8	Passive House	Alamo, CA	12	3,000	4	7.5

Our comparison of the Passive House consumption data to the consumption data obtained for a sample of six ZNE homes shows pronounced differences between the two home types during the peak hours of both the cooling and heating season. Passive House load is between 36% and 46% lower than the ZNE load between 4:00 p.m. and 9:00 p.m. in the summer and is 0% and 46% lower between 5:00 a.m. and 8:00 a.m. in the winter (Figure 12).

Figure 12. Passive House and ZNE Seasonal Load Comparisons



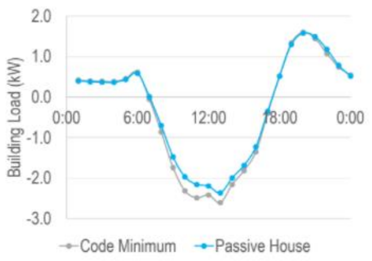
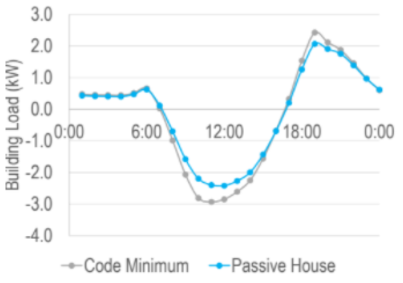
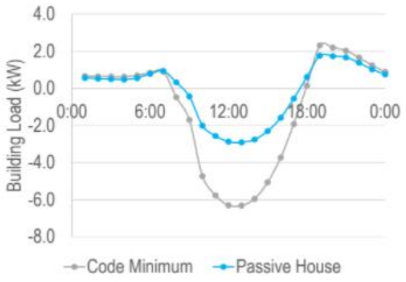
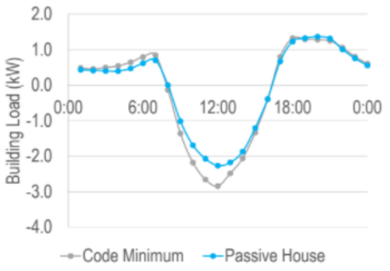
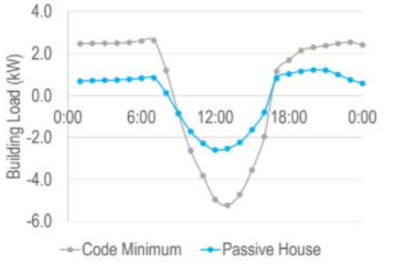
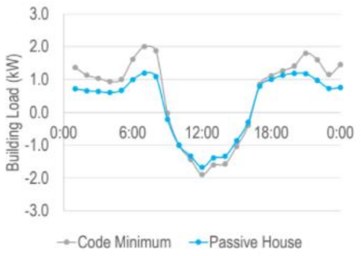
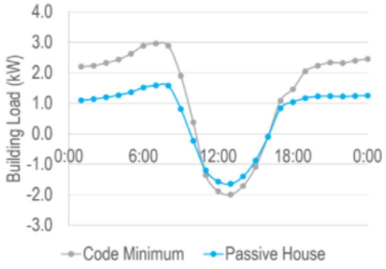
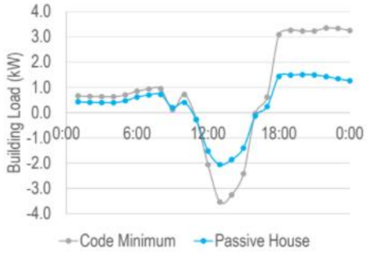
Interviewees also mentioned the seasonal impact of Passive House design on peak load. Several interviewees specifically noted that seasonal variation in solar output paired with electrification of space heating could eventually shift the peak load in California to winter. Interviewees mentioned that the Passive House standard is capable of delivering significant benefits in reducing peak winter load.

> *I think if let's say that we were talking about mostly Passive House buildings, as I just said earlier, Passive Houses have a very, very slow or low rate of change...If they're operated properly, they're going to stay at a much more modest temperature. Yes, of course, if you don't run the AC, while you're away at the office, the temperature may rise three degrees, but that's a far cry from 15 or 20 degrees. And so just talking about the ramp rate itself, you would significantly smooth or lower ramp rates, if we were talking about all Passive House buildings, because the amount of power they need at four or five o'clock in the afternoon peak consumption is going to be just much, much lower than most normal buildings, typical buildings.*

Load Shape

Existing literature suggests that Passive Houses have flatter load shapes than code-compliant homes, particularly during the evening ramp-up in usage. Engineering modeling simulations of typical California homes performed by Integral Group and presented at the 2017 North American Passive House Network annual conference show that Passive Houses have between 3% and 46% lower ramp rates than code-compliant homes depending on season and climate zone (Gracik and Sanborn 2017; Integral Group staff modeled 2019 CA Code Compliant prototypical homes and compared them to equivalent homes built to meet the Passive House standard). Modeled ramp rate reductions were lower for California coastal climate zones and higher for inland mountain climate zones. The ramp rate reduction was highest in winter (compared to other seasons) across all climate zones. Figure 13 reproduces the conference paper results. Interviews also confirmed that Passive House design reduces ramp rate compared to code-compliant construction.

Figure 13. Ramp Rate Comparisons Between Passive House and Built-to-Code Homes in California

Climate Zone	Coastal	Inland Valley	Inland Mountain
Summer Day			
Ramp Rate Reduction	7%	12%	46%
Peak - Valley Reduction	6%	16%	46%
Swing Season Day			
Ramp Rate Reduction	3%	12%	21%
Peak - Valley Reduction	4%	13%	35%
Winter Day			
Ramp Rate Reduction	12%	21%	46%
Peak - Valley Reduction	26%	35%	48%

Source: Gracik and Sanborn (2017)

In addition to alleviating the ramping of the grid, our research findings suggest that Passive House buildings having a less “peaky” load profile than code-build housing. Load “peakiness” is generally represented by the load factor. Load factor is defined as the ratio of the average load divided by the peak load in a given time period. As part of the same 2017 NAPHN conference presentation, Integral Group simulated electric demand at the neighborhood scale and compared system load factors across 100 code-compliant ZNE homes and 100 Passive Houses.[47] Table 15 shows the

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[47] The analysis also modelled 800 code-compliant existing homes. However, those results are not included here because existing homes do not have the same rate of PV penetration as ZNE and Passive Houses and are therefore not an analogous comparison.

results of the simulation efforts as presented in the conference proceedings. As can be seen in the table, the Passive House standard achieves higher load factors than code-compliant ZNE homes in nearly all scenarios.

Table 15. Load Factor Comparisons

Season	Climate	Code- Compliant ZNE Homes	Passive Houses
Summer system load factor	Coastal	14%	17%
	Inland valley	11%	14%
	Inland mountain	23%	27%
Swing season system load factor	Coastal	18%	21%
	Inland valley	21%	26%
	Inland mountain	11%	14%
Winter season system load factor	Coastal	16%	18%
	Inland valley	16%	18%
	Inland mountain	19%	19%

Source: Gracik and Sanborn (2017)

Load Predictability and Resiliency

Passive Houses have high thermal mass, which means they can store excess heating and cooling mass for extended period of times. This, in turn, creates a more predictable load than a typical home. Passive Houses ride through excess waves of cold and hot weather in a predictable fashion, causing less uncertainty in terms of the electric demand.

> “*Essentially, the Passive House is almost immune to a heat wave. It can ride days out before it acknowledges that there's a heat wave, and to be able to do that resilience piece plus load shifting. That's just a tremendous benefit.*”

A study by Rocky Mountain Institute found that in the event of a power outage due to a winter storm, homes with Passive House-standard building envelopes can maintain safe indoor temperatures for significantly longer than code-compliant new buildings, lasting over six days before indoor temperature falls below 40˚F (Ayyagari et al. 2020; This temperature represents a threshold for severe cold stress for healthy populations). While the study included simulations during a cold weather event, hours of safety are relevant for heat waves as well (Ayyagari et al. 2020). This benefit of the Passive House standard is particularly relevant for areas with extreme weather events.

Load Flexibility

In addition to flattening the overall load curve and reducing peaks, Passive House design can enable on-demand change in the load curve, thus delivering load shifting benefits. Our secondary research and interviews

suggest that Passive Houses can adjust space conditioning based on grid needs, floating through peak times with little to no impact on comfort.

One of the interviewees reported simulating the load shifting capabilities of the Passive House Buildings. Their analysis shows that by aligning HVAC modes to grid capacity, Passive House buildings are capable of delivering upwards of ten hours of load shift without impacting resident comfort. Furthermore, by deploying precooling or preheating strategies during the day, Passive Houses can leverage daytime solar generation and enable the building's thermal mass to maintain cooler or warmer temperatures respectively during evening hours and into the night without incurring any additional cooling or heating load.

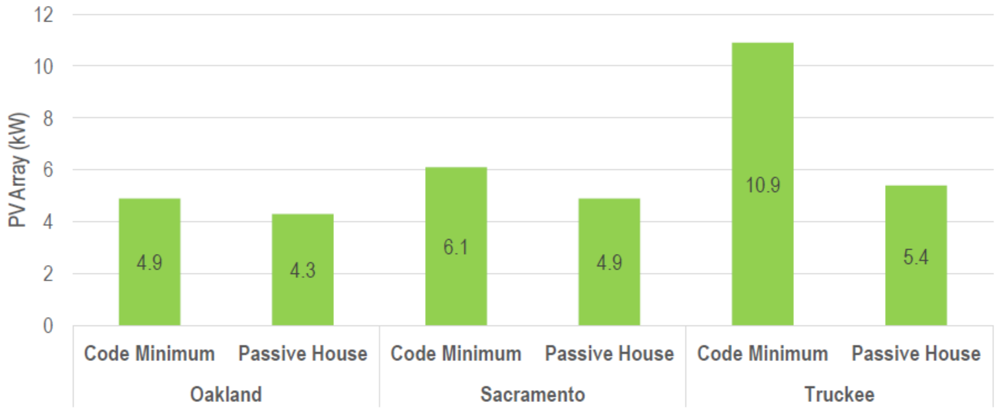
According to several interviewees, such interventions can be automated and, when applied at scale, can act as a reliable and dispatchable grid resource that reduces peak load by acting as energy storage for off-peak daytime solar generation.

> *And so one of the things the passive house allows you to do that the normal building standard does not…I can move when I use my energy…I can move it to the time that my PV panels, my own panels are producing power. So I can self-consume my own power and let the grid stay stable…A normal house to-code would not respond as well to that, because its temperature would be going all over the place, and its envelope, it is not very good. And so you don't get that, that shifting of load ability in a normal house, whereas in the Passive House you do, cause it's pretty much guaranteed performance.*

Reduced Rooftop PV Overgeneration

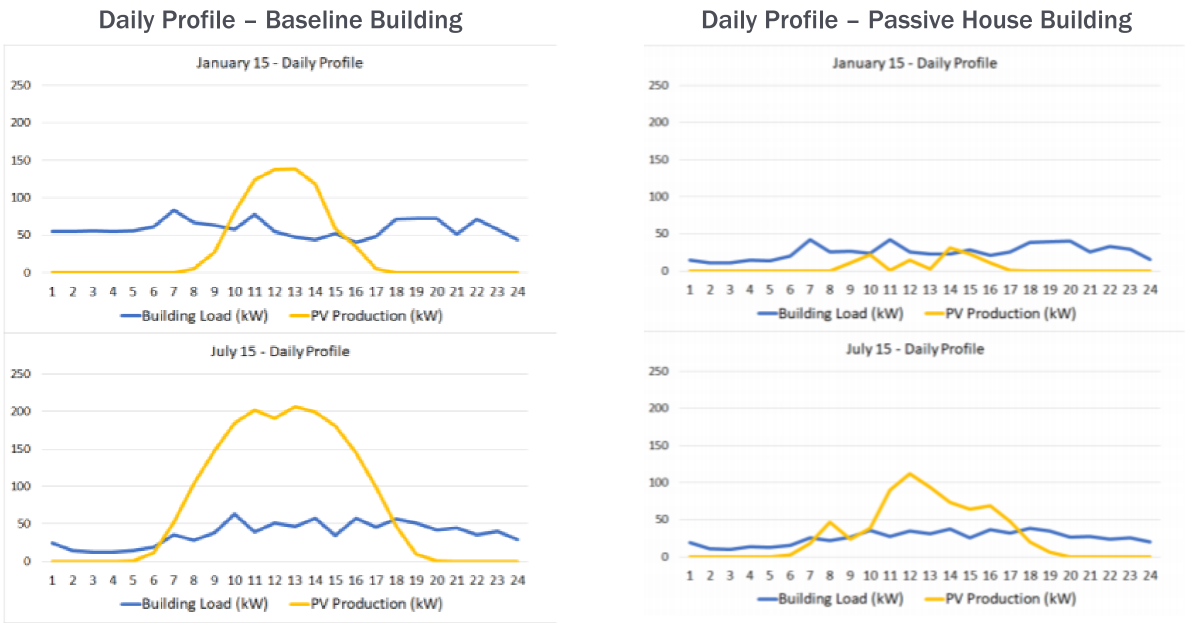
As mentioned above, neither Passive House standard has a requirement for solar PV, but both recognize and encourage integration of solar into Passive House design. Interviews confirmed that rooftop PV is almost always included in Passive House design in practice. Since rooftop PV is commonly integrated into Passive Houses, we explored whether solar sizing and production differ from non-Passive House residential new construction. Results of the literature review suggest that Passive Houses require fewer solar panels. Based on the engineering models of prototypical, residential new construction homes developed for three California geographies to reflect to-code and Passive House compliant building practices, Passive House construction requires up to 50% smaller PV arrays.

Figure 14. Solar PV Sizing of Passive House and Code-Compliant Homes



Building load and solar energy output simulations of a ZNE baseline home and a Passive House completed as part of another case study show that Passive House design, by reducing the annual and peak loads, can decrease the mismatch between the energy production and energy use, thus helping reduce solar overproduction (White, Lisa and Alison Lindburg 2020; Results are based on simulation of two building both designed to meet Net Zero standard, with one designed to meet a minimum code baseline Building America 2009 benchmark while the other met PHIUS+ 2015 performance targets). Figure 15 below (reproduced from the case study) demonstrates the benefit of the Passive House design in reducing solar overproduction.

Figure 15. Comparison of Building Load and Solar Production of ZNE Baseline and Passive House Construction



Daily Profile – Baseline Building

Daily Profile – Passive House Building

Figure reproduced from White and Lindburg (2020)

Interviews with experts, however, offered mixed feedback. Some interviewees agreed with the results from the literature review and stated that because the current building code in California requires calculations to determine solar specifications based on normative construction and assumptions around electrical use of the home, an all-electric Passive House is going to use less energy than an all-electric to-code house, thus requiring less solar generation. As such, the Passive House standard can help alleviate solar overproduction during the day. Others noted that the California code requirement for solar integration calls for much smaller solar PV systems than what is being installed on either ZNE homes or Passive Houses in practice and, thus, may not impact sizing. One interviewee stated that there is no good methodology for determining the size of the solar PV system on new construction, regardless of whether it is Passive House or code-compliant construction.

> “*The problem is that solar PV, the use of solar and the use of renewable energy, is totally dependent on the behavior of the occupants in the building, and their appliances too. But you don't know, you have no idea generally how many people are going to be living there, how long they're going to be living there, how often they're going to be doing laundry with their condensing dryers, how often they cook versus do takeout, and COVID and non-COVID certainly have an impact on that kind of thing… I used to do a lot of solar PV inspections as a HERs Rater on all kinds of buildings, and I never saw a solar projection that I felt was accurate. Now, maybe there are some solar installers and consultants out there that are very accurate, but I am not convinced that that's the case.*”

Impacts to the Electric Grid

The 2019 California Energy Code requires all newly constructed low-rise residential buildings to have a solar photovoltaic (PV) system starting in 2020 (CEC 2020).[48] This requirement is likely to substantially increase the amount of rooftop PV adoption in California, on top of almost 1.3 million completed installations (SEIA n.d.). Electric Vehicle (EV)

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[48] As defined in the California Energy Commission’s fact sheet about solar photovoltaic systems, a low-rise residential building is “A building, other than a hotel/motel, that is occupancy group: R-2, multifamily, with three habitable stories or less; or R-3, single family; or U-building, located on a residential site.”

adoption is also rising in California. According to the California Energy Commission, the number of EVs in California has increased about 28% from 2017 to 2020 (CEC 2021). This increasing penetration of renewables and EVs in California is contributing to a phenomenon known as the “duck curve,” wherein mid-day PV generation (which tails off during the afternoon) combined with the increase in load in the afternoon as people come home from work has caused a steep afternoon ramp in net electricity demand. The afternoon ramp is exacerbated by EVs, which are frequently plugged in when people come home from work.

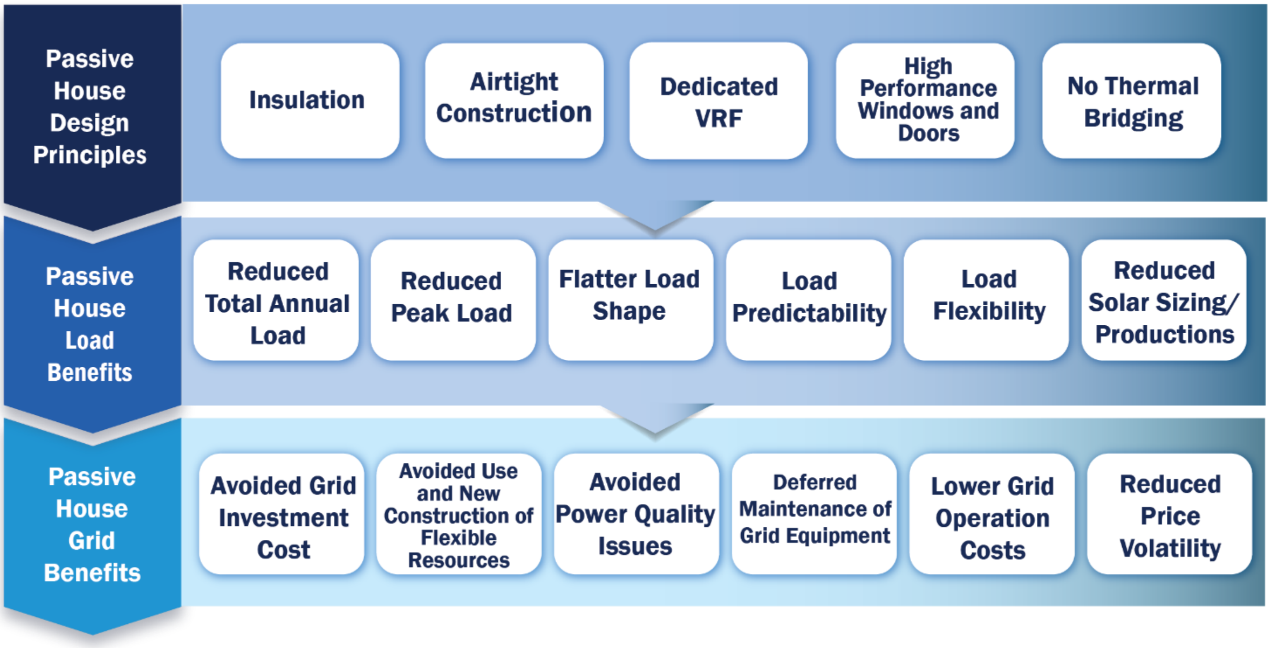
Operating a reliable electric grid requires balancing electric supply and demand almost instantaneously. Balancing supply and demand requires designing a grid that can serve the peak load demand, regardless of how often that peak occurs. The higher the peak load is relative to the average load, the less efficient the grid is on a per-kWh basis. Furthermore, the grid has to be able to respond immediately to changes in load, which requires a sufficient number of flexible generation resources that can quickly increase and decrease production as load changes. Generally speaking, maximizing the efficiency of the electric grid (and hence minimizing the cost to operate) requires flat, reliable load that is easy for the grid operator to balance.

The steepening ramp associated with the duck curve is exacerbating the challenge of managing supply and demand on the California grid by increasing the need for additional flexible generation in order to maintain reliability. In response, California is pursuing multiple avenues for “flattening” the duck curve such as increasing demand response program participation and introducing time-of-use rates for load shifting. As described above, our research identified multiple benefits of the Passive House standard on the building demand for energy:

- Reduced annual load
- Reduced peak load
- Flatter load shape
- More predictable load
- Increased load flexibility
- Reduced solar overgeneration

Each of those benefits has the ability to impact the electric grid operation at the system level when deployed more broadly, thus resulting in tangible grid-level benefits. This is particularly true for new developments of Passive House communities. Figure 16 below shows some of the potential grid benefits that our literature review identified as resulting from widespread deployment of Passive Houses:

Figure 16. Passive House Grid Benefits



Avoided Grid Investment Costs for New Developments. Because Passive Houses have lower total electric consumption, lower peak load, and less PV overgeneration than code-built homes, they put less demand on the distribution system. As a result, a substation and feeder serving a Passive House community can serve more homes than the same substation and feeder could serve if the community was built to-code. Furthermore, Passive Houses have less uncertainty in their load shapes than to-code homes. Because distribution circuits are designed to serve a 1-in-10 scenario for the highest expected load, having lower uncertainty bands around the load forecast for a community reduces the size of distribution infrastructure required. Together, the reduced demand and lower uncertainty associated with new Passive House communities lowers the costs associated with building the required electric infrastructure.

- **Deferred Maintenance on Existing Circuits.** In addition to reducing investment costs for new developments, the flatter and more consistent load shapes of Passive Houses can lead to avoided capacity upgrades on existing circuits, since infrastructure can serve more homes with the existing capacity before having to upgrade. For example, an Electric Power Research Institute (EPRI) study in 2017 found that ZNE homes, which have high levels of rooftop PV, are expected to overload laterals by about 16% (EPRI 2017). Mitigating that overload would require upgrades to the circuits. Because Passive Houses would slow the speed at which laterals are overloaded, the construction of Passive Houses rather than ZNE homes can defer those upgrades. Additionally, lower loads, peak loads, and backflow from PV overgeneration reduces wear-and-tear on grid equipment such as transformers, extending their lifetimes and deferring maintenance costs.
- **Avoided Use and New Construction of Flexible Resources.** Passive Houses, by virtue of their flatter load shape, reduced peak demand, reduced PV overgeneration, and demand response potential compared to code-built houses, reduce the need for the flexible generation resources required to balance supply and demand and maintain power quality. In the near term, widespread construction of Passive Houses would reduce the need for flexible generation resources. In the long term, widespread construction of Passive Houses would reduce the need to build new flexible resources, such as expensive peaker plants, by slowing the rate of growth of peak demand and the steepening of the evening ramp.

> *All of our demand side issues on the grid are based on these peak loads, hot summer day, right? The grid has a certain capacity, we're adding new construction, and if all your new construction has a much educed peak load, say half or, even better, then you don't have to build as much new capacity into the grid. So there's a new generation that you don't have to build, because you're going to a higher efficiency standard.*

- **Avoided Power Quality Issues on Distribution Lines.** High levels of PV overgeneration on an electric circuit can cause challenges with voltage control and harmonics from transients in the PV generation. Mitigating these power quality issues can require equipment upgrades. Because Passive Houses have lower electric load and hence lower PV overgeneration, they contribute less to the power quality concerns associated with PV.

- **Lower Costs to Operate the Grid.** Together, the benefits of widespread Passive House deployment described above could theoretically lead to substantially lower operating costs for the grid. While the amount of these cost savings for Passive Houses specifically has not been quantified in the literature, a whitepaper from the Sacramento Municipal Utility District examined the impact of halving air conditioning load during peak periods and found that the capacity value alone was estimated to be several thousand dollars per home (Ceniceros and Vincent 2006).

While the grid benefits from widespread deployment of Passive Houses described above have been widely hypothesized in the Passive Houses community, there is limited quantitative research confirming the impacts of Passive Houses on the grid. This is unsurprising given the lack of Passive House construction to date. However, there are a few studies that have investigated this question for ZNE homes and found that high levels of rooftop PV can indeed exacerbate the duck curve, cause voltage control issues, reduce grid asset utilization, and increase line losses. An EPRI study from 2017 found that adding deep levels of energy efficiency (which is achieved by Passive Houses) and minimizing the required residential PV can mitigate some of these negative effects. Further research is needed, however, in order to more precisely quantify the impacts of Passive Houses on grid operations and maintenance.

5. BEM Load Shape Analysis

In this section, we focus on the results of a single house type and location, SF-2 in CZ14, as a case study, particularly since our BEM analysis resulted in 1,549 load shapes for the scenarios presented in Section 3.2.1. When useful, we make comparisons to other house types and locations. This section describes the annual savings impacts on summer and winter daily demand profiles and explores interactions with solar and precooling scenarios.

5.1 Load Shape Analysis Key Findings

We summarize our key findings here and describe them in the subsections below in more detail.

- Annual energy (kWh) savings impacts
    - PH design's ability to alter the impact on the grid is primarily a result of how it affects household electricity used for comfort: heating, ventilation/fans, and air conditioning/cooling (HVAC) loads.
    - PH performance over T24 increase as HVAC percentage of household usage increases, saving up to 30% of HVAC annual kWh in more severe CZs.
    - PH designs reduce heating and cooling loads but increase fan loads, which can dampen savings heating and cooling savings when low annual conditioning requirements exist (e,g,, CZ07).
    - PH underperforms T24 in annual kWh in MFLR buildings in mild climates (CZ07).
    - In CZs where PH underperforms T24 in terms of kWh, the losses are typically off-peak, but in these scenarios, PH designs still outperform T24 during peak heating and cooling load (kW) periods.
    - The reported annual savings of these PH principles are likely conservative. For performance parameters, like window glazing and SHGC, PHI does not explicitly prescribe values, so we assumed the T24 values. This may not be as aggressive as expected in practice for PH construction. PH prescription for the same parameters has values lower than T24, so we assigned the T24 values.
- Daily load (kW) impacts
    - The PH house produces an hourly summer HVAC peak more than 30% lower than a T24 equivalent home.
    - The PH design may shift the peak by an hour, but the primary impact is the overall peak reduction.
    - PH design can save much more during winter nighttime peaks than during summer, saving more than 50% of HVAC peak load.
- Solar impact
    - PV generation provides some load shedding early in the peak window but is not always sufficient to further reduce the peak.
- Precooling impacts
    - Precooling can delay the need for active cooling by as much as an hour.
- Managed portfolio as a grid asset
    - A portfolio of precooled PH homes engaged in utility smart thermostat programs has the potential to flatten the load of the population-wide aggregate portfolio and will make better use of on-site midday solar generation.

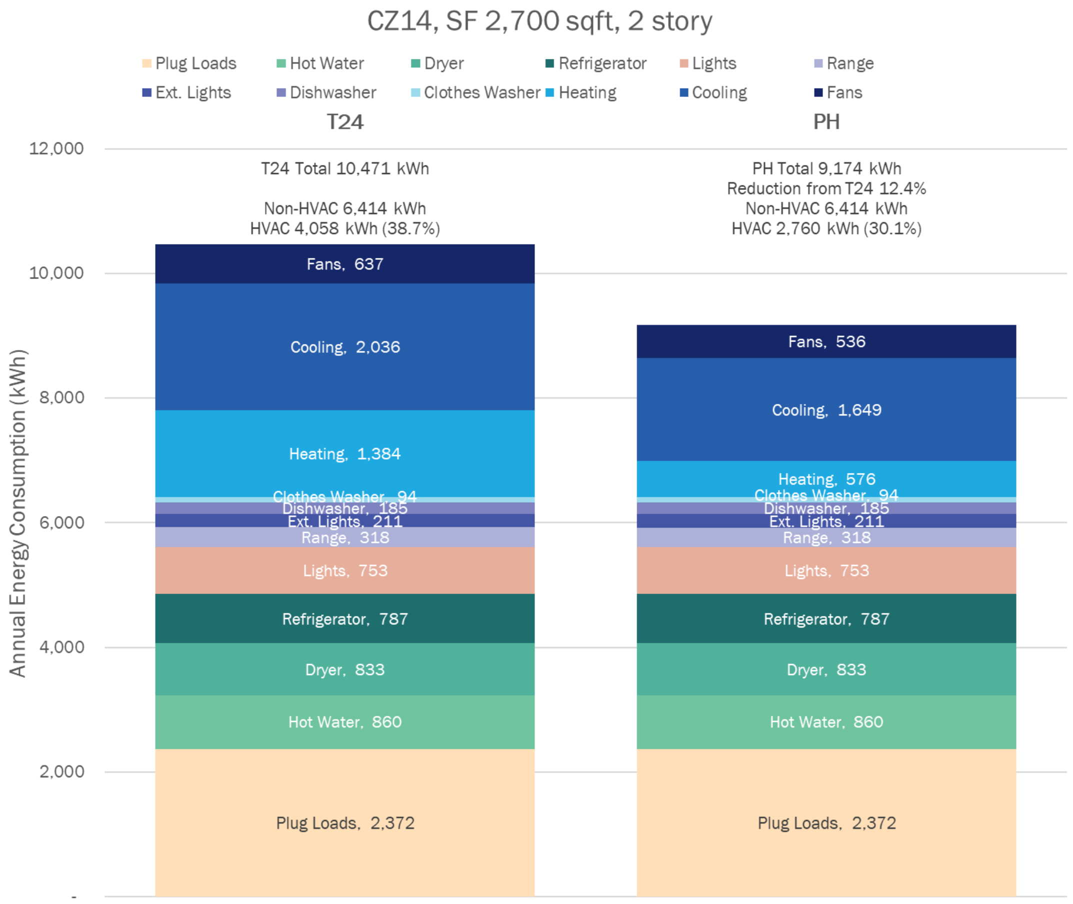
5.2 Energy (kWh) Savings Impacts

5.2.1 Total Annual Energy (kWh) Impacts

For our example case, SF-2 located in CZ14, Figure 17 presents the annual energy usage of homes built to meet PH and T24 prescriptions. As a matter of design, the non-HVAC end-uses consume the same amount of energy every hour in both homes and represent the energy end-use service demand as if the same occupants lived in both homes and behaved identically in each. These include hot water, lights, dishwasher, refrigerator, clothes washer, dryer, range, plug loads, and exterior lights.

The T24 annual household energy consumption is 10,471 kWh. The non-HVAC portion is 6,414 kWh annually, leaving 39% for HVAC.[49] This HVAC portion represents the only part of the household's energy that PH design could affect.

Figure 17. Annual Energy Consumption by End Use



For SF-2 in CZ14, the T24 house uses 10,471 kWh per year, and the PH house reduces this total by more than 12%. Table 16 compares the energy savings per unit for all nine scenarios,[50] which shows SF-2 consistently saves more over T24 than SF-1 and MFLR. This does not yet take into account any solar impacts as PV is not yet a requirement for T24. We will consider the impact of solar later.

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[49] This HVAC portion of energy use is comparable to CBECC T24 baseline scenarios evaluated under the CASE Study.

[50] Recall that the MF residential building is an eight-unit structure.

We observed a few important trends in annual energy usage. For each house type, the total annual energy use increases as the CZ becomes more extreme. This increase is strictly due to the additional HVAC load required to meet the more extreme heating and cooling loads. For example, for the SF-1 model, the percentage of T24 household energy for HVAC ranges from around 11% in CZ07 to 31% in CZ14. This is consistent with the 2019 RASS, which shows that the average statewide HVAC usage is 18%.[51] As the HVAC percentage of household usage increases, there is more opportunity for savings from a PH home. For CZ14, where the savings are significant, PH reduced heating, cooling, and fan loads. In moderate CZs, PH reduced heating and cooling loads but increased ventilation loads. Better insulation and thermal mass of PH require less cooling and heating, however, tighter houses require more ventilation (fans). In milder CZs, e.g. CZ07, with low heating and cooling loads, increased ventilation loads outweigh the reduced heating and cooling needs, leading to the increased energy use seen in Table 16 below.

Table 16. Annual Whole-House Savings Comparison by House Type

Home Type	CZ (Conditioning Level)	Energy Use per unit (kWh)		% Reduction	HVAC Energy Use (kWh and % of Total)				% Reduction
		T24	PH	PH	T24		PH		PH
SF-1	CZ07 (Low)	5,774	5,692	1.4%	608	11%	525	9%	13.6%
SF-2		7,608	7,389	2.9%	1,164	15%	945	13%	18.8%
MFLR		4,726	4,800	-1.6%	320	7%	394	8%	-23.2%
SF-1	CZ04 (Moderate)	6,067	5,875	3.2%	899	15%	706	12%	21.4%
SF-2		7,925	7,645	3.5%	1,478	19%	1,198	16%	18.9%
MFLR		4,812	4,804	0.2%	401	8%	394	8%	1.8%
SF-1	CZ14 (Extreme)	7,401	6,802	8.1%	2,265	31%	1,666	24%	26.4%
SF-2		10,471	9,174	12.4%	4,058	39%	2,760	30%	32.0%
MFLR		5,546	5,201	6.2%	1,174	21%	6,631	16%	29.4%

In practice, a PHI- or Phius-certified home will likely save more than is demonstrated in this study. Aiming for PH Certification is an exercise in maximizing the performance of a specific building in a specific location and orientation and may lead architects and designers to define significantly better performance parameters (e.g., SHGC, slab insulation, eaves, orientation), which are choices, not requirements. Recall the performance parameter definitions and descriptions in Section 3.3: if a parameter was not explicitly prescribed to meet the code, we applied the T24 value. This important assumption leads us to a conservative estimate of how PHI and Phius can perform relative to T24.

Table 16 also shows there are smaller savings in very mild climates (e.g., CZ07) with low HVAC needs. For the MFLR scenarios, PH principles only begin to improve results over T24 when there is a moderate conditioning load (e.g., CZ04). We examine the drivers of this in the following discussion on HVAC-only load.

5.2.2 Annual HVAC Energy (kWh) Impacts

Energy savings are only achieved by affecting the HVAC load, and Table 16 shows what fraction of this load can be reduced with PH principles. The PH house reduces the HVAC energy use for the SF-2 house in CZ14 from 4,058 kWh to 2,760 kWh for 32% savings. Figure 18 isolates the HVAC portions for CZ14 SF-2 (our case study house) and CZ04 SF-1 for comparison. For CZ14, where the PH savings are significant, PH reduced heating, cooling, and fan loads. In moderate CZs like CZ04, however, PH principles reduced heating and cooling loads but increased ventilation/fan loads compared to T24. In these cases, better insulation and thermal mass of PH require less cooling and heating, leading to

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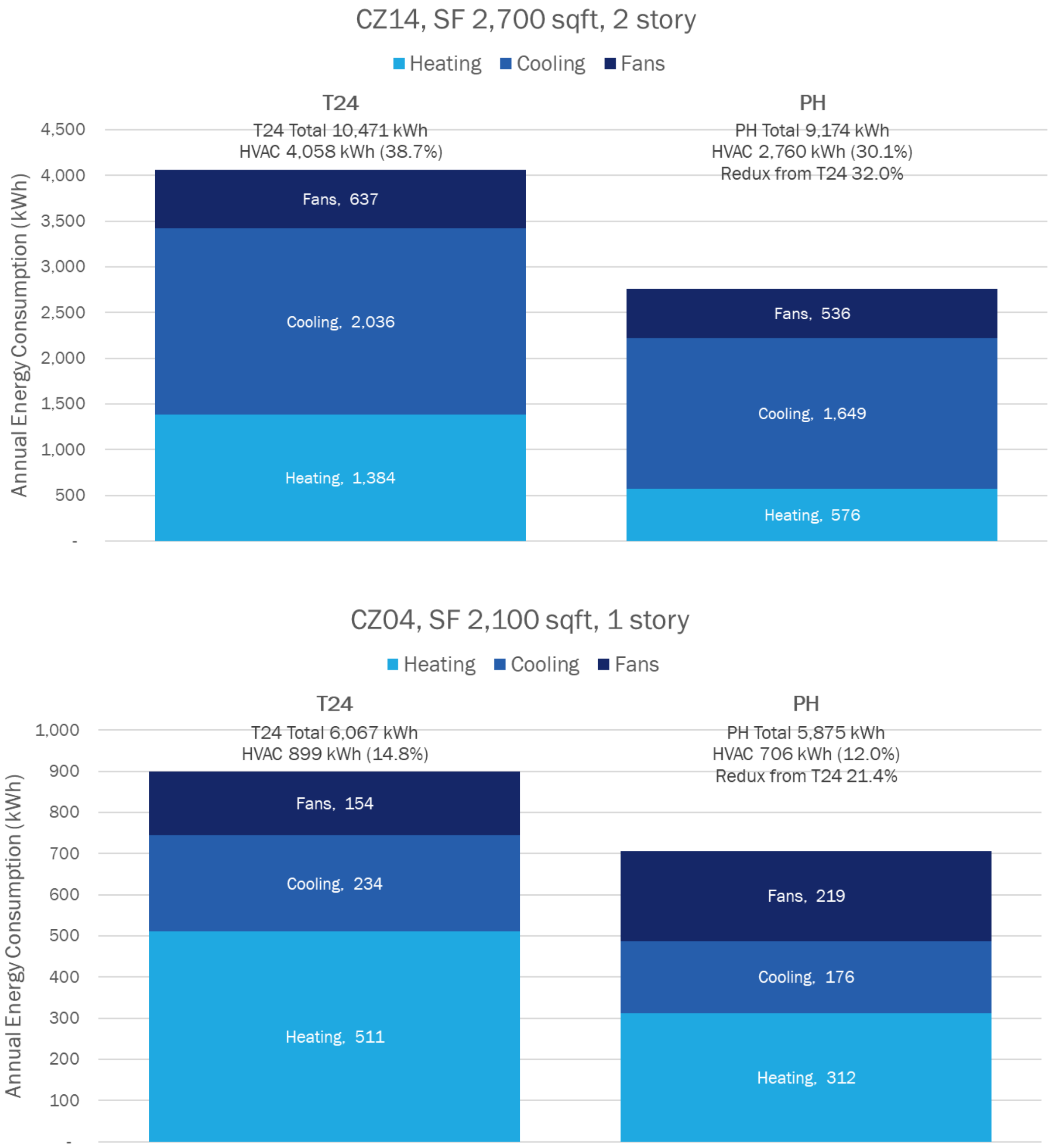
[51] California Energy Commission. "Executive Summary volume, Figure 1-1." 2019 California Residential Appliance Saturation Study Publication Number: CEC-200-2021-005-ES.

less energy use overall. However, tighter houses require more ventilation (fans) to keep the air moving and clean. In even milder climates like CZ07, these higher fan loads outweigh the benefits of lower heating and cooling needs leading to the underperformance highlighted in Table 16.

Figure 18. Annual HVAC Consumption. Top CZ14 SF-2, Bottom CZ04 SF-1



5.3 Heatmaps of 8760 Hourly Load

The SF-2 in CZ14 heatmaps[52] in Figure 19 illustrate the entire year of hourly load data with T24 on the left and PH on the right. Each heatmap represents the total household load (kW) for all 8760 hours of the year starting on January 1, hour 1, in the top left corner. Every row represents a single day from hour 1 to 24 from left to right. Each day is stacked from January 1 on the top to December 31 at the bottom. Hotter colors (e.g., red) represent higher loads, while colder colors (e.g., green) represent lower loads.

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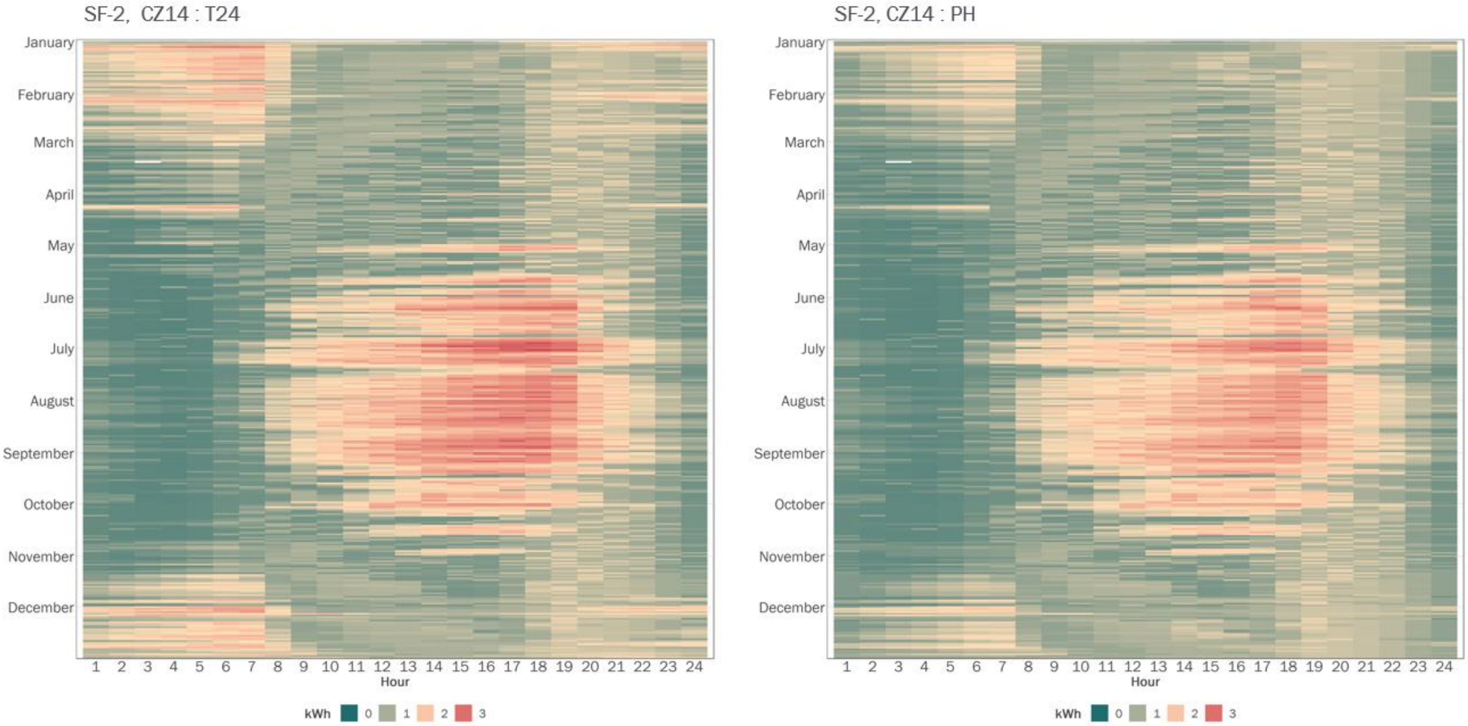
[52] The heatmaps illustrate the kW load for each of the 8760 hours in the year. If one were to sum the load over the entire year, they would arrive at the total annual usage for that house listed in Table 16.

We observe similar patterns between the two heatmaps. The band of high afternoon usage (hours 14–20) occurs throughout the year but peaks from June to October due to increased cooling needs. Winter nighttime loads are low most of the year, but elevated beginning in the evening (hours 20–24) and peaking in the early morning (hours 1–8) in January, February, and December, driven by heating needs.

Figure 19. Household Load (kW) Heatmap of T24 (left) and PH (right) for SF-2 in CZ14

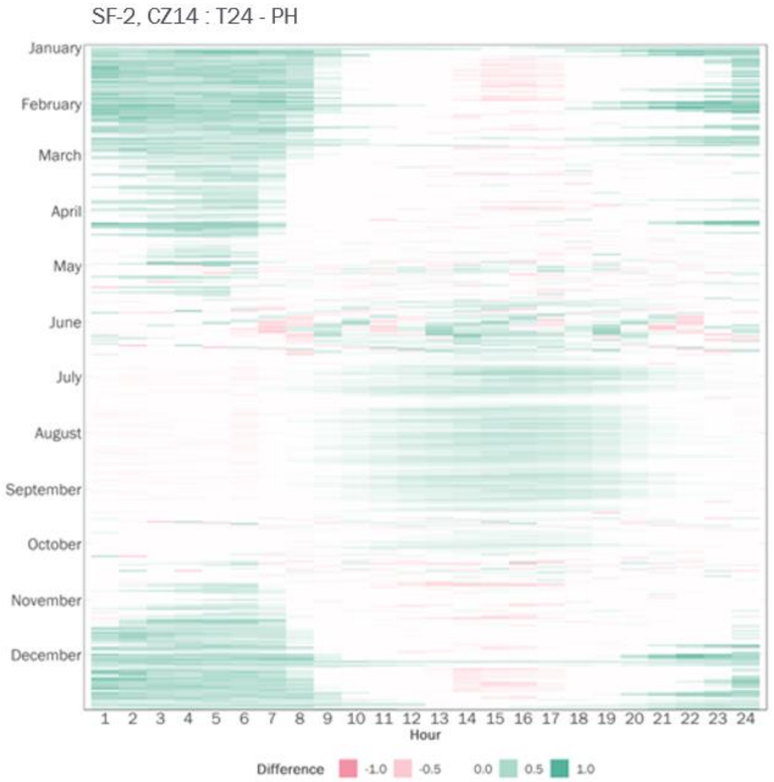


With an initial inspection, these two plots look almost identical with all the same patterns; however, the differences are evident visually by the slightly smaller red regions (less peaky-ness) in the PH heatmap than in the T24 heatmap. For example, both have a cooling peak in the summer driven by the hot Palmdale summer, but the PH peaks have an overall lower load (less red). Similarly, the cold spell in January and February required less heating (less red) in the early hours in the PH home compared to the modeled T24 home.

Taking the numerical difference (T24 minus PH kW) between these two heatmaps illustrates where the variations between the houses exist, as shown in Figure 20. In this plot, green represents where the PH hourly load is lower than T24 (hourly load savings), red represents where PH has a higher load than T24, and white represents where the loads are the same. The overwhelmingly green color of the plot demonstrates that the PH house saves energy over the entire year. The obvious pattern in this difference heatmap is the five sections of green at all four corners and the center, which are the same seasonal regions identified in Figure 19 where heating or cooling loads are greatest.

Recall that PH principles can lower heating and cooling loads, which are seasonal, but may increase the annual ventilation load, which operates all year. The increase in ventilation loads is evident in Figure 20 as the smaller red regions and ridges between the green regions. For example, there is a ridge of red or green all year in the afternoon from hours 14 to 17. During the summer peak, the green region indicates the HVAC savings dominate the plot. However, minimal heating or cooling load is required from January to April and October to December, and the increased PH fan loads are evident in red.

Figure 20. Household Load (kW) Heatmap of the Difference between T24 and PH SF-2 in CZ14



In the CZ14 scenario, the increased fan loads occur off-peak throughout the year, but the savings from the heating and cooling outweigh this small ventilation load increase for a 32% annual energy savings for the year. However, in milder climates where heating and cooling are almost non-existent throughout the year (e.g., CZ07), increased ventilation can reduce or negate the heating and cooling savings entirely.

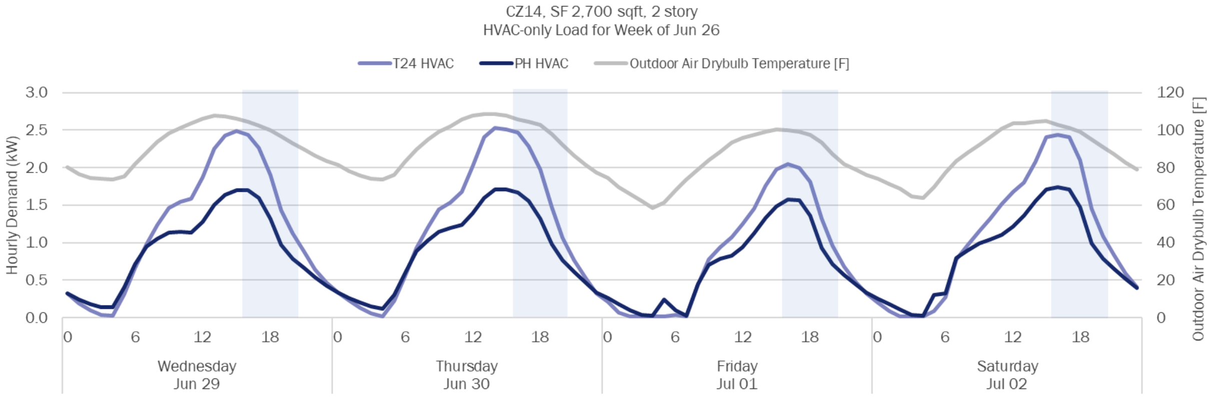
In practice, a PHI- or Phius-certified construction would likely save more HVAC energy since the occupant is likely to open a window for ventilation during pleasant weather rather than keep the house sealed and run ventilation fans.

5.4 Daily Load (kW) Impacts

In this section, we examine electric load on two specific weeks to illustrate how PH principles impact specific peak summer and winter loads. The standard TMY3 weather input data for the BEM modeling have typical average hourly weather, not extreme events. We can, however, focus on the hottest and coolest days of the year to understand how the houses perform under these conditions.

As discussed in Section 5.3, the reduction in HVAC loads occur during peak heating and cooling times of the day and year. Figure 21 illustrates HVAC-only load use during a representative hot week at the end of June, with Thursday exceeding 108°F. The PH house peaks are lower than the T24 peak, reducing them by over 30%. For reference, the figure also includes shaded regions representing typical summer peak windows from 4:00 p.m.–9:00 p.m.

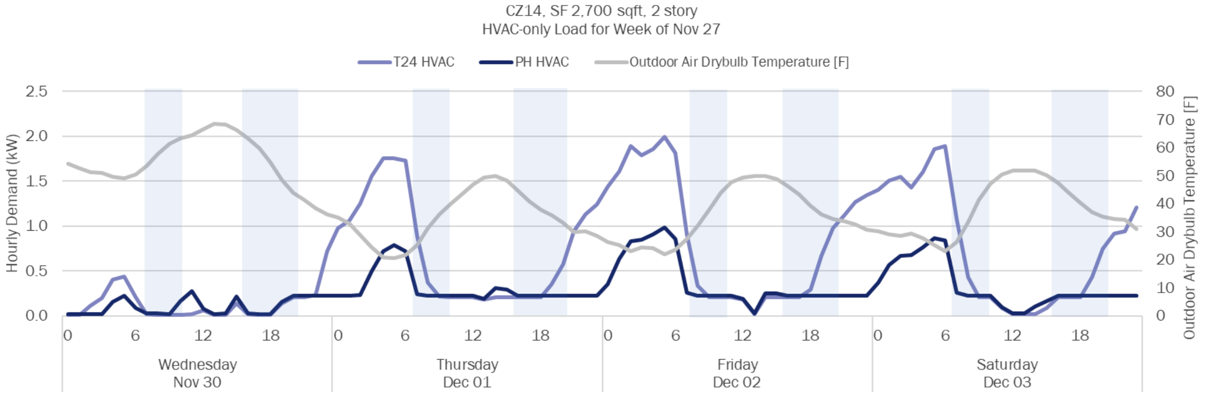
Figure 21. Summer Peak Reduction From HVAC



Also notable in Figure 21 is the slower ramp rate and slightly more pronounced skew in the PH peak curve, making it appear to lean more to the right than the T24 curve. This indicates a slower rise in indoor temperature from better insulation and other performance characteristics. This lower ramp rate may help the PH design to shift the peak by an hour, but the primary impact is the overall reduction in load.

Summer HVAC savings should help reduce stress on the electric grid as the typical afternoon system peak ramps up. However, the PH concept is most beneficial to winter savings. Figure 22 illustrates a cold week at the end of November where the nighttime temperature drops to 20°F. The HVAC use in the PH home on that Thursday morning reduced the afternoon peak heating load by over 50%. It also delayed when the heating load began, shifting all-electric HP heater loads entirely out of the evening peak window. This Winter figure also includes a shaded typical morning peak window from 7 a.m. to 10 a.m. for reference. This perspective is increasingly important as portions of the grid shift to winter peaking rather than summer peaking. While this house model is not Winter peaking, the higher levels of insulation shifted most of the heating load out of this sample morning peak window.

Figure 22. Winter Peak Reduction From HVAC

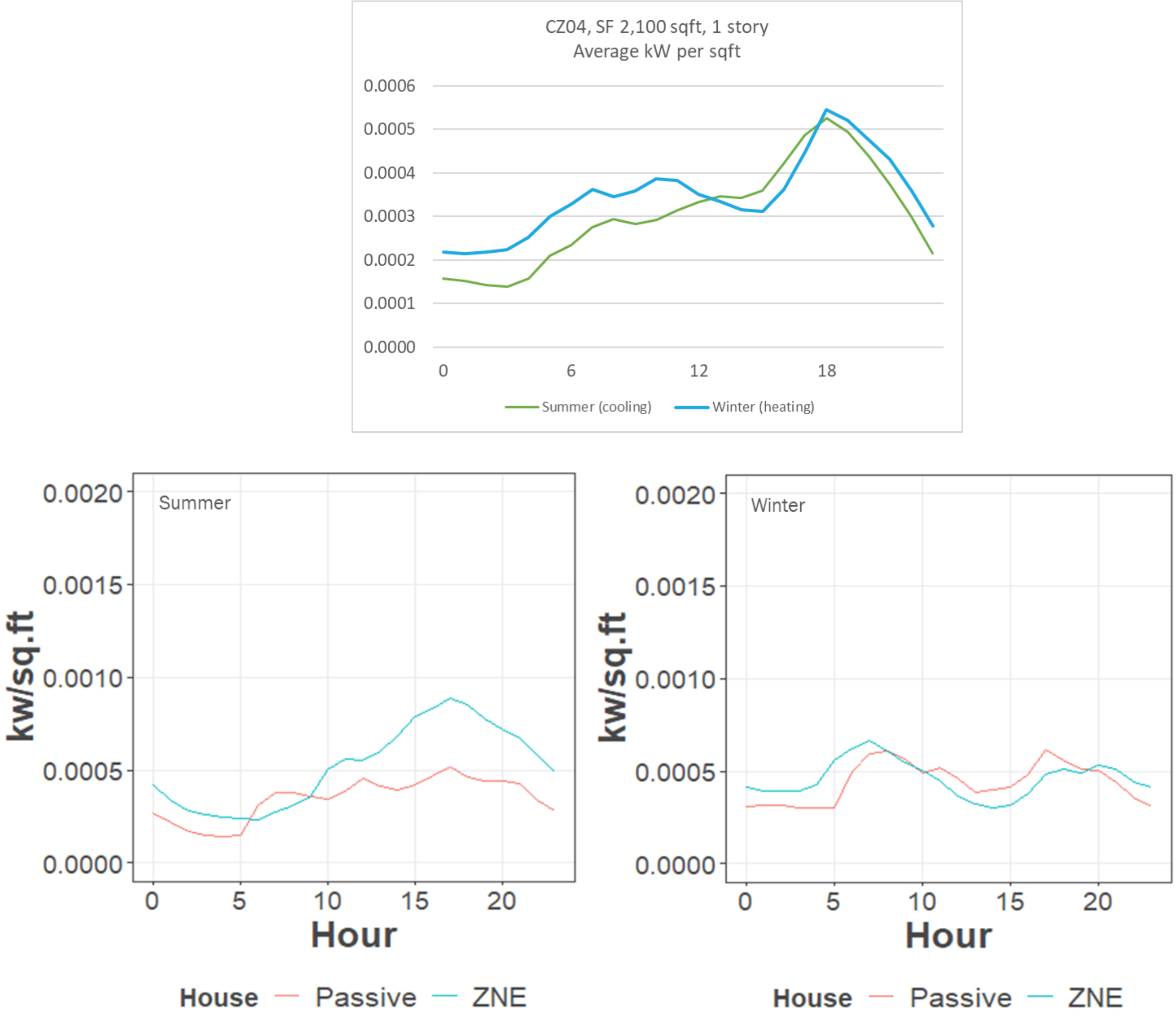


The load figures above are the results of numerical models based on expected energy use in a typical California home. While there are other modeling platforms, PH-specific and otherwise, which may produce similar or different results, we can compare the results in the table to a measured actual PH household. Our Phase I research, summarized in Section 4, reviewed the measured energy use of several certified PH residential buildings. These homes are all in CZ04 a similar CZ convenient for comparison to our San Jose CZ04 houses. The constructed homes are of various sizes, so we normalize the load per sq. ft. for comparison.

When normalized, our modeled average load peaks around 0.0005 kW/sq. ft. in Summer and Winter, as shown on the top of Again, note that our modeled houses are not replicas of the measured households.

Figure 23. This is on par with the measured Sunnyvale household. In the figure, the top chart is from the current study showing the normalized average daily load in the Summer (June – August) and Winter (November – February). The bottom charts are snapshots (also shown above in Figure 12) from the Phase I study for Summer (left) and Winter (right). The values between this study and the Phase I results are similar, which indicates our modeling appropriately represents PH construction. The shapes of the curves are a little different due to cascading impacts from underlying assumptions about hourly household energy usage (e.g., cooking, water heating, laundry, plug loads, etc.). Again, note that our modeled houses are not replicas of the measured households.

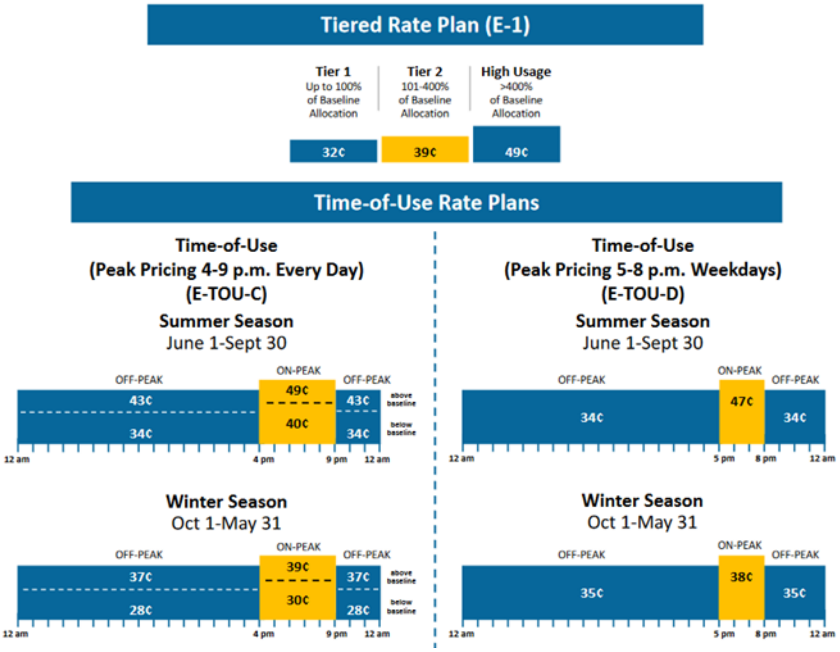
Figure 23. Comparison of modeled to actual PH homes.
Top: Modeled CZ04 home from this study. bottom: Phase I analysis comparing seasonal PH to ZNE construction.



5.5 Residential Energy Cost

Table 16 highlighted that PH barely outperforms T24 in mild CZs (e.g., CZ07), but in Section 5.4 we showed that that some of the heating and cooling savings occur during peak demand hours. Effective December 1, 2022, the California IOUs adopted time of use (TOU), or resource adequacy, rates to provide residential consumers a higher price signal during the early evening when the grid may experience potential resource adequacy limitations. In PG&E territory, for example, the E-TOU-C rate occurs during the five-hour window from 4:00 p.m. to 9:00 p.m. with seasonal and tiered variations. This seasonality and tiered rate structure is illustrated in Figure 24. As consumers use energy in a billing cycle, they pay the 'below baseline' or Tier 1 rate until they reach their baseline when they begin to pay at the 'above baseline' or Tier 2 rate.

Figure 24. PG&E Residential Time of Use (or Resource Adequacy) Windows[53]



Note: PG&E. "Residential Rate Plan Pricing." Accessed Dec. 1, 2022, https://www.pge.com/pge_global/common/pdfs/rate-plans/how-rates-work/Residential-Rates-Plan-Pricing.pdf

The baseline referred to in the PG&E rate example is specific to each household, location, and other factors. For simplicity, we apply 'below baseline' E-TOU-C rates to all households in this study. Table 17 lists the annual energy costs for each house type and location. The percent dollar savings track is almost identical to the percent household energy savings shown in Table 16. Since most of the winter and summer peak loads shown in Figure 21 and Figure 22 occur outside of the 4:00 p.m.–9:00 p.m. TOU window, no significant improvement in the percentage for bill savings emerges. Precooling (discussed in Section 5.7) and other additional controls will likely improve this in practice. Amongst Multi-Family Low-Rise buildings in milder CZs, e.g. CZ07, increased ventilation loads outweigh the reduced heating and cooling needs, leading to increased energy costs as shown in the table below.

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[53] PG&E "Residential Rate Plan Pricing" guide, last accessed Dec. 1, 2022, https://www.pge.com/pge_global/common/pdfs/rate-plans/how-rates-work/Residential-Rates-Plan-Pricing.pdf.

Table 17. Annual Household Energy Cost Estimates

Home Type	CZ	Total Energy Cost ($ per unit)		
		T24	PH	PH
Single-Family (1 Story)	CZ07	$ 1,727	$ 1,703	1.4%
Single-Family (2 Story)		$ 2,278	$ 2,213	2.8%
Multi-Family Low-Rise		$ 1,412	$ 1,434	-1.5%
Single-Family (1 Story)	CZ04	$ 1,812	$ 1,757	3.0%
Single-Family (2 Story)		$ 2,371	$ 2,292	3.3%
Multi-Family Low-Rise		$ 1,439	$ 1,438	0.1%
Single-Family (1 Story)	CZ14	$ 2,234	$ 2,055	8.0%
Single-Family (2 Story)		$ 3,178	$ 2,790	12.2%
Multi-Family Low-Rise		$ 1,674	$ 1,571	6.2%

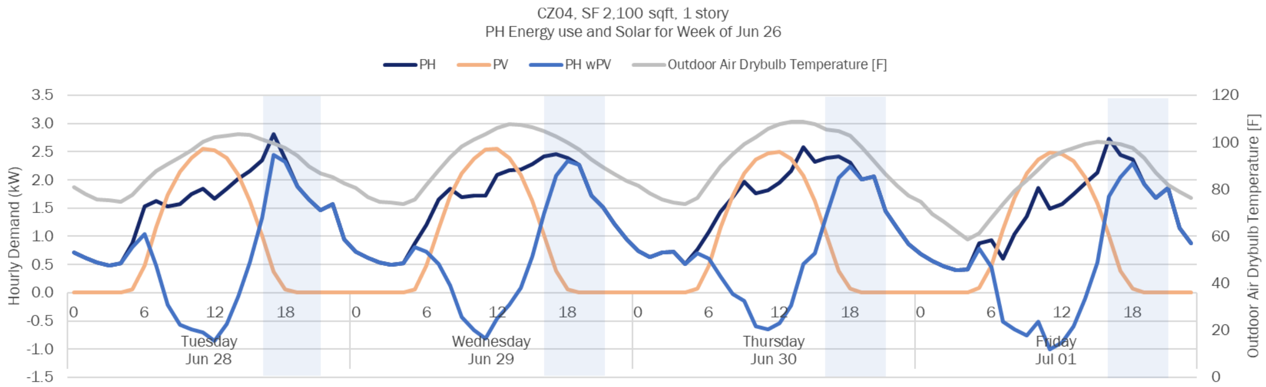
Solar PV

Figure 25 highlights the PH total household energy demand and the available solar generation for the same daily load curves presented in Figure 21. The PH line represents the total hourly load of the house, PV shows the hourly solar generation available, and PH wPV (i.e., with PV) is the combined curve: PH - PV.

PV generation precedes and exceeds the midday PH household demand, resulting in midday backflow of PV load back to the grid. This allows for shedding (reduction) of household load during the afternoon, which both reduces the household demand and may help supply other users on the grid as overall grid demand is increasing. This shedding declines as the sun begins setting (beyond 6:00 pm, or 18:00 hours), where the opportunity to reduce peak demand quickly declines.

Additionally, as solar drops off, the steep ramp rate (or slope) of the net household demand curve (PH wPV) between noon and 6:00 p.m. is much greater than the hourly demand increase of the PH house without PV. This directly amplifies the so-called ‘duck curve’ by more dramatically ramping up demand into the peak window. Some of this solar and solar-driven ramp rate could be absorbed with battery storage or could be utilized during precooling scenarios discussed next.

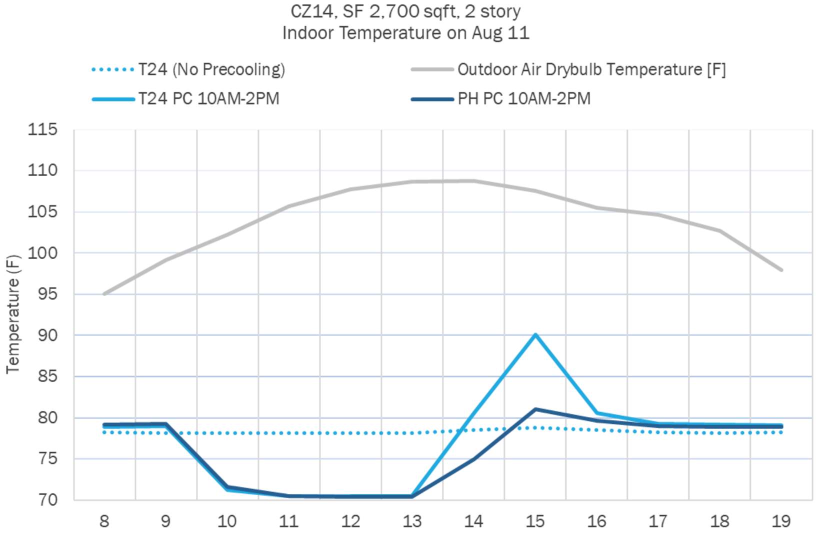
Figure 25. Solar PV Profile



5.6 Precooling

Figure 26 illustrates a single day with a precooling window from 10:00 a.m.–2:00 p.m. (14:00 hours) where the thermostat is set to 70° F. This four-hour precooling period is followed immediately with a two-hour lockout where the air conditioner does not run at all.[54] In the SF homes in moderate to extreme CZs, precooling PH homes delayed the temperature rising back to the setpoint by about an hour. The T24 home rapidly returned to 78°F within the first hour and reached almost 83°F by the second hour. The PH home, however, took two hours to return to 78°F. This one additional hour of delay for cooling demonstrates the benefits of better insulation and a tighter house.

Figure 26. Daily Profile with 10:00 a.m.–2:00 p.m. (14:00 hours) Precooling Window



5.7 Managed Portfolio as a Grid Asset

Our research demonstrates that an individual PH home can reduce the peak of an afternoon summer load when compared to the T24 equivalent home. Beyond reducing the peak load, it can slow the ramp rate before the peak and may potentially shift the peak out by an hour or so. This is all beneficial to the baseline grid. However, aggregating an

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[54] This two-hour lockout was derived by reviewing the thermal responses of the PH homes. In general, they took about two hours to return from 70°F to 78°F. This method provided a uniform method for comparing different precooling runs.

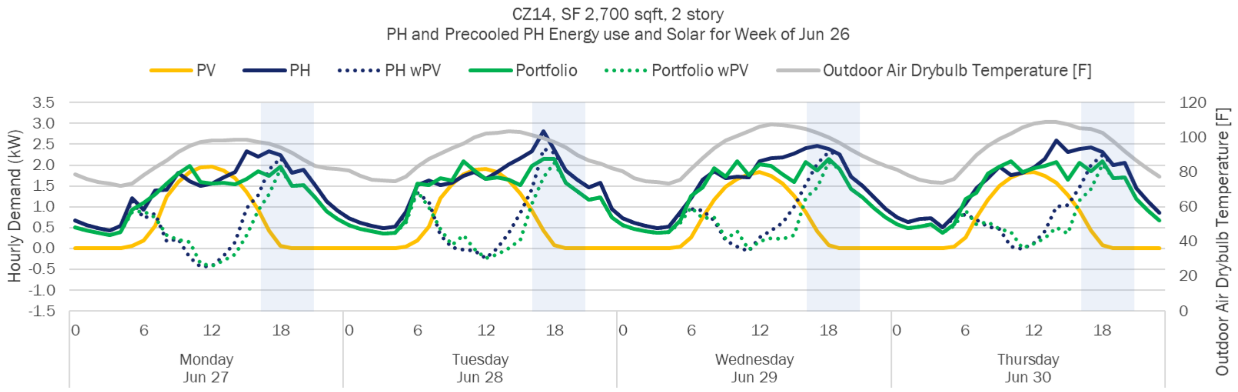
entire neighborhood of PH homes enrolled in utility smart thermostat programs has the potential to flatten the load. Table 18 outlines a percentage of homes operating under five precooling windows, each followed by an immediate two-hour lockout period.

Table 18. Distribution of Precooling Windows for Population Impacts

Precooling Window	% Of Homes
6:00 a.m.–10:00 a.m.	22%
8:00 a.m.–12:00 p.m.	22%
10:00 p.m.–2:00 p.m.	35%
12:00 p.m.–4:00 p.m.	20%
2:00 p.m.–6:00 p.m.	1%

The benefits of aggregating this portfolio of precooled PH homes is illustrated in Figure 27. Compared to the non-precooled home, the average portfolio home has a slightly higher load in the late morning as a result of the additional HVAC demand needed to precool some of the homes to 70° F. In the afternoon, as the non-precooled houses begin to see increased demand, the average portfolio home begins to see a decrease in load, lowering the peak as it approaches the RA period. Adding solar to these two scenarios demonstrates that an early precooling period can make better use of local PV generation.

Figure 27. Average Household Energy Use of a Portfolio of Precooled homes compared to non-Precooled PH Homes



In this example, the percentages are not optimized but chosen to show a rough approximation of the aggregate load. Additionally, the two-hour lock out modeled here is not a common method for restricting air conditioning load. In practice, a baseline study to determine the thermal capacitance of each home and a subsequent optimization algorithm would be necessary to properly balance the combination of the precooling appropriate window for each home with the optimal number of homes in each window.

With those caveats in mind, the aggregate portfolio curve is flatter and could potentially reduce the average household peak during the shaded peak RA window period. However, precooling comes at a cost, and this active management practice may increase the total energy use for that day. If the properly optimized portfolio can reduce peak by shifting more load forward in the afternoon, more solar PV can be used on-site rather than sent back to the grid.

6. Grid Impact Analysis Activities

This section describes the representative feeders we analyzed for this study using the approach described in Section 3.2.3, and provides additional details on the key metrics and thresholds analyzed.

6.1 Summary of IOU Feeders

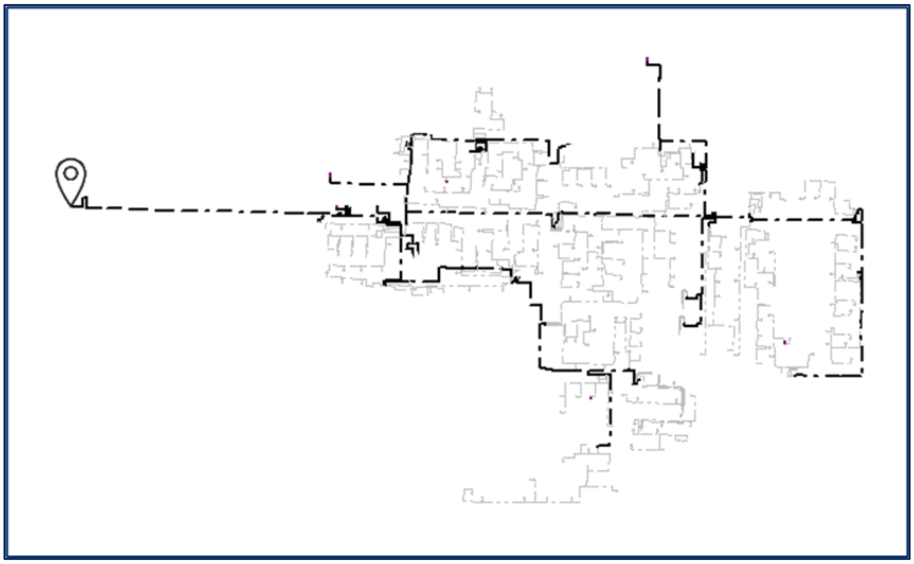
We reviewed the data provided by the electric IOUs. For this report, we evaluated key metrics at the feeder level; however, the models from the IOUs included more detailed information at the component level along each feeder. Key information review is discussed in the sections below.

6.1.1 SCE

SCE Sample Feeder Description

The two SCE feeders in the analysis are SCE – Paint, shown in Figure 28, and SCE – Mark, shown in Figure 29. Both are primarily residential, radial distribution feeders.[55] SCE – Paint is in a suburban location and has 94% residential load with 99% of that residential load being SF. SCE – Mark is in a more urban location and has 83% residential load with 55% of that residential load being SF.

Figure 28. SCE - Paint Feeder



Source: Visualization of IOU-provided CYME models. Pins indicate substation locations

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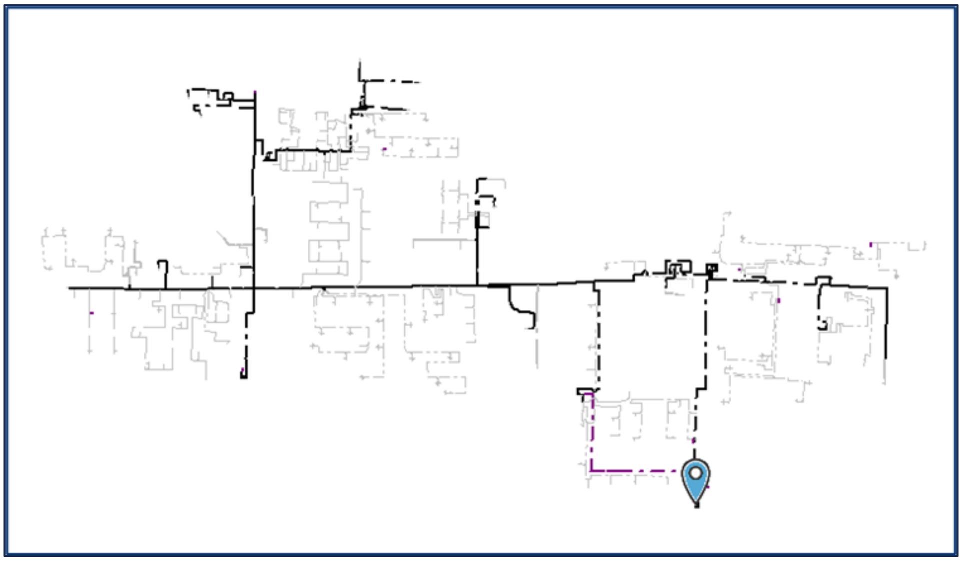
[55] A radial distribution feeder is a feeder in which there is only one path from the substation to each node inside the feeder.

Figure 29. SCE – Mark Feeder



Source: Visualizations of IOU-provided CYME models. Pins indicate substation locations

SCE Load and Customer Data

SCE provided 8760 load data for each feeder. This load data provides information for the whole feeder, disaggregated into customer segments (agricultural, commercial, industrial, and residential) and further into residential home types (SF and MF). Both feeders only have commercial and residential load. The commercial load 8760 data is used to represent the commercial component of the counterfactual baseline, as discussed in Section 3. The full feeder load is also used to represent the utility-provided baseline case.

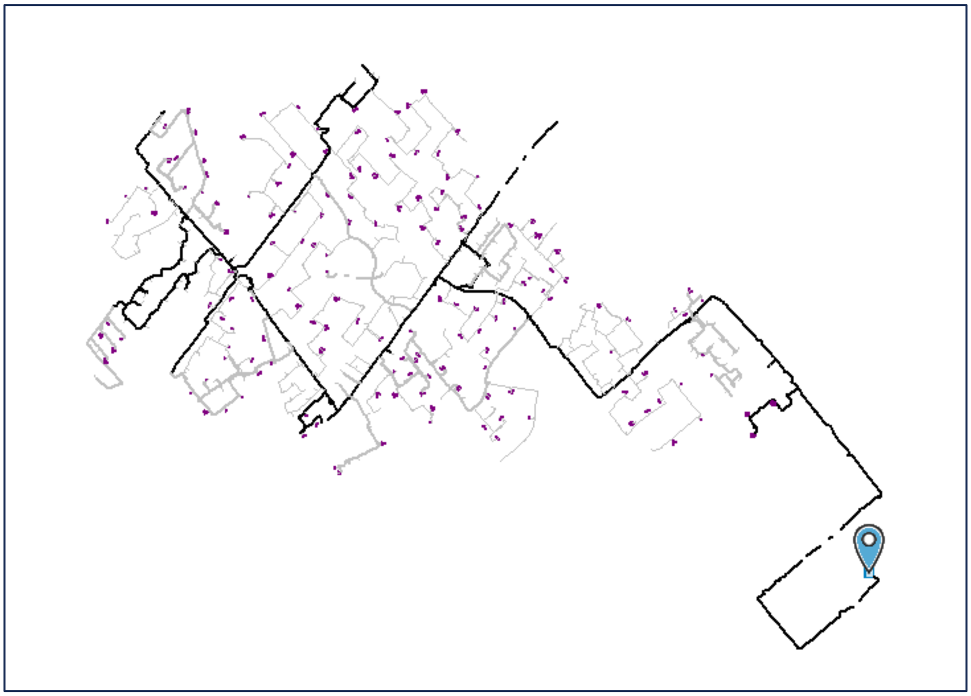
SCE also provided residential customer counts, split into SF and MF. We used this data to create the counterfactual baseline from Section 3.

6.1.2 PG&E

PG&E Sample Feeder Description

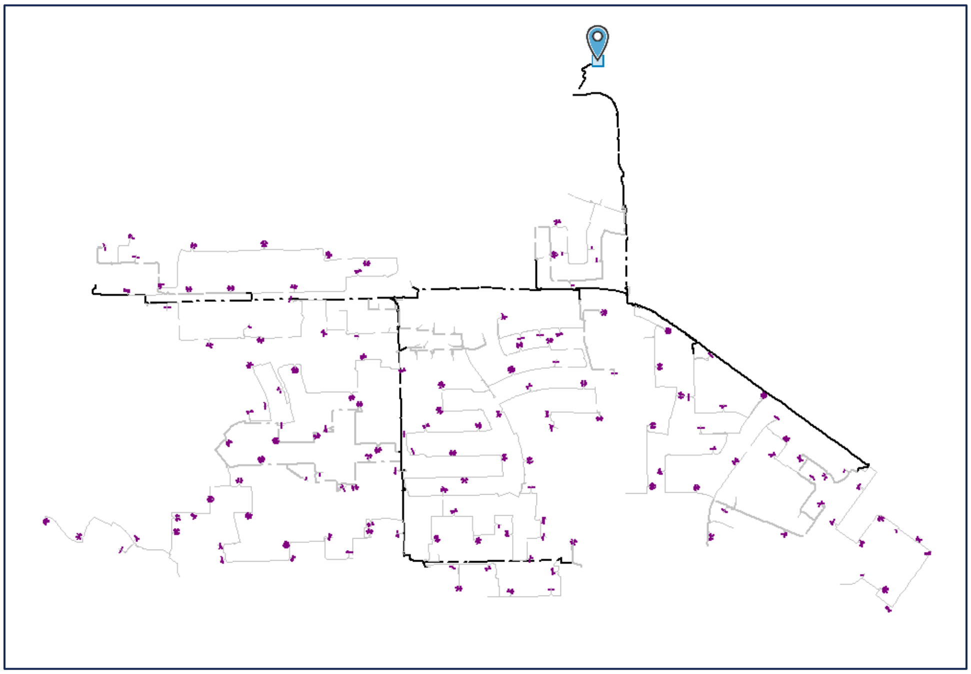
The two PG&E feeders in the analysis are PG&E – McKee, shown in Figure 30, and PG&E – Edenvale, shown in Figure 31. Both are primarily residential, radial distribution feeders located in largely suburban areas. PG&E – McKee has 94% residential load with 50% of that residential load being SF. PG&E – Edenvale has 90% residential load with 100% of that residential load being SF. Due to the way PG&E manages their distribution models, the transformers are bypassed and therefore, are not included in the element loading analysis. This is not a concern since we found the conductors are the driving force for overloading and required upgrades for the feeders analyzed in this study. We note, however, that transformer results are not available for PG&E. Therefore, no conclusions should be drawn about transformer impacts for the PG&E grid impacts.

Figure 30. PG&E – McKee Feeder



Source: Visualizations of IOU-provided CYME models. Pins indicate substation locations.

Figure 31. PG&E – Edenvale Feeder



Source: Visualizations of IOU-provided CYME models. Pins indicate substation locations.

6.2 Key Analysis Metrics

As discussed in Section 3, we conducted analysis scenarios on the IOU provided grid infrastructure. To complete this analysis, we determined standard metrics. Each of these metrics guides the interpretation of the results by indicating important aspects of the feeder condition. Different metrics are expected to be most relevant under different scenarios as detailed below.

The metrics used to evaluate the grid scenarios are listed below:

- Element overload, the percent of equipment rating across any element (based on current for conductors and apparent power for transformer).
  - Indicates need for system upgrades. Avoiding an interconnection upgrade construction project due to element overload reduces costs.
  - Expected overload in conductors and transformers in peak cases.
  - Not expecting backfeed cases to cause element overload.
  - Maximum threshold set at 105%.
- Voltage, the percent of nominal voltage at any node.
  - Indicates the need for mitigation projects; avoiding these projects reduces costs.
  - Expected undervoltage in peak cases.
  - Expected overvoltage in backfeed cases.
  - Thresholds set at 100+/- 5% of nominal voltage.
- Annual Energy, the total kWh throughout the year.
  - Identifies total energy savings possibilities outside of the grid operation questions evaluated in this analysis.

7. Grid Impact Analysis Results

Here, we present the results, discussions, and recommendations based on the distribution feeder analysis.

7.1 Overall Grid Impacts Key Findings

We summarize our key findings here and describe them in the subsections below in more detail.

- Grid impacts
  - Using PH homes lowers the total annual energy use on a feeder compared with T24; however, the grid benefits associated with this annual energy savings are minimal.
  - Peak kW is lower when PH homes are used. In practice, peak loading drives grid construction upgrades, so lower peak loading can save interconnection upgrade costs by avoiding or deferring upgrades.
  - A feeder with less penetration of solar PV is less likely to have extreme voltage issues compared to a feeder with high solar PV penetration. For the models in this study, there was negligible difference in feeder overvoltage results between T24 and PH for new construction homes with solar PV sized according to the appropriate new construction code.
  - Methods used in this study did not account for load diversity among homes on a given feeder. All new homes are assumed to be identical in size, orientation (N, S, E, W), and load shapes. These homogenous assumptions create more extreme results, as shown in the comparison of as-found utility baselines versus counterfactual baselines for SCE – Paint and PG&E – McKee. A more realistic diversity of loads may result in less extreme peak design results (i.e., fewer grid upgrades required, or more capacity to add homes before a grid upgrade would be required).
- Avoided/deferred grid upgrade construction costs
  - Overall, PH versus T24 for new growth can have a significant impact on grid upgrades and construction costs, but the impact is highly situational. Table 19 includes examples of grid upgrade cost savings for this analysis). Depending on factors like the loading, feeder topography, and the location of new growth, the impact of PH homes may or may not be enough to impact costs from constructions and upgrades.
    - When a feeder is very underloaded or near overloaded even without new growth, the impact of PH versus T24 will not be enough to change what elements of the feeder are over the threshold. Underloaded feeders will have enough capacity to accept homes regardless of building code and near overloaded feeders will require upgrades for any new growth regardless of building code.
    - In the specific case where the feeder is close to overloading but with some capacity remaining, PH allows more homes to be built without requiring upgrades due to lower peak loading.
    - For the feeders modeled for this study, the PH team found adding PH homes lowered maximum loading relative to T24 homes. However, lower maximum loading does not always translate to a cost reduction for utility upgrades (e.g., to counter overloaded conductors). Exceedances above the threshold depend on relative location of loads along the feeder, and feeder topology/configuration. Often there is a "cluster" of lines that are overloaded. While the PH homes lower the maximum loading of the cluster, it may not be enough to bring the load below the threshold. In this case, the same grid construction projects must be carried out to mitigate the overload regardless of PH or T24.

- Transformer aging and lifespan are affected by loading. Higher loads may decrease the lifespan of a transformer, so using PH homes may extend the life of transformers relative to T24 homes, thus delaying the investment.

Table 19. Avoided/Deferred Interconnection Upgrade Costs (Reconductoring)

Feeder	Upgrade Planning Threshold %	+T24 ft. overloaded	+PH ft. overloaded	Approximate PH cost savings ($)
SCE – Mark	85%	75.6	0	$20,000
SCE - Mark + 275 of each home type	100%	727.5	49.9	$180,000
SCE - Paint (counterfactual)	85%	8,022.3	2,783.2	$1,400,000
SCE - Paint (utility-provided)	100%	2,783.1	2,782.9	$0
PG&E - McKee (counterfactual)	100%	12,631.8	11,417.8	$316,000
PG&E - McKee (utility-provided)	85%	1,773.6	1,773.6	$0
PG&E - Edenvale	100%	3,344.3	3,344.3	$0

Source: Study team model results and estimated costs of approximately $260/linear foot reconductoring.[56]

- New home feeder location/distribution and home type (SF-1 story, SF-2 story, MFLR) effects
    - The impact of PH versus T24 new growth is greater if all the new homes are in one location (e.g., a new subdivision going in) than if the homes were to be spread out along the feeder. Our models showed that when a new subdivision is added, it brings the lines near the new growth closer to overload. Thus, using PH homes may prevent more of those local lines from requiring upgrades.
- SF and MF loads behaved similarly in this analysis. Feeders with more MF load are more likely to experience higher load growth concentrated in a smaller area due to the dense nature of multi-family housing. This is another example of the locational impact described above where PH can be beneficial in deferring grid investments.

7.2 SCE Grid Analysis and Impact Results

This section discusses key grid impacts for the core scenarios (counterfactual baseline, T24 growth, and PH growth) based on our analysis, followed by a short summary. As described in Section 3, we evaluated the impact on two feeders for SCE: SCE – Paint and SCE – Mark.

7.2.1 SCE – Paint with Counterfactual Baseline Loads and Backfeed

We evaluated SCE – Paint using the core scenarios of the counterfactual baseline, T24 growth, and PH growth. We present the grid impact for the counterfactual baseline and related growth cases in this section, including backfeed scenarios.

We chose the number of new homes to be 500 SF-two story homes in accordance with the procedures described in Section 3.4.4. This represented a 20% growth rate for the number of homes on the feeder. Using SCE's hosting capacity

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[56] Ref. pge.com/pge_global/common/pdfs/for-our-business-partners/interconnection-renewables/Unit-Cost-Guide.pdf accessed 2022-12-01 $260/ft underground non-Bay area costs.

tool, the team identified the geographic area of SCE – Paint and identified two logical end point locations for reasonable future growth were chosen, as shown in Figure 32 below. The new load was split evenly between these two locations.

Figure 32. SCE - Paint Feeder: Split Location for New Construction Homes

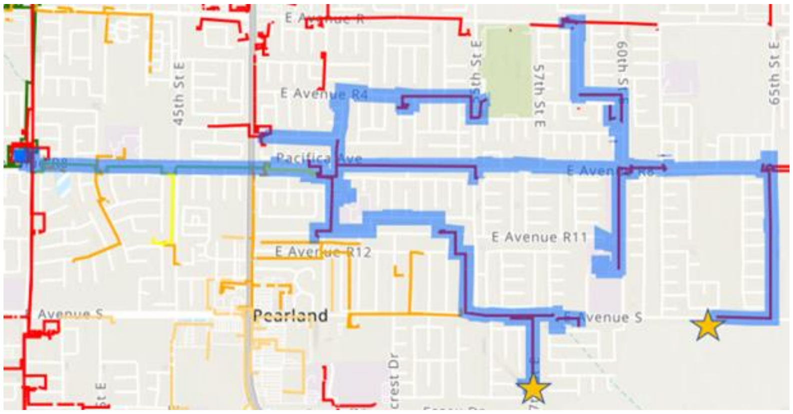
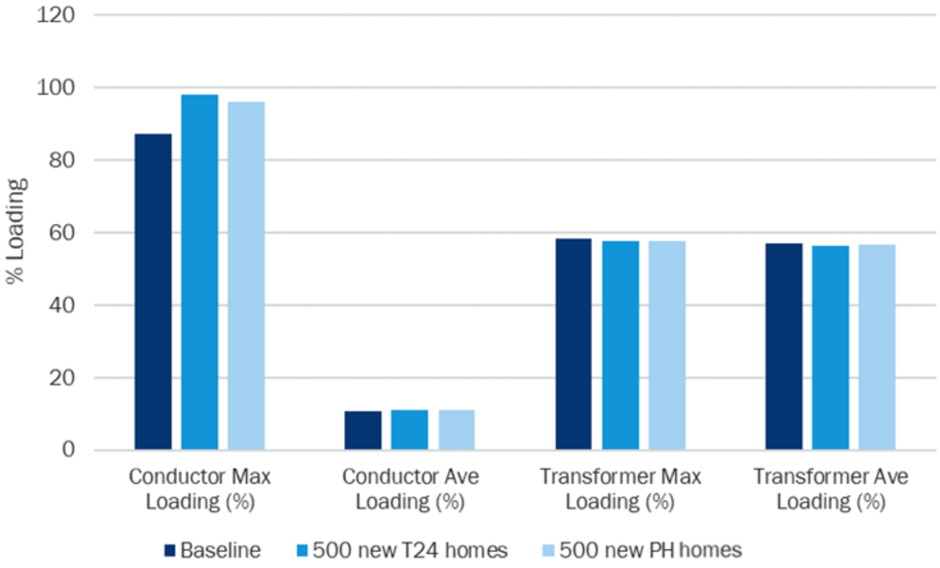


Figure 33 shows the loading above 100% element rating (kW) for conductors and transformers on the feeder.[57] The PH growth scenario has a maximum conductor loading that is 2.0% less than the T24 scenario, and a maximum transformer loading 0.2% higher than the T24 scenario. These differences are negligible from a grid impact or grid planning perspective for feeders such as this one that are not near the maximum load limit.

Figure 33. SCE - Paint Feeder: Results Summary



However, reconductoring upgrade cost savings for PH homes could be substantial when the feeder load is near the planning limit. When 500 SF T24 homes are added, 8,022 ft. of conductor would need to be reconductored to remain under 85% loading.[58] When 500 SF PH homes are added, that length is 2,783 ft. of conductor. For this case using an

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[57] The team used 100% as the planning threshold for conductors where the maximum conductor loading was loaded to above 100%, and 85% for underloaded conductors. Both 100% and 85% are design planning points that utilities may consider when planning conductor upgrades.

[58] An industry standard planning limit of 85% is sometimes used for underloaded feeders; however, the passive house team did not confirm planning limits with each individual IOU for this study.

85% threshold, the difference between lengths of overloaded conductor is a significant difference of 5,239 ft. This leads to $1.4M in avoided costs, as shown in Table 19.

Voltage variations are not significant between these T24 and PH scenarios when the circuit is not close to fully loaded

The range of voltages on SCE – Paint for each counterfactual baseline scenario is presented in Table 20. The T24 growth scenario has a lower minimum voltage than the PH growth scenario, but not enough to push below the 95% threshold. For the backfeed scenarios, the PH scenario has a higher maximum voltage than the T24 scenario by 0.01% due to lower load. Both voltages remain under the 105% threshold. Thus, there is no practical difference between PH and T24 with respect to voltage issues due to backfeed for this feeder.

Table 20. SCE – Paint Feeder: Voltage Results

	Maximum V (PU) (% of nominal voltage)	Minimum V (PU) (% of nominal voltage)
Counterfactual baseline	103.00%	97.90%
T24 growth with counterfactual baseline – peak	103.00%	96.89%
T24 growth with counterfactual baseline – backfeed	103.00%	97.08%
PH growth with counterfactual baseline – peak	104.69%	103.00%
PH growth with counterfactual baseline – backfeed	104.68%	103.00%

Note: The planning threshold for voltage at SCE is +/-5% of nominal

PH homes in moderate to extreme CZs use less energy than T24 equivalents, which translates directly to annual feeder energy reductions

Table 21 shows the total annual energy for the SCE – Paint feeder with a counterfactual baseline. As shown, using PH homes for the new developments reduced the total annual energy by 648.9 MWh compared to using T24 homes. This is a direct extension of the household energy savings comparisons described in detail in Section 5.

Table 21. SCE – Paint: Total Annual Feeder Energy

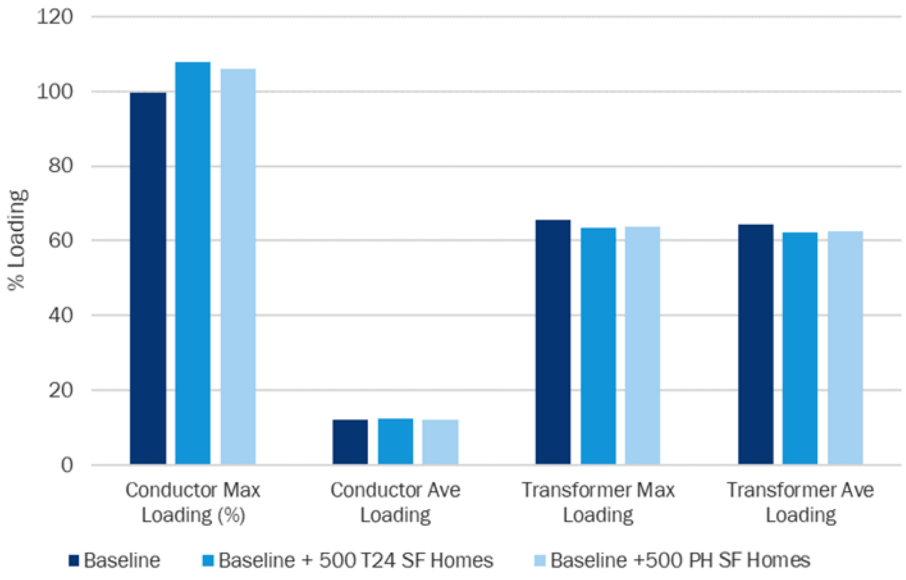
	Total Annual Feeder Energy Consumption (MWh)	Comparison to the Base Case (MWh)	PH Minus T24 Comparison (MWh) [A]
Counterfactual baseline	28,687.53	n/a	n/a
T24 growth with counterfactual baseline	30,715.34	2,027.81	n/a
PH growth with counterfactual baseline	30,066.48	1,378.95	(648.86)

[A] Negative values indicate PH is lower energy than T24.

7.2.2 SCE - Paint with Utility-Provided Baseline Loads

In addition to the core scenarios, we also evaluated SCE - Paint using the utility-provided baseline (existing) house loads. The grid impact for the utility-provided baseline and related growth cases are presented in this section. This baseline was modeled according to the description in Section 3.4.4. Here, 500 SF homes were added for the T24 and PH growth scenarios. Figure 34 shows the loading above current rating for conductors and transformers on the feeder. The PH growth scenario has a maximum conductor loading 1.8% less than the T24 scenario, and a maximum transformer loading 0.2% higher than the T24 scenario.

Figure 34. SCE - Paint Feeder (Existing Baseline Loads as Provided by SCE): Results Summary



Similarly, when 500 SF T24 homes are added, 2,783.1 ft. of conductor would need to be reconductored to remain under 100% loading, and when 500 SF PH homes are added, that number is 2,782.9 ft. of conductor. This is only 0.2 ft. less than the T24 case. Thus, for this case, using a 100% threshold, the difference between lengths of overloaded conductor is practically zero and there is no significant benefit of PH over T24 from this avoided upgrade cost perspective.

While the conductor maximum loading is significantly lower for PH, the amount of reconductoring required is almost the same for PH and T24. This is because conductor maximum loading does not always correlate linearly to the length of conductor that needs to be replaced for a given planning threshold (e.g., 85% or 100%). Conductor overloading for a given feeder will depend on the relative location of loading along the feeder and the feeder topology/configuration.

The range of voltages on SCE – Paint for each utility-provided baseline scenario is presented in Table 22 below. The T24 growth scenario has a lower minimum voltage than the PH growth scenario, but not enough to push it below the 95% threshold.

Table 22. SCE - Paint (Existing Baseline Loads as Provided by SCE): Voltage Results

	Maximum V (PU) (% of nominal voltage)	Minimum V (PU) (% of nominal voltage)
Utility-provided baseline (peak)	103.00	97.03
T24 growth with utility baseline (peak)	103.00	96.12
PH growth with utility baseline (peak)	103.00	96.39

Note: The planning threshold for voltage at SCE is +/-5% of nominal

Table 23 shows the total annual energy for the SCE – Paint feeder with utility-provided baseline. As shown, using PH homes for the new developments reduced the total annual energy by 648.9 MWh compared to using T24 homes.

Table 23. SCE - Paint (Existing Baseline Loads as Provided by SCE): Total Annual Feeder Energy

	Total Annual Feeder Energy Consumption (MWh)	Comparison to the Base Case (MWh)	PH Minus T24 Comparison (MWh) [A]
Utility-provided baseline (peak)	23,715.86	n/a	n/a
T24 growth with utility baseline (peak)	25,743.67	2,027.81	n/a
PH growth with utility baseline (peak)	25,094.80	1,378.94	(648.87)

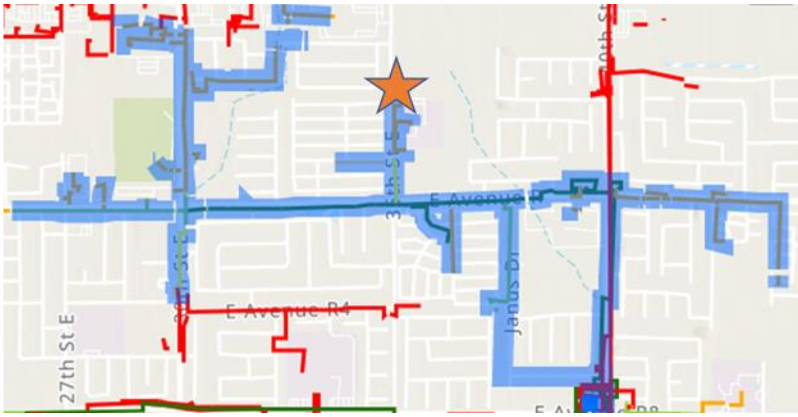
[A] Negative values indicate PH is lower energy than T24

7.2.3 SCE - Mark with Counterfactual Baseline Loads and Backfeed

The team evaluated SCE – Mark using the core scenarios of the counterfactual baseline, T24 growth, and PH growth. Additionally, SCE – Mark included two cases with additional load to test the limits of the feeder. The grid impact for the counterfactual baseline and related growth cases are presented in this section.

The number of new homes at a 20% growth rate was 200 SF-two story homes and 200 MF homes in accordance with the procedures described Section 3.4.4. Using SCE's hosting capacity tool, the team identified the geographic area of SCE – Mark and chose one area for reasonable future growth, as shown in Figure 35.

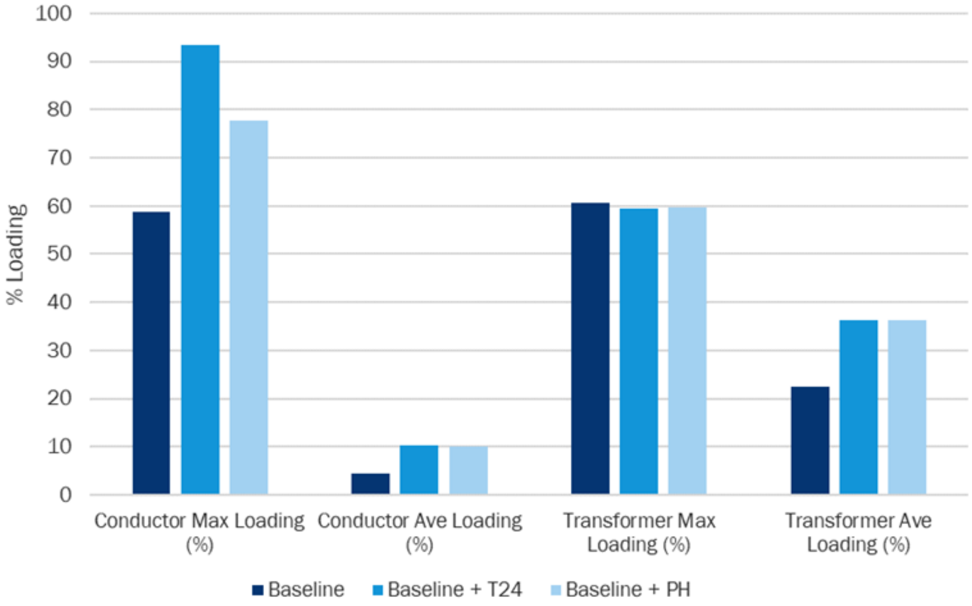
Figure 35. SCE - Mark Feeder - Single Location for New Construction Homes



Source: SCE capacity map with locational marker added by study team

Figure 36 shows the loading above element rating for conductors and transformers on the feeder. The PH growth scenario has a maximum conductor loading 20.2% less than the T24 scenario, and a maximum transformer loading 0.4% higher than the T24 scenario.

Figure 36. SCE - Mark Feeder: Results Summary



Regarding feet of overloaded conductor, when 200 SF and 200 MF T24 homes are added, 75.6 ft of conductor would need to be reconductored to remain under 85% loading. When 200 SF and 200 MF PH homes are added, no conductor would need to be reconductored to remain under 85% loading. For this case with an 85% threshold, the difference between lengths of overloaded conductor is 75.6 ft. This is what drives the $20,000 in avoided costs, as shown in above Table 19.

The range of voltages on SCE – Mark for each scenario is presented in Table 24. The T24 growth scenario has a lower minimum voltage than the PH growth scenario, but not enough to push it below the 95% threshold. For the backfeed scenarios, the PH scenario has a lower maximum voltage than the T24 scenario by 0.01% in this case. Both voltages remain under the 105% threshold. For the extended growth scenarios, the T24 extended growth scenario has a 0.01% lower minimum voltage than the PH extended growth scenario. Both remain above the 95% threshold.

Table 24. SCE – Mark: Voltage Results

	Maximum V (PU) (% of nominal voltage)	Minimum V (PU) (% of nominal voltage)
Counterfactual baseline	105.26%	100.38%
T24 growth with counterfactual baseline – peak	103.00%	99.68%
T24 growth with counterfactual baseline - backfeed	104.46%	103.00%
PH growth with counterfactual baseline - peak	103.00%	99.81%
PH growth with counterfactual baseline - backfeed	104.45%	103.00%
T24 extended growth (peak)	103.00%	99.59%
PH extended growth (peak)	103.00%	99.60%

Note: The planning threshold for voltage at SCE is +/-5% of nominal

Table 25 shows the total annual energy for the SCE – Mark feeder with utility-provided baseline. As shown, using PH homes for the new developments reduced the total annual energy by 812.0 MWh compared to using T24 homes. Additionally, even with the 50 additional SF homes and 50 additional MF homes, the PH extended growth scenario still has lower yearly energy consumption than the T24 extended growth scenario.

Table 25. SCE – Mark: Total Annual Feeder Energy

	Total Annual Feeder Energy Consumption (MWh)	Comparison to the Base Case (MWh)	PH Minus T24 Comparison (MWh) [A]
Counterfactual baseline	24,378.86	n/a	n/a
T24 growth with counterfactual baseline – peak	28,335.80	3,956.94	n/a
T24 growth with counterfactual baseline – backfeed	28,335.80	3,956.94	n/a
PH growth with counterfactual baseline – peak	27,523.78	3,114.92	(812.03)
PH growth with counterfactual baseline – backfeed	27,523.78	3,114.92	(812.03)
T24 extended growth (peak)	28,830.42	4,451.56	n/a
PH extended growth (peak)	28,703.12	4,324.26	(127.30)

[A] Negative values indicate PH is lower energy than T24.

The 20% growth scenario described above did not result in an overloaded grid, so an additional case was run with an additional 225 of each SF and MF T24 homes. This resulted in a maximum conductor loading of 103.83%. For the PH homes, however, 275 of each type put the maximum conductor loading at 103.11%. Therefore, if all new homes were built to PH standards, then at least an additional 50 (22% more) SF and MF homes could be built without exceeding the maximum conductor loading from the smaller number of T24 homes. The team selected the amount of additional load for these scenarios to reach near but not exceed a threshold maximum of 105% rated conductor loading. This additional scenario resulted in avoided reconductoring costs of $180,000, as shown in Table 19.

7.2.4 SCE Discussion

Element Loading (% of Rated kW Value)

Adding 20% more homes on both feeders had different impacts relative to the T24 growth on element loading. On SCE – Paint, a 20% growth rate led to 500 additional homes where the PH conductor maximum loading was only 2% lower than that of T24. This indicated no practical difference in grid impacts between PH and T24 loads when the loading is below the planning limit. On SCE - Mark, however, a 20% growth of 200 homes new homes led to the PH conductor maximum loading 17% below T24. An important note is that the additional load on SCE – Paint was split between two connection locations on the feeder, while SCE - Mark had all the additional load stemming from one location. New home tract location may impact these effects, which could be explored further in future studies.

We also explore conductor loading in terms of maximum growth. Building PH homes will allow planners to add more homes without additional distribution grid loading than building under the T24 standard. On SCE - Mark, adding 225 each of SF and MF T24 homes put the maximum conductor loading just below 104% loading. If those homes are assumed to be PH, then 275 of each type could be added with less maximum conductor loading than the fewer number of T24 homes. This is an additional 50 homes, or 22% more homes.

Voltage (% of Nominal Value)

The minimum voltage in the peak loading cases is slightly higher on both feeders when load is added as PH instead of T24, which makes sense due to the lower PH household load. However, the difference is small (<1%) and all cases had voltages within the +/- 5% threshold of nominal. During hours with solar PV backfeed, the lower PH load may exacerbate voltage issues (e.g., overvoltage). In the SCE analysis, however, the PH load exceeded the T24 load at the backfeed hour, so the maximum backfeed voltage is slightly lower (<1%) using PH. Since the peak hour could change when real, diverse load shapes are used, possible voltage issues arising from solar PV are highly feeder dependent and should be analyzed on a case by case basis. In general, feeders with a high ratio of peak solar generation to load will be more likely to be subject to overvoltage issues.

Total Annual Energy (kWh)

Total annual energy is reduced by adding homes as PH rather than T24. In the case of SCE – Paint the savings are 2.1% and for SCE – Mark the savings are 2.9%.

7.3 PG&E Grid Analysis and Impact Results

This section provides key grid impact findings for the core scenarios (counterfactual baseline, T24 growth, and PH growth) based on our analysis using the two PG&E feeders: PG&E – McKee and PG&E -- Edenvale.

7.3.1 PG&E - McKee with Counterfactual Baseline Loads

We evaluated PG&E - McKee using the core scenarios of the counterfactual baseline, T24 growth, and PH growth. We present the grid impact for the counterfactual baseline and related growth cases in this section.

We determined the number of new homes to be 650 SF homes and 115 MF homes in accordance with the procedures described in Section 3.4.4. The represents 20% growth overall.[59] Using PG&E's integration capacity analysis tool, the team identified the geographic area of PG&E - McKee, and selected two locations for reasonable future growth, as shown in Figure 37. The new load was split between these two locations.

Figure 37. PG&E - McKee Feeder - Split Location for New Construction Homes

Source: PG&E capacity map with locational markers added by study team

Figure 38 shows the loading above 100% element rating for conductors on the feeder. The PH growth scenario has a maximum conductor loading that is 2.55% less than the T24 scenario, which for a fully loaded conductor, could mean the difference between the IOU requiring an upgrade or not.

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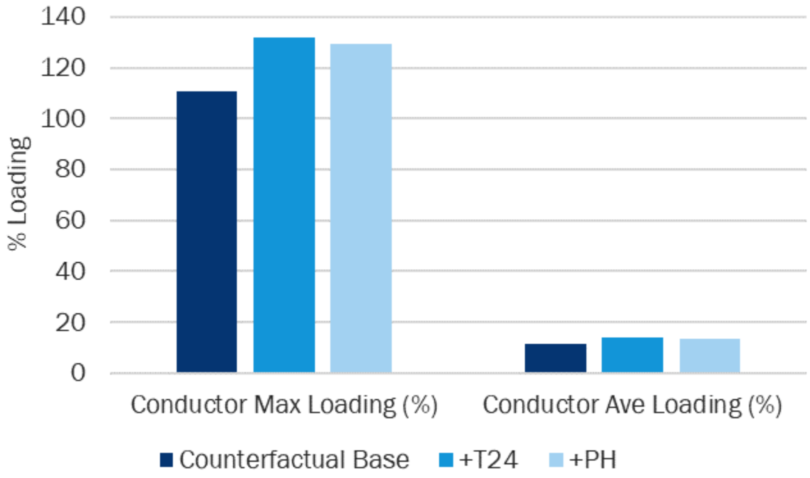
[59] The growth split for PG&E – McKee is not 50/50 between SF and MF homes and instead is an 85/15. For McKee, the team considered 50/50 loading between MF and SF peaks instead of a 50/50 split across number of buildings. This difference in assumption is not expected to affect the grid impacts conclusions for this feeder.

Figure 38. PG&E - McKee Feeder: Results Summary (Counterfactual Baseline)



Regarding feet of overloaded conductor, if 650 SF homes and 115 MF T24 homes were added, 12,631.82 ft. of conductor would need to be reconductored to remain under 100% loading. When these homes are added as PH, 11,417.75 ft. of conductor would need to be reconductored to remain under 100% loading. For this case, the difference between lengths of overloaded conductor is a significant difference of 1,214.08 ft. This leads to $316,000 in avoided costs, as shown in Table 19.

The range of voltages on PG&E - McKee for each counterfactual baseline scenario is presented in Table 26. The T24 growth scenario has a lower minimum voltage than the PH growth scenario, but not enough to push below the 95% threshold.[60]

Table 26. PG&E - McKee: Voltage Results (Counterfactual Baseline)

	Maximum V (PU) (% of nominal voltage)	Minimum V (PU) (% of nominal voltage)
Counterfactual baseline	104.60%	99.75%
+650 SF, 115 MF new T24 homes	104.50%	97.53%
+650 SF, 115 MF new PH homes	104.51%	97.84%

Note: The planning threshold for voltage at PG&E is +/-5% of nominal.

Table 27 below shows the total annual energy for the PG&E - McKee feeder with counterfactual baseline. As shown, using PH homes for the new developments reduced the total annual energy by 131.05 MW compared to using T24 homes.

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[60] From a grid upgrades perspective, if the voltage were closer to the limits, the range of voltage variation between the Phius and T23 scenarios would materially matter in terms of voltage violations. For this analysis, no violations occurred that would result in the need for a capacitor bank or regulators.

Table 27. PG&E – McKee: Total Annual Feeder Energy (Counterfactual Baseline)

	Total Annual Feeder Energy Consumption (MWh)	Comparison to the Base Case (MWh)	PH Minus T24 Comparison (MWh)[A]
Counterfactual baseline	44,625.67	n/a	n/a
+650 SF, 115 MF new T24 homes	47,514.01	2,888.35	n/a
+650 SF, 115 MF new PH homes	47,382.96	2,757.30	(131.05)

[A] Negative values indicate PH is lower energy than T24.

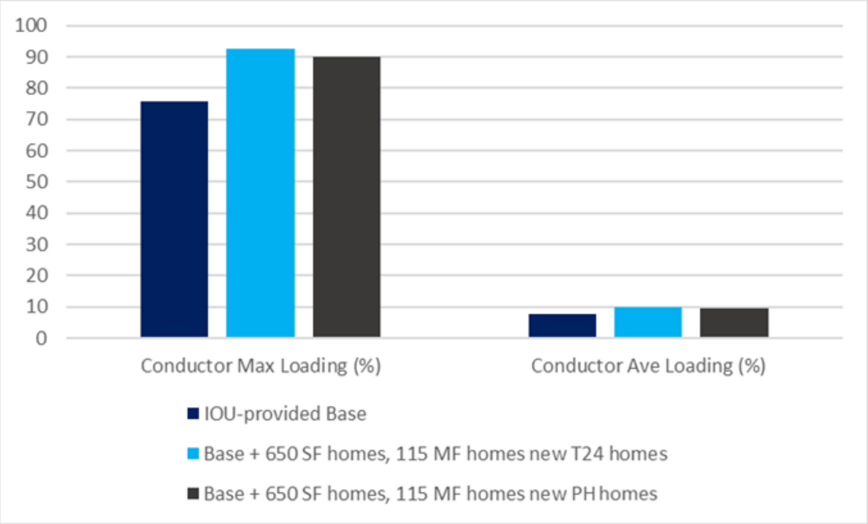
7.3.2 PG&E - McKee with Utility-Provided Baseline Loads

In addition to the core scenarios, PG&E - McKee was also evaluated using the utility-provided baseline. The grid impact for the utility-provided baseline and related growth cases are presented in this section.

We modeled the utility-provided baseline for PG&E - McKee as described in Section 3.4.4. In this case, 650 SF-one story homes and 115 MF homes were added for the T24 and PH growth scenarios.

Figure 39 below shows the loading above current rating for conductors on the feeder. The PH growth scenario has a maximum conductor loading 2.39% less than the T24 scenario.

Figure 39. PG&E - McKee Feeder: Results Summary (utility-provided baseline loads)



Regarding feet of overloaded conductor, when 650 SF homes and 115 MF T24 homes are added, 1,773.54 ft. of conductor would need to be reconductored to remain under 85% loading. When these homes are added as PH, 1,773.54 ft. of conductor would need to be reconductored to remain under 85% loading. This is equal to the T24 case. For this case, with an 85% threshold, the difference between lengths of overloaded conductor is zero.

The range of voltages on PG&E - McKee for each utility-provided baseline scenario are presented in Table 28. The T24 growth scenario has a lower minimum voltage than the PH growth scenario, but not enough to push below the 95% threshold.

Table 28. PG&E - McKee: Voltage Results (Utility-Provided Baseline Loads)

	Maximum V (PU) (% of nominal voltage)	Minimum V (PU) (% of nominal voltage)
As found baseline (IOU-provided capacity)	104.73%	101.43%
As found baseline (IOU-provided 8760 load profile)	104.77%	101.93%
+650 SF, 115 MF new T24 homes	104.68%	100.03%
+650 SF, 115 MF new PH homes	104.70%	100.31%

Note: The planning threshold for voltage at PG&E is +/-5% of nominal.

Table 29 below shows the total annual energy for the PG&E – McKee feeder with utility-provided baseline. As shown, using PH homes for the new developments reduced the total annual energy by 131.05 MW compared to using T24 homes.

Table 29. PG&E – McKee: Total Annual Feeder Energy (Utility-Provided Baseline)

	Total Annual Feeder Energy Consumption (MWh)	Comparison to the Base Case (MWh)	PH Minus T24 Comparison (MWh)[A]
As found baseline (IOU-provided)	32,358.05	n/a	n/a
+650 SF, 115 MF new T24 homes	35,246.40	2,888.35	n/a
+650 SF, 115 MF new PH homes	35,115.35	2,757.30	(131.05)

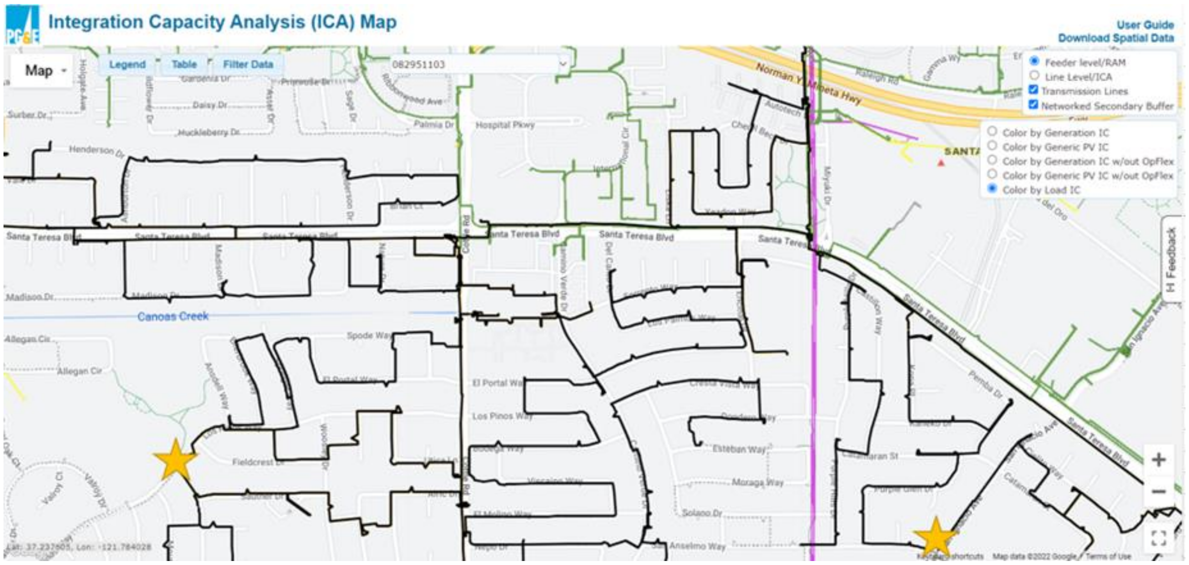
[A] Negative values indicate PH is lower energy than T24.

7.3.3 PG&E - Edenvale Feeder with Counterfactual Baseline Loads

The team evaluated PG&E - Edenvale using the core scenarios of the counterfactual baseline, T24 growth, and PH growth. The grid impact for the counterfactual baseline and related growth cases are presented in this section.

The team determined the number of new homes to be 700 SF homes in accordance with the procedures described Section 3.4.4. Using PG&E’s integration capacity analysis tool, we identified the geographic area of PG&E – Edenvale and chose two areas for reasonable future growth, as shown in Figure 40.

Figure 40. PG&E - Edenvale Feeder - Single Location for New Construction Homes



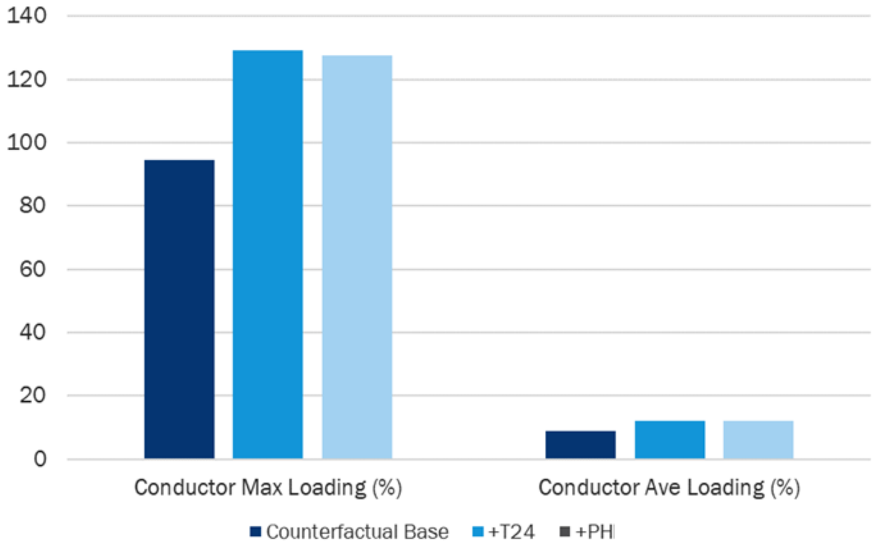
● Feeder level/RAM
○ Line Level/ICA
☑ Transmission Lines
☑ Networked Secondary Buffer

○ Color by Generation IC
○ Color by Generic PV IC
○ Color by Generation IC w/out OpFlex
○ Color by Generic PV IC w/out OpFlex
● Color by Load IC

Source: PG&E capacity map with locational markers added by study team

Figure 41 below shows the loading above element rating for conductors and transformers on the feeder. The PH growth scenario has a maximum conductor loading 1.82% less than the T24 scenario.

Figure 41. PG&E - Edenvale Feeder - Results Summary



Regarding feet of overloaded conductor, when 700 SF T24 homes are added, 3,344.31 ft of conductor would need to be reconductored to remain under 100% loading. When 700 SF PH homes are added, 3,344.31 ft of conductor would need to be reconductored to remain under 100% loading. For this case, the difference between lengths of overloaded conductor is zero.

The range of voltages on PG&E - Edenvale for each scenario is presented in Table 30. The T24 growth scenario has a lower minimum voltage than the PH growth scenario, but not enough to push below the 95% threshold. For the backfeed scenarios, the PH scenario has the same maximum voltage as the T24.

Table 30. PG&E - Edenvale Feeder: Voltage Results

	Maximum V (PU) (% of nominal voltage)	Minimum V (PU) (% of nominal voltage)
Counterfactual baseline	104.98%	103.10%
+700 SF new T24 homes	104.97%	101.73%
+700 SF new PH homes	104.97%	101.89%

Note: The planning threshold for voltage at PG&E is +/-5% of nominal

Table 31 below shows the total annual energy for the PG&E - Edenvale feeder with counterfactual baseline. As shown, using PH homes for the new developments reduced the total annual energy by 134.9 MW compared to using T24 homes.

Table 31. PG&E - Edenvale Feeder: Total Annual Feeder Energy

	Total Annual Feeder Energy Consumption (MWh)	Comparison to the Base Case (MWh)	PH Minus T24 Comparison (MWh) [A]
Counterfactual baseline	23,477.39	n/a	n/a
+700 SF new T24 homes	24,801.17	1,323.78	n/a
+700 SF new PH homes	24,666.27	1,188.88	(134.90)

[A] Negative values indicate PH is lower energy than T24.

7.3.4 PG&E Discussion

Element Loading (% of Rated Value)

With added PH load, the conductor maximum loading for both PG&E feeders is lower than the added T24 load. For both, the PH conductor maximum loading is only a few percentage points lower than that of T24 (2.55% for PG&E – McKee and 1.82% for PG&E – Edenvale). Both PG&E feeders had two locations for load growth, and the PH reduced peak load is similar to that of SCE – Paint, which also had two locations for load growth.

Voltage (% of Nominal Value)

The minimum voltage in the peak loading cases is slightly higher on both feeders when load is added as PH instead of T24. This makes sense due to the lower load. However, the difference is small (<1%) and all cases had voltages within the +/- 5% threshold of nominal.

Total Annual Energy (kWh)

Total annual energy is slightly reduced by adding homes as PH rather than T24. In the case of PG&E - McKee the savings are 0.28% and for PG&E - Edenvale the savings are 0.54%.

8. Summary Conclusions and Recommendations

This study aimed to explore the potential grid benefits of all-electric homes built using PH principles versus T24 building code-compliant homes. To explore this possibility, the team first designed scenarios that would test multiple all-electric SF and MF homes in a broad range of California CZs. Next, the team constructed the houses in EnergyPlus building energy modeling software. For each scenario, the team generated annual hourly energy use load shapes. Finally, we obtained grid topology data of the relevant distribution feeders from the electric IOUs and, using the load shapes, estimated the benefits of PH construction on those portions of the grid.

Overall, adopting PH principles in California residential new construction would make all new homes potential grid assets while reducing the energy consumption and peak load below that of the current T24 code. Leveraging these techniques to reduce average household energy usage will also lower operating costs for homeowners. For example, a portfolio of precooled PH homes engaged in utility smart thermostat programs has the potential to flatten the load of the population-wide aggregate portfolio, significantly reduce aggregate ramp rate, further reduce peak demand, and better leverage on-site midday solar generation.

8.1 Household Performance

8.1.1 PH Principles

For a comparison to T24, we considered both PHI and Phius to inform our PH models. Both code bases provide construction and performance requirements that vary in detail and value in their prescription. Broadly speaking, Phius is more prescriptively stringent and is better adapted to the US market and CZs, but PHI utilizes an annual energy target without explicitly prescribing all parameters. Ultimately, we pulled the best values prescribed between them and developed a representative framework using PH principles. Neither code base explicitly prescribes values for all performance characteristics. For parameters not defined, we assumed the T24 prescriptive values, which may not be as aggressive as expected in practice for PH construction. Using these PH Principles, we developed three residential models (SF-1, SF-2, and MFLR) and tested all in three different CZs across California.

The SF-1 and SF-2 PH models outperformed T24 in all modeled CZs. The PH MFLR outperformed T24 in moderate and extreme HVAC regions but underperformed in mild climates (e.g., CZ07 of Coastal San Diego). PH design's ability to reduce overall household energy and benefit the grid comes down to how it will affect household electricity used for comfort through HVAC loads. With better insulation and other improvements, any PH will save energy when heating or cooling is needed. Since the house has a tighter envelope, however, fans must run more often to maintain good ventilation in the house. In mild CZs like CZ07, PH will reduce heating and cooling loads when operating, but the increase in fan loads may outweigh the more efficient heating and cooling savings.

The SF homes reduced total annual household energy by a few percent in a mild CZ to around 10% in extreme climates. The MFLR consumed a few percent more energy per unit in the mild CZ, showed a slight percent savings in a moderate CZ, and saved almost about 6% in an extreme CZ.

The more efficient envelope from PH principles can only reduce energy consumption in a household by reducing HVAC usage. The more extreme the CZ, the higher the percentage of household energy attributed to HVAC, and the larger percentage is reduced through PH design. In the T24 SF homes, HVAC energy use ranges from 10-15% of the total in a mild CZ, 15-20% in moderate, and 30-40% in extreme. PH principles will reduce HVAC usage by about around 15%, 20%, and 30% in a mild, moderate, and extreme CZ, respectively.

8.1.2 PH as a Grid Resource

The PH principles can reduce annual household HVAC energy use over a T24 home. These annual benefits translate to significant peak load savings. During a peak summer day, PH can also reduce the HVAC peak load by almost 30% is an extreme CZ. On a winter nighttime peak, the energy savings can be upwards of 50% of HVAC load. The PH design might shift the peak load by an hour and slightly reduce the ramp rate, but the overall peak reduction is the primary impact.

Precooling the house can further delay the need for air conditioning by as much as an hour more than the T24 precooled house. Precooling may be further beneficial if the energy needed to precool the house occurs midday when solar generation is high.

A portfolio of precooled Phius homes on different precooling optimized schedules and engaged in utility smart programs has the potential to flatten the load of the aggregate population-wide portfolio, reduce the ramp rate, further reduce peak by a little, and make use of on-site solar generation.

8.1.3 Conclusions and Recommendations

- Energy savings from PH principles increase based on HVAC-usage levels. This has the potential to significantly reduce the carbon footprint from residential new construction.
- A PH home could reduce peak load by about 30% in the Summer and over 50% in the Winter. Employing PH principles will shave and flex load at critical resource adequacy windows every day.
- Additional research and analysis is needed to build from the initial groundwork provided in this study, including:
    - More exploration is needed to assess dynamic and dispatchable flexible load possibilities beyond the brief precooling analysis involved in this study and should include solar-storage combinations.
    - More use of diversified prototypes should be explored in future studies as this study was limited to initial exploration of select principles and scenarios in a short timeframe. For example, future analysis should incorporate more of the PH principles (orientation, optimized windows and overhangs, and thermal mass).

8.2 Grid Impacts

8.2.1 Grid Element Loading

With lower energy use per PH household, one obvious result is that adding PH homes to a feeder will use less energy and reduce the peak load compared to the same number of added T24 homes. As a result, the conductor’s maximum loading will be lower. Building PH homes could allow more growth at the same level of distribution grid loading than building more T24 homes. Our SCE analysis showed that over 20% more PH homes than T24 homes could be added to our sample feeder without exceeding grid element loading limits. Each existing feeder has different capacity and loading benefits, but this could be one strategy for delaying upgrades or avoiding overloaded feeders.

Adding PH households, with their reduced load compared with T24 households, could also improve the grid's reliability and resiliency. Reduced loads per household would allow for more hosting capacity for EV charging and reduce stress on individual grid components.

8.2.2 Voltage

Voltage regulation in distribution systems ensures electrical equipment connected to the grid receives a stable and consistent voltage. Operating within a narrow voltage range prevents damage to appliances and electronics and maintains reliable power delivery to consumers, especially when load fluctuations occur on the line. It also helps protect against issues like overheating, reduced lifespan, and malfunctioning of electrical devices due to inconsistent voltage levels. Increased load density, line length, load variations, power factor, cable size, transformer reactance, motor starting, circuit design, distributed generation sources like solar PV and EVs, and more can lead to voltage fluctuations depending on the level of penetration.

In this study, the only difference in impacts to voltage between housing types is the impact from solar PV. The minimum voltage in the peak loading cases is slightly higher on feeders when PH homes are added instead of T24 homes. This is a direct result of the less load. Having higher voltage helps meet voltage regulation requirements, but the difference is small with all cases within the +/- 5% threshold of nominal. With the lower PH load, however, solar backfeed will be higher than that of the T24 equivalent and may exacerbate voltage issues. In the cases for this study, this was not an issue. Additionally, it is difficult to draw conclusions from this observation since the peak hour could change when real, diverse load shapes are used.

8.2.3 Conclusions and Recommendations

- Building PH homes versus conventional T24 homes will reduce feeder loads per household and delay the cost of feeder component upgrades
- Twenty percent more PH homes than T24 minimum homes could be added to an unconstrained feeder without exceeding maximum loading constraints, which would delay the need for substation upgrades.
- Adding PH with solar PV will increase the minimum voltage on a feeder compared to T24 homes with the same PV capacity, but still well within regulation specifications.
- Additional research on the benefits to grid reliability should be considered. Adding PH homes with their reduced load will reduce the impact on grid elements and also allow additional hosting capacity for EV charging.

8.3 Potential Future Work

Future research and analysis can build upon this study to fully understand the grid benefits of PH design in CA's energy code. This study demonstrates that there are many potential grid benefits worth further exploration. Thus, further PH comparisons to the T24 modeling platform should be undertaken. This should be done working closely with PHI and Phius modelers to identify gaps in the modeling and improvements to the approach. Suggestions for how future work can build upon this study are summarized below.

- **Expanded Model Responses:** More questions could be explored with these T24 and PH models. One extension could model the same houses in all California CZs. Before expanding the range, however, further exploration of household responses to additional controls (passive and active) should be undertaken. In this study, we briefly tested overhanging eaves, excessive thermal mass, and precooling conditions, but these were outside the scope of work. Our precooling exploration indicates a good alignment with active demand response programs and could open new program offerings.
- **Deeper comparison of PHI, Phius, and T24 modeling differences:** The primary aim of the current study was to explore the potential grid benefits from PH principles and to determine if deeper research and analysis should

be considered. With that charge, prescriptive parameters from the PHI and Phius code bases were aggregated to develop a more generic house based on these principles. This aggregation was necessary primarily due to differences and capability gaps between T24 and the respective PH modeling platforms. With the current study, we have demonstrated the grid impacts are potentially significant, so it will be critical to better compare the various PH and T24 modeling platforms to quantify differences and improve the code-based modeling platforms on both sides. This should directly involve the owners of the PH packages to demonstrate how they accurately model T24 as well.

- **Grid Reliability Modeling for PH:** In this study, we conducted a deterministic analysis to explore the impact of PH designs on the feeder level infrastructure. In addition to what we presented in this report, PH principles may provide additional significant reliability and resilience benefits when deployed in large scale due to their long thermal time constants. Furthermore, prevalent deployment of PH principles may increase the hosting capacity of distribution feeders to better accommodate electric vehicles (EVs) and PV generation.
    - **DER, Residential PV, and EV Accommodation in Distribution Feeders:** Because of the differences between PH and T24 houses load curves, when each is fully deployed in a feeder, the amount of EVs and PVs that can be added to those feeders without making any significant upgrades can be different. Additionally, this study confirmed that the location of new houses on the feeders has an impact on the capacity of feeders, which warrants further study to more clearly identify Distributed Energy Resource (DER) deployment impacts on distribution feeders. Comparing the capability of distribution feeders to accommodate EVs and PVs when the homes are PH rather than T24 is an important extension of the work in this study. For instance, representative feeders from different IOUs in California could be selected, and PVs and EVs accommodated in the distribution feeders assessed using power flow simulations. The difference between the capital investment needed for grid upgrades when PH is deployed could be quantified. The total potential ratepayer savings in California from deferred/avoided feeder upgrades could be extrapolated from the results of such a study.
- **Reliability**: A reliable power system is both resource-adequate and secure. The security aspect of reliability mainly depends on the infrastructure. Therefore, the demand side load benefits of PHs may not significantly impact grid security. On the other hand, load behavior affects the system's resource adequacy. The intermittent and stochastic behavior of renewable resources, as well as the increasing penetration of these resources on the California grid, may be a concern for the reliable operation of the grid. Intrinsic features of PHs, such as a long thermal time constant and the fact that they can maintain comfortable indoor temperatures for hours without operating heating or cooling, make them a very attractive resource for demand response. They can respond to grid events while minimizing customer discomfort. The flexibility of PHs to respond to resource fluctuations decreases the reliability-related risks of integrating more renewable resources into the grid. The effectiveness of utilizing PHs in demand response programs to enhance the grid's reliability is worth more in-depth investigation. The savings from avoided extra resource adequacy requirements can be estimated by performing a reliability study on the CAISO grid using power flow analysis and comparing T24 and PH new construction scenarios.
- **Resilience**: In recent years, extreme weather conditions such as heat waves and winter storms have occurred more frequently and have been causing grid emergency conditions (e.g., the winter storm Uri in Texas in 2021 and the heat waves in California in the summer of 2022). How PHs behave during these extreme weather conditions and how their behavior impacts the grid in these conditions in comparison to other houses (e.g., T24 houses) when they exist on a large scale is essential to understand through further modeling and analysis. Using stochastic modeling of the CAISO grid, the potential savings from deployment of Phius versus T24 during low probability high impact events can be estimated for California.

APPENDIX A. LITERATURE REVIEW REFERENCES

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