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Memorandum

Phase I – Summary of the Existing Literature: Grid Benefits of Passive Houses

To: Rory Cox, California Public Utilities Commission (CPUC)

From: Opinion Dynamics Evaluation Team

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Introduction and Research Objectives

California is a leader in using building codes to encourage energy-efficient building construction, and additions and alterations to, residential and nonresidential buildings. The 2019 California 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). The California Public Utilities Commission (CPUC) Energy Division is interested in how widespread deployment of Passive House construction, which could offer further energy savings and grid benefits above and beyond the 2019 Energy Code requirements, could offer benefits to the electric grid. More specifically, the CPUC is interested in achieving the following study objectives:

- 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
- Quantify the potential circuit-level grid benefits of widespread Passive House new construction in California

To ensure an informed and thoughtful approach, we structured our research efforts in two phases, as described below. The focus of the study is on residential single and multi-family new construction Passive House buildings in California.

- **Phase I: Establish Existing Knowledge Base.** The goal of Phase I is to develop an understanding of the current state of knowledge regarding potential grid benefits from Passive House construction.
- **Phase II: Grid Benefit Assessment.** The goal of Phase II is to expand on research from Phase I to quantify potential Passive House electric grid impacts. This effort will involve 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.

This memorandum presents findings from Phase I of the research effort.

Summary of Findings

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.

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, 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.

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, 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.

Research Methodology

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.

Detailed Findings

This section describes our research findings. 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.

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 House'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 1). 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 1. 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

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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.

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

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.

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.

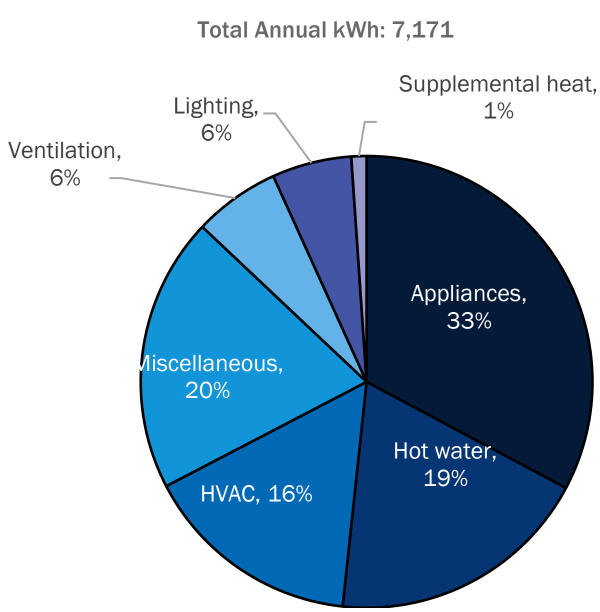
Impact of the Passive House Standard on Building Electric Load

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.

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 1 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 1. Passive House Energy Consumption

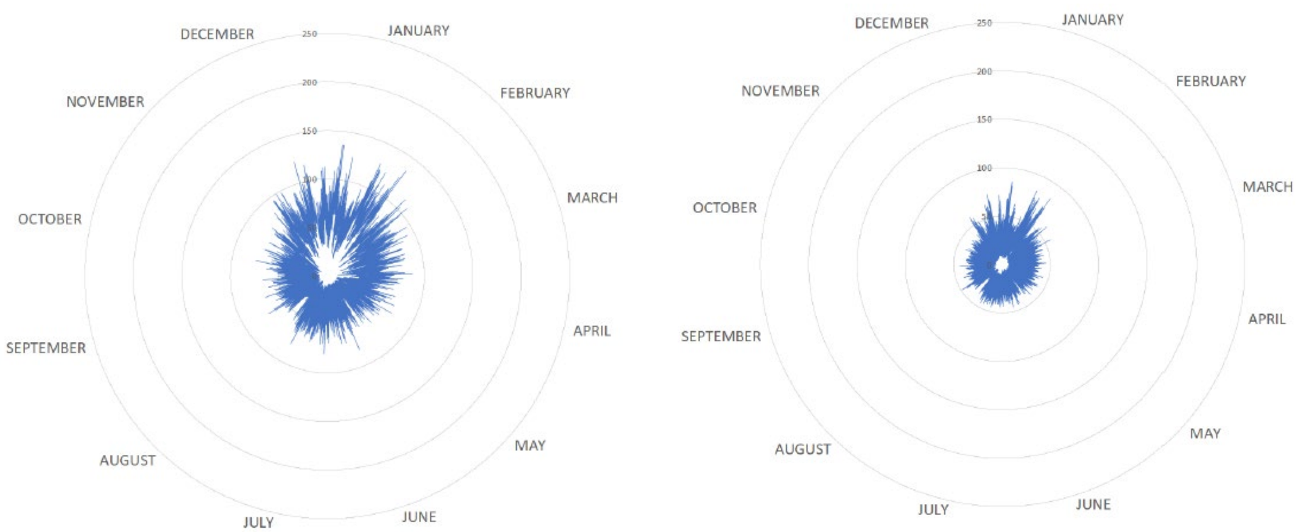


Annual Load

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[1], as shown in Figure 2. 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.

Figure 2. 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

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.

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

primary energy demand,[2] 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.[3] 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.

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 2 summarizes key details on the Passive and ZNE homes that were a part of our analysis.

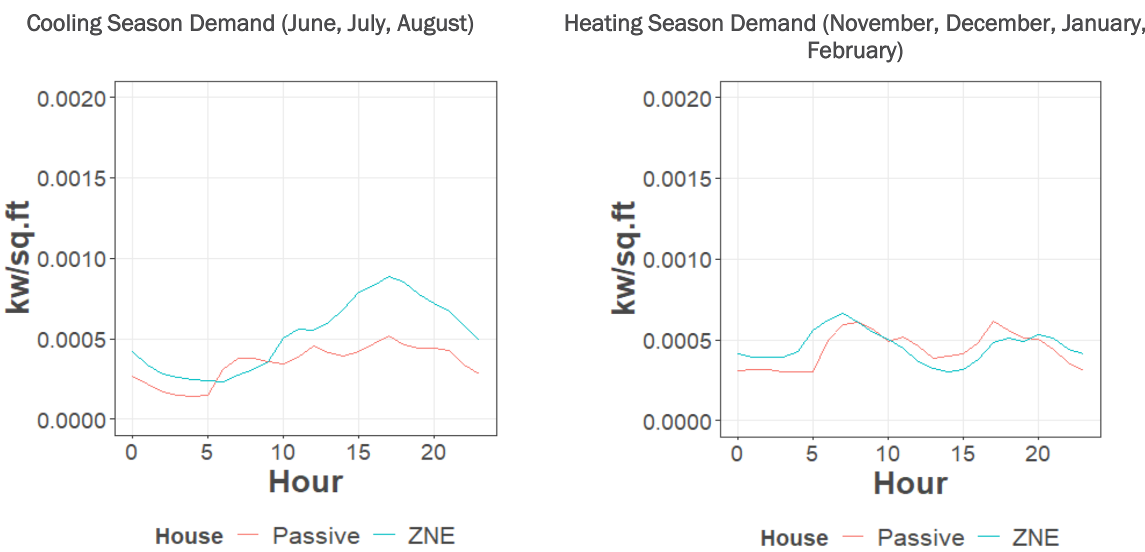
[2] Primary energy demand is the amount of energy that must be generated at the source to meet the total energy demand of a building.
[3] California has some of the most comprehensive and ambitious clean energy policies in the world. Senate Bill 100 commits California to get 100 percent of its electricity 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.

Table 2. 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 3).

Figure 3. Passive House and ZNE Seasonal Load Comparisons



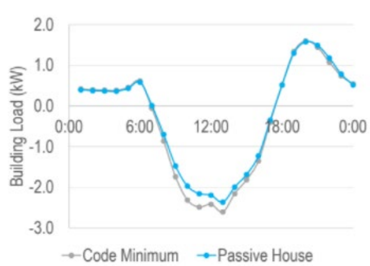
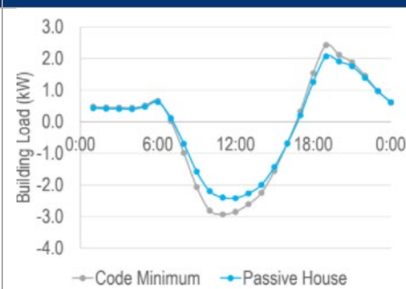
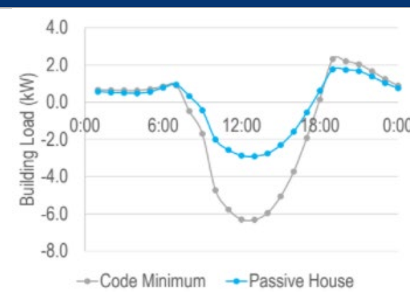
Interviewees also mentioned the seasonal impact of Passive House design on peak load. Several interviewees specifically noted that seasonal variation in solar output paired with electrification of space heating could eventually shift the peak load in California to winter. Interviewees mentioned that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

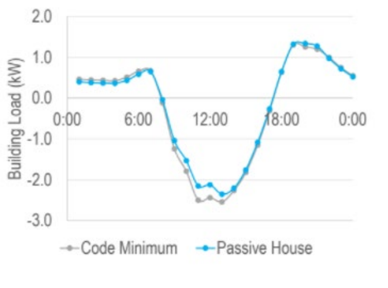
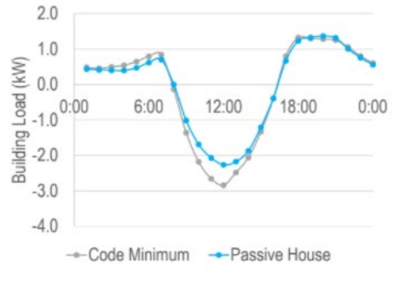
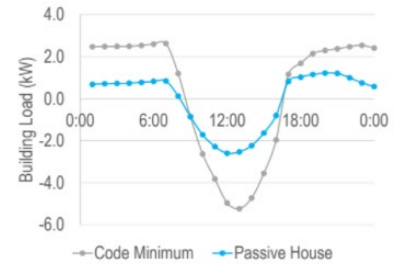
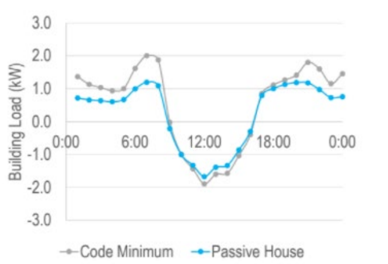
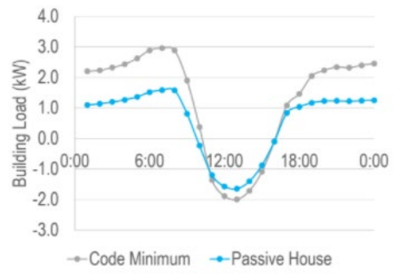
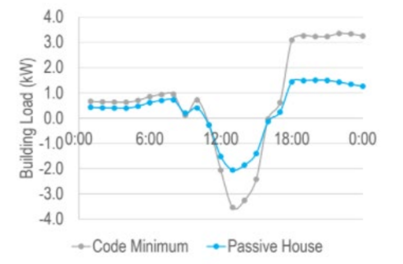
> *I think if let's say that we were talking about mostly Passive House buildings, as I just said earlier, Passive Houses have a very, very slow or low rate of change...If they're operated properly, they're going to stay at a much more modest temperature. Yes, of course, if you don't run the AC, while 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 4 reproduces the conference paper results. Interviews also confirmed that Passive House design reduces ramp rate compared to code-compliant construction.

Figure 4. 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%

Climate Zone	Coastal	Inland Valley	Inland Mountain
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.[4] Table 3 shows the 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 3. Load Factor Comparisons

Season	Climate	Code- Compliant ZNE Homes	Passive Houses
Summer system load factor	Coastal	14%	17%
	Inland valley	11%	14%

[4] 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.

Season	Climate	Code- Compliant ZNE Homes	Passive Houses
	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.

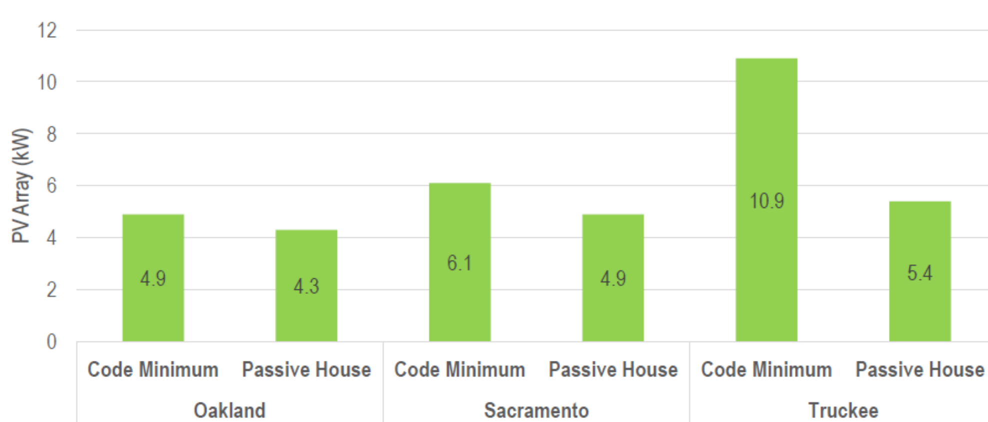
According to several interviewees, such interventions can be automated and, when applied at scale, can act as a reliable and dispatchable grid resource that reduces peak load by acting as energy storage for off-peak daytime solar generation.

> *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 5).

Figure 5. 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 6 below (reproduced from the case study) demonstrates the benefit of the Passive House design in reducing solar overproduction.

Figure 6. Comparison of Building Load and Solar Production of ZNE Baseline and Passive House Construction

Daily Profile – Baseline Building | Daily Profile – Passive House Building

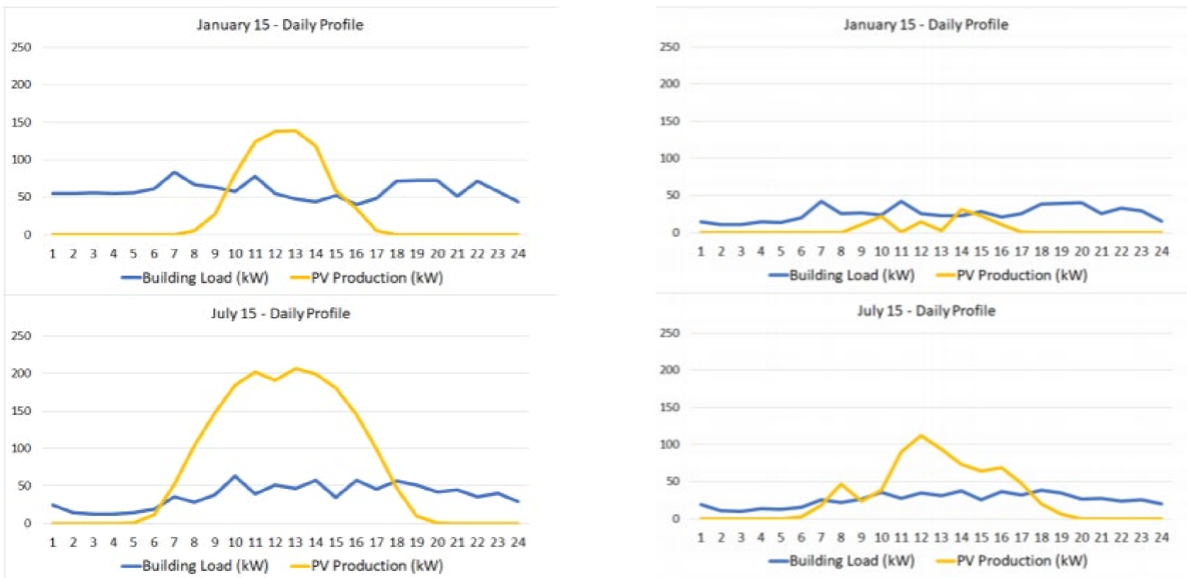


Figure reproduced from White and Lindburg (2020)

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).[5] 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) 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.

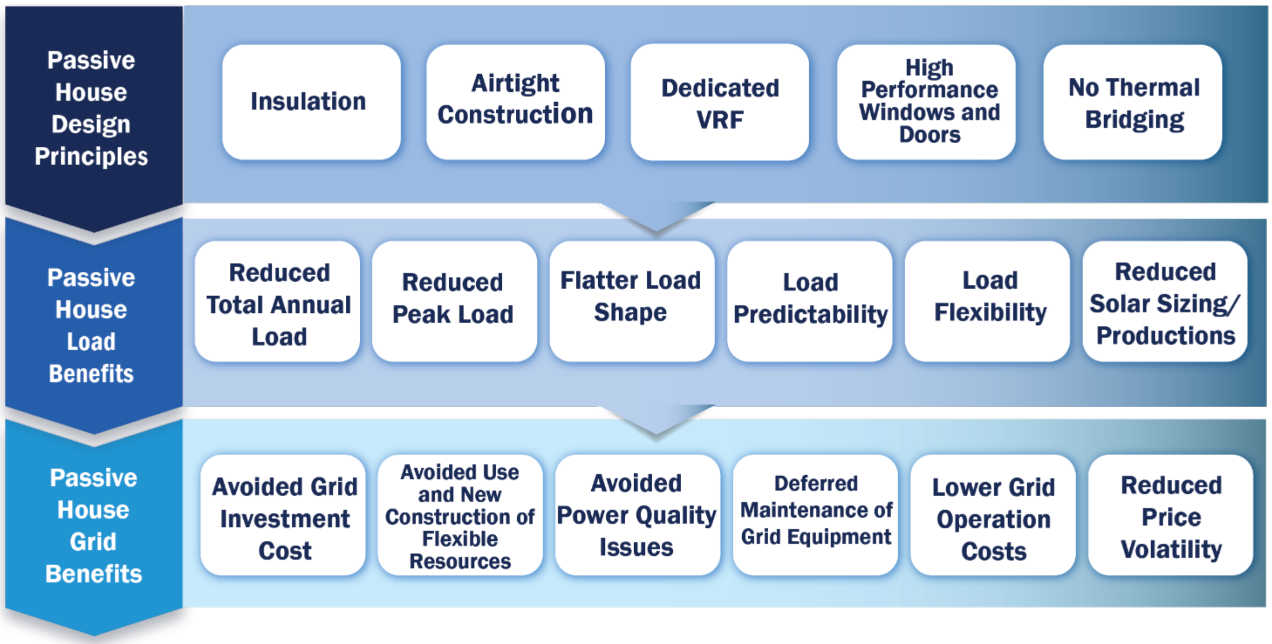
The steepening ramp associated with the duck curve is exacerbating the challenge of managing supply and demand on the California grid by increasing the need for additional flexible generation in order to maintain reliability. In response, California is pursuing multiple avenues for “flattening” the duck 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 7 below shows some of the potential grid benefits that our literature review identified as resulting from widespread deployment of Passive Houses:

[5] 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.”

Figure 7. 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.

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