DOCKETED	
Docket Number:	20-DECARB-01
Project Title:	Building Initiative for Low-Emissions Development (BUILD) Program
TN #:	239883
Document Title:	Attachment A to CALSSA's Public Comments on the BUILD Program Preliminary Design Document
Description:	N/A
Filer:	System
Organization:	California Solar & Storage Association
Submitter Role:	Public
Submission Date:	9/30/2021 11:40:13 AM
Docketed Date:	9/30/2021

Comment Received From: California Solar & Storage Association
Submitted On: 9/30/2021
Docket Number: 20-DECARB-01

Attachment A to CALSSA's Public Comments on the BUILD Program Preliminary Design Document

Additional submitted attachment is included below.

Assessment of GHG Reduction Technologies for Water Heating Electrification in California

J.R. Plaisted – Flagstaff Research

November 2020

Table of Contents

1 – Introduction & Summary Findings

As California looks to reduce greenhouse gas (GHG) emissions through a combination of renewable generation and electrification of end uses, this study investigates one of the largest sources in the built environment: water heating. While there has been a progressive trend towards electrification in appliances, including heat pumps for space conditioning and induction stovetops for cooking, water heating is the largest GHG emitter in many buildings and remains almost exclusively powered by natural gas in California.

To assess the potential for GHG reduction from the electrification of water heating statewide, we evaluated:

- Solar water heating (SWH) with electric backup
- Heat pump water heaters (HPWH) powered by grid electricity
- Heat pump water heaters with solar photovoltaics (PV)

Tankless natural gas and solar water heating with gas backup were also modeled for comparison because they are other common options for upgrades from traditional water tanks heated by gas. We developed thirteen different configurations of these technologies deployed either standalone or together in tandem for both residential and multifamily commercial markets.[1] Each configuration was evaluated for cost and performance in all 16 California climate zones covering 14 separate utility tariffs. Detailed hourly simulation results were compiled into the following key metrics to assess the potential of each technology configuration across geographies and market segments:

- Annual GHG emissions
- Annual operating cost
- Simple payback
- GHG incentive targets

Electricity consumption varies by technology and region. Heat pumps run on electricity and include backup electric resistance heating elements that are used when the ambient air temperature is too low for heat pump operation or increased hot water demand requires faster recovery. Solar water heating systems with electric backup also include backup electric resistance heating elements that are used when the solar resource is not sufficient to heat water. Because the conversion of solar energy to heated water is significantly more efficient than a heat pump compressor loop, the electric element is used less often for solar than for a heat pump, resulting in lower emissions. However, solar systems are traditionally more

[1] Note that "residential" as used in this report refers to single-family residential. Multifamily residential is referred to as "multifamily" or "multifamily commercial." Solar water heating can be a good option for small commercial customers such as laundromats, but the majority of "commercial" activity is multifamily housing.

expensive than heat pumps on an installed cost basis. If the federal Investment Tax Credit (ITC) for solar is extended, the installed costs become relatively close in warm climate configurations.

Solar water heating for multifamily housing presents one of the best options for water heating electrification, either with electric element backup or in combination with a heat pump. These systems typically include large hot water tanks that can store enough heat from the sun to meet 24 hours of hot water demand on most days.

Powering the electric backup with onsite PV has the lowest emissions, but represents the most expensive option. If a customer is not otherwise installing a PV system, installing enough PV only to power a heat pump is generally not an option because it is difficult to absorb the fixed costs of a PV installation for such a small amount of capacity.[2] Installing enough PV for the whole building along with a heat pump requires more investment than most customers are willing to consider when upgrading a water heating system. Heat pumps with incremental PV are therefore only a practical option for new construction or significant remodels. SWH with incremental PV is also an option to fully eliminate GHG emissions in these instances. Although not explicitly modeled, such a configuration requires only half as much PV due to the lower electric usage in SWH systems.

Installing solar water heating without changing the backup heat source from gas to electric can be the best option for near-term GHG reduction because it avoids the cost of onsite electrical upgrades and can immediately reduce natural gas consumption for water heating by 78%. Since this study focuses primarily on electrification of water heating, solar retrofits to gas heaters are modeled only for comparison purposes.

Table 1 contains a summary of key findings. While the upfront costs of SWH are higher, the annual operating costs are significantly lower and come with deeper GHG reductions. Additionally, SWH almost completely avoids the use of electricity during summer peak periods when switching from gas to electricity.

[2] The average PV capacity required to net out heat pump operation in the study is 1 kW in residential and 12 kW in multifamily/commercial.

Table 1. Summary of average statewide results for HPWH and SWH in water heating applications.

	Residential Water Heating		Multifamily/Commercial Water Heating	
	HPWH	SWH	HPWH	SWH
Installed Cost[3]	$3,014	$5,263 - $7,945	$24,000	$38,071-$50,170
Average Change in Utility Bill[4]	$133 increase	$76 decrease	$349 decrease	$1,743 decrease
GHG Reduction[5]	81%	91%	81%	90%
Energy Factor[6]	2.0	4.3	2.3	4.5
Peak Electricity Consumption[7]	88 kWh	6 kWh	1,121 kWh	51 kWh

More detailed findings of the study include the following.

Solar water heating and heat pumps offer significant GHG savings

Table 2 outlines the average statewide GHG reduction from each of the studied configurations across the three market segments studied as compared to traditional natural gas baselines. For residential and multifamily water heating, HPWH technologies reduce GHG emissions by 81%. HPWH reductions assume no refrigerant loss during operation and full recovery in recycling the HPWH units at end of life. Failure to do so could reduce GHG savings by an estimated 10 - 15% from the study findings.

When SWH is combined with electric backup, GHG reductions reach 90-91%, which is the highest level of reduction found in our study with the deployment of a single technology.

The addition of onsite solar PV to source HPWH or SWH electrical usage makes it possible to eliminate GHG emissions.

---

[3] Reflects current market installation costs excluding lifetime maintenance & replacement. The range for SWH represents the difference between warm and cold climate configurations and does not include federal ITC.
[4] Change reflects the statewide average increase or decrease in customer utility bill when changing from the baseline gas water heater.
[5] GHG reductions do not include the negative potential effects of refrigerant loss, which are discussed later in section 9 of the study.
[6] Energy Factor is defined by the total delivered energy to the load divided by total electricity consumption. This energy factor departs from standard rated Energy Factors (EF) as it accounts for resistance element consumption during periods of high load and during low temperature conditions.
[7] Total electrical consumption during utility peak summertime period, which is 4:00 – 9:00 PM June to September for most utilities.

Table 2. Average statewide reduction in annual GHG emissions by technology & market segment

	Residential Water Heating	Multifamily/Commercial Water Heating	Commercial Pool Heating
HPWH	81%	81%	78%
SWH + Electric	91%	90%	89%
HPWH + PV	100%	100%	-

Our evaluation of commercial pool heating showed that the use of HPWH technology in this segment can achieve a 78% reduction in GHG emissions over gas boilers, but as a practical measure will often be limited in contribution by the electrical service supplied to the building. To achieve the reported level of GHG reduction, the building electrical demand would increase by 45-60 kW, requiring an upgrade of service and transformers in some cases. Lastly, we evaluated a hybrid SWH + Electric scenario that achieved an 89% reduction in GHG when paired with heat pump backup with the additional benefit of SWH decreasing peak coincident summer loads that would otherwise result in increased demand charges.

SWH technology can provide a 52% reduction in GHG emissions when retrofitted onto existing gas boilers without electrification. GHG reduction is lower for this approach but the cost is also much lower with the use of unglazed polymer solar collectors.

Utility bill savings from water heating electrification are mostly limited to multifamily markets and residential solar water heating

In the residential segment, heat pumps cannot overcome the low cost of natural gas in California for the markets studied. Figure 1 shows the annual savings of heat pumps and solar water heaters when replacing natural gas heaters across California's 16 climate zones. In the best performing market, HPWH's come within $7 of break even against natural gas and in the worst the consumer bill increased by $265. As a statewide average, the deployment of heat pumps into the residential market results in an average increase of $133 to the annual water heating bill for consumers. SWH with electric backup performs better, with the poorest performing market resulting in an annual bill increase of $31 and the best market providing a savings of $187. As a statewide average, the deployment of solar water heaters into the residential market results in an average annual savings of $76. In contrast, SWH technologies displacing natural gas provided annual savings ranging from a low of $107 to a high of $272 with a statewide average of $192 in annual savings.

The primary driver for reduced or negative annual savings in the residential segment is simple: natural gas is incredibly cheap for California homeowners. The average statewide cost of natural gas in the study was $1.59/therm, which is equivalent to $0.05/kWh-thermal. In comparison, the blended electricity cost is five times higher. To provide any annual savings, the efficiency of water heating technologies must exceed that of natural gas fired tanks beyond this ratio. That does not occur with HPWH in the residential segment.

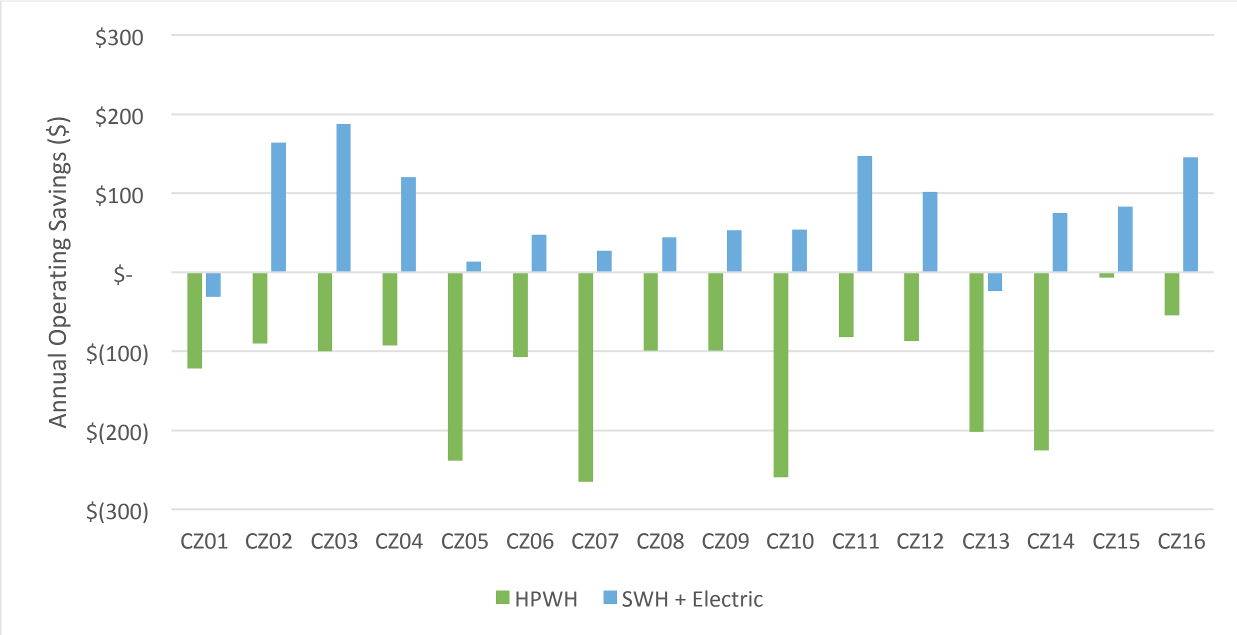


Figure 1. Annual savings realized from operating residential HPWH and SWH + Electric as compared to storage type gas water heaters across California's 16 climate zones[8]

Multifamily/commercial markets have the potential to provide much more robust annual savings using HPWH and SWH with electric backup. For SWH, modeled savings ranged from $695 to $2,545 statewide, with an average of $1,743. HPWH ranged from a cost increase of $961 to savings of $1,532, with an average of $349 in savings. This is possible because the lower energy charges in commercial tariffs compete favorably with the operating costs of gas heaters.

Solar water heating systems avoid peak demand periods for electricity use

Load shaping is essential in water heating electrification. As the fuel for this end use is shifted to electricity, it will cause problems for the electric grid if a significant amount of the new electricity consumption occurs during time-of-use (TOU) peak hours. Detailed hourly modeling shows that SWH technologies use little to no energy during peak summer demand periods.

Figure 2 shows annual heat maps of electrical usage for SWH with electric backup and HPWH units in Climate Zone 3, which is representative of other climates in this behavior. During the 4:00 – 9:00 PM summer peak period, the SWH system consumes only 1 kWh compared to HPWH consumption of 94 kWh in the same period. The driver behind this behavior is that the clear hot summer days that drive peak load on the grid also drive peak thermal production in SWH systems. The result is that SWH technologies with their built-in thermal storage are inherently peak avoidant. When electricity is consumed by SWH systems for backup heating, it is usually for thermal recovery during cloudy winter days.

[8] See Appendix A for a map of climate zones.

Results are similar for the commercial configurations of SWH and HPWH technologies as outlined in Figure 3. During the peak period, a standard SWH system consumes 33 kWh compared to 1,274 kWh for HPWH. For commercial buildings that typically see their peak demand during this period, such low energy usage illustrates the potential for load shaping with SWH to avoid increased building demand charges.

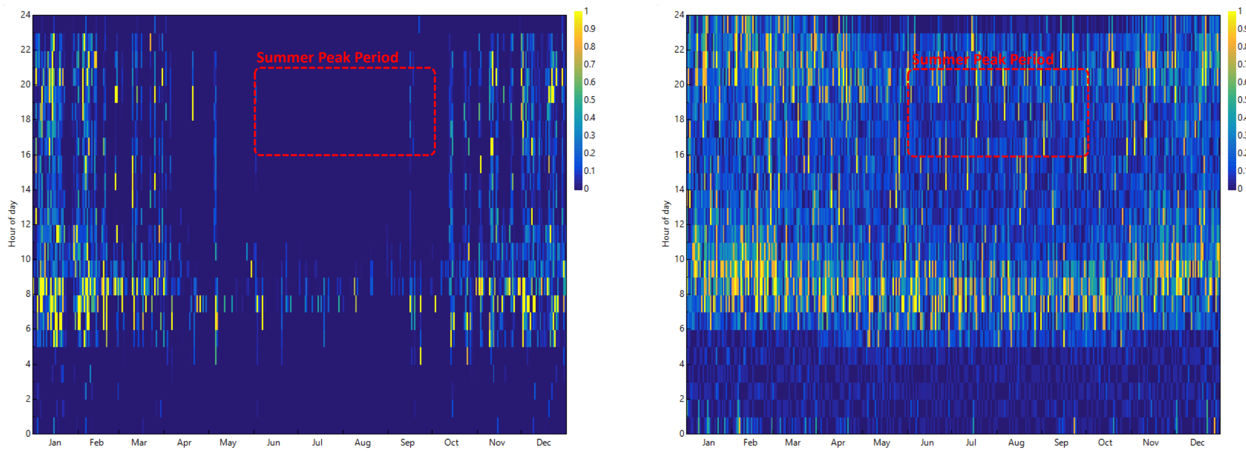


Figure 2. Heat maps of residential electricity use for SWH + Electric (left) and HPWH (right) in Climate Zone 3. The summer peak TOU period is indicated. Legend is scaled with a peak of 1 kWh.

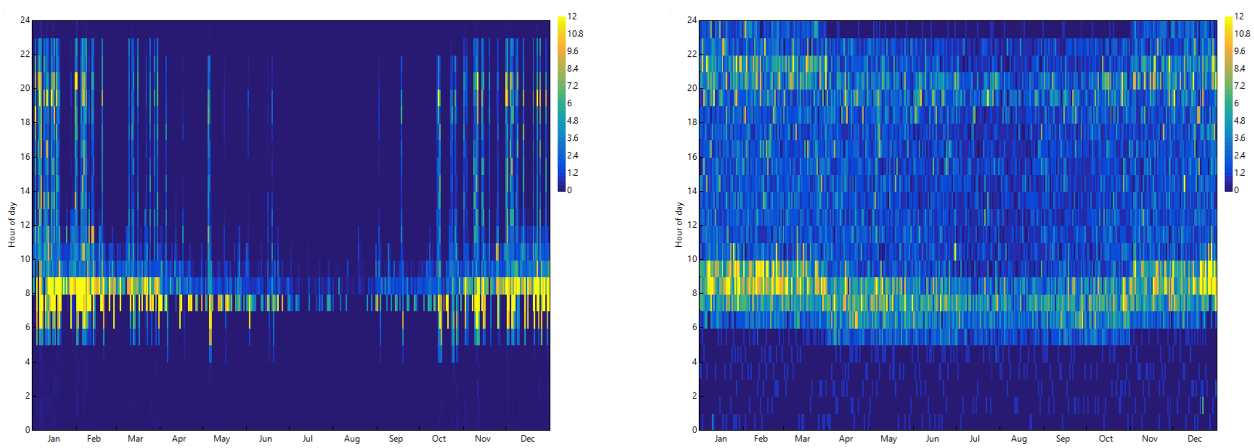


Figure 3. Heat maps of energy use for multifamily/commercial SWH + Electric (left) and HPWH (right) in Climate Zone 3. Legend is scaled with a peak of 12 kWh.

The best technology varies by geography and market segment

Our results on target GHG incentive levels indicate that each market segment, geography, and level of market maturity has a favored technology. No single technology addresses all markets in the most efficient manner. Table 3 summarizes our findings on the average GHG incentive levels necessary to drive consumer adoption in a mature market scenario across markets.

Target GHG incentive levels were determined by calculating the incentive amount necessary to create a 10 year simple payback in residential and 5 year in multifamily commercial. The incentive was then normalized by dividing it by the GHG emissions saved over the 25 year analysis period to yield a technology agnostic $/ton GHG reduction metric. Technology configurations with lower GHG incentives represent the lowest cost of marginal GHG reduction for a market sector and are bolded.

Table 3. Average state GHG incentives needed for customer adoption in mature markets ($/metric ton). Leading technology configurations are highlighted.

	Residential Water Heating	Multifamily Commercial Water Heating	Commercial Pool Heating
SWH + Electric	$133	**$28**	**$38**
HPWH	-	$90	**$36**
HPWH + PV[9]	**$94**	$122	-

[9] Assumes that the incremental PV for HPWH is augmenting an existing design as would occur in the new construction market.

2 – Background & Market Opportunity

To illustrate the impact of water heating on GHG emissions for the built environment, we modeled a 2,500 ft^2 home built to modern 2016 California Title 24 building standards using Energy Plus modeling software[10] from the US Department of Energy. The results for two representative California climate zones are illustrated in Figure 4.

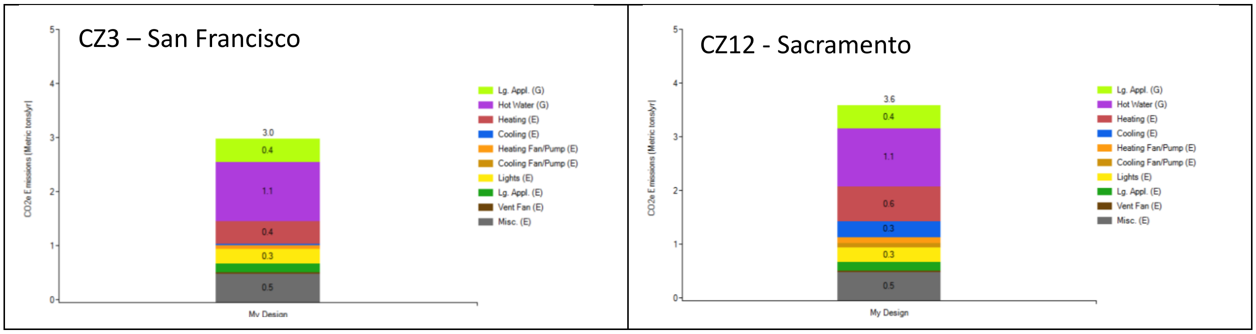
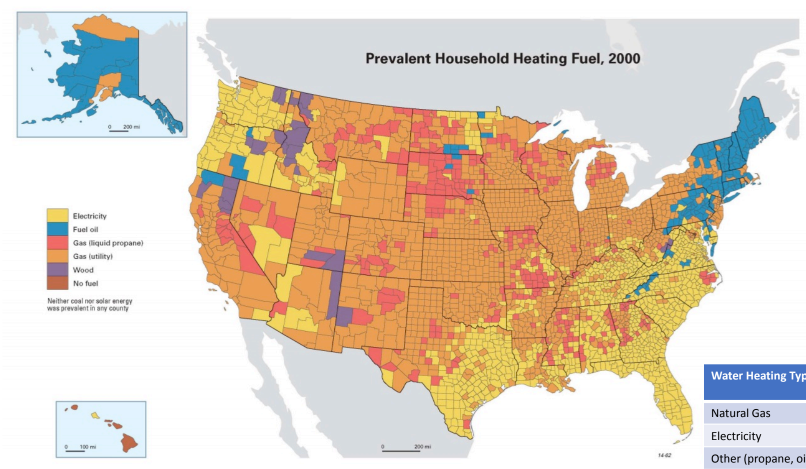


Figure 4. Breakout of carbon emissions by end use for 2,500 ft2 home in two California climate zones.

With the move to more efficient building envelopes, high efficiency HVAC systems, and the predominance of LED lighting, water heating has emerged as one of the largest GHG sources in residential buildings. Depending on climate, water heating can comprise 25-35% of the overall carbon footprint for a modern residential home. Within California, gas water heaters represent the overwhelming majority of installations. The number of installed gas units provides for significant GHG reduction potential in California as well as a larger national market (Figure 5) to support the scale necessary for transformational technologies to reach cost effectiveness.



Water Heating Type	Existing Households
Natural Gas	56.3 Million
Electricity	55.1 Million
Other (propane, oil, …)	6.8 Million
Total	118.2 Million

Figure 5. Distribution of water heating fuels nationally by county[11] and market share by existing household.[12]

[10] The simulations were specified as having the cooktop, dryer, and water heater as gas appliances. All other appliances, including the heating/cooling system were electric, which is common for new construction in most climate zones.

[11] https://www.census.gov/population/www/cen2000/censusatlas/pdf/14_Housing.pdf

3 – Evaluated Technologies

With storage tank gas heaters and boilers being predominant in California for both residential and commercial applications, we selected a set of technically mature GHG reduction technologies that can be deployed in the market today. The sections below summarize each of the technologies selected for evaluation.

- **Condensing Gas Tankless:** While traditional storage tank heaters have efficiencies of 67% (0.67 UEF[13]), newer condensing tankless units have operating efficiencies up to 94%. Among the technologies evaluated in this study, this is the only one that has seen significant market adoption. Gas Tankless is evaluated for comparison purposes only and is not an electrification strategy.
- **Heat Pump Water Heaters:** After several generations of products released over the past decade with varying degrees of performance (Shapiro and Puttagunta 2016, Sparn et al. 2014, Amarnath and Bush 2012), the current 'all-in-one' products (heat pump + tank combined in a single device) available from leading US manufacturers are typical of what is in US market today. This product class displays a typical UEF of 3.5 using electricity as the fuel source.
- **Solar Water Heating:** Solar water heating systems are available in many forms including Integral Collector Storage, thermosiphon, and active systems based on open-loop or closed-loop designs. While all system types are commercially viable and have been deployed at scale globally, we selected active closed loop systems for evaluation as they have a price to performance ratio similar to the other product classes, but are applicable to all California climate zones. This product class displays a high EF on the range of 3.0 – 6.5 in California depending on climate and application.
- **Solar Thermal Systems for Pool Heating:** Traditionally based on low-cost unglazed polymeric collectors with simple controls and no need for storage,[14] solar thermal pool heating is often very cost effective and widespread.
- **Heat Pump Pool Heaters:** While based on the same thermodynamic principle as heat pump water heaters, these systems have higher efficiencies displaying a EF equivalent in the 3.0 – 6.0 range. Similar to solar thermal systems, heat pumps require no attached storage in this application.

---

[12] https://www.eia.gov/consumption/residential/data/2015/hc/php/hc1.6.php

[13] The Uniform Energy Factor (UEF) is a measure of water heater efficiency developed by the US Department of Energy and represents the thermodynamic efficiency of the unit as a fraction of thermal energy delivered divided by the source energy input to the unit. For heat pump water heaters the UEF is equivalent to the coefficient of performance (COP) with the inclusion of standby losses from the tank.

[14] In pool heating applications for both solar & heat pumps, the several thousands of gallons of water in the pool acts as thermal storage and can be allowed to float 2-5 °F to store a day's worth of energy generation.

Natural Gas Water Heaters

Figure 6. Examples of 40 gallon residential tank gas heater (left), 199 kBTU/hr residential condensing tankless (center), and 75 gallon commercial (right) gas tank water heaters used for analysis.

The predominant baselines for residential and multifamily water heating in California are the gas storage heaters shown in Figure 6. Current residential units operate with a Uniform Energy Factor (UEF) of 0.67, meaning that 67% of the supplied energy is delivered as hot water. Modern condensing tankless units can increase the UEF to 0.94 and are evaluated as a GHG reduction measure alongside solar thermal and heat pump technologies.

Heat Pump Water Heaters

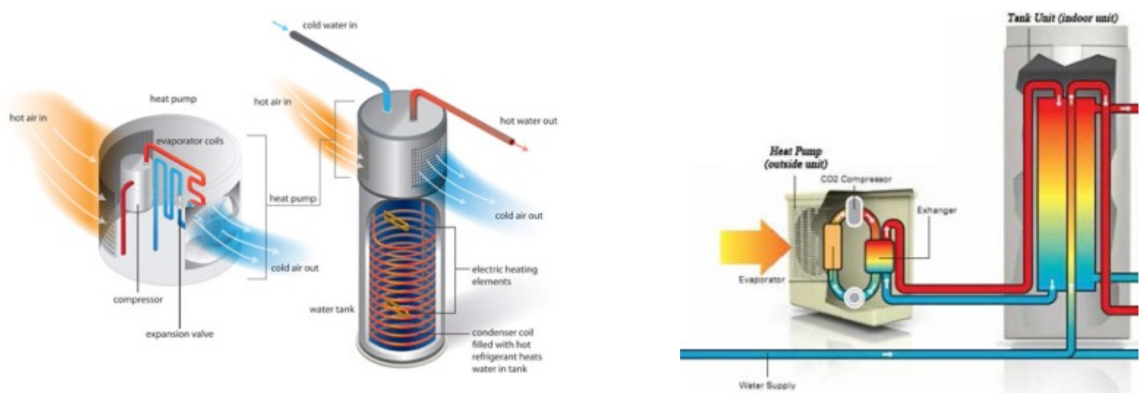


Figure 7. Residential HPWH system types present in US market. Cutaway diagrams of 'All-in-One' (left) & EcoCute™ 'split system' (right).

Heat Pump Water Heaters (HPWH) currently in the US market come in one of two variations: the 'all-in-one' design where the heat pump and storage tank are integrated into a single unit and the 'split system' where the heat pump and the storage tank are installed as separate units. While most heat pumps operate on R134a or R410a refrigerants, there are variants of the split systems referred to as EcoCute™ that are based on low GHG CO_2 refrigerants and capable of high performance in cold climates, but at increased cost. Based on current price points and market share, we selected the all-in-one HPWH style for both residential & commercial water heating applications. Figure 8 shows units representative of the residential & commercial all-in-one units used in the analysis.

Figure 8. Examples of 50 gallon residential HPWH (left) and 119 gallon commercial HPWH (right) used for analysis.

Solar Thermal Systems for Water Heating

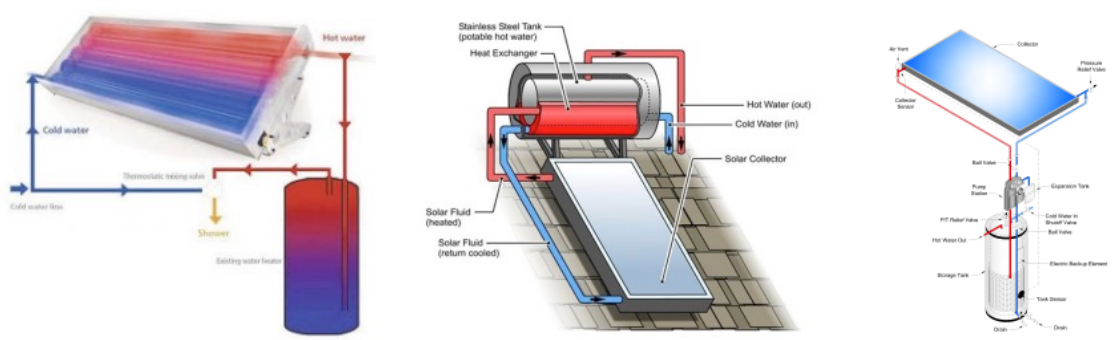


Figure 9. Common styles of solar water heating systems. Integral Collector Storage (left), thermosiphon (middle), active closed-loop (right).

Several styles of solar water heating systems have been successfully commercialized over the past 50 years. These range from passive Integral Collector Storage (ICS) and thermosiphon system with no moving parts to active systems containing circulating pumps and controls (Figure 9). Passive system variants have found broad adoption from the mild Mediterranean climates to Australia and Asia. Such systems are also common in the mild coastal climates of California that do not experience hard-freeze conditions and have good solar resources. Active systems have higher price points as a result of additional components, but typically provide higher performance levels and the possibility to operate in hard-freeze climates. As a result, these systems have found popularity in Europe and the US including the varied climates of California.

While both passive and active systems provide similar price to performance ratios, we standardized on closed-loop active systems as they can reliably perform in all 16 California climate zones and readily scale from single panel residential applications to the dozen or more required for multifamily. Figure 10 shows typical rooftop installations for both residential and multifamily applications.

Figure 10. Examples of installed solar thermal panels in residential (left) and commercial or multifamily (right).

Solar Thermal Systems for Pool Heating

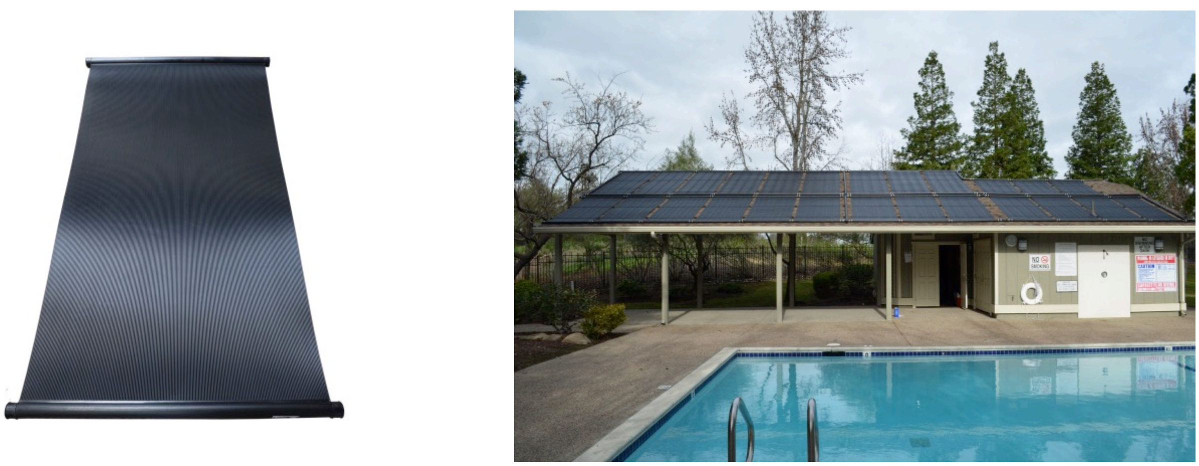


Figure 11. Typical uninsulated polymer pool panel (left) and installed commercial system (right).

Unlike water heating applications that require collectors to operate in 150+ degree F high temperature conditions, pool heating is a low temperature 80 degree F application that employs low-cost unglazed polymer collectors with simplified mounting structures (Figure 11). In these systems, pool water is directly circulated through the collectors and no additional storage is necessary. In hard freeze climates, the solar array is isolated and drained for the winter season.

Heat Pump Pool Heaters

Heat pump pool heaters operate on the same refrigerant cycle as heat pump water heaters, but at much higher thermal capacity and without any storage component. Units for these applications often have capacities of ten or twenty times those of their water heating counterparts and as a result of the large air volumes being circulated, they are almost always located outdoors. Figure 15 shows a typical 50kW-thermal version of an outdoor unit used for pool heating applications.

Figure 12. 50 kW-thermal commercial pool heat pump heater.

4 – Assumptions on System Configurations and Costs

System configurations were developed for each of the market segments: residential water heating, multifamily water heating, and commercial pool heating. Within each market, several different configurations of each technology and sometimes combinations of technologies were evaluated. Solar water heating was evaluated with electric backup for the main analysis of water heating electrification, but was also modeled with gas tank and tankless backup for comparison purposes. Heat pump water heaters were evaluated using utility sourced electricity as well as site sourced electricity from solar PV. For each segment and configuration, we defined an appropriate equipment set to be simulated as well as the underlying cost assumptions using available data for both the current market condition and a reduced cost mature market scenario as defined in the sections below.

Residential Water Heating

Our assumptions for this segment were based on a typical 2,500 ft^2 residential home with 2-3 occupants using a combined 55 gallons per day (GPD) of hot water. This corresponds to the medium draw profile in the UEF rating system and is expected to be representative of the average California home. Based on this daily usage, the configurations in Table 4 were evaluated.

Table 4. Specific technologies evaluated for residential applications.

Technology	Description
Gas Tank	• 40 gallon gas storage water heater • 40,000 BTU/hr recovery rate, 0.67 UEF
Gas Tankless	• Fully condensing tankless water heater • 199,000 BTU/hr recovery rate, 0.94 UEF
HP	• 50 gallon all-in-one heat pump water heater • 1.2 kW-thermal heat pump capacity, 4.5 kW backup elements
SWH (Warm Climate)	• 80 gallon solar storage tank with 4.5 kW backup element • Single 4' x 10' selective surface flat plate solar collector • Active closed-loop glycol configuration
SWH (Cold Climate)	• 80 gallon solar storage tank with 4.5 kW backup element • Two 4' x 8' selective surface flat plate solar collectors • Active closed-loop glycol configuration
PV	• 1 kW of mono-Si modules with 97.5% efficient inverter

While gas storage and gas tankless were simulated as standalone solutions, solar thermal and heat pumps were assessed with different backup fuel sources as indicated in Table 5.

Table 5. Evaluated backup configurations for solar water heating & heat pump water heaters.

Configuration	Description
SHW + Gas Tank	• Solar Thermal solution with gas storage backup
SWH + Gas Tankless	• Solar Thermal solution with gas tankless backup
SWH + Electric	• Solar Thermal solution with tank integrated 4.5 kW element backup
HPWH	• Heat pump using utility grid sourced electricity
HPWH + PV	• Heat Pump using site sourced solar PV electricity with grid backup

Initial costs for each configuration were estimated from available sources in terms of both equipment cost and total installed price. In addition to current market pricing, we estimated a mature market scenario where market volumes drove equipment pricing down by 15% and installation costs were assumed to be equal to the capital equipment costs. A summary of initial installation costs for each configuration is shown in Figure 13 for both the current and mature market cases. Details for each configuration follow.

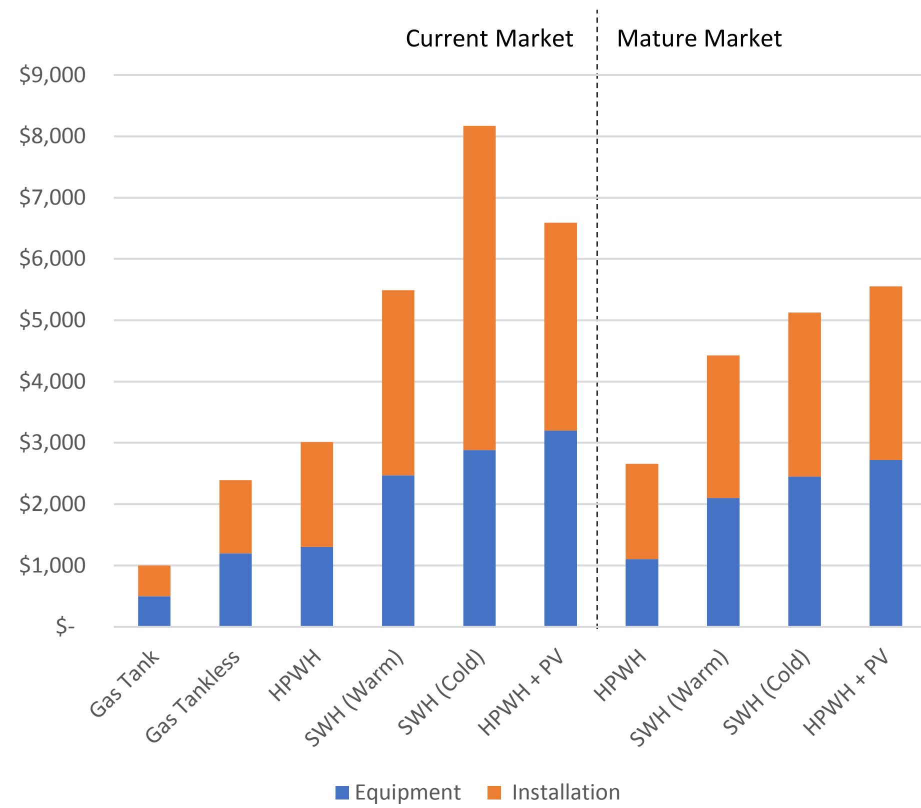


Figure 13. Current and mature market pricing for residential technologies and configurations.

In the case of solar water heating, we evaluated current market costs from the CSI-Thermal program during the past 3 years for both warm and cold climate configurations. As indicated in

Figure 14, which shows the full CSI-Thermal dataset of all residential systems within the period, the analysis resulted in a median installed cost of $37.27/therm or $5,263 for the warm climate configuration and $51.46/therm with a system cost of $7,945 for the cold climate configuration.[15] As an indication that mature market pricing is achievable, there have been systems installed at or below mature market pricing within the current CSI-Thermal program. Current market equipment costs for each configuration were provided by a leading manufacturer supplying equipment the program installers.

Figure 14. Residential installed cost data from California CSI-Thermal database.

For heat pump water heaters, we evaluated equipment pricing from multiple big box retailers yielding an average contractor equipment price of $1,299. Current market installation costs were taken from a market study performed by ADM Associates (ADM Associates 2016) that found an average installation cost of $1,265 in the Sacramento area where heat pumps are replacing existing electric resistance heaters. The combined installed cost of $3,014 includes

[15] For the SWH + Electric configuration, we included an incremental charge of $225 for materials & labor to run 240 VAC service to the water heater location as this is within the scope of a C-46 solar contractor.

the cost of running a 240 VAC line from the main panel.[16] It should be noted that we are not assuming any costs related to site specific installation constraints that would include items like main panel upgrades or ducting for space constrained systems that would significantly increase the installation costs when encountered.

The cost of the photovoltaic system in the HPWH + PV configuration was estimated at $3.80/W-STC based on 2019 residential cost data for the California market from LBNL Tracking the Sun report (Barbose and Darghouth 2019).

Equipment costs of gas storage and tankless heaters were similarly estimated from big box equipment pricing of $499 and $1,076 respectively and double that for turnkey installed costs of $998 and $2,152. This pricing was not reduced for the mature market scenario as both technologies already have achieved mature market positions.

Multifamily Water Heating

While there is a wide variation in multifamily units ranging from small duplexes up to 200+ unit high-rises, we selected a 20 unit low-rise apartment complex with a central hot water system for the analysis. This building size is large enough to accurately capture the general economics of multifamily water heating and is representative of the broader class of buildings. The water heating draw was determined based on the ASHRAE service water heating manual (ASHRAE 2015) at 42 gallons per day per unit or 840 gallons per day for the building. Based on this daily draw level, the configurations in Table 6 were evaluated.

Table 6. Specific technologies evaluated for multifamily applications.

Technology	Description
Gas Tank	• Two 75 gallon commercial gas storage water heaters • 75,000 BTU/hr recovery rate
HPWH	• Two 119 gallon commercial all-in-one heat pump water heaters • 10 kW-thermal heat pump, 12 kW backup element
SWH (Warm Climate)	• Twelve 4' x 10' selective surface flat plate solar collectors • 600 gallon unpressurized tank with load-side heat exchanger • Active closed-loop drainback configuration
SWH (Cold Climate)	• Sixteen 4' x 10' selective surface flat plate solar collectors • 600 gallon unpressurized tank with load-side heat exchanger • Active closed-loop drainback configuration
PV	• 12 kW of mono-Si modules with 97.5% efficient inverter

[16] When replacing a gas heater with a 4.5 kW electric heater, 240 VAC service must be brought to the water heater location for $450. This cost is estimated as twice that of the solar installation since C-36 plumbing contractors cannot run high voltage lines and thus subcontract the work.

Four separate configurations of solar thermal and heat pump technologies were assessed for the commercial segment as outlined in Table 7.

Table 7. Evaluated backup configurations for solar thermal and heat pumps.

Configuration	Description
SWH + Gas Tank	• Solar Thermal solution with gas tank backup
SWH + Electric	• Solar Thermal solution using 120 gallon auxiliary tank with 12 kW resistance element backup
HPWH	• Heat pump using grid sourced electricity
HPWH + PV	• Heat Pump using site sourced solar PV electricity

Similar to the residential segment, initial costs for each technology and configuration were estimated from available sources in terms of equipment cost and total installed price. In the same manner as residential, we assumed a mature market 15% cost reduction in equipment and an installation cost equal to the equipment cost. A summary of these costs for each configuration is shown in Figure 15 for both the current and mature market cases. Details of each cost buildup follow.

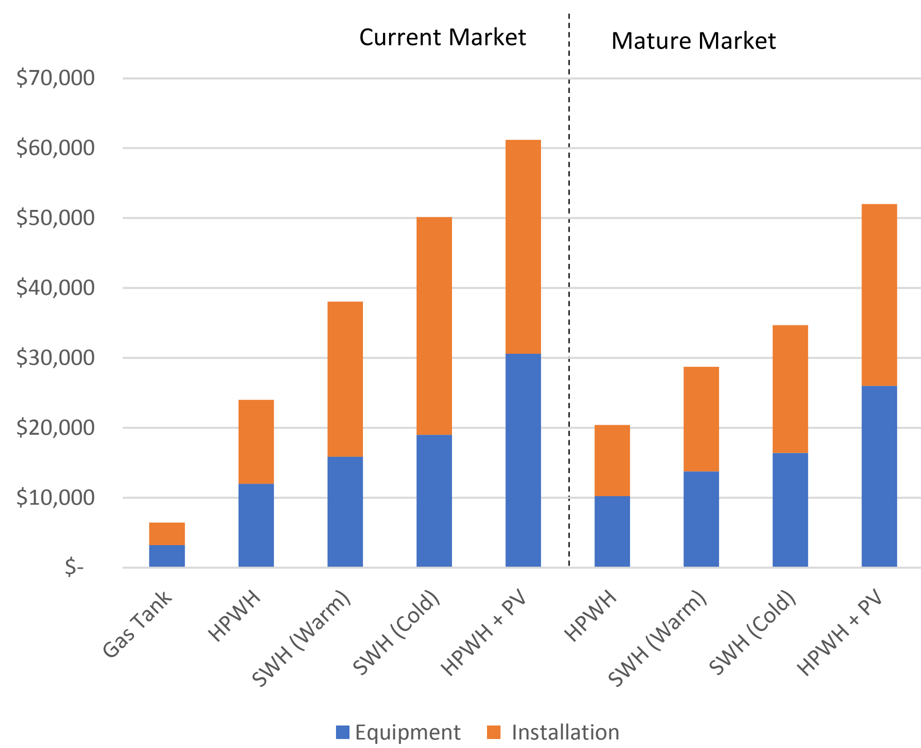


Figure 15. Current and mature market pricing for multifamily technologies and configurations.

For solar water heating technologies, we evaluated current installation costs from the CSI-Thermal program during the past 3 years for active closed-loop systems in both warm and cold climate configurations. As indicated in Figure 16 for the full CSI-Thermal dataset of multifamily systems from the period, the analysis provided a median installed cost of $20.19/therm resulting in systems costs of $38,071 for the warm climate configuration and $50,170 for the cold climate. Current market equipment costs for each configuration were provided by one of the largest manufacturers supplying equipment to CSI-Thermal program installers.

While residential models of heat pump water heaters are available from several major manufacturers, only one offered a commercial variant, with an estimated dealer price of $6,000 per unit for the equipment and $24,000 installed for the pair of units presented in Figure 16.

The cost of the photovoltaic system in the HP + PV configuration was estimated at $3.10/W-STC based on 2019 residential cost data for the California market from LBNL Tracking the Sun report (LBNL 2019).

Equipment costs for each 75 gallon gas storage heater was estimated from big box equipment pricing of $1,614 per unit and a turnkey installed costs of $6,446 for the pair. This pricing was not reduced for the mature market scenario as the technology is already mature in terms of equipment design and installation volumes.

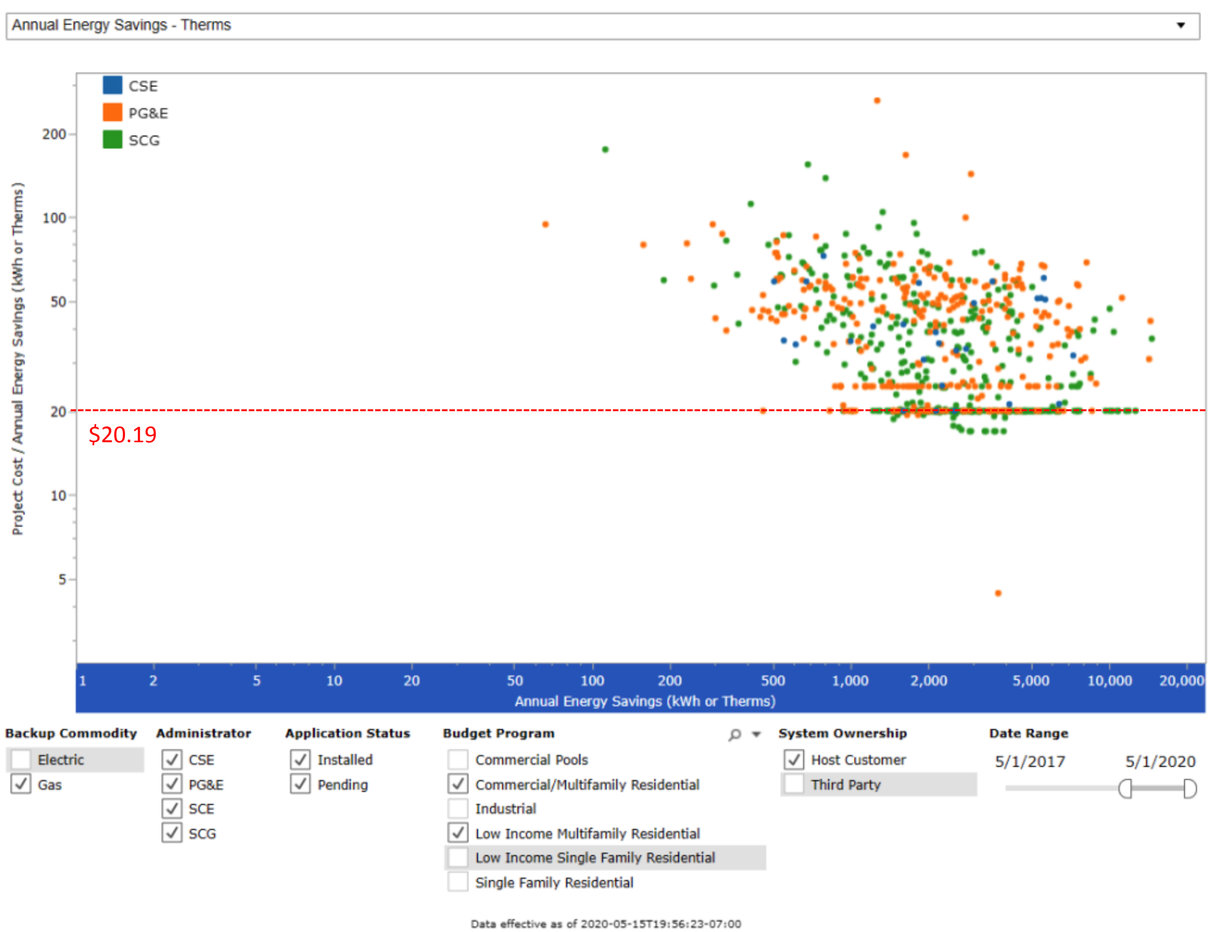


Figure 16. Commercial installed cost data from California CSI-Thermal database.

Commercial Pool Heating

Commercial pool sizes range from small 1,000 ft^2 pools found in hotels and multifamily complexes to full course 50 meter Olympic pools at 13,500 ft^2. For our analysis, we selected a 2,300 ft^2 25 meter short course outdoor pool found at community recreation centers, fitness facilities, and school campuses. We assumed the pool was outdoors, uncovered, and open seasonally for 6 months a year during the summer. Based on this heating load profile, the configurations in Table 8 were evaluated.

Table 8. Specific technologies evaluated for commercial pool heating.

Technology	Description
Gas Boiler (warm climate)	• 500 kBTU/hr boiler at 84% efficiency
Gas Boiler (cold climate)	• 700 kBTU/hr boiler at 84% efficiency
HPWH (warm climate)	• 150 kW-thermal of heat pump capacity
HPWH (cold climate)	• 200 kW-thermal of heat pump capacity
SWH	• 1,725 ft^2 of unglazed polymer pool panels

Three separate configurations of solar thermal and heat pump technologies were assessed for this as outlined in Table 9.

Table 9. Evaluated backup configurations for solar thermal and heat pumps in commercial pool heating application.

Configuration	Description
SWH + Gas Boiler	• Solar Thermal solution with existing gas boiler backup
HPWH	• Replacement of gas boiler with heat pump of same thermal capacity
SWH + HPWH	• Solar Thermal with heat pump backup

Similar to other segments, initial costs for the technologies and configurations were estimated from available sources in terms of equipment cost and total installed price. As with the water heating applications, we assumed a mature market cost reduction of 15% in equipment and an installation cost equal to the equipment cost. Summary costs for each configuration are shown in Figure 17 for both the current and mature market cases. Details of each cost buildup follow.

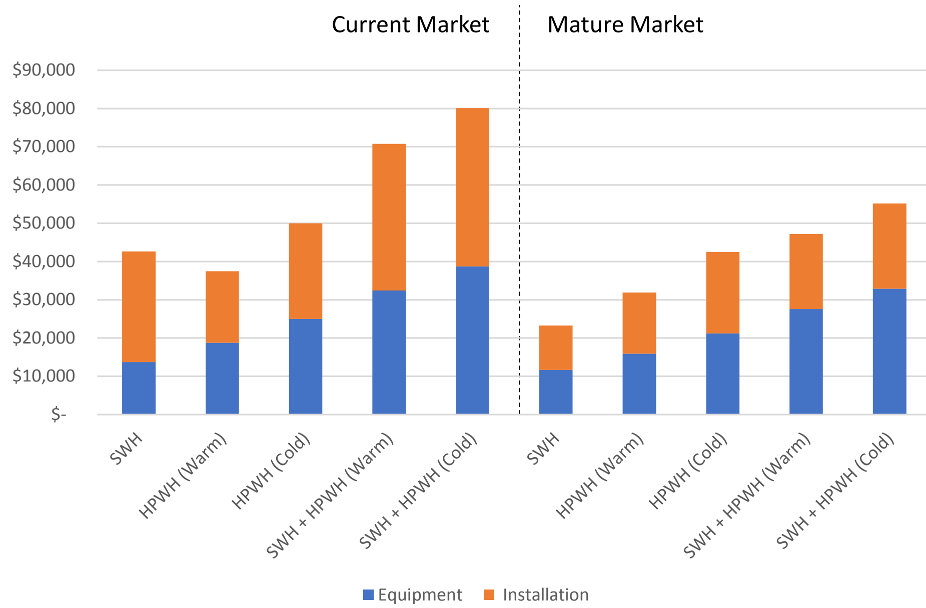


Figure 17. Current and mature market pricing for commercial pool technologies and configurations.

For the solar thermal configuration, we evaluated current market costs from the CSI-Thermal program during the past 3 years with polymeric unglazed collectors, resulting in a sample of 144 systems. As indicated in Figure 18 for the full CSI-Thermal dataset of commercial systems from the period, the analysis provided a median installed cost of $11.86/therm resulting in a SWH system cost of $42,618. Current market equipment costs were provided by one of the largest manufacturers supplying equipment to CSI-Thermal program installers.

While large 150 - 200 kW-thermal commercial heat pumps are available, their weight and size often limits them to being ground mounted in retrofit applications, which may not be possible at existing sites. Our selection of smaller 50 kW-thermal units allows the possibility of being rooftop mounted. In the case of being paired with solar thermal, both technologies can utilize the same piping and connection infrastructure. Equipment pricing for 50 kW-thermal units was taken from commercially available units on the market for $6,250.

In the configurations where solar thermal is paired with heat pumps, we reduced the installation costs for the supplemental heat pump by 50% from the standalone case with the assumption that many of the soft costs in customer acquisition and permitting were already burdened in the solar sale and that the piping and pool interconnection is used by both heat sources.

Figure 18. Commercial installed cost data from California CSI-Thermal database.

25-Year Analysis Period & Calculation of Net Lifetime Cost

We standardized on a 25-year analysis period for all technologies and system configurations. The driver for this timeframe is that the primary components of solar configurations (SWH collectors and PV modules) have 25-year lifetimes with scheduled maintenance mid-life for storage tanks and inverters. In contrast, conventional water heaters (tankless, gas tank, heat pump) typically require replacement due to sedimentation and corrosion on the same schedule assumed for solar storage tanks in year 12. To calculate lifetime installed costs for each configuration over the analysis period, we assumed:

- System maintenance was performed on all systems in year 12.
- A discount rate of 5% was applied to these costs to create a net present cost of this scheduled maintenance.[17]
- For solar thermal, solar photovoltaic, and heat pump systems, we assumed that materials used for maintenance would be purchased at mature market pricing 15% lower than today's cost.
- Service labor costs were assumed equal to the cost of the equipment being replaced.

[17] This means a $1,000 service cost in year 12 would equate to $557 in today's dollars.

Table 10 outlines the service performed in year 12 for each of the evaluated configurations. To calculate the net lifetime cost of each configuration, maintenance costs were added to the first costs outlined earlier. Finally, a net cost of each configuration was calculated by subtracting the legacy baseline technology (gas tank) to obtain the net incremental cost of deploying each alternative configuration assuming the legacy installation was at or near end of life. It is this incremental cost that is used together with the annual savings to determine simple payback and other financial measures of the study.

Table 10. 12 year maintenance assumptions by technology and market segment.

Technology	Residential Service	Commercial Service
Gas Tank	• Full system replacement	• Full system replacement
Gas Tankless	• Full system replacement	• N/A
HPWH	• Full system replacement	• Full system replacement
SWH	• Tank replacement • Glycol replacement	• $1,500 miscellaneous service[18]
PV	• Inverter replacement[19]	• Inverter replacement[20]

Because commercial pool heating systems do not have storage tanks subject to scaling or corrosion, we did not schedule component replacement in year 12 and instead provided a 15% reserve on the equipment costs for service. Additionally, large commercial boilers used in these applications have design lives past 12 years so we did not net out this baseline cost from each configuration.

Treatment of Federal Investment Tax Credit (ITC) & State Incentives

With the 30% federal ITC set to revert back to a 10% level for commercial in 2022, we eliminated it from all residential use cases and assumed a 10% ITC with MACRS depreciation for multifamily water heating applications as there is no sunset date for that federal subsidy. Lastly, commercial pool heating is not eligible for the ITC so it was not applied to that segment.

While there have been state incentives for solar thermal and many Community Choice Aggregators are offering incentives for heat pumps, we stripped these from the analysis to present an unbiased baseline for each technology with a view towards what future state incentives might look like for this market segment to achieve GHG reduction goals.

[18] Commercial system design assumes an unpressurized polymer lined 600 gallon storage tank. Because these tank types are indirect systems, they are not subject to sedimentation or galvanic corrosion that limits other tank designs.
[19] Inverter replacement was priced at $0.10/W-STC for residential.
[20] Inverter replacement was priced at $0.05/W-STC for commercial.

5 – Results: Residential Water Heating

An assessment of residential GHG reduction using solar water heating and heat pumps shows high potential from both technologies in every climate zone (Figure 19). The deepest reduction for a single measure is from solar water heating with electric backup, which results in a statewide average 91% reduction in GHG emissions. Heat pumps achieved an average statewide GHG reduction of 81% when deployed as a standalone technology and eliminate emissions when deployed in tandem with 1 kW of incremental PV.[21]

Deploying heat pump and solar PV technologies may be reasonable in new home construction because solar PV will already be installed for other electric loads and 1 kW of additional PV can be installed at the same cost. However, installing 1 kW of PV for the heat pump load is not a reasonable option if a customer is not already installing solar PV as part of the same project.[22] In the retrofit market, it will be rare that a customer can afford solar PV installation and water heating electrification at the same time.

If water heating is not electrified, SWH can still provide GHG reductions of 78% with existing gas tank backup and 83% using gas tankless.

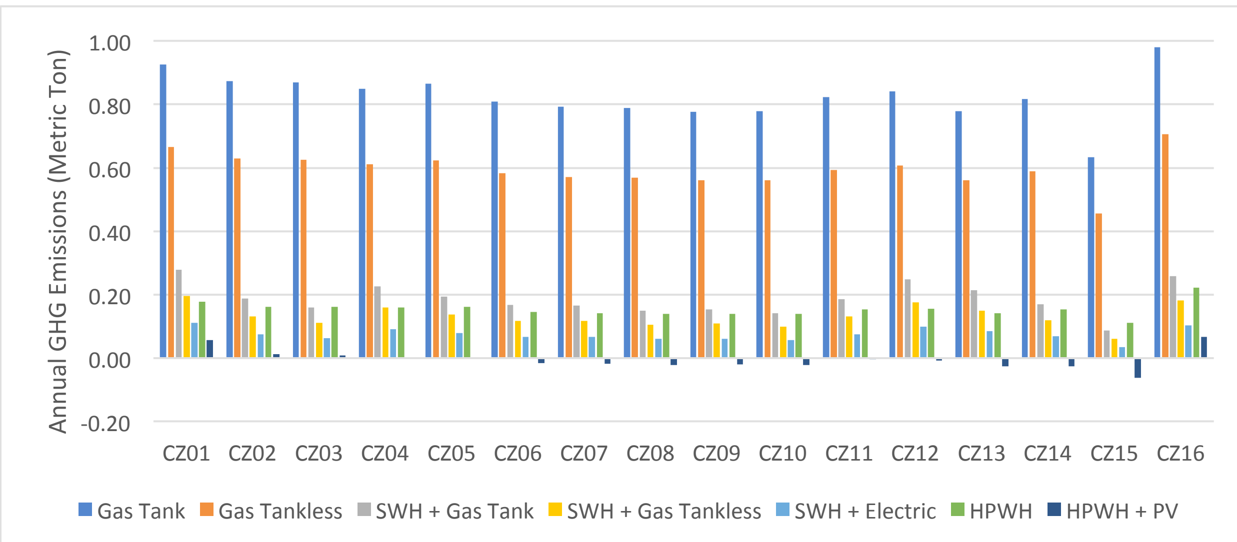


Figure 19. Annual GHG emissions for residential water heating configurations.

Evaluation of annual operating costs illustrates a high degree of variability depending on technology, climate, and utility territory (Figure 20). As an example of this variability,

---

[21] While not directly evaluated as a use case, it is possible to pair photovoltaics (PV) with SWH to drive the element consumption. In such a configuration, only 500 W of PV would be necessary to fully eliminate GHG emissions.

[22] The analysis of photovoltaics + heat pump assumed a full scale 5-7 kW PV system was deployed with an incremental 1 kW for the heat pump. A 1 kW PV system cannot be deployed at the $3.10/W cost used in this study.

traditional water heaters fueled by natural gas in Climate Zone 9 (Pasadena) cost only $152 per year to operate, whereas the same configuration in Climate Zone 3 (San Francisco) costs more than twice as much at $327 per year. While the base water heating load in Climate Zone 3 is only 12% higher, the gas rate is 92% higher through a combination of being in Pacific Gas & Electric service territory combined with high baseline home heating loads that push water heating usage into the excess tier nearly year round. The potential for annual savings is higher in regions with high water heating loads and natural gas costs, as can be seen in Figure 20.

For any water heating electrification technology, it is difficult to overcome the relative cost of the source fuels. At a blended cost basis of $1.80/therm, Pacific Gas & Electric has one of the highest gas costs in the state. However, on a kWh-thermal basis, the cost of natural gas at $0.06/kWh-thermal compares favorably to the blended electricity cost of $0.25/kWh in the same utility territory. Given the ~4X increase in source fuel cost, the increase in operating efficiency of the heat pump would need to be at least that much to break even.

The Energy Factor (EF) is a standard measure of energy efficiency for heating systems. The EF needs to be higher than the fuel price differential to produce customer savings. The annual EF of the SWH systems analyzed in this study averages 4.3 across all climate zones, and SWH is therefore able to overcome the differential in fuel costs for most markets. The annual EF of heat pumps averages 2.0 across all climate zones such that they are operating at ~3 times the thermodynamic efficiency of a traditional gas storage heater, making it difficult to achieve annual savings in California markets.

The annual modeled EF of the heat pumps in this analysis is below their typical rated Uniform Energy Factor (UEF) of ~3.5 due to two factors. The first is that units engage their resistance elements (COP = 1) at temperatures below 40 F. Similarly, during periods of high draws, the units will engage the resistance elements for fast recovery as the heat pump operates with only one tenth the thermal recovery rate of a traditional gas tank heater. These factors are not accounted for in the standardized rating procedures that generate the rated UEF, but they are incorporated in our simulation models. Together, these two factors result in resistance backup elements consuming 31% of total heat pump electricity demand in Pacific Gas & Electric territory.

As a result, it is more expensive for consumers to run heat pumps than traditional gas water heaters. Heat pump efficiency is not sufficient to overcome the disparity in fuel pricing for the climates and utility territories studied. The territory closest to breakeven was Imperial Irrigation District (Climate Zone 15) where heat pumps consume a low electric cost of $0.12/kWh on the current tariff and can nearly compete against natural gas in the region.

If customers generate their own electricity, it clearly provides the best system operating costs. Pairing 1 kW of incremental PV with heat pumps results in operating costs near or below zero in all climate zones.

Because of their higher EF, SWH systems with electric backup are able to provide annual savings in nearly every climate zone.[23] This system efficiency is seen in the portion of the time that SWH heats water from solar without relying on the backup element. An average of 77% of the water heating load is covered without any fuel cost on a statewide basis. Also, most of the electricity to support the residual load is consumed during off peak hours.

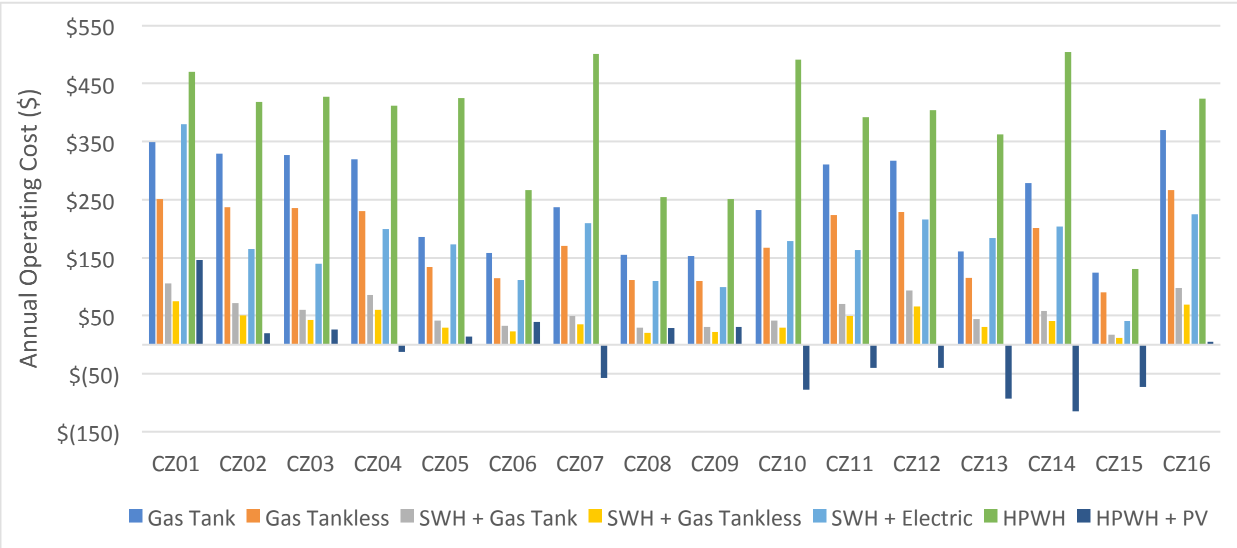


Figure 20. Annual operating costs for residential water heater configurations.

Note that these costs are for system operation. A discussion of whether any annual savings are high enough to justify the installed costs of the technology follows.

For configurations with reduced operating costs compared to traditional gas heaters, combining bill savings with system installation costs produces results for simple payback, as shown below in Table 11. It is important to remember a few points when evaluating simple payback.

- This analysis does not consider incentives that may exist for SWH and HPWH technologies. Because this study looks to evaluate what incentive levels might be set by the state to promote GHG emission reductions, we do not include any state incentives in the calculations or the residential federal ITC tax credits that are set to expire in 2022. If the ITC is extended, the payback for SWH and PV systems will improve significantly.
- We are not including any fuel inflation or discount rates. To the degree these are relevant they are assumed to be equal and net each other out.
- We eliminated any results that had negative annual savings or a simple payback that was beyond twice the 25-year analysis period.

[23] The exception is Climate Zones 1 and 13, where a weaker solar resource and lower natural gas costs inhibit savings. Climate Zone 13 is unique in having high electricity costs (Pacific Gas & Electric) and low natural gas costs (Southern California Gas).

With those assumptions stated, only certain configurations provided reasonable paybacks without incentives under current market pricing. Tankless gas heaters provide paybacks within their operating life in utility territories with high natural gas pricing such as Pacific Gas & Electric, but not the lower cost and more temperate climates of Southern California Gas or San Diego Gas & Electric territories. When installed with 1 kW incremental capacity of a PV system, heat pumps can be cost effective in most climate zones. However, when installed as a standalone measure typical in the existing home market, heat pumps have negative paybacks in in all Climate Zones.

Table 11. Simple payback for residential configurations (no incentives).

	Residential - Current Market					
Climate Zone	Gas Tankless	SWH + Gas Tank	SWH + Gas Tankless	SWH + Electric	HPWH	HPWH + PV
CZ01	22	34	35			31
CZ02	24	32	35	45		21
CZ03	24	31	34	40		21
CZ04	24	24	27	39		19
CZ05	42	39	45			37
CZ06	49	44				
CZ07	33	30	35			22
CZ08	50	45				
CZ09		46				
CZ10	33	29	35			21
CZ11	25	34	37			18
CZ12	24	25	28	47		18
CZ13	48	48				25
CZ14	28	25	30			16
CZ15						32
CZ16	21	30	32			17
	Residential - Mature Market					
Climate Zone	Gas Tankless	SWH + Gas Tank	SWH + Gas Tankless	SWH + Electric	HPWH	HPWH + PV
CZ01	22	19	20			22
CZ02	24	18	20	25		15
CZ03	24	17	19	22		15
CZ04	24	17	21	28		14
CZ05	42	27	35			26
CZ06	49	31	41			38
CZ07	33	21	27			15
CZ08	50	31	41			36
CZ09		32	42			37
CZ10	33	20	27			15
CZ11	25	19	21	28		13
CZ12	24	17	22	34		13
CZ13	48	33	43			18
CZ14	28	18	23	46		12
CZ15		36	49	41		23
CZ16	21	17	18	28		12

While not meeting paybacks within the analysis period without subsidies, SWH systems are able to provide reasonable annual savings. If current state and federal incentives were applied, the 25-50 year paybacks illustrated for the current market drop considerably and would be within the analysis period.

Moving from the current market to mature market conditions, we find that consumer financials improve for SWH as well as HPWH deployed with solar PV. Several more markets become viable for both technologies. While these technology configurations would still need subsidies to achieve high market penetration, they are economically viable in a mature market setting.

However, even at reduced mature market pricing, standalone HPWH technology does not provide reasonable consumer financials. This is not due to installed equipment pricing, but a lack of meaningful annual savings due to the generally high electricity costs in California when compared to natural gas. The systems cannot generate significant annual savings for the consumers until gas prices escalate or utility tariffs change substantially below the current blended statewide price of $0.25/kWh found in our study.

To answer the question of how state incentive levels could be structured in a way agnostic to technology, but still providing the state the lowest cost of GHG reductions for each market segment, we calculate a targeted "GHG incentive" ($/metric ton CO_2) that could drive adoption of each technology. The calculation of the target GHG incentive level is straightforward and can be described as:

- Assume that consumers will be willing to adopt technologies with a simple payback of 10 years in residential, and 5 years in multifamily given a 25 year product life.
- Calculate the upfront incentive amount that would need to be provided to bring the net cost of the equipment to the consumer down to a 10 year (residential) or 5 year (commercial) payback.
- Calculate the total GHG reduction (metric tons) provided by the technology over the 25 year operating life compared to the baseline gas technology.
- Divide the incentive amount necessary to drive adoption ($) by the GHG reduction (metric ton) to produce a $/metric ton GHG incentive necessary to drive consumer adoption.

Table 12 shows the targeted GHG incentive levels necessary to drive adoption by technology and climate zone. In both the current and future market, heat pumps deployed with PV provide the lowest cost of GHG reduction for the state at an average cost of $166 and $94/ton in the current and future markets respectively.

Table 12. GHG incentive targets ($/metric ton) for residential configurations.

	Residential - Current Market					
Climate Zone	Gas Tankless	SWH + Gas Tank	SWH + Gas Tankless	SWH + Electric	HPWH	HPWH + PV
CZ01	184	361	382			200
CZ02	204	331	373	291		152
CZ03	206	315	363	277		157
CZ04	215	208	257	188		144
CZ05	273	247				216
CZ06	305	269				
CZ07	272	236	296			169
CZ08	315	271				
CZ09		279				
CZ10	279	231	294			164
CZ11	226	368	410			139
CZ12	218	225	271	202		132
CZ13	316	313				192
CZ14	243	208	266			116
CZ15						253
CZ16	165	307	335			120
	Residential - Mature Market					
Climate Zone	Gas Tankless	SWH + Gas Tank	SWH + Gas Tankless	SWH + Electric	HPWH	HPWH + PV
CZ01	184	132	151			116
CZ02	204	116	146	125		68
CZ03	206	107	140	112		72
CZ04	215	98	169	117		58
CZ05	273	145	216			131
CZ06	305	162	239			163
CZ07	272	127	206			80
CZ08	315	164	244			162
CZ09		170	250			167
CZ10	279	124	204			73
CZ11	226	136	167	142		51
CZ12	218	110	179	130		46
CZ13	316	192	268			101
CZ14	243	103	179	143		29
CZ15		205	306	173		148
CZ16	165	102	124	122		40

However, instead of debating that one technology be incentivized to the exclusion of another, we believe that the leading technology within a market segment should set the price of GHG reductions and that all qualifying technologies should have access to incentives at that same level. As an example, heat pumps with solar PV backup may be an ideal choice for a new home builder in Livermore who is already installing solar PV as part of the state mandate. However, it would be difficult to install a heat pump in a 50-year old home in the high Sierras that is not already getting a solar PV system. In this case, SWH with electric backup may make more sense.

In short, selecting a single technology champion across all markets, utilities, and climates would lock out customers whose site specific needs make a secondary or tertiary technology choice more pragmatic to install. With a set GHG incentive level, policy makers can be agnostic to the GHG reduction technology deployed for water heating electrification.

As examples of upfront system incentives that would result from GHG incentive targets of $166/ton in the current market and $94/ton in a mature market:

- HPWH's would carry an average incentive of $2,780 in the current market and $1,575 in a mature market.[24]
- Incentives for SWH would average $3,112 in the current market and $1,763 in a mature market.

While our analysis only considered a subset of heat pump and solar technologies, we believe incentives should apply to all electrification configurations on the basis of GHG reduction potential. Within the heat pump category this would include split systems like the high efficiency EcoCute CO_2 systems. Within SWH it would include all technologies suitable to any particular climate zone including thermosiphon and integral collector storage.

The proposed target incentive levels are based solely on GHG reductions from basic system performance. Incentives structures could also weigh additional system benefits including: elimination of high GHG potential refrigerants, load shaping, and reduced reliance on utility infrastructure.

[24] We are not applying the GHG incentive to the total reduction of the HPWH + PV configuration, only the portion associated with the heat pump itself. While the solar PV makes the heat pump cost effective to the consumer, we believe PV is not in need of additional market subsidies when deployed as part of a heat pump installation.

6 – Results: Multifamily Water Heating

The GHG reduction potential in multifamily water heating largely mimics that of the same technologies deployed in the residential sector as shown in Figure 21. Solar water heating with electric backup reduces GHG emissions 90% on the typical multifamily building. This compares to a 81% reduction with heat pumps alone and elimination of GHG emissions when deployed in tandem with 12 kW of solar PV[25].

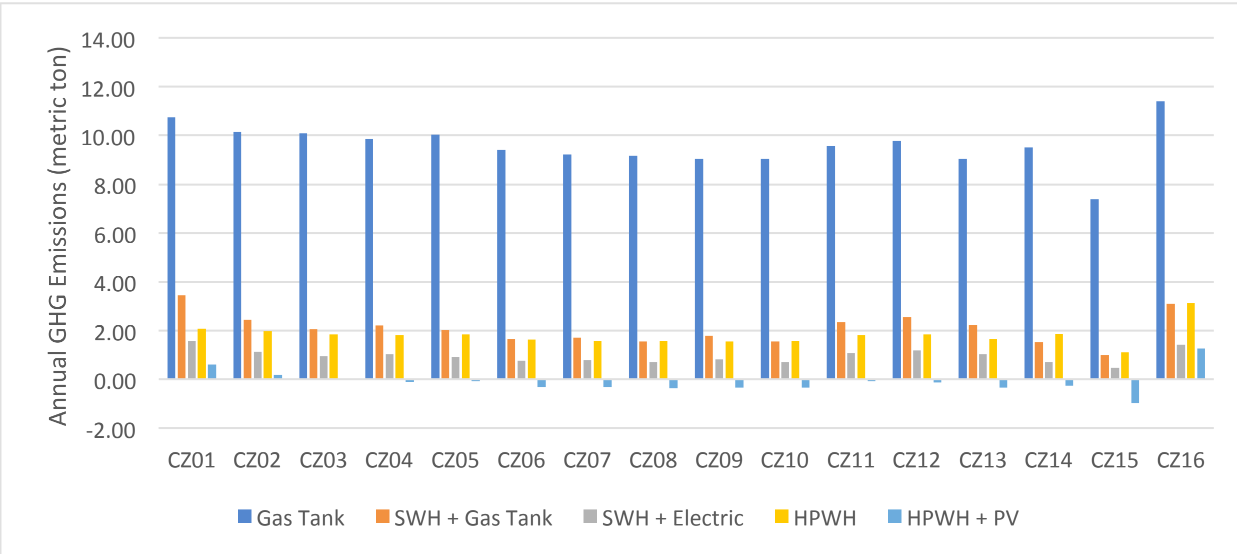


Figure 21. Annual GHG emissions for multifamily water heating configurations.

Annual operating costs for SWH follow the same general trends as GHG reductions (Figure 22). Depending on climate zone and utility, annual savings range from a low of $695 in Climate Zone 13 (Fresno) to a high of $2,383 in Climate Zone 10 (Riverside). The average statewide annual savings was $1,743 for SWH systems with electric backup.

In contrast to the residential results, heat pumps are generally able to achieve annual savings when compared to the natural gas baseline. This is primarily due to the lower electricity rates available on commercial tariffs while natural gas rates in the multifamily segment closely mimic residential. The blended statewide electricity costs used by heat pumps in the commercial segment was nearly half that of residential at $0.15/kWh. On a statewide basis, the average annual savings for heat pumps is $856 in climates with annual savings, with exceptions in Climate Zones 5, 6, 8, 9, 13, and 16 where annual operating costs actually increased compared to the natural gas baseline. If those Climate Zones with increased operating costs are included, the statewide average savings reduces by more than half to $349.

[25] Similar to residential, GHG emissions can be eliminated from the SWH + Electric case with the addition of 6 kW PV.

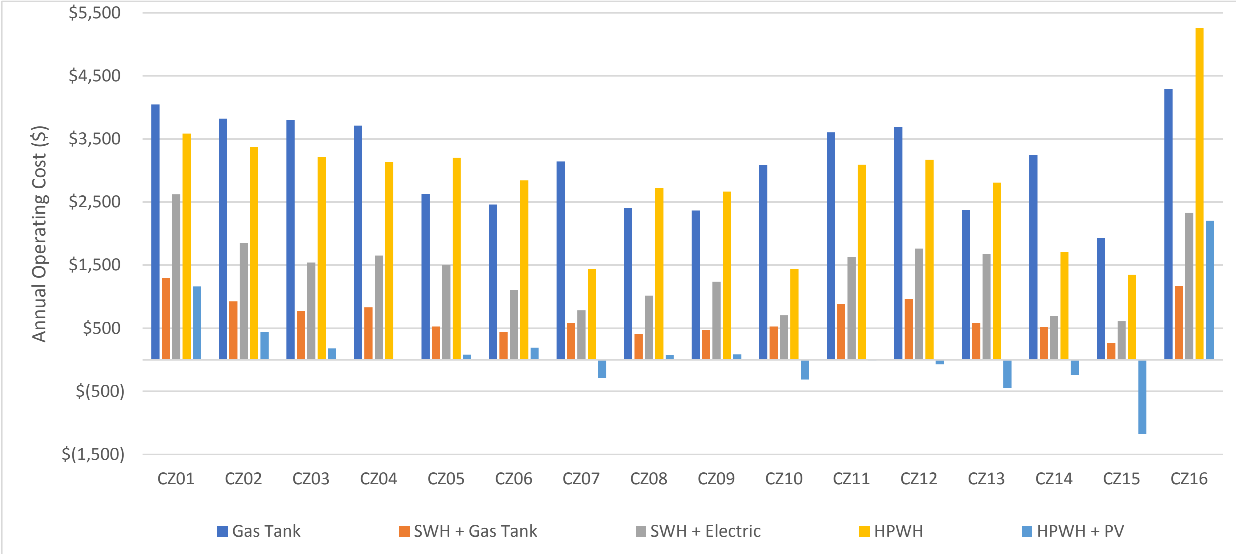


Figure 22. Annual operating costs for multifamily water heater configurations.

Simple payback for commercial systems is illustrated in Table 13. The same residential assumptions apply with the exceptions that for SWH the post-2022 federal ITC at 10% is included and depreciation follows the MACRS schedule. Heat pumps are depreciated following the building schedule. If the ITC is extended above 10%, the payback for SWH systems will improve significantly.

SWH at scale provides paybacks well within the analysis period in most markets. Heat pumps deployed standalone can compete in select territories (Climate Zones 7, 10, and 14), but the low annual savings in other markets places them out of reach. For customers that are otherwise installing photovoltaics, heat pumps with PV is cost effective in almost all climate zones, but is not as cost effective as the deployment of SWH technologies.

In a cost reduced mature market, SWH shows strong advantages over HPWH deployed alone or in tandem with photovoltaics. Should the commercial market mature to volumes where such pricing is supported, SWH would require only modest incentives to meet the 5-year simple paybacks demanded by most multifamily building owners for 25-year equipment.

Table 13. Simple payback for multifamily configurations (no incentives).

	Multifamily - Current Market				Multifamily - Mature Market			
Climate Zone	SWH + Gas Tank	SWH + Electric	HPWH	HPWH + PV	SWH + Gas Tank	SWH + Electric	HPWH	HPWH + PV
CZ01	12	20		19	8	13	44	16
CZ02	11	14		16	8	9	45	13
CZ03	11	13	43	15	7	8	34	12
CZ04	8	10	44	15	8	7	35	12
CZ05	11	18		21	11	12		18
CZ06	12	15		24	11	10		20
CZ07	9	8	15	16	9	6	12	13
CZ08	12	14		23	11	10		19
CZ09	13	18		24	12	12		20
CZ10	9	8	16	16	9	6	12	13
CZ11	12	14		15	8	7	39	12
CZ12	9	10	49	14	8	7	39	12
CZ13	13	28		19	13	20		16
CZ14	9	8	17	16	8	5	13	13
CZ15	14	15	44	17	13	10	34	14
CZ16	10	15		26	7	9		21

GHG incentives for the multifamily segment were calculated using the same methodology as residential and are shown below in Table 14. Both the current and mature market are led by SWH as the lowest cost provider of GHG reductions, corresponding to incentive levels of $64 and $28/ton in the current and mature markets respectively. This would lead to the following proposed upfront system incentives.

- A HPWH installation would carry an average incentive of $12,448 in the current market and $5,446 in a mature market.
- For SWH, the incentive would be $13,808 in the current market and $6,041 in a mature market.

Table 14. GHG incentive targets ($/metric ton) for multifamily configurations.

	Multifamily - Current Market				Multifamily - Mature Market			
Climate Zone	SWH + Gas Tank	SWH + Electric	HPWH	HPWH + PV	SWH + Gas Tank	SWH + Electric	HPWH	HPWH + PV
CZ01	104	94		157	48	48	82	120
CZ02	95	83		150	42	37	88	112
CZ03	88	76	109	143	37	30	84	106
CZ04	50	43	112	143	42	15	86	105
CZ05	67	62		164	60	35		127
CZ06	72	60		176	64	32		137
CZ07	60	38	89	155	52	9	61	116
CZ08	73	61		179	66	32		139
CZ09	80	69		183	72	39		142
CZ10	60	37	92	158	52	9	64	118
CZ11	106	88		150	49	18	91	111
CZ12	57	47	115	143	49	19	88	105
CZ13	88	81		171	79	51		130
CZ14	52	32	93	151	45	4	65	112
CZ15	98	76	144	185	89	41	110	140
CZ16	83	75			33	34		135

7 – Results: Commercial Pool Heating

GHG reduction potential for commercial pool heating is different than for water heating applications in that low cost polymeric solar thermal collectors are very efficient and cost effective at reducing peak summer loads, but their contribution tapers in the cooler months of early spring and late fall. As a result, base load reduction for SWH as a standalone measure in this application is less than domestic water heating. However, these reductions are achieved at a much lower price point.[26]

Because the pool heating load has less coverage from polymer panels on an annual basis, solar water heating with electric resistance backup is impractical for pools that require heating in the early spring and late fall. For this reason, we have evaluated SWH with heat pump backup as an additional configuration for this market segment.

Summary results for GHG reductions are shown below in Figure 23. SWH deployed with heat pump backup achieves an 89% reduction. When deployed as a standalone measure, heat pumps are able to achieve a 78% GHG reduction.

SWH with gas boiler backup reduces annual emissions 52%. As a low cost option this technology provides cost-effective GHG reduction, but it is not part of the electrification of water heating.

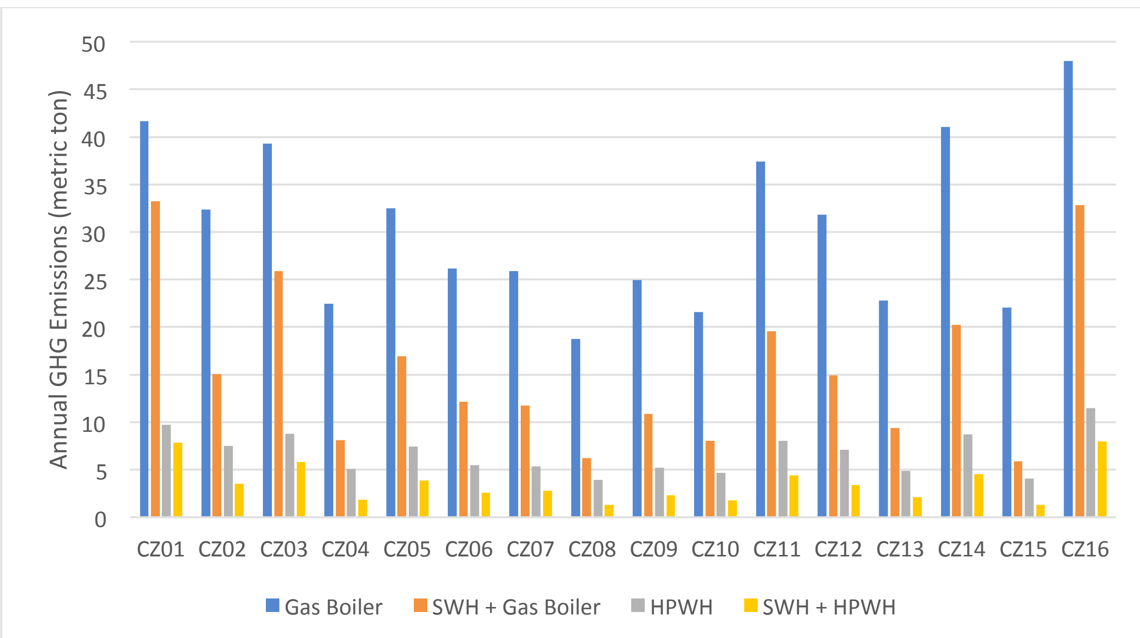


Figure 23. Annual GHG emissions for commercial pool heating configurations.

[26] As an example, the average load reduction on boiler energy use ranges from 20 - 73% across climate zones with an average statewide reduction of 52%. This compares to an average statewide reduction of 79% for the equivalent case in multifamily water heating. However, commercial pools have been installed under the CSI-Thermal program at a levelized cost nearly half that of domestic water heating applications ($11.86/therm vs. $20.19/therm).

When deployed as a standalone measure, heat pumps consume electricity at $0.15/kWh, similar to the blended rate for multifamily water heating. As illustrated in Figure 24, on a statewide basis the average annual savings for heat pumps is $4,305, with a low of $1,163 in Climate Zone 5 (Santa Maria) and a high of $9,347 in Climate Zone 14 (Inland San Diego).

When deployed in tandem with SWH, heat pump consumption is reduced and moved slightly off peak for a blended rate of $0.14/kWh. On a statewide basis, the average annual savings for this configuration is $7,070.

Annual savings for SWH using gas boiler backup range from a low of $3,171 in Climate Zone 1 (Arcata) to a high of $6,725 in Climate Zone 11 (Redding). The average statewide annual savings was $4,878.

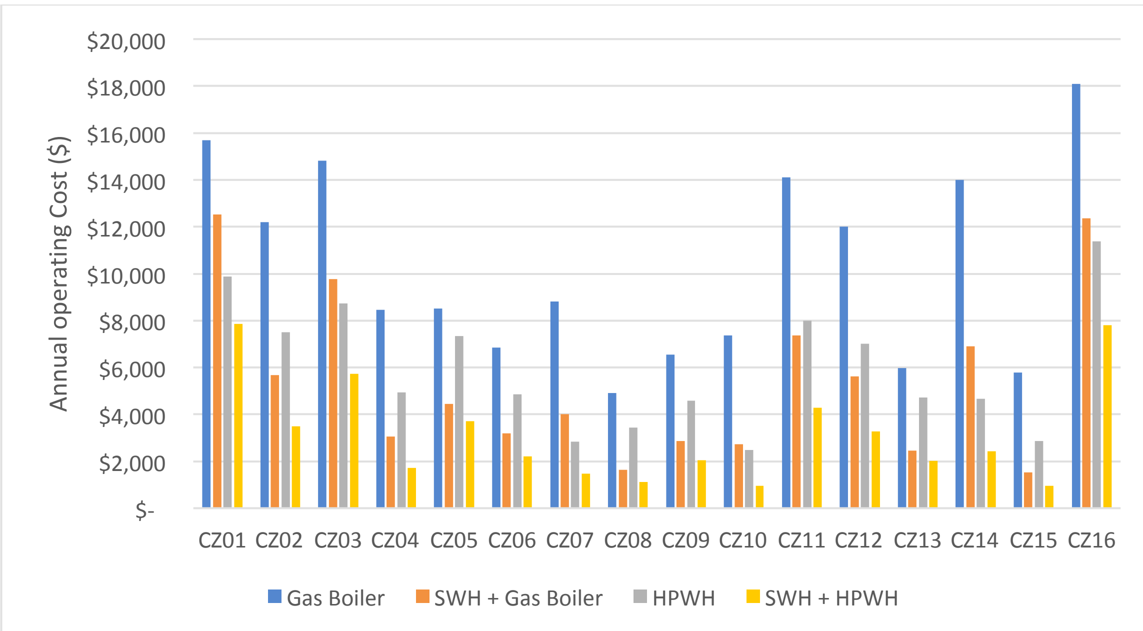


Figure 24. Annual operating costs for commercial pool heating configurations.

Simple payback for commercial pool systems is illustrated in Table 15. Here we see the economics of solar and heat pumps in serving low temperature applications without the need for supplemental hot water tanks. With few exceptions, heat pumps are able to be competitive within their design life across climate zones within the current market. Under mature market conditions, systems can come close to achieving target economics of 5-year paybacks within several markets. Adding SWH to a HPWH can increase GHG reduction while maintaining similar or improved paybacks in many climate zones.

Table 15. Simple payback for commercial pool configurations (no state incentives).

	Current Market			Mature Market		
Climate Zone	SWH + Gas Boiler	HPWH	SWH + HPWH	SWH + Gas Boiler	HPWH	SWH + HPWH
CZ01	16	10	12	9	9	8
CZ02	8	12	11	4	11	7
CZ03	10	10	10	5	8	7
CZ04	9	12	12	5	11	8
CZ05	12	38	17	7	32	11
CZ06	14	22	18	7	19	12
CZ07	10	7	11	6	6	8
CZ08	15	30	22	8	25	15
CZ09	13	22	18	7	19	12
CZ10	11	9	13	6	8	9
CZ11	7	10	10	4	6	7
CZ12	8	9	9	4	7	6
CZ13	14	35	21	8	30	14
CZ14	7	5	7	4	4	5
CZ15	12	15	17	6	13	11
CZ16	9	9	9	5	6	6

GHG incentives for pool heating applications were calculated using the same methodology as domestic water heating and are shown in Table 16. The current market is led by heat pumps with an average statewide incentive level of $48/ton. In a mature market, both heat pumps deployed as a standalone measure as well as in tandem with SWH can achieve an incentive levels of $36-38/ton. This would lead to the following proposed upfront system incentives.

- A HPWH installation for a warm climate installation would carry an average incentive of $28,608 in the current market and $21,456 in a mature market.
- For solar water heating with heat pump backup, the incentive would be $32,352 in the current market and $24,264 in a mature market.

Table 16. GHG incentive targets ($/metric ton) for commercial pool heating configurations.

	Current Market			Mature Market		
Climate Zone	SWH + Gas Boiler	HPWH	SWH + HPWH	SWH + Gas Boiler	HPWH	SWH + HPWH
CZ01	161	37	64	54	26	30
CZ02	39	56	69	0	42	29
CZ03	73	37	57	6	25	23
CZ04	63	60	95	0	45	41
CZ05	75	61	82	17	50	43
CZ06	90	65	101	25	53	54
CZ07	73	0	79	9	14	32
CZ08	107	98	146	35	81	83
CZ09	89	69	106	25	55	58
CZ10	78	46	102	12	30	46
CZ11	36	38	54	0	9	18
CZ12	42	30	55	0	20	16
CZ13	96	84	121	29	69	68
CZ14	27	0	27	0	0	0
CZ15	71	65	113	15	51	60
CZ16	55	27	42	0	4	13

8 – Opportunities to Further Cross Leverage Technologies

In several of the configurations evaluated, we paired technologies together (SWH, HPWH, and PV) to gain deeper savings or avoid peak summer energy use. Although only a limited set of pairings was presented, we believe there are many additional combinations that can provide advantages to specific markets and geographies.

SWH with Heat Pump Backup

An example of further cross leveraging would be to combine SWH and HPWH technologies for multifamily water heating. With 600 gallons of thermal storage, SWH systems provide a large thermal reservoir that a low capacity HPWH could supplement overnight when utility rates and building demand are at a minimum. In practice, the SWH system would carry the majority of the load from spring through early fall and the HPWH would provide heating on cloudy winter days during low-cost periods. Because the SWH system is providing a large storage capacity that is otherwise unutilized during these times, the HPWH portion of the system can be installed at fractional cost compared to a standalone HPWH solution. While not explicitly studied, solutions of this style are likely to grow and programs need to be flexible in allowing the deployment of multiple technologies for building decarbonization.

Hybrid PV/Thermal Solutions

Although we evaluated SWH and PV as separate technologies, there are products in the market that combine PV and Thermal generation within the same panel. Generally referred to as hybrid PV/Thermal solutions (PVT), these systems leverage the fact that PV panels are 20% efficient at converting sunlight to electricity with the balance converted to heat. While standard PV panels reject that heat to the surrounding air, hybrid PV/Thermal panels place a thermal absorber in close proximity to the PV laminate to recover this waste heat and deliver it to water heating and pool heating loads.

In applications where PV and SWH panels may compete for available roof space, PV/Thermal products can provide opportunities by combining both technologies within the same footprint. While not explicitly modeled for this study, most PV/Thermal products carry SRCC OG-100 thermal performance ratings and PV module nameplate ratings that allow their benefits to be calculated using the same methodology used in this study. To the degree PV/Thermal products approximate the price to performance ratio of the active closed loop systems evaluated in this study, we expect the results to be similar.

Hybrid PV/Thermal systems are on the market today. If incentives are calculated according to the best fit technology for water heating electrification and hybrid systems are eligible, growth in this segment can be expected.

9 – Additional Discussion and Findings

In the preparation of simulated configurations and cost models, several questions arose regarding the treatment of particular assumptions or aspects of the results that we thought bore further discussion, but were not core to our findings. This section provides some additional context on these topics.

Electrical Service Upgrades

The cost models used in the study assume the building has sufficient existing electrical service to support the change from natural gas to electric water heating. The only costs considered were for running existing electrical service from the distribution panel to the water heater location. While this assumption often holds for modern construction, it often does not for legacy buildings.

As an example of this limitation, many older homes built in California before the wider adoption of air conditioning have only 24 kW (100 Amp) electrical service supplied to them. At 4.5 kW, residential heat pumps would consume nearly 20% of the total available electrical service. Often this spare capacity is not available in older structures as it has been consumed through subsequent remodels and the installation of additional circuits. In these cases, a main panel upgrade is required at costs exceeding $2,000 for the retrofit market. Such upgrades can present challenges to electrification unless the investment can be amortized over additional end uses such as solar PV and EV charging. Water heating deployed as a standalone measure is not sufficient to justify such an expense.

Extending this residential limitation to commercial markets, multifamily water heating requires 24 kW of capacity and pool heating 45-60 kW. While we presumed such service capability already existed, any upgrades to provide it would require deep investment.

Demand Charges & Load Shifting

While both SWH and HPWH technologies can theoretically avoid coincident peak demand charges as outlined in Appendix B, this capability is not embedded into current product offerings. Ensuring the avoidance of demand charges requires the building load to be monitored and the thermal storage aspects of HPWH and SWH systems be used to limit electrical usage during peak periods. Ensuring that demand management is part of any deployed solution when fuel switching from natural gas to electricity will be required to achieve the savings outlined in the study.

GHG Impact of Refrigerants at End of Life

In evaluating the GHG reduction potential of HPWH technologies, we assumed that the units were recycled at the end of their useful life to reclaim the refrigerant charge. Many refrigerants used in the heat pumps we evaluated, including R-134a and R-410a, have high GHG potential if released to the atmosphere during disposal instead of being reclaimed through a proper recovery program.

To illustrate this point, the 50 gallon residential HPWH evaluated in the study has a 624 gram charge of R-134a, which if released has the GHG emission equivalent of 892kg of CO_2. Over the 25 year analysis period, this would result in 1.78 tons[27] of potential GHG emissions (EPA 2014) that would reduce the study savings of 14 tons by 13% if not properly recovered. While refrigerant charge depends on unit construction and thermal capacity, the potential losses in GHG reduction would be on this scale for multifamily and pool heating applications as well.

[27] R124a has a Global Warming Potential (GWP) of 1,430 as compared to a GWP of 1 for CO2.

References

ADM Associates (2016). *Heat Pump Water Heater Field Testing Report.*

Amarnath, A.; Bush, J. (2012). *Heat Pump Water Heaters: Field Evaluation of New Residential Products.*

American Society of Heating Refrigeration and Airconditioning Engineers - ASHRAE (2015). *2015 ASHRAE Handbook – HVAC Applications, Chapter 50 – Service Water Heating.*

Barbose, G.; Darghouth, N. (2019). *Tracking the Sun – Pricing and Design Trends for Distributed Photovoltaic Systems in the United States.*

California Air Resources Board - CARB (2019). *California Greenhouse Gas Emissions for 2000 to 2017*

Carew, N.; Larson, B.; et al (2018). *Heat Pump Water Heater Electric Load Shifting: A Modeling Study.*

Environmental Protection Agency - EPA (2014). *Greenhouse Gas Inventory Guidance – Direct Fugitive Emissions from Refrigeration, Air Conditioning, Fire Suppression, and Industrial Gasses.*

Itron (2019). *California Solar Initiative (CSI) Thermal Impact Report.*

Jordan, U; Vajen K. (2005) *DHWcalc: Program to Generate Domestic Hot Water Profiles with Statistical Means for User Defined Conditions.*

Shapiro, C; Puttagunta S. (2016) *Field Performance of Heat Pump Water Heaters in the Northeast.*

Sparn, B.; Hudon, K.; Christensen, D. (2014). *Laboratory Performance Evaluation of Residential Integrated Heat Pump Water Heaters.*

Wilcox, S.; Marion, W. (2008). *Users Manual for TMY3 Data Sets.*

Appendix A - Simulation Modeling Tools & Assumptions

Detailed hourly simulation models were built for each of the technology configurations in residential, multifamily and commercial pool market segments. These models provide high granularity hourly energy usage profiles that were then used in the utility rate analysis to predict annual operating costs and annual GHG emissions. Our primary simulation tool for performance modeling is TRNSYS[28], which is also believed to be employed in the online incentive calculators used by the California Energy Commission and by Itron in their final report on the CSI-Thermal program (Itron 2019). TRNSYS was supplemented by other tools as needed. These tools are detailed in Table 17 to provide a complete energy performance and annual operating cost assessment of each technology. Further details of how each configuration and base case were modeled is provided in the following sections.

Table 17. Summary of simulation tools employed in the analysis.

Simulation Tool	Description & Application
TRNSYS	• Developed by the UW-Madison Solar Energy Lab • General purpose annual simulation tool with full component libraries for solar collectors, storage tanks, heat exchangers, heat pumps, and swimming pools • Used in the analysis to calculate detailed thermal performance of heat pumps & solar thermal technologies for water heating & pool heating applications
SAM	• System Advisor Model (SAM) developed by the National Renewable Energy Laboratory (NREL) • Multi-technology simulation platform capable of modeling technologies including solar photovoltaic & solar thermal • Includes a utility rate calculator capable of accurately modeling annual operating costs & savings based on hourly results and specified utility tariffs on a tiered and TOU basis • Used in the analysis to model annual solar PV performance and annual energy costs for each configuration
BEopt	• Building Energy Optimization Tool (BEopt) developed by NREL • Provides detailed hourly modeling of building energy use based on specified floor plan and construction details for any climate • Used in the analysis to provide baseline energy usage (gas + electric) for residential homes in each climate to calculate pre and post-installation utility bills to provide accurate annual savings for each configuration • Also used to calculate temperatures in attached garages where residential heat pumps are located for performance modeling

[28] www.trnsys.com

Weather Data & Baseline Residential Modeling

All simulations require hourly weather and solar irradiance data to properly calculate baseline loads and the performance of each technology. While many simulations employ TMY3 weather data (Wilcox and Marion 2008) associated with specific cities, our analysis uses hourly weather data in EnergyPlus format for each of the 16 California Climate zones[29] (Figure 25) so as to be more broadly applicable to regions of the state.

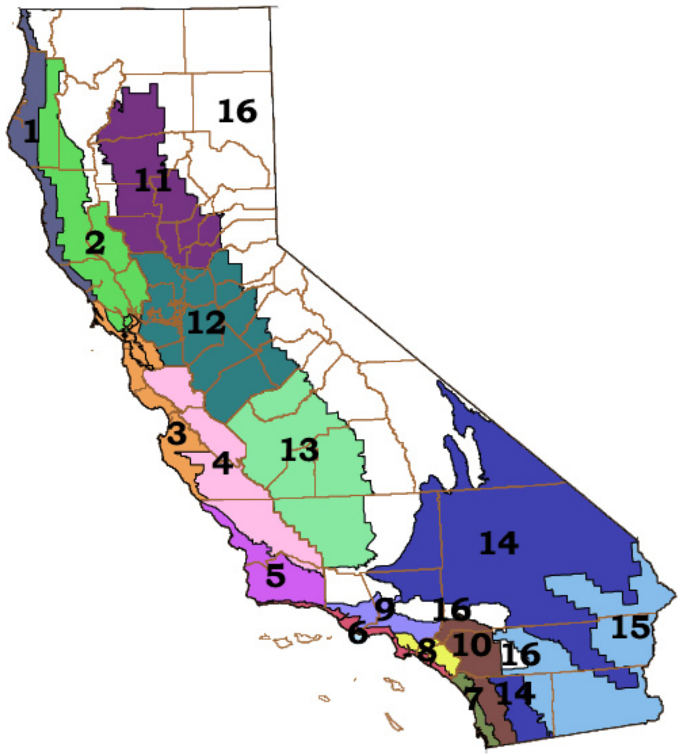


Figure 25. Map of 16 California climate zones.

Modeling of Baseline Residential Loads

To assess savings in the residential segment, we used BEopt to simulate a typical 2,500 ft^2 residence built to 2016 California Title 24 energy standards with gas appliances. The resultant baseline electricity and gas usage were stored to evaluate the impact of either gas reduction measures such as tankless or solar thermal as well as fuel switching water heating from gas to electric in the case of heat pumps and solar thermal with electric backup. In these scenarios, we compared the pre-measure utility bill with the post-measure utility bill to calculate annual electric bill savings. Where solar PV was considered, the PV generation was netted from the post-measure utility bill on a net-metered basis.

[29] https://energyplus.net/weather-region/north_and_central_america_wmo_region_4/USA/CA-Zones

Additionally, BEopt was used to model the temperature inside the attached garage where residential water heaters are assumed to be located. Because heat pump efficiency is driven by the surrounding air temperature, the calculation of the garage environment was critical for accurate modeling of heat pumps in the residential setting. Figure 26 shows a heat map of both garage and outside ambient temperatures illustrating the benefit residential heat pumps enjoy by being in this semi-conditioned space. Residential applications where the heat pump is installed or ducted outdoors will result in a performance decrease from study results. For multifamily applications, we assume the heat pump is operating in an unconditioned space, which is often alongside the building, on the rooftop, or in the open parking structure below the building.

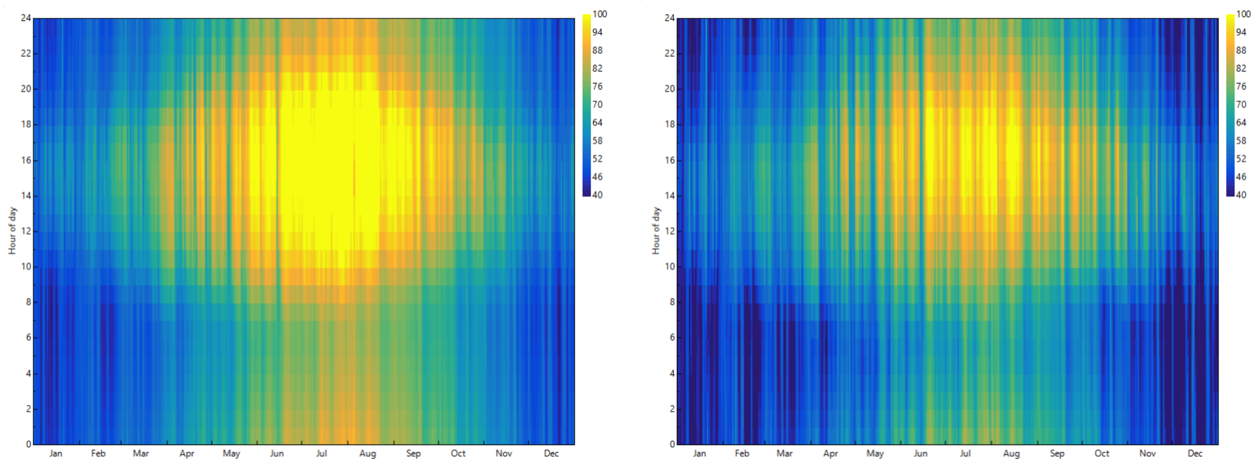


Figure 26. Heat pump environmental operating temperatures for garage (left) and outdoor air (right) in Climate Zone 16 (Tahoe region). The lower legend of 40 F indicates the limit of heat pump operation before backup resistance heating engages.

Modeling of Hot Water Draw Patterns

The daily draw consumption of 55 gallons residential and 840 gallons commercial were converted to granular draw volumes over the course of the year using a semi-stochastic model developed at the university of Kassel under the scope of the International Energy Agency solar heating and cooling program (Jordan and Vajen 2005). These fine grained draw profiles were necessary to accurately capture the interaction of the primary heating source (solar, heat pump) with the backup source (gas, electric resistance) over the course of the day and year as hot water draws vary significantly and can create high peak loads.

Solar Thermal Water Heating

Beyond the climate and water heating load, the key driver for solar water heating performance is the efficiency of the collector. In the US, solar thermal collectors are certified to SRCC Standard OG-100, which defines efficiency as a function of solar irradiance, water operating temperature, and the outside ambient temperature. While there are many different collector constructions available in the market, our analysis focused on selective surface flat plate collectors for water heating and unglazed polymer collectors for pool heating. Figure 27 illustrates solar thermal collector efficiency for each of these constructions as a function of operating temperature for several of the top manufacturers present in the SRCC listings for each product class. The heavy dashed lines in the figure represents the average performance within each product class and what was used in the simulation models.

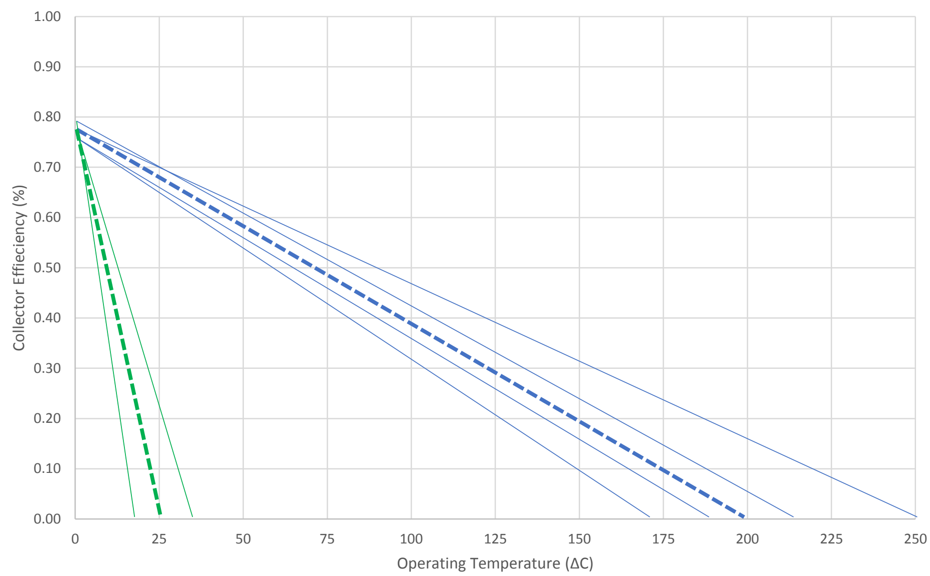


Figure 27. SRCC OG-100 collector efficiency curves for glazed selective surface (blue) & unglazed polymer (green) under full sun (1000 W/m^2). Individual sample collectors are shown as light solid lines. Average collector performance used in simulations is illustrated by the thick dashed lines.

Heat Pump Water Heating

Similar to solar collectors, heat pumps have an operating efficiency driven by the difference in temperature between the water being heated and the ambient temperature the unit is operating in. Performance maps for all-in-one heat pumps have been experimentally determined for the general product class (Carew et al. 2018, Sparn et al. 2014). The performance map used in our simulations was taken from the Ecotope study and is reproduced below in Figure 28. At environmental temperatures below 4.5 degrees C, heat pump operation was ceased and the resistance heating was engaged for our models.[30] As a final point of model calibration, we compared the average statewide EF of 2.0 from our residential models with BEopt 2.8 using DoE EnergyPlus 8.8.0 as the simulation engine. The results from EnergyPlus indicated a statewide EF of 1.85 to 2.12 based on default parameters or the updated parameters used in our models respectively.

---

[30] This reflects the operating logic of most all-in-one designs as they do not have a defrost cycle and instead disengage the heat pump to avoid freezing the coil at ambient temperatures below 40 F.

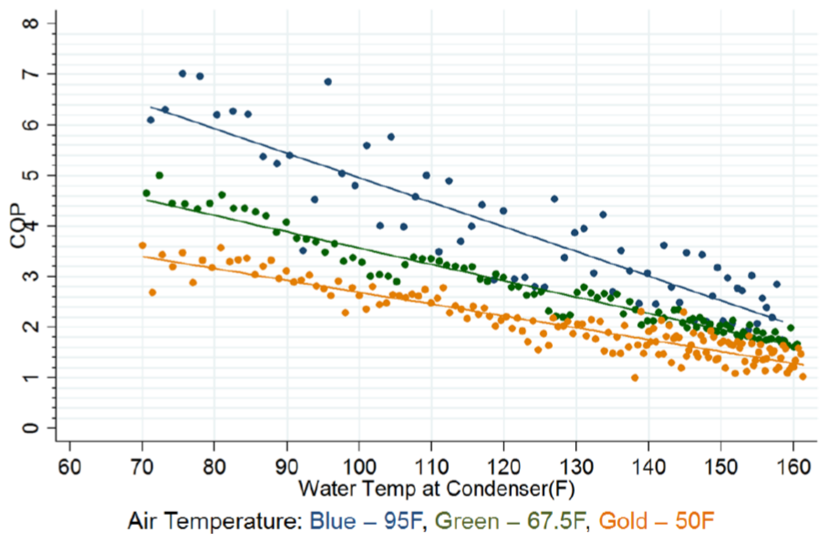


Figure 28. Heat pump efficiency (COP) as a function of water heater & environmental temperature (Carew et al. 2018).

Appendix B – Utility Rates & Carbon Emission Factors

Annual operating costs were calculated for each configuration across market segments and the 16 climate zones. Each climate zone was associated with a primary utility for both gas and electric as outlined in Table 18 using the most likely rate structures within each utility presented in Table 19. In some cases, the gas and electricity services were provided by separate utilities. Additionally, some climate zones had multiple utilities present and we selected the one we believed to be most representative for the region.

Table 18. Association of gas and electric utilities to climate zones.

Climate Zone	Electric Utility	Gas Utility
1	Pacific Gas & Electric	Pacific Gas & Electric
2	Pacific Gas & Electric	Pacific Gas & Electric
3	Pacific Gas & Electric	Pacific Gas & Electric
4	Pacific Gas & Electric	Pacific Gas & Electric
5	Pacific Gas & Electric	Southern California Gas
6	Southern California Edison	Southern California Gas
7	San Diego Gas & Electric	San Diego Gas & Electric
8	Southern California Edison	Southern California Gas
9	Southern California Edison	Southern California Gas
10	San Diego Gas & Electric	San Diego Gas & Electric
11	Pacific Gas & Electric	Pacific Gas & Electric
12	Pacific Gas & Electric	Pacific Gas & Electric
13	Pacific Gas & Electric	Southern California Gas
14	San Diego Gas & Electric	San Diego Gas & Electric
15	Imperial Irrigation District	Southern California Gas
16	Pacific Gas & Electric	Pacific Gas & Electric

Table 19. Gas and electric utility tariffs used in the analysis.

	Residential		Commercial	
Utility	**Gas Rate**	**Electric Rate**	**Gas Rate**	**Electric Rate**
Imperial Irrigation District	-	D	-	GS
Pacific Gas & Electric	G-1	E-TOU-C	GM	B-10
San Diego Gas & Electric	GR	TOU-DR	GM	TOU-M
Southern California Edison	-	TOU-D-PRIME	-	TOU-GS-1
Southern California Gas	GR	-	GM	-

Calculation of Natural Gas Charges

For residential configurations with gas backup, we assessed the gas usage in each climate using BEopt to determine the amount of baseline and excess gas consumption to provide an accurate estimate of the blended gas cost used for water heating.[31] In commercial applications we assumed the large water heating loads were at the excess natural gas rate under the utility tariff.

Calculation of Electricity Charges

Each utility, with the exception of the Imperial Irrigation District, operates on a Time Of Use (TOU) tariff that varies by hour of day and season for electricity charges. Annual operating costs for configurations with electric backup required that the cost of the new electric water heating load be calculated on an hourly basis throughout the year against these TOU tariffs. This was done by implementing each of the utility tariffs in Table 18 into the utility rate calculator of the SAM tariff engine along with the electrical demand for the water heating configuration. The result of the simulation was an annual operating cost for the configuration as well as a blended $/kWh rate consumed under the TOU tariff.

An example of this approach to TOU calculations is shown in Figures 29 and 30 that illustrate the SAM utility tariff definition and heat maps of hourly energy usage for two different configurations in Climate Zone 3 (Bay Area). In this example, electric rates vary from a low wintertime baseline of $0.20/kWh to a peak summer rate of $0.40/kWh for energy above the baseline. Ideally, any configuration capable of avoiding summer peak period (4:00 – 9:00 PM) will have lower annual operating costs.

As illustrated in Figure 30, the solar thermal configuration is advantaged with a low baseline energy use as well as a near complete avoidance of energy consumption during peak summer periods.[32] The combination of these factors results in a blended annual energy cost of $0.23/kWh for solar thermal as compared to $0.25/kWh for the heat pump.

[31] Most California utilities charge separate baseline and excess rates for gas consumption during the month based on allowances within their territory. In many cases, the excess rate can be 35+% over the baseline rate and needs to be accounted for.

[32] This is a result of high daytime solar resources that charge the solar storage tank to maximum temperature during the day to supply evening loads without the need of the backup element. The same solar resource that drives peak AC demands also eliminates peak coincident water heating loads in solar thermal systems.

Period	Tier	Max. Usage	Max. Usage Units	Buy ($/kWh)	Sell ($/kWh)
1	1	6.8	kWh daily	0.31761	0.31761
1	2	1e+38	kWh daily	0.40278	0.40278
2	1	6.8	kWh daily	0.25417	0.25417
2	2	1e+38	kWh daily	0.33934	0.33934
3	1	8.2	kWh daily	0.22052	0.22052
3	2	1e+38	kWh daily	0.30569	0.30569
4	1	8.2	kWh daily	0.20319	0.20319
4	1	1e+38	kWh daily	0.28836	0.28836

Weekday

	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm	11pm
Jan	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	4	4	4
Feb	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	4	4	4
Mar	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	4	4	4
Apr	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	4	4	4
May	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	4	4	4
Jun	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2
Jul	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2
Aug	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2
Sep	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2
Oct	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	4	4	4
Nov	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	4	4	4
Dec	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	4	4	4

Weekend

	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm	11pm
Jan	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	4	4	4
Feb	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	4	4	4
Mar	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	4	4	4
Apr	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	4	4	4
May	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	4	4	4
Jun	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2
Jul	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2
Aug	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2
Sep	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2
Oct	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	4	4	4
Nov	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	4	4	4
Dec	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	4	4	4

Figure 29. Pacific Gas & Electric E-TOU-C rate for Climate Zone 3 (Bay Area).

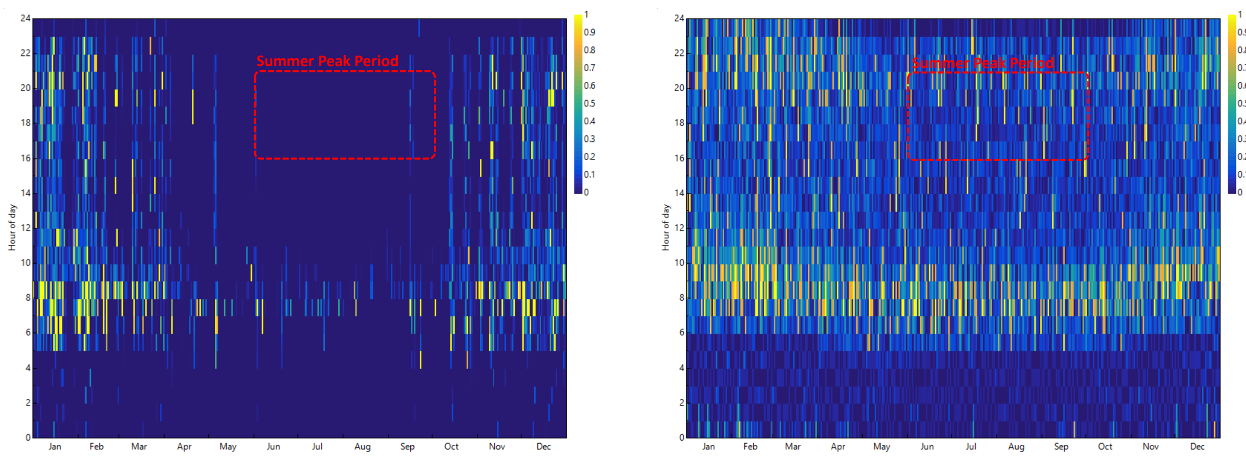


Figure 30. Heat maps of residential electricity use for solar thermal system (left) and heat pump (right) in Climate Zone 3 (San Francisco). The summer peak TOU period is indicated. Legend is scaled with a peak of 1 kWh.

Treatment of Demand Charges in Commercial Segments

While residential tariffs operate exclusively on energy charges ($/kWh), commercial tariffs are comprised of similar TOU energy charges ($/kWh) as well as demand charges ($/kW). Depending on the on-site loads and usage patterns, demand charges can make up a quarter or more of the typical electrical bill.

While it was reasonable to model a residential building profile based on standard construction to calculate baseline electrical usage, the variance in commercial building types and loads made the generation of such a profile impractical. After assessing the demand profiles for both solar and heat pump systems, we decided to exclude demand charges from the annual operating costs for both heat pumps and solar water heating systems. While this may be seen as an aggressive assumption in favor of electrifying the commercial water heating segment, we believe it is supported based on the following observations and assumptions:

- Water heating loads are not generally coincident with other peak building loads such as lighting and air conditioning that occur in the late afternoon and early evening. Electrical demand for solar thermal and heat pump systems peak mid-morning as the systems recover from early morning shower draws. More importantly, these systems have minimal power demand in summer evenings when solar thermal systems have fully charged storage tanks and heat pump systems are operating at higher efficiency with elevated ambient temperatures (Figure 31).
- Commercial solar thermal systems have large storage tanks (600 gallons) capable of storing an entire day's water heating load. While not having such large storage volumes, commercial heat pump systems do have sufficient reserve capacity (240 gallons) to be pre-charged at elevated temperatures ahead of peak demand periods such that they can ride through 15 - 60 minutes peak coincident demand if enabled with appropriate controls.

While we believe these simplifying assumptions are reasonable for a broad market analysis, care should be applied to actual installations in the commercial segment to ensure that proper demand controls are installed as part of heat pump and solar water heating installations using electric backup to enable the level of annual savings presented by this study.

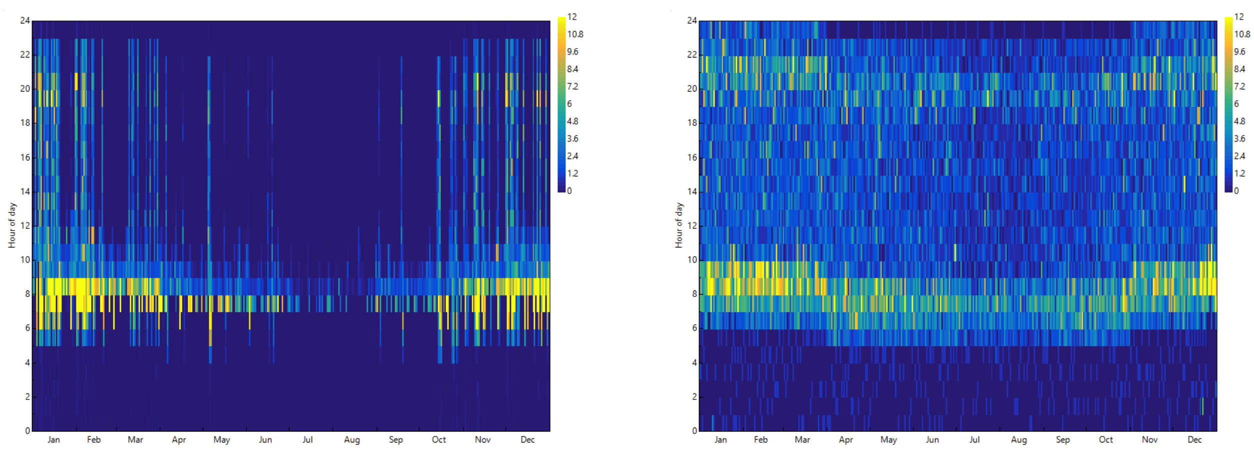


Figure 31. Heat maps of energy use for multifamily solar thermal system (left) and heat pump (right) in Climate Zone 3 (San Francisco). Legend is scaled with a peak of 12 kW.

Calculation of Carbon Emissions

Carbon emissions for grid supplied electricity were taken from the 2019 California Greenhouse Gas Emission Inventory (CARB 2019) as shown in Figure 32. In 2017, the overall carbon intensity of electricity used in California was 0.45 lb/kWh. We assumed a linear reduction in emissions towards a fully decarbonized grid in 2045 to arrive at an average carbon intensity of 0.22 lb/kWh used in the analysis.

Carbon emissions for natural gas are straightforward and based on the carbon and energy content of natural gas at 0.40 lbm/kWh-thermal.[33] While there is potential to reduce the carbon intensity of the natural gas through Renewable Natural Gas (RNG), we did not include any future reductions in the analysis.

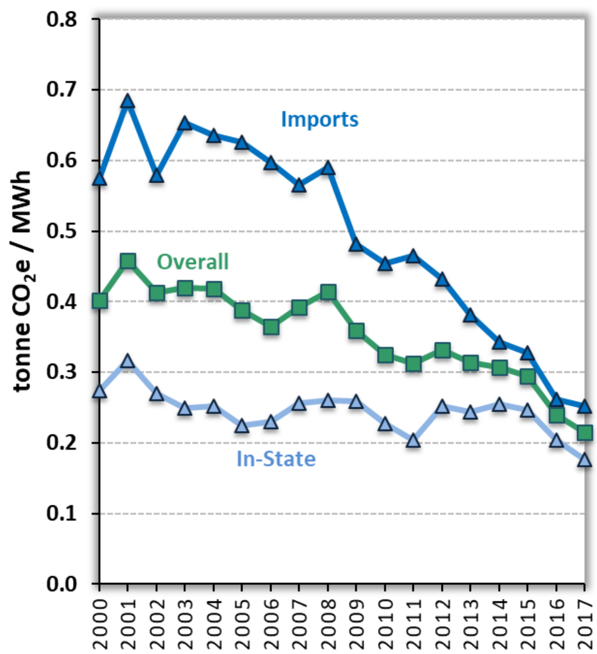


Figure 32. Carbon intensity of California electricity supply. Figure courtesy California Air Resource Board (CARB 2019).

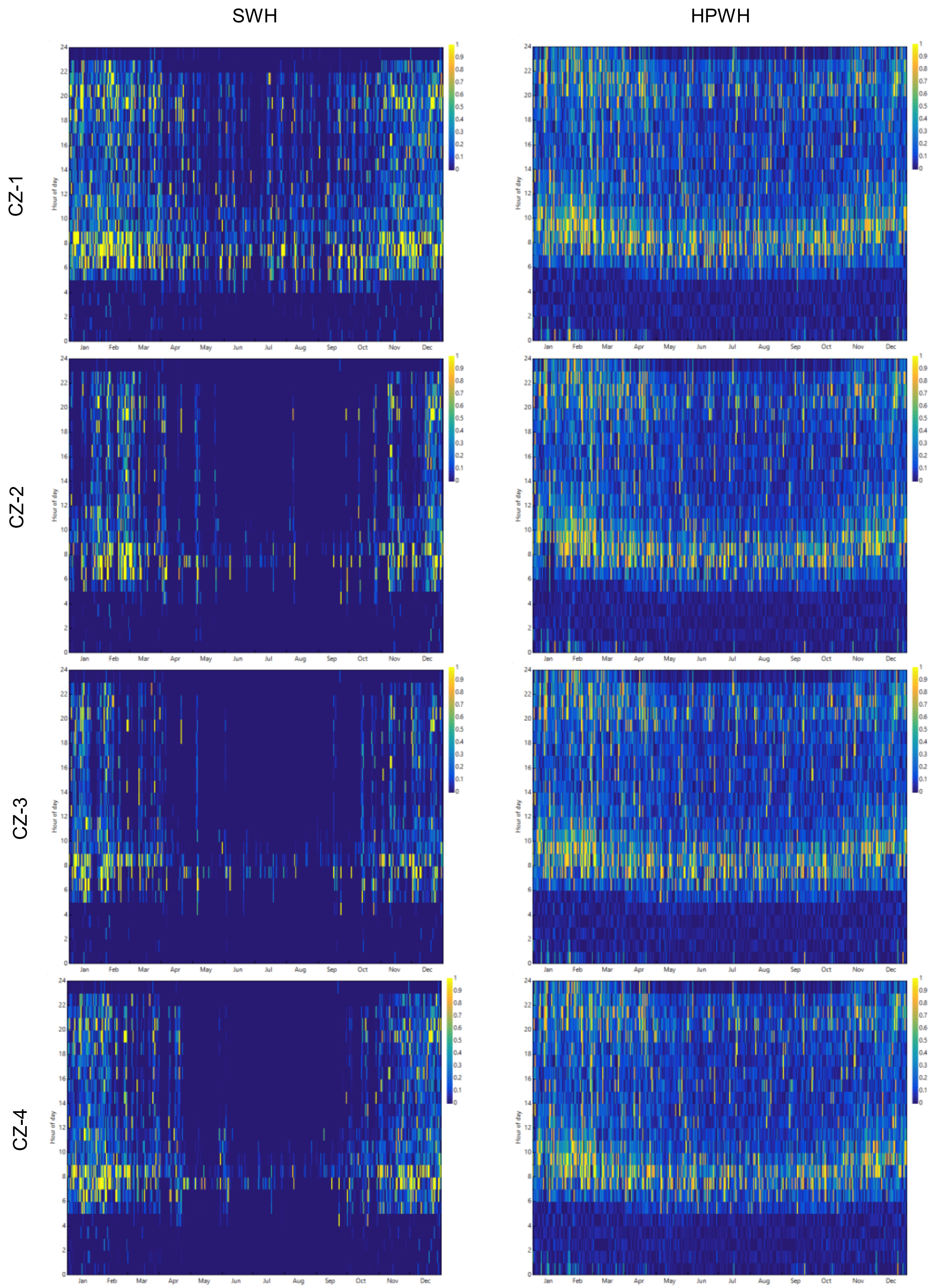
[33] https://www.eia.gov/environment/emissions/co2_vol_mass.php

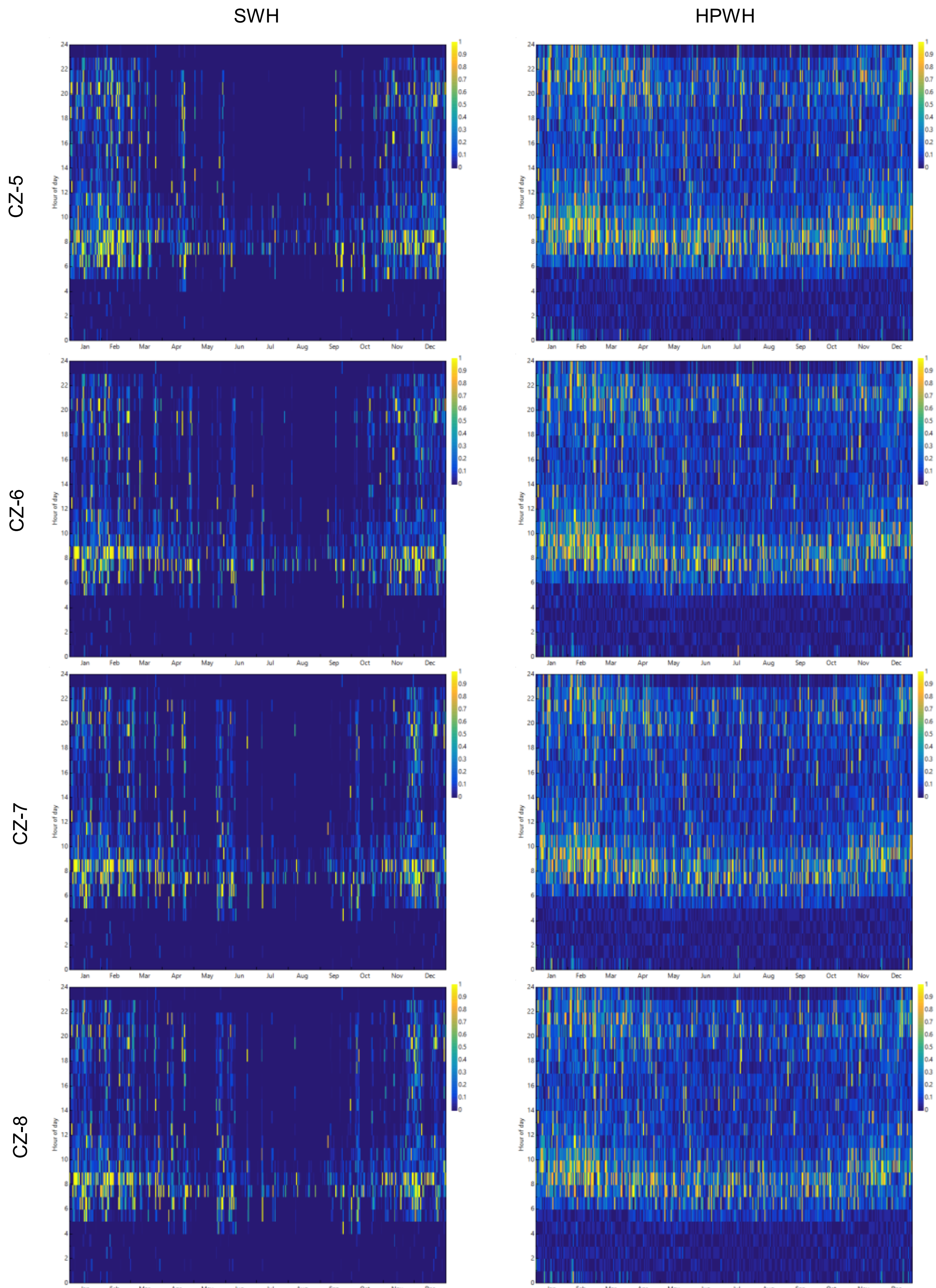
Appendix C – Residential Electricity Use Profiles

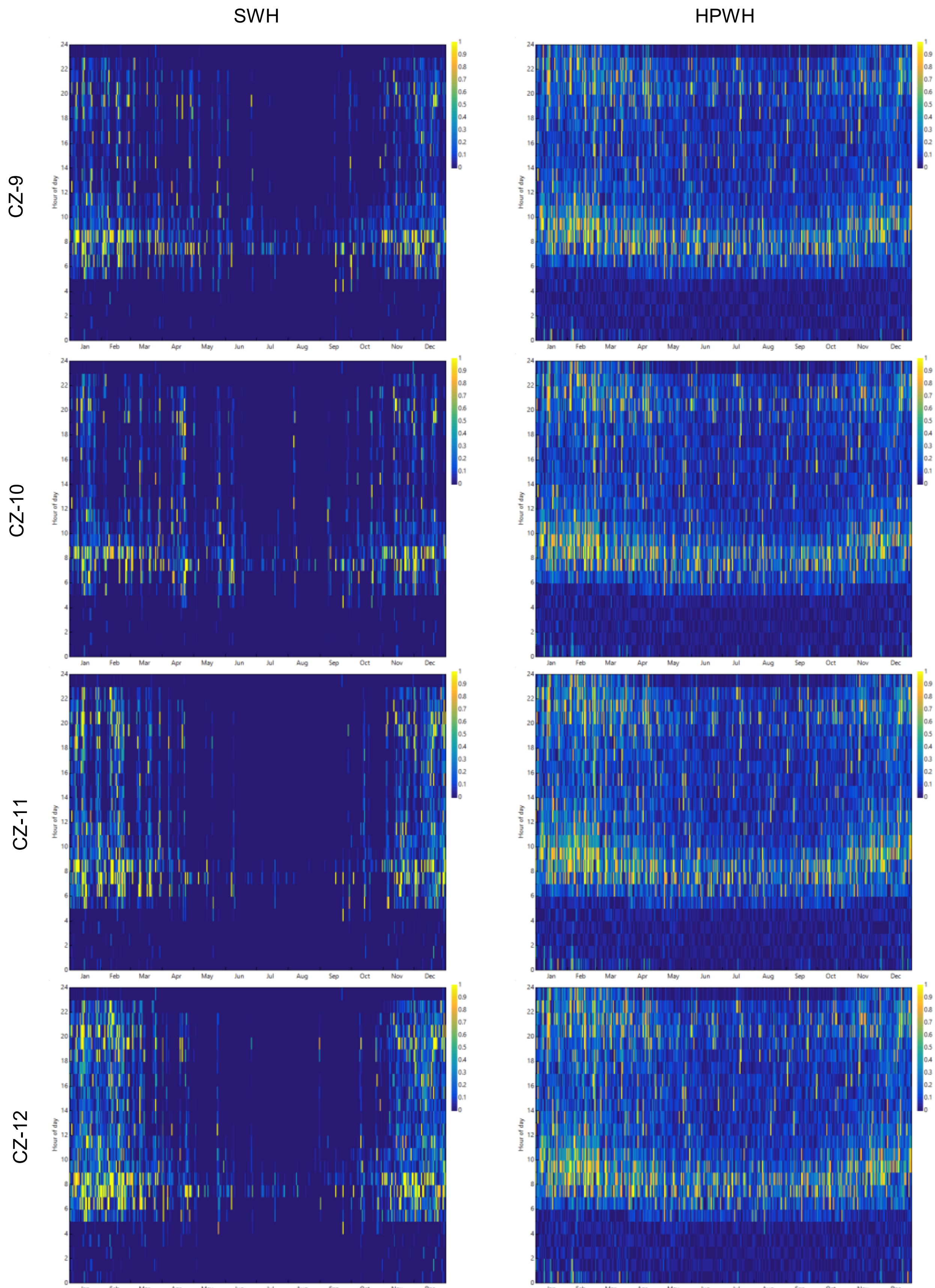
The heat maps on the following pages show detailed hourly electricity use over the typical year for both solar water heaters (SWH) with electric backup and heat pump water heaters (HPWH) over all 16 climate zones. Figures 2 and 30 from the study were extracted from these profiles. Scale on residential profiles is 0 to 1 kW.

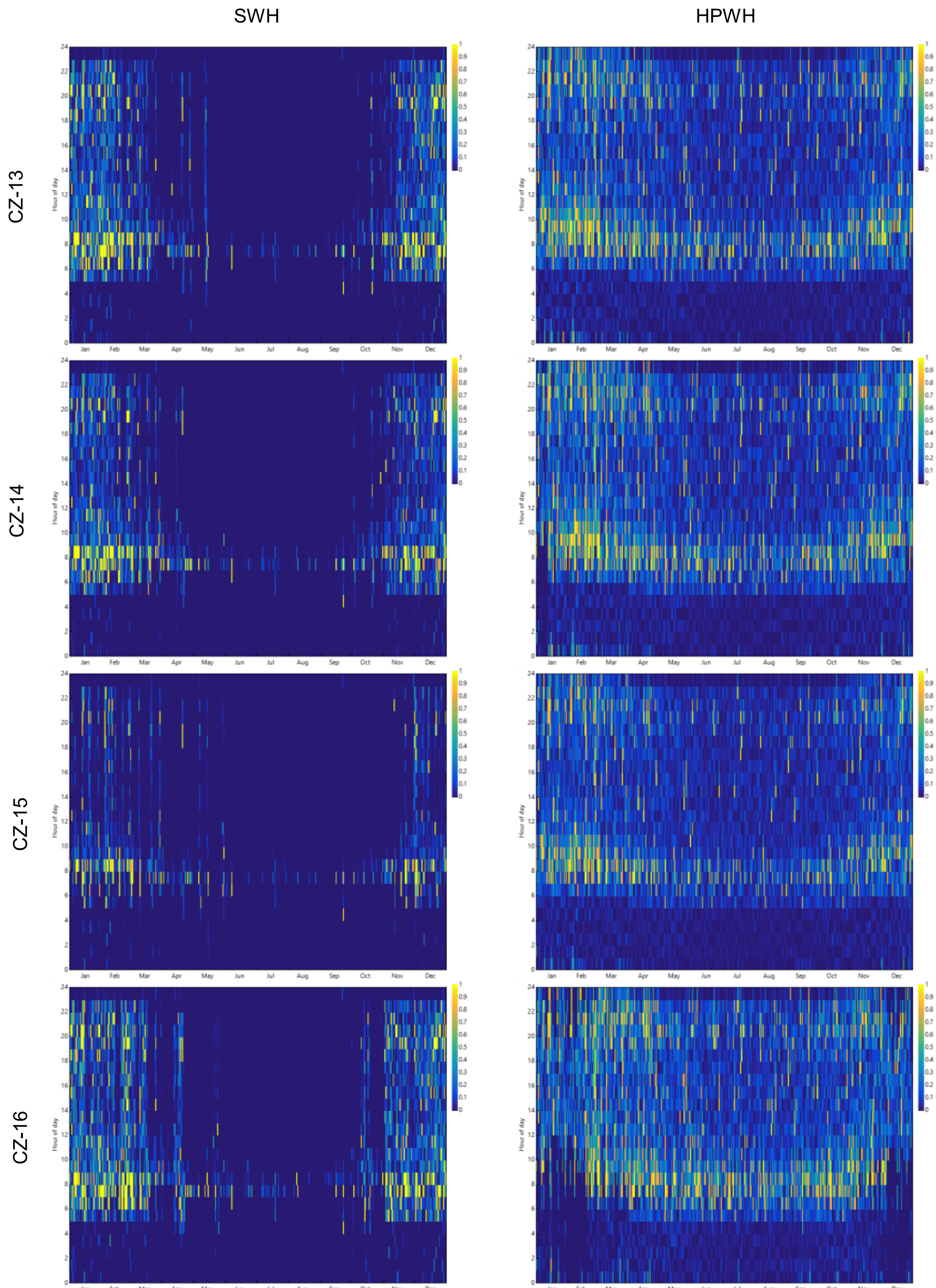
These heat maps demonstrate that solar water heating systems do not rely on the backup electric element for a majority of hours per year. Heat pumps use electricity whenever they are heating water, with the compressor loop using less electricity and the backup element using more electricity.

For both residential and multifamily, the biggest water heating load is in the late morning. Rate design to support water heating electrification could include reduced volumetric charges in those hours.


SWH
HPWH
CZ-1
CZ-2
CZ-3
CZ-4
Hour of day
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

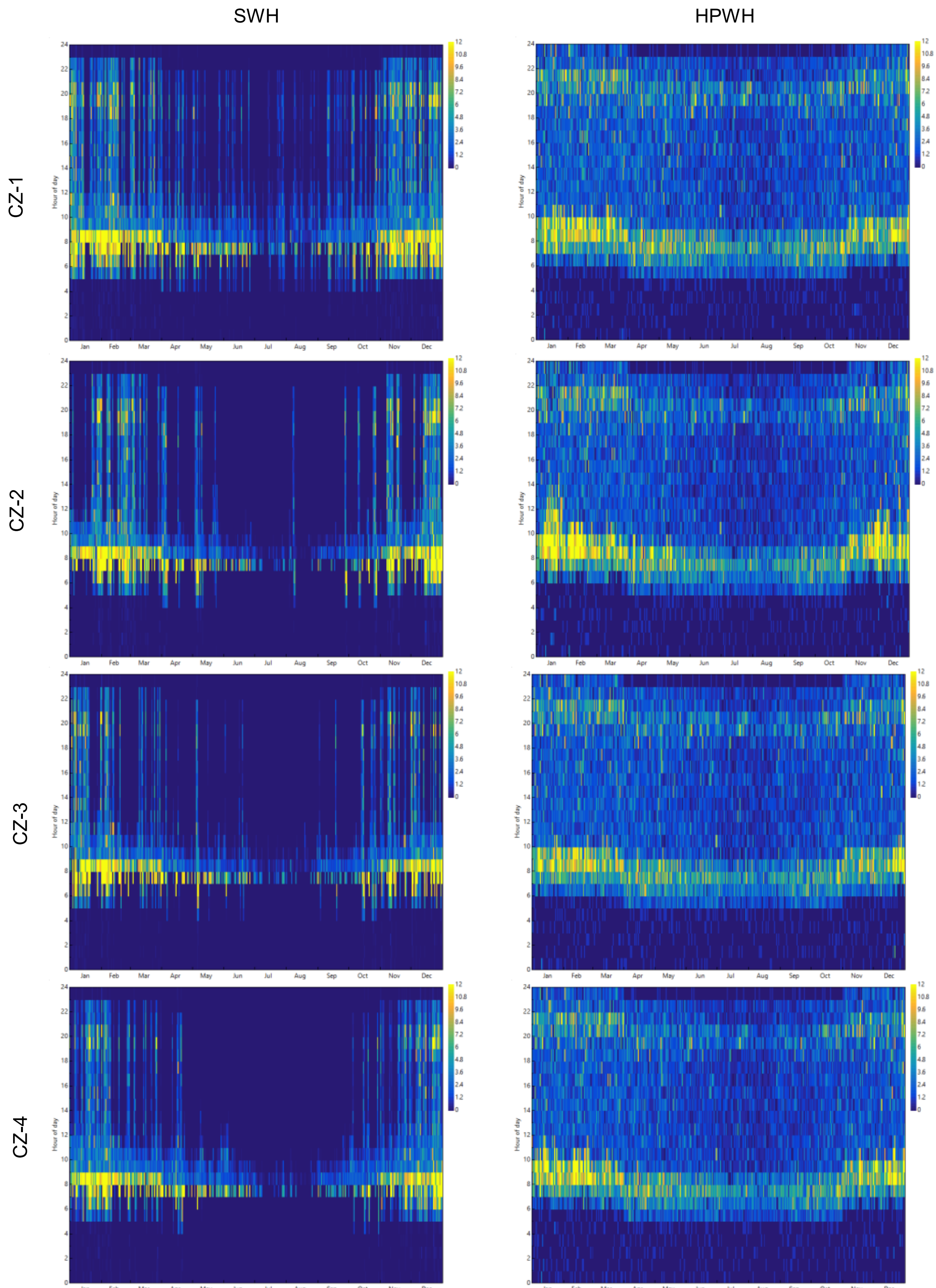

SWH
HPWH
CZ-5
CZ-6
CZ-7
CZ-8
Hour of day
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

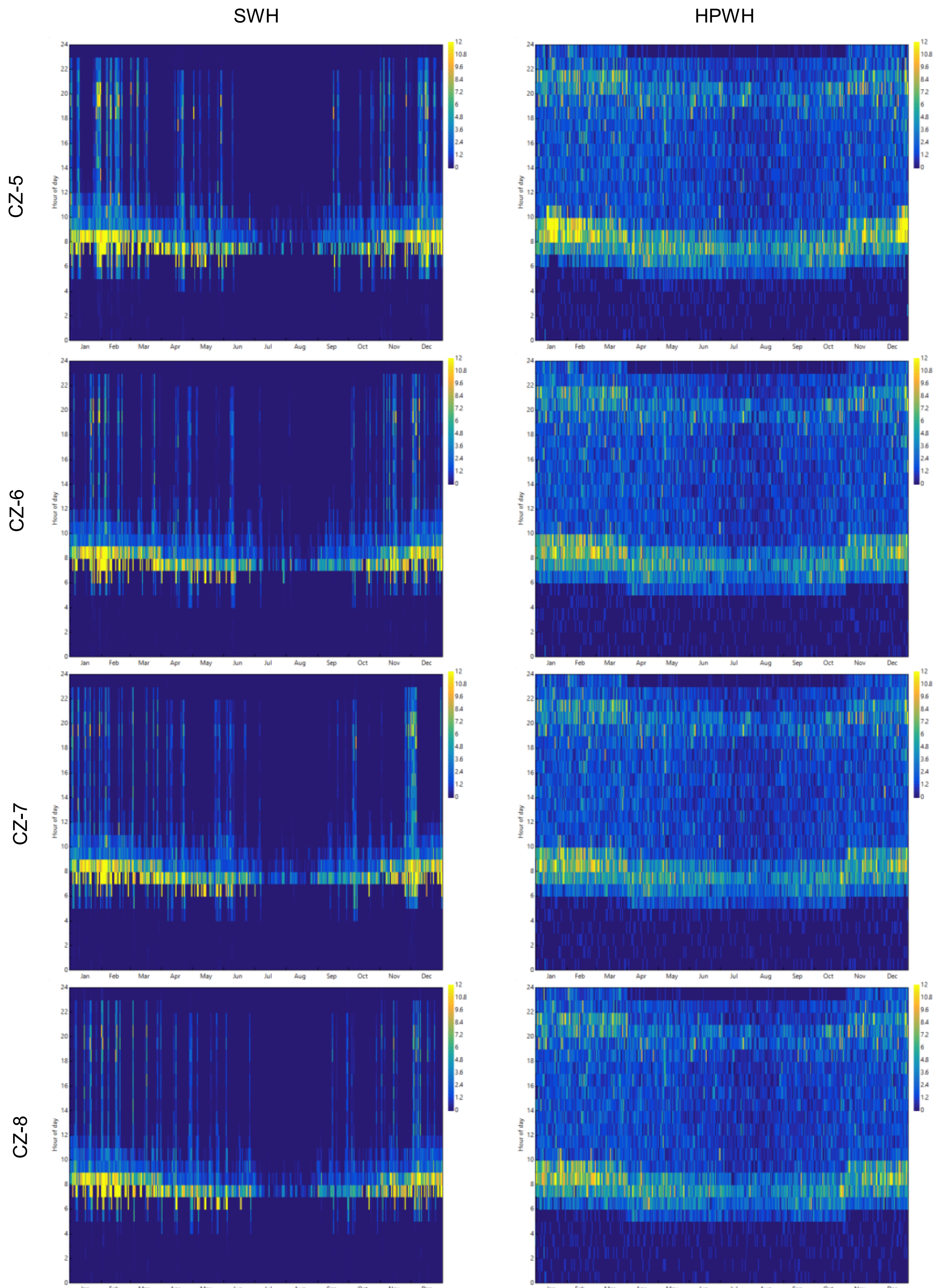

SWH
HPWH
CZ-9
CZ-10
CZ-11
CZ-12
Hour of day
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

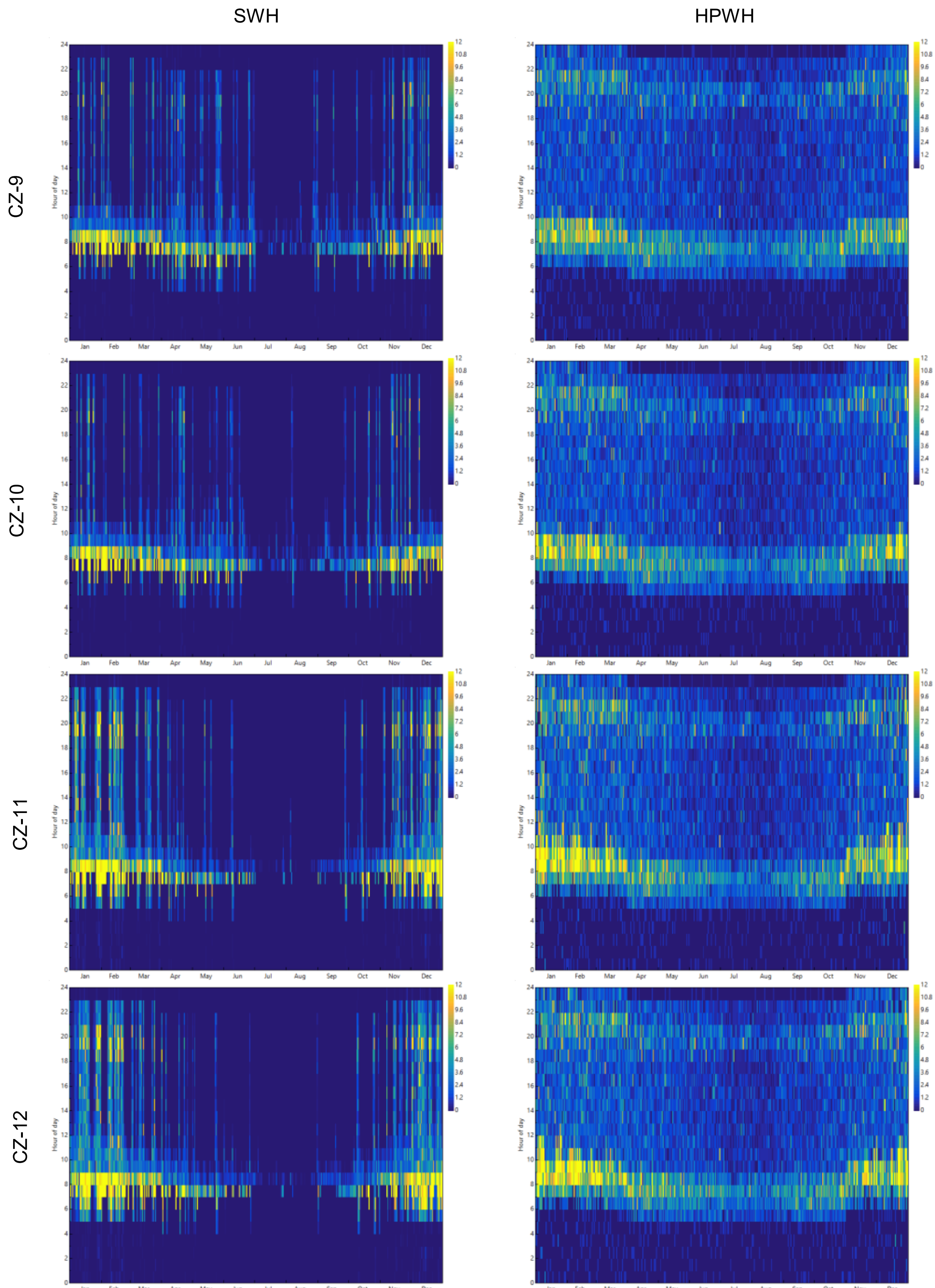

SWH
HPWH
CZ-13
CZ-14
CZ-15
CZ-16
Hour of day
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

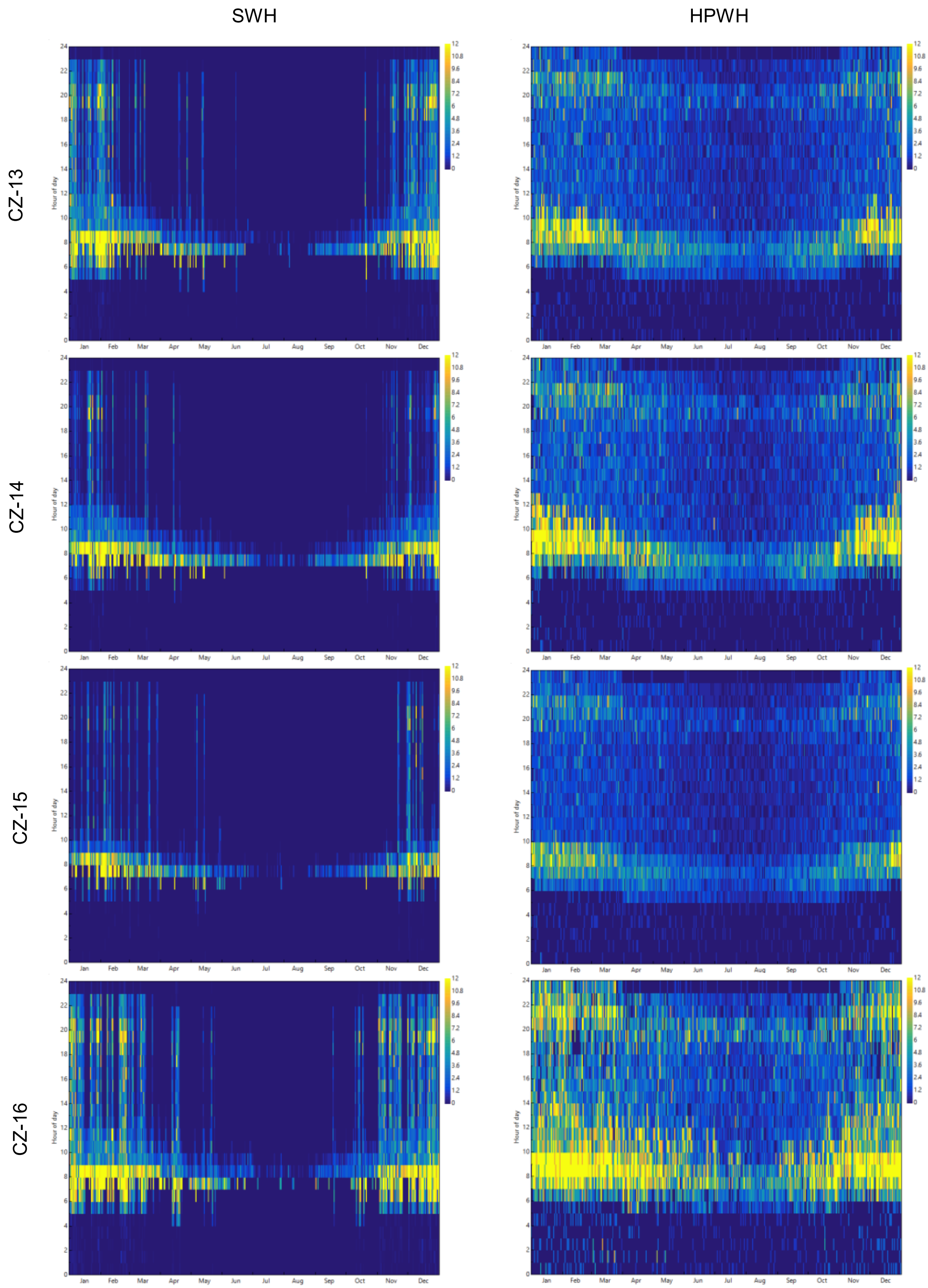
Appendix D – Multifamily Electricity Use Profiles

The heat maps on the following pages show detailed hourly electricity use over the typical year for both solar water heaters (SWH) with electric backup and heat pump water heaters (HPWH) over all 16 climate zones. Figures 3 and 31 from the study were extracted from these profiles. Scale on multifamily profiles is 0 to 12 kW.


SWH
HPWH
CZ-1
CZ-2
CZ-3
CZ-4
Hour of day
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
0 2 4 6 8 10 12 14 16 18 20 22 24
0 1.2 2.4 3.6 4.8 6 7.2 8.4 9.6 10.8 12

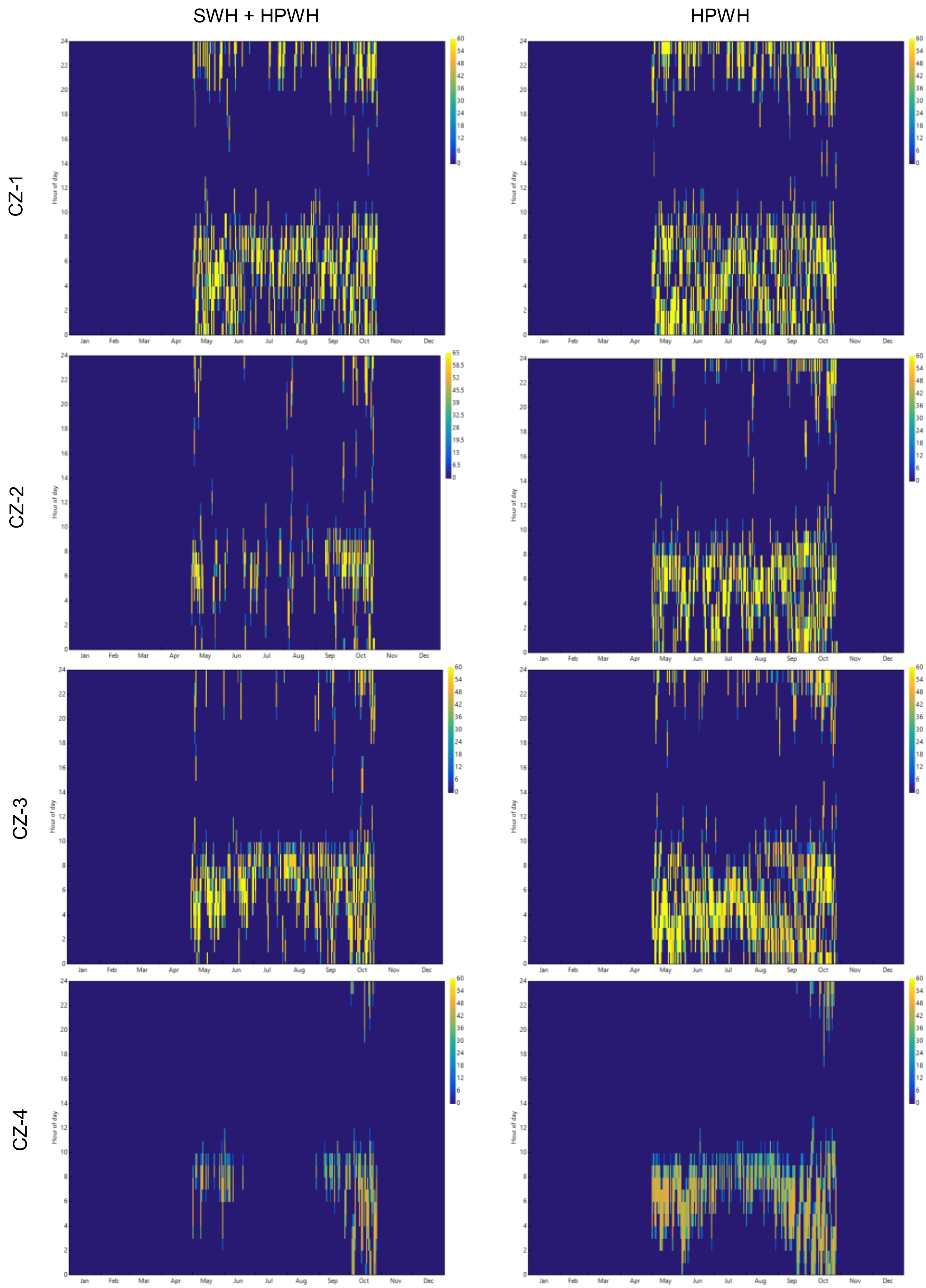

SWH
HPWH
CZ-5
CZ-6
CZ-7
CZ-8
Hour of day
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

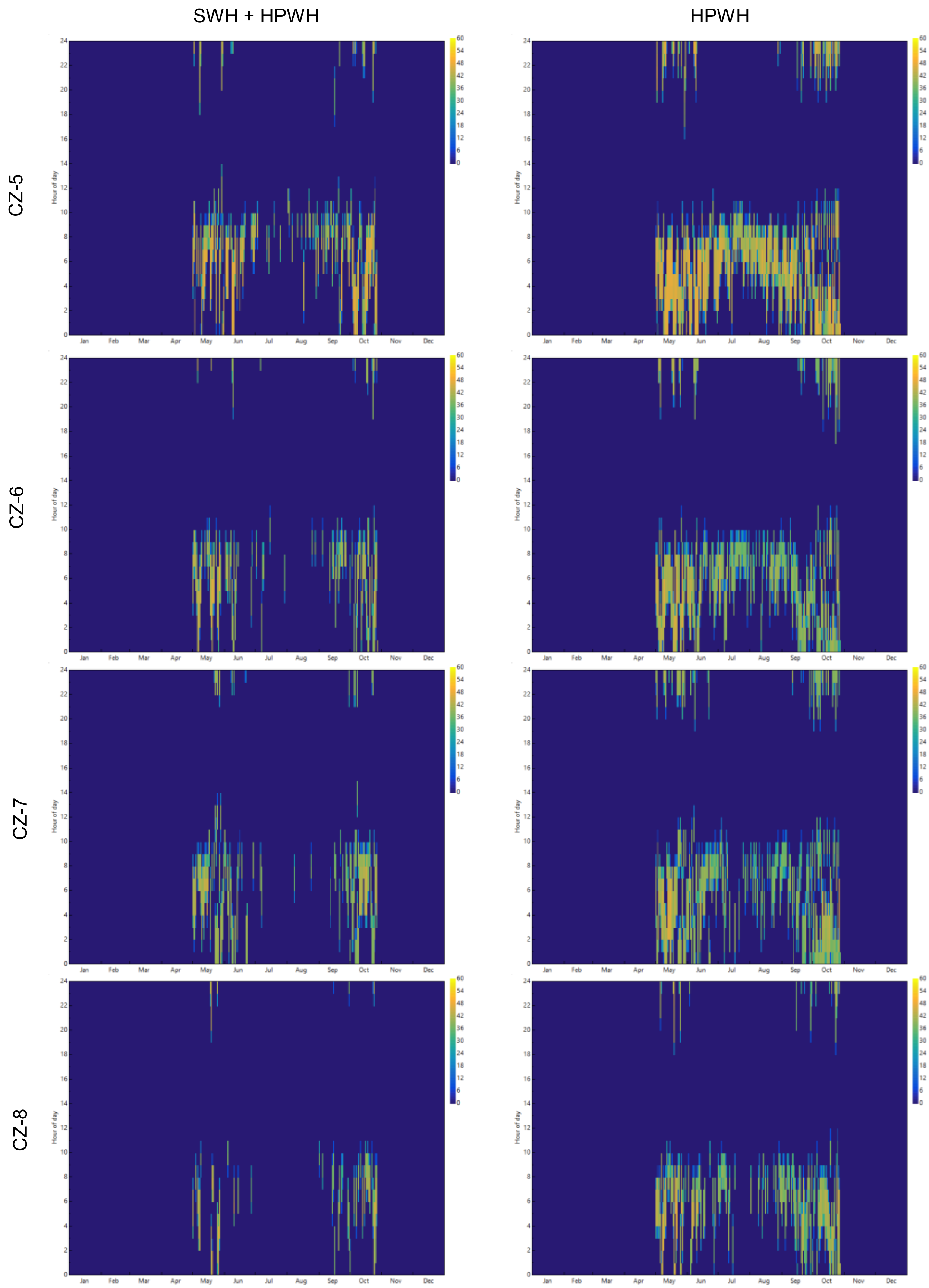

SWH
HPWH
CZ-9
CZ-10
CZ-11
CZ-12
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

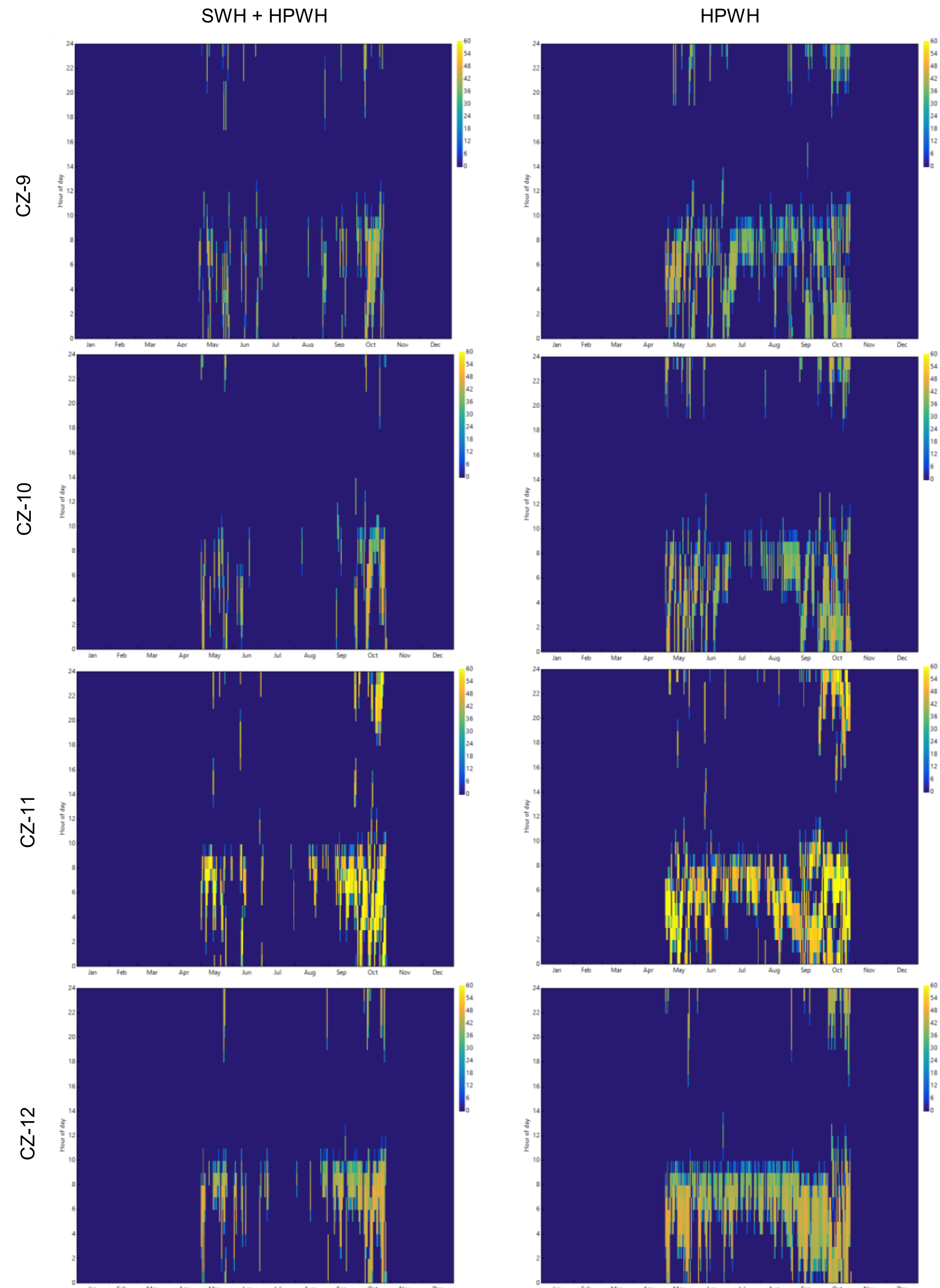

SWH
HPWH
CZ-13
CZ-14
CZ-15
CZ-16
Hour of day
0 2 4 6 8 10 12 14 16 18 20 22 24
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
0 1.2 2.4 3.6 4.8 6 7.2 8.4 9.6 10.8 12

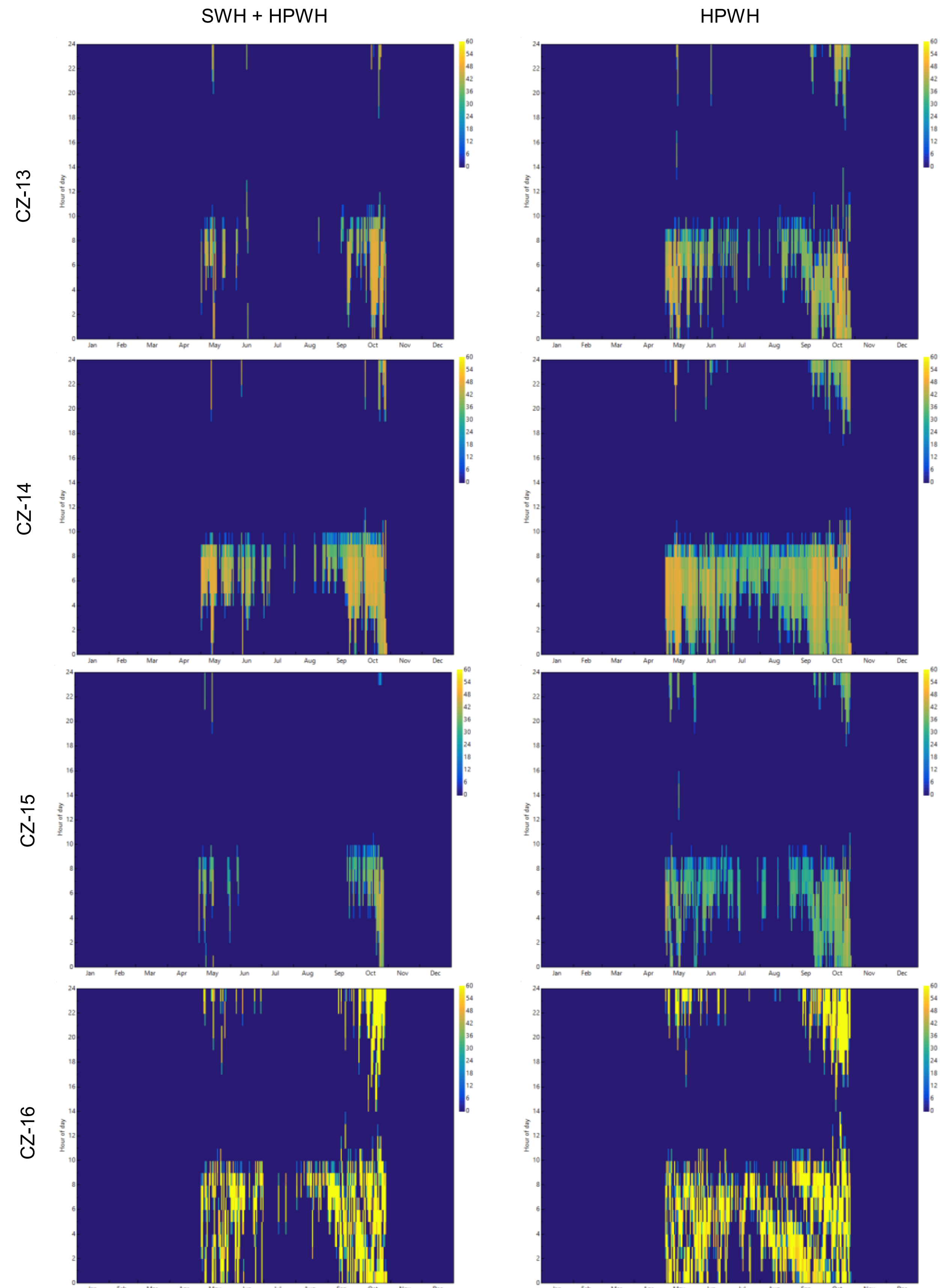
Appendix E – Commercial Pool Electricity Use Profiles

The heat maps on the following pages show detailed hourly electricity use over the typical year for both solar water heaters (SWH + HPWH) with heat pump backup and heat pump water heaters (HPWH) over all 16 climate zones. Scale on commercial pool profiles is 0 to 60 kW.


SWH + HPWH
HPWH
CZ-1
CZ-2
CZ-3
CZ-4
Hour of day
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


SWH + HPWH
HPWH
CZ-5
CZ-6
CZ-7
CZ-8
Hour of day
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
0 6 12 18 24 30 36 42 48 54 60


SWH + HPWH
HPWH
CZ-9
CZ-10
CZ-11
CZ-12
Hour of day
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


SWH + HPWH
HPWH
CZ-13
CZ-14
CZ-15
CZ-16
Hour of day
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec