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The Building Electrification Technology Roadmap (BETR)

A BETR Path to Decarbonization for California Efficiency Programs

Technical status, barriers, and paths to advancing electrification technologies in residential and commercial buildings.

Prepared By:

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BETR is a collective representation of the lead and advising authors' research and professional judgments regarding the findings, rather than an account of every authors' position on each technology. Different interpretations are likely within the diversity of the parties working on, or impacted by, electrification.

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1. Introduction

1.1. Why Building Electrification

The Building Electrification Technology Roadmap (BETR) was prepared for the California-based funding organizations in 2020, while the year was on course to break the record for the hottest annual global and U.S. temperatures – joining eight of the other top 10 years just since 2010.[1]

The changing Sierra snowpack increases risk of floods and water shortages; drier forests are more vulnerable to fires; and hotter temperatures lead to more smog, which can damage lungs. While climate change often feels like an intractable dilemma, many solutions for addressing buildings' role in climate change are readily available and accessible today. Building electrification, or the shift from gas appliances to all-electric appliances and technologies powered by an increasingly clean grid, is widely recognized as a critical pathway for achieving significant greenhouse gas (GHG) emission reduction.

In order to meet its landmark 2045 carbon neutrality goal, the State of California has set ambitious targets necessary to reduce and avoid existing emissions across all sectors, with the building sector targets shown in Figure 1.[2,3]

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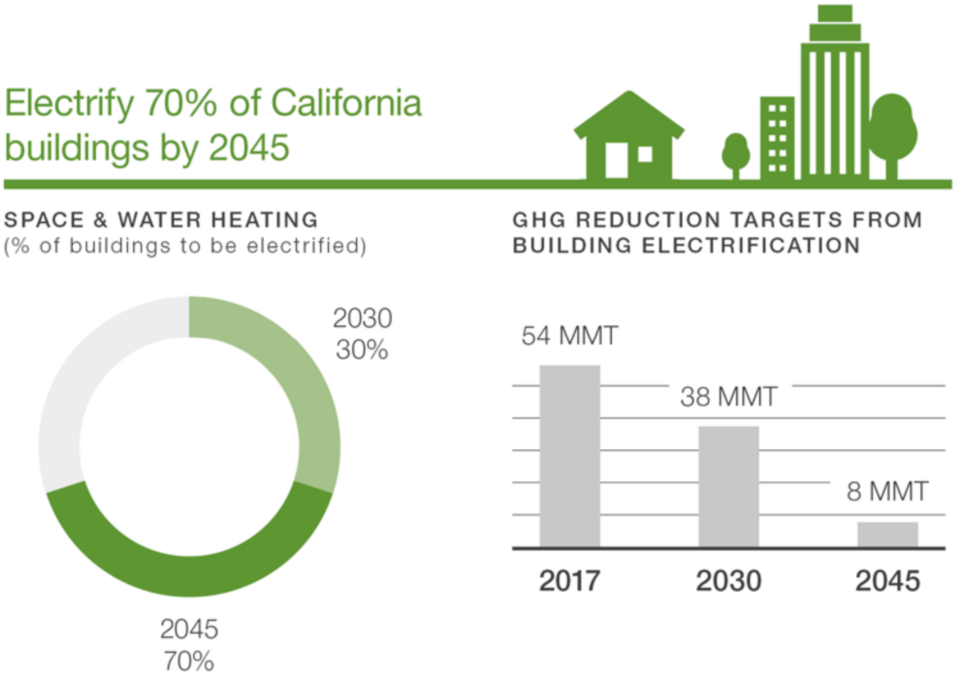
[1] NOAA 2020

[2] State of California 2018, Executive Order B-55-19 to Achieve Carbon Neutrality

[3] SCE 2019, Pathway 2045

FIGURE 1: ROLE OF BUILDING ELECTRIFICATION TOWARD CALIFORNIA GHG REDUCTION GOALS

Source: NBI Based on SCE 2019, Pathway 2045



Cities, industries, and companies are following suit, adopting climate action plans that include commitments to reduce emissions. Through December 2020, 40 cities in California have adopted all-electric building mandates or preferences in their building permitting and 40 more are in process.[4] Many large public institutions such as the University of California system have set targets for significant emission reduction across their building portfolios. Private sector companies are also setting aggressive energy and emission reduction targets, sending a clear message to customers and shareholders. High-profile building labeling program leaders such as the U.S. Green Building Council (USGBC) and the International Living Future Institute both offer zero carbon building certifications.

Although power generation and transportation get much of the attention for carbon emissions, buildings are also a big contributor to global emissions. Nationally, approximately 27% of the total natural gas consumption occurs directly in residential and commercial buildings.[5] In California, the emission from buildings' energy and fuel use account for more than one quarter of the state's total emissions, as shown in Figure 2.

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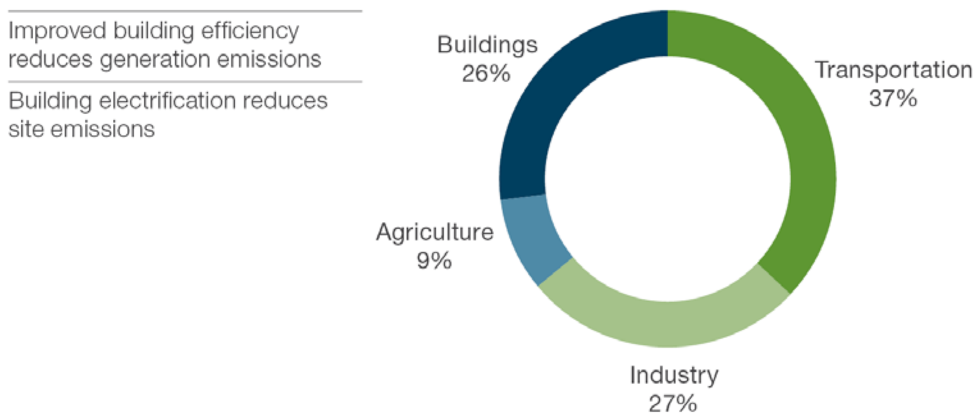
[4] Gough, M., Sierra Club, 2020, California Cities Lead the Way to a Gas-Free Future

[5] EIA 2020

FIGURE 2: CALIFORNIA END-USE GREENHOUSE GAS EMISSIONS



Building electrification is increasing in markets, programs, and policies driven by the advancement in electric technologies that can deliver greater efficiency per unit of energy, improve conditions for occupant health, safety and indoor environmental comfort, and support policies and goals to reduce GHG emissions.

1.2. A Green Grid is Not Enough

Using renewable energy to power buildings is already an effective way to reduce carbon emissions in the state of California, where renewables reached more than 32% of energy production in 2018. By 2045, 100% of the state's retail electricity sales are targeted to be met by renewables. In California natural gas provides 70% of all energy in the average home and 30% on average in commercial buildings.[6] Direct site natural gas use, combined with leakage in delivery, can be responsible for as much as 60% of the CO_2 emissions of a mixed-fuel home. As grid-delivered electricity gets cleaner, the importance of building technologies grows. Transitioning away from direct use of fossil fuels (i.e. natural gas, propane) on-site is the next step in the energy transformation.

Keeping the grid reliable requires a continuous balancing act between supply (power plants) and demand (mostly at buildings), and as more of the grid mix comes from variable resources like wind and solar the balance becomes harder to maintain. *When* energy is used is becoming nearly as important as *how much* energy is used. Smart electrification, leveraging digital technology to enable two-way communication between the utility and its customers, will allow buildings to enable and accelerate the transformation to a carbon-neutral economy.

A recent study by the California-based company Energy and Environmental Economics (E3) summarizes the range of GHG savings from electrification of a whole home and points out that as renewable energy increases on the grid,

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[6] The term "natural gas" is the most commonly used term, but the term "fossil gas" is gaining use as a more accurate term for the methane-based, fossil-derived fuel.

these emissions become a larger proportion of the total and thus become an increasingly critical challenge to our decarbonization goals.[7]

"Electrification is found to reduce total greenhouse gas emissions in single family homes by 30% – 60% in 2020, relative to a natural gas-fueled home. As the carbon intensity of the grid decreases over time, these savings are estimated to increase to ~80% – 90% by 2050, including the impacts of upstream methane leakage and refrigerant gas leakage from air conditioners and heat pumps." (E3 2019 Study)

Significantly reducing building site carbon emissions requires rapid and broad adoption of efficient electric technologies, many of which are available today but aren't yet widely adopted. We must electrify buildings to meet the state's climate action goals.[8] We also need to prepare for emerging products that can provide the same or better level of service as incumbent technologies.

Our BETR research shows that replacing fossil fuel-based systems in four categories—space and water heating, cooking, and laundry systems—cuts carbon emissions by over 75% for those four end-uses across multiple major California climate zones (see graphs in Section 8.0: Residential Packages and Impacts).

Although the use of multiple fuels in homes and buildings has a long history of meeting our comfort and technical needs, on-site natural gas combustion must have a limited future. "The sooner the BETR" should be our motto moving forward.

Although the use of multiple fuels in homes and buildings has a long history of meeting our comfort and technical needs, on-site natural gas combustion must have a limited future. "The sooner the BETR" should be our motto moving forward.

1.3. Equitable Electrification

Building electrification offers societal and equity benefits beyond GHG emission reductions. The shift from gas appliances to all-electric appliances and technologies powered by an increasingly clean grid has the potential to improve air quality inside and outside. The natural gas supply chain contributes to air pollution in several ways including leaking, venting, and combustion of natural gas. Gas has many pollutants including particulates, methane, volatile organic compounds (VOCs), nitrogen oxides (NOx), and sulfur oxides (SOx). The spotlight is currently on indoor air quality associated with internal gas appliances and the outdoor exposure to air pollution that communities living near gas power plants experience—often in lower-income neighborhoods.

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[7] E3 2019, Residential Building Electrification in California

[8] Billimoria, S. et. al. Rocky Mountain Institute 2018, The Economics of Electrifying Buildings

[9] LBNL 2015, Results of California Healthy Homes Indoor Air Quality Study

Electrifying homes will have a huge positive impact on the people who live in communities that have long suffered the negative effects of climate change:[10]

"California has taken significant steps to ensure that it reaches equitable outcomes by addressing the communities that have long been injured and/or left behind by its environmental and energy policies. Policies like SB 535 acknowledge that the benefits of the growing clean energy economy must reach those communities, largely low-income communities of color, that have disproportionately suffered the environmental and economic impacts of our long-term reliance on fossil fuels. A comprehensive strategy for addressing this disparity is still needed, but the patchwork of actions and policies in place have already begun to have a significant impact in environmental justice communities."

– Greenlining Institute 2019

As this study was being completed the California Air Resources Board (CARB) took a major step in support of building electrification, by adopting a groundbreaking resolution that commits significant action on emissions from gas appliances in buildings from both a climate and a public health perspective (NOx emissions).[11] The resolution states that CARB will support the CEC and other agencies to adopt standards in the 2022 code cycle that will result in stronger gas stove ventilation standards and electrification of appliances for all new buildings. This is the clearest commitment that CARB has made to-date to address the climate and health impacts from gas appliance emissions in the buildings sector.

To help ensure that electrification is both affordable and accessible, programs should prioritize technologies that offer energy efficiency and demand flexibility. This would help lower utility bills for all-electric buildings and reduce the energy burden on low-income communities. Electrification also creates opportunities for expansion of clean and green technology companies providing paths for people to learn new skills and to access living wage jobs. To help ensure everyone in their jurisdiction or service area has equal access to workforce development, organizations pursuing electrification can take proactive steps to engage with disadvantaged communities when developing workforce training.[12]

1.4. About The BETR

The BETR is a guide for utilities and other organizations developing, implementing, and supporting electrification technology programs as a way to advance high efficiency technologies, reduce GHG emissions, and improve public health. It's the first study to characterize the industry status of a comprehensive set of electrification technologies that replace traditional combustion technologies, site barriers to adoption, and the road to accelerate adoption. Although developed and written to guide efficiency

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[10] Greenlining Institute, 2019, [Equitable Building Electrification]

[11] CARB, 2020 [California Indoor Air Quality Program Update]

[12] The [BlueGreen Alliance] is an entity working with the nation's largest unions and environmental organizations to create and maintain quality jobs and build a stronger, fairer economy.

programs, the recommended actions can also inform manufacturers, the design community, owners, and policymakers.

Audience: Program administrators, policymakers, and industry advocates for all-electric technologies.

Goal: Accelerate the adoption of highly efficient electric technologies that displace gas technologies.

Objectives:

- **Status.** Characterize the readiness and adoption barriers for electrification technologies.
- **Guidance.** Provide targeted actions, by technology, needed to support building electrification, carbon reduction, energy efficiency, and research programs over the next 10 years.

Electrification Technology: For the purpose of this study electrification technologies are those that replace combustion technologies or appliances with systems that use electricity to provide the same service.

This study characterizes developed electric technologies that could replace incumbent gas technologies across four major end-use areas.[13] They all have low current market adoption and need a range of approaches to rapidly increase market penetration.

The study includes both new and existing buildings, residential and commercial sectors, and five building types as shown in Table 1.

TABLE 1: THE BETR END-USES AND BUILDING TYPES

End-Uses (4):	 Space Heating	 Water Heating	 Cooking	 Clothes Drying and Laundry
Vintages (2):	New and Existing			
Sectors (2):	Residential and Commercial			
Building Types (5):	Single Family | Multifamily | Small Commercial | Large Commercial | Higher Education and Institutional			

[13] Fireplaces, barbeques, portable outdoor heaters, and other small combustion-fueled appliances were not studied.

Cost References

While this study does not address the cost and market penetration of electric technologies, other resources about these critical components of building electrification exist. For example, a June 2018 study by E3 offers a detailed assessment of societal and customer economics of building electrification and the market barriers and opportunities.[14] The E3 study makes a compelling case in evaluating a scenario with high electrification adoption for all sectors across California with building electrification having the lowest potential net cost of the contributing sectors.

An additional E3 study dives deeply into residential electrification. The findings show that all-electric residential new construction is expected to be lower cost with commonly available technology than gas-fueled new construction in homes with air conditioning and without incentives or intervening policies.[15]

All-electric residential new construction is expected to be lower cost with commonly available technology than gas-fueled new construction in homes with air conditioning and without incentives or intervening policies.

The variables for economic assumptions are wide and highly dependent on the local energy price, demand charges, and quantity and time of energy use. Installation costs will vary widely based on location, contractor knowledge, available incentives, and dynamic pricing changes as product adoption increases.

While lifecycle savings look promising in most scenarios, the energy efficiency industry must recognize that overcoming real and perceived first cost barriers are critical factors to advance all the technologies identified in this study.

BETR Framework

The four end-use areas shown in Table 1 are the core of the BETR, as their electrification technologies have the greatest potential to reduce overall GHG emissions in California. Within each of the end-use sections (Space Heating, Water Heating, Cooking, and Laundry) the research team organized the content to address these three key questions:

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[14] E3 2018, CEC Deep Decarbonization in a High Renewables Future

[15] E3 2019, IBID

1	2	3
What is the impact and importance of this end-use?	What is the technical status of the technologies and where are they on the road to availability?	What can we do to overcome barriers to adoption?

From that foundation, the BETR is organized in the following sections:

1.0 Introduction. Why building electrification? This section also defines the audience and objectives of the roadmap.

2.0 Roadmap Methodology. This section introduces the methodology and the “Matrix” tool with which the research team investigated existing resources and characterized the status of a wide range of electrification technologies across several topics, or parameters. It also describes the framework used to represent the roadblocks and recommendations by technology and by market transformation channel.

3.0 – 6.0 Technologies on the Road to Electrification. There is a section for each end-use technology, which introduces the impact and importance of the end-use in relation to building electrification. Each end-use section includes details of the status of the technologies across the range of scoring areas, which is followed by roadblocks and recommendations to advance high-priority technologies. Information is provided at both a high-level, via summary tables, and in bulleted lists which give more specifics on each technology status or recommendation. **The four sections are:**

3.0 Space Heating

4.0 Water Heating

5.0 Cooking

6.0 Clothes Drying and Laundry

7.0 Impacting Factors. This section discusses grid integration and refrigerants that impact the advancement of the technologies.

8.0 Residential Examples and Impacts. This section shifts the lens to the building level and provides examples of single-family and multifamily packages of all-electric technologies. This section also includes the energy saving and emission-reduction potential for the packages across three California climate zones.

9.0 Conclusions and Commonalities. The overall findings and key recommendations shared through the lens of five common strategies that advance all building electrification strategies.

Appendices. The Appendices contain a number of valuable references and resources, such as the research team’s literature search list, electrification resources, and manufacturers’ survey results.

- **The BETR Summary Companion Document.** The BETR Summary is an overview of the research team’s key technology findings and recommendations for overcoming barriers. This companion document to the full Roadmap serves as a high-level guide for utilities and organizations working to advance building electrification programs and decarbonization policies in the state of California.

Download the Summary Report here.

2. Roadmap Methodology

This section introduces the method by which the research team investigated existing and up-and-coming electric technologies that displace combustion technologies in buildings. It introduces the Matrix tool as well as the technologies and the parameters by which the research team evaluated each technology. It also describes the framework used to develop the list of roadblocks and recommendations for each of the four technology end-use categories.

2.1. Technologies and Characterization Methodology

To compare technologies, the project team characterized the current status of dozens of building electrification technologies across several parameters. These qualitative characterizations were used to compare technology status, identify recommendations, and highlight trends identified in this roadmap. The team developed a table (Matrix) and data visualization tool (Technology Assessment Graphics, or TAG tool) to serve as an internal assessment tool to inform the development of this roadmap. The Matrix and TAG tool were also provided to the BETR funders for their use in posing additional queries and combinations.

As mentioned earlier, the project team considered technologies across four end-uses, which account for the great majority of potential GHG emission reduction opportunities. The research team evaluated 38 different electrification technologies in various stages of commercial development or market deployment as shown in Table 2. In the context of this report, the term “technology” refers to a specific type of equipment that serves a given end-use (e.g. a heat pump water heater).

TABLE 2: LIST OF 38 TECHNOLOGIES ASSESSED FOR BUILDING ELECTRIFICATION BY END-USE

SPACE HEATING	WATER HEATING	COOKING	CLOTHES DRYING AND LAUNDRY
240V ASHP, Split System, conventional refrigerant	Unitary 240V HPWH, conventional refrigerant	Commercial Electric Cooking Equipment: Oven, Fryer, etc.	Heat Pump Dryer
240V ASHP, Split System, low-GWP refrigerant	Central HPWH, conventional refrigerant	Commercial Induction Range	Combo Washer-Dryer (Condenser Dryer)
Packaged Terminal Heat Pump	Central HPWH, low-GWP refrigerant	Commercial Electric Cooking Equipment: Combination Oven	CO_2 Laundry System
240V ASHP Packaged RTU, conventional refrigerant	Unitary 240V HPWH, low-GWP refrigerant	Residential Drop-In/Slide-in/Stand-Alone Induction Range	Electric Resistance Dryer
240V ASHP Packaged RTU, low-GWP refrigerant	Unitary 120V HPWH, conventional refrigerant	Commercial Induction Full Size Wok Range	Ultrasonic Dryer
Heat Recovery Chiller	Unitary 120V HPWH, low-GWP refrigerant	Commercial Electric Cooking Equipment: Chain Broiler	
Mini-Split ASHP	Solar Thermal Assisted WH	Commercial Countertop Induction Hob/Wok	
120V ASHP, Split System, <5 ton, conventional refrigerant	Electric Resistance WH: Point of Use Distributed, Tankless	Residential Countertop Induction Hob	
120V ASHP, Split System, <5 ton, low-GWP refrigerant Variable Refrigerant Flow		Commercial Electric Resistance Range	
Electric Resistance Boiler Ground (and Water) Source Heat Pump		Residential Electric Resistance Range	
Combo Small Packaged ASHP+DHW			
Integrated Heat Pump Boiler and Domestic Water Heater			
Non-Vapor Compression Heat Pump			

Because barriers and applicability can vary across different building types, each technology was evaluated separately for buildings of different sectors (multifamily, single family, small commercial, large commercial, and higher education/institutional). Scoring also represented both new construction and retrofit applications.

To summarize, qualitative characterizations were made across:

- A data set of 38 technologies
- Four end-uses (space heating, water heating, cooking, and laundry/clothes drying)
- Five sectors (multifamily, single family, small commercial, large commercial, and higher education/institutional)
- Vintages (new construction and existing building retrofits)

Taking all of these factors into consideration, the research team evaluated a total of 145 unique combinations. The team also identified a selection of internationally available and upcoming technologies across the same four end-uses. These technologies were not scored in the Matrix, in large part because it's difficult to predict market availability and industry awareness. However, select international electrification products were included in each end-use section. They represent future high-priority opportunities for increased product availability to electrify the four primary end-uses.

The same basic technology may be available in a wide range of configurations. The team separated technologies to a limited extent where the differences in technology status, roadblocks, and recommendations were significant. For example, heat pump water heaters were separated into unitary and central systems, and unitary systems were separated further based on voltage and refrigerant type. For convenience and readability, this report uses only two voltages: 120V (typically used in single-family homes and small commercial applications) and 240V. The team determined that for the purposes of this report, the distinction between single-phase 120V electricity and everything else was the most important. Therefore, the 240V designation is intended to be somewhat general: products in this category may have nominal voltage of 208V, 230V, 240V, or even 480V for some commercial equipment.

Scoring Parameters

Each technology received scores across 10 different qualitative parameters, which are described below. Scores ranged from 1 to 3, with 3 being the highest score a technology could receive in each parameter. Five of these parameters represented the areas of greatest comparative variation and interest to the Roadmap audience and are shown as 'first-priority parameters' below. The first two parameters – 'technology readiness' and 'product availability' – provide the initial lens regarding building electrification potential.

If a product scores low in 'technology readiness' and 'product availability', then the work to advance that technology must occur in parallel with technical development. If a product scores high in both 'technology readiness' and 'product availability,' the next two parameters – 'ease of application' and 'product awareness' – should become a higher priority when designing electrification program activities.

Lastly, but most critically, the ‘GHG Impact’ score reflects a technology’s emission reduction potential relative to other electrification options. 100% of the technologies assessed in the BETR reduce emissions when compared to gas-fueled technologies, but the lower Global Warming Potential (GWP) products will offer the greatest GHG reductions – although many are not yet on the market (see Section 7.1 Refrigerants).

The technologies that score high in ‘readiness’ and ‘availability’ have the most potential to overcome their roadblocks, which will establish an easier road to market. After that, buildings and institutions can transition to up-and-coming low-GWP products and international products.

FIRST-PRIORITY PARAMETERS:

Technology Readiness

1. Anticipated to be fully technologically ready in 6-10 years
2. Anticipated to be fully technologically ready in 1-5 years
3. Technologically ready

U.S. Product Availability

1. Low or no availability
2. Moderate availability
3. Readily available

Ease of Application (product and site compatibility)

1. Low applicability / Significant barriers
2. Medium applicability / Some barriers
3. General applicability / Few to no barriers

Awareness (market and industry)

1. Low awareness (technology is generally unknown to market and most of industry)
2. Moderate awareness (much of market has heard of technology; most industry players lack firsthand experience)
3. Widespread awareness of technology (market is familiar; industry has experience and is using)

Scale of Greenhouse Gas (GHG) Reductions (compared to other electrification measures of the same end use)

1. Low GHG reductions
2. Moderate GHG reductions
3. High GHG reductions

Figure 3 shows how the Matrix tool was used to score air source heat pumps.

FIGURE 3: EXAMPLE OF SCORING WITHIN THE MATRIX TECHNOLOGY ASSESSMENT

Source: Joyce, E. Arup for BETR 2020

End Use	Sector	NC vs Retrofit	Measure-Level Tech Description	Technology Readiness	Thoughts	Awareness	Thoughts	Product Availability	Thoughts
Space Heating	Multifamily	EB	120V ASHP, split system, <5 ton, conventional refrigerant	3	exists from maj	2	relatively uncomm	2	120V not widely a
Space Heating	Single Family	EB	120V ASHP, split system, <5 ton, conventional refrigerant	3	exists from maj	2	relatively uncomm	2	120V not widely a
Space Heating	Small Comm	EB	120V ASHP, split system, <5 ton, conventional refrigerant	3	exists from maj	2	relatively uncomm	2	120V not widely a
Space Heating	Multifamily	EB	120V ASHP, split system, <5 ton, low-GWP refrigerant	2	not in US mark	1	not on the market	1	
Space Heating	Single Family	EB	120V ASHP, split system, <5 ton, low-GWP refrigerant	2	not in US mark	1	not on the market	1	
Space Heating	Small Comm	EB	120V ASHP, split system, <5 ton, low-GWP refrigerant	2	not in US mark	1	not on the market	1	
Space Heating	Large Comm	NC+EB	240V ASHP packaged RTU, conventional refrigerant	3		3	very common & we	3	
Space Heating	Higher Ed & Insti	NC+EB	240V ASHP packaged RTU, conventional refrigerant	3		3	very common & we	3	
Space Heating	Small Comm	NC+EB	240V ASHP packaged RTU, conventional refrigerant	3		3	very common & we	3	
Space Heating	Large Comm	NC+EB	240V ASHP packaged RTU, low-GWP refrigerant	3	est availability :	2	lower market awar	1	
Space Heating	Higher Ed & Insti	NC+EB	240V ASHP packaged RTU, low-GWP refrigerant	3	est availability :	2	lower market awar	1	
Space Heating	Small Comm	NC+EB	240V ASHP packaged RTU, low-GWP refrigerant	3	est availability :	2	lower market awar	1	
Space Heating	Higher Ed & Insti	NC+EB	240V ASHP, split system, conventional refrigerant	3	mature	3	very common & we	3	mature
Space Heating	Multifamily	NC+EB	240V ASHP, split system, conventional refrigerant	3	mature	3	very common & we	3	mature
Space Heating	Single Family	NC+EB	240V ASHP, split system, conventional refrigerant	3	mature	3	very common & we	3	mature
Space Heating	Small Comm	NC+EB	240V ASHP, split system, conventional refrigerant	3	mature	3	very common & we	3	mature
Space Heating	Higher Ed & Insti	NC+EB	240V ASHP, split system, low-GWP refrigerant	2		2	lower market awar	2	Emerging Tech, fe
Space Heating	Multifamily	NC+EB	240V ASHP, split system, low-GWP refrigerant	2		2	lower market awar	2	Emerging Tech, fe
Space Heating	Single Family	NC+EB	240V ASHP, split system, low-GWP refrigerant	2		2	lower market awar	2	Emerging Tech, fe
Space Heating	Small Comm	NC+EB	240V ASHP, split system, low-GWP refrigerant	2		2	lower market awar	2	Emerging Tech, fe
Space Heating	Large Comm	NC+EB	Electric Resistance Boiler	3	commercially a	3		3	commercially avai
Space Heating	Higher Ed & Insti	NC+EB	Electric Resistance Boiler	3	commercially a	3		3	commercially avai
Space Heating	Multifamily	NC+EB	Electric Resistance Boiler	3	commercially a	3		3	commercially avai
Space Heating	Large Comm	EB	Ground Source Heat Pump	3	many installatic	3		2	better option in cc
Space Heating	Large Comm	NC	Ground Source Heat Pump	3	many installatic	3		2	better option in cc
Space Heating	Higher Ed & Insti	EB	Ground Source Heat Pump	3	many installatic	3		2	better option in cc
Space Heating	Higher Ed & Insti	NC	Ground Source Heat Pump	3	many installatic	3		2	better option in cc
Space Heating	Multifamily	EB	Ground Source Heat Pump	3	many installatic	3		2	better option in cc
Space Heating	Multifamily	NC	Ground Source Heat Pump	3	many installatic	3		2	better option in cc
Space Heating	Single Family	NC+EB	Ground Source Heat Pump	3	many installatic	2		2	better option in cc
Space Heating	Small Comm	NC+EB	Ground Source Heat Pump	3	many installatic	2		2	better option in cc
Space Heating	Higher Ed & Insti	NC+EB	Integrated Heat Pump Boiler and Domestic Water Heater	1	not yet comme	1	very limited awarei	1	not yet commerci
Space Heating	Multifamily	NC+EB	Integrated Heat Pump Boiler and Domestic Water Heater	1	not yet comme	1	very limited awarei	1	not yet commerci
Space Heating	Multifamily	NC+EB	Integrated Heat Pump Boiler and Domestic Water Heater	1	not yet comme	1	very limited awarei	1	not yet commerci
Space Heating	Single Family	NC+EB	Integrated Heat Pump Boiler and Domestic Water Heater	1	not yet comme	1	very limited awarei	1	not yet commerci
Space Heating	Small Comm	NC+EB	Integrated Heat Pump Boiler and Domestic Water Heater	1	not yet comme	1	very limited awarei	1	not yet commerci

‘Second-priority parameters’ inform the creation of the Roadmap in specific cases where barriers were considered so significant, they caused the technology to fall outside the bounds of the first-priority parameters.[16]

[16] In a few cases (less than 10%), information was unavailable to make the characterization in a second-priority parameter area.

SECOND-PRIORITY PARAMETERS:

Impact of Enabling Technologies

1. No applicable enabling technologies (impact is not significant)
2. Enabling technologies can improve performance by less than 20%
3. Enabling technologies can improve performance by at least 20%

GHG Impact Data Availability

1. Low-to-minimal GHG data available: anecdotal sources, no broad studies
2. Moderate GHG data available: 1+ broad study and/or detailed case studies
3. Good GHG data available: multiple broad studies, field studies, and/or lab research

Energy Impact Data Availability

1. Low-to-minimal energy data available: anecdotal sources, no broad studies
2. Moderate energy data available: 1+ broad study and/or detailed case studies
3. Good energy data available: multiple broad studies, field studies, and/or lab research

GHG/GWP Optimization

1. This technology still requires significant development to minimize emissions/GWP
2. Technology is acceptable but needs some improvements.
3. Technology reduces emissions/GWP as much as it can

Standards / Ratings Available

1. DOE efficiency and performance standards, test procedure available, ENERGY STAR program/rating available
2. DOE efficiency and performance standards, test procedure available
3. No DOE standards, ENERGY STAR program, or similar are available

Scoring Sources and Methodology

To make these qualitative characterizations across the many permutations of technologies, sectors, end-uses, and building vintages, and across all 10 parameters, the team performed a comprehensive literature review of more than 40 existing reports, narratives, and white papers. We also drew upon the knowledge of subject matter experts within the core project team (NBI, BDC, Arup, and EPRI) as well as other organizations. A comprehensive list of data sources included in the literature are listed in the Appendix.

International Product Search

Beyond North America, building electrification is a growing trend, especially in parts of East Asia and Western Europe, where natural gas is much more expensive than electricity. Other factors, such as real estate market dynamics, policies, and typical building designs have driven innovation in electric technologies.

Bringing international products to the U.S. market can help accelerate adoption of emerging electrification technologies. In the single family residential sector, European and Japanese manufacturers (among others) have made significant progress in developing 120V heat pumps. Adapting these products for the U.S. market could address a significant barrier for existing building retrofits: relying only on 120V electricity avoids the cost and complication of upgrading wiring to support 240V appliances. For multifamily buildings, central heat pump water heaters currently under development will provide solutions for existing midsize and larger buildings currently served by central natural gas-fired water heater systems. In single family and multifamily homes, a variety of innovative solutions are expected to become available soon in the U.S. for water heating (various heat pump options) and space heating (such as window-mounted heat pumps that replace window air conditioners and provide heat).

As momentum grows for building electrification in the U.S. and Canada, many international manufacturers see an opportunity to bring their existing and upcoming products to North America. Manufacturers, understandably, do not readily disclose intentions and timing for product introductions. They have an array of considerations including the complexities of displacing current product lines, estimations of market penetration, and variations in policy trends, building design, appliance preferences, equipment testing, and safety and labeling requirements that vary between countries. These technologies merit continued industry consideration and discussion with manufacturers to smooth the road for U.S. adoption.

2.2. Framework for Roadblocks and Recommendations

This study follows a common and effective framework used in technology logic models to group the roadblocks (barriers) into channels. Within each end-use section, the roadblocks and recommendations for building electrification technologies are organized by technology first and then by channel. The channels are shown in Table 3. For space and water heating the channels are further notated with the historic efficiency reference to the following market pathways:

- Upstream: Manufacturers, production and availability
- Midstream: Suppliers, distributors, installers, designers and site issues
- Downstream: Consumers, building owners, facility managers

TABLE 3: THE SOLUTION CHANNELS, TARGET ENTITIES AND ROADBLOCK EXAMPLES

	Solution Channel: Technology	Market	Programs	Policies – Standards*
Target Entities	• Product Manufacturers • Researchers • Demonstration Partners	• Suppliers, distributors, installers • Designers • Retailers • Consumers: building owners, facility managers	• Utilities • Government (city) • Collaborations and national programs	• State policies • City policies • Public utility commissions (PUC)
Roadblock Examples	• Product technical progress and development. • Displacement of existing product lines. • Market availability. • Warranty and resiliency issues. • Independent lab or field demonstration on performance data. • Manufacturer engagement.	• Low product awareness or confidence. • Lack of product data and examples. • Timely supply chain product availability. • Workforce capacity, training, design and installation guidance. • Contractor business models. • Site application or technical issues.	• Eligibility as an efficiency program measure. • ENERGY STAR alignment. • Multiple programs without coordination across products and markets. • Absence of financing and no or low incentives. • Incentive prioritization and cost effectiveness.	• Policies on fuel pricing. • Time-of-use rates • Codes, standards, and regulations. • Tax credits. • Clear regulatory trend and timeline to electrification. • Absence of city leadership for electrification reach codes.

* These are generally applicable across all electrification technologies but are noted when relevant to a particular end-use technology.

3. Space Heating

3.1. Impact and Importance

The opportunities and challenges of decarbonizing space heating technologies in buildings are vast. Space heating is the largest overall driver of fossil fuel use in California buildings, with wide variations by building type. Space heating averages nearly one-third of total residential building energy use in California, and natural gas accounts for the vast majority (82%) of all home heating fuel. [17] Nearly all (96%) residential forced air furnaces in California burn natural gas, which was an increase of almost 10% from 2013 to 2019.[18,19]

In commercial buildings, fossil fuel technologies heat approximately 40% of southern California buildings and 65% of northern California buildings.[20] Efforts to electrify these space-heating systems are a high priority due to their large current impact on state emissions.

Space heating electrification efforts currently focus on applying heat pump technologies, which are 3-5 times more efficient than standard electric or gas heating systems. Heat pump product applicability, maturity, and barriers vary by building type, climate, application, and sector. Given that space heating is a significant energy end-use across all building types, it is important to get these distinctions right.

Heat pump (HP) equipment for space heating has been around for decades and is well suited to the generally moderate California climate. However, it represents a low percentage of current home heating systems (only 2% of heated California homes used heat pumps as their primary heat source), and their use in commercial buildings varies from approximately 16% in Northern to 40% in Southern California.[21] Figure 4 shows heat pump penetration in Southern California Edison's (SCE) service territory is much greater than in the northern

[17] EIA 2015, EIA RECS table CE3.5

[18] Calmac 2012, California Lighting and Appliance Study

[19] EIA RECS 2009

[20] Synapse 2018, Decarbonization of Heating Energy Use in California Buildings

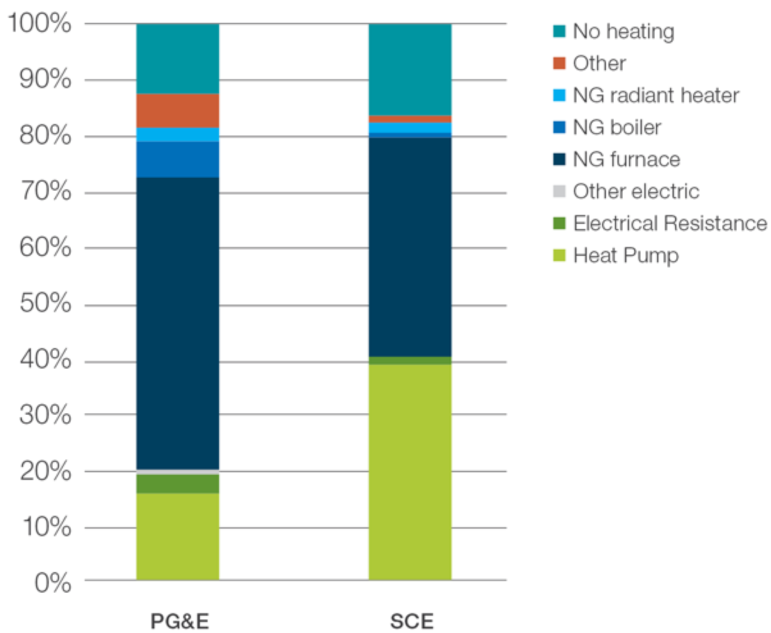
[21] Synapse, IBID

colder area of Pacific Gas and Electric's (PG&E) service territory where approximately 65% of commercial heating is done by natural gas.

Electric resistance heating technology (e.g. electric reheat coils, electric hot water boilers) remains common, especially in older buildings. While electric resistance heating systems are mature and cheap to install, they are dramatically inefficient and expensive to operate. Many building energy codes and programs already recognize this truth by limiting or banning electric resistance heating technology and encouraging heat pump space heating technology.

FIGURE 4: COMMERCIAL HEATING FUEL TYPE AND DISTRIBUTION OF EQUIPMENT BY CA UTILITY

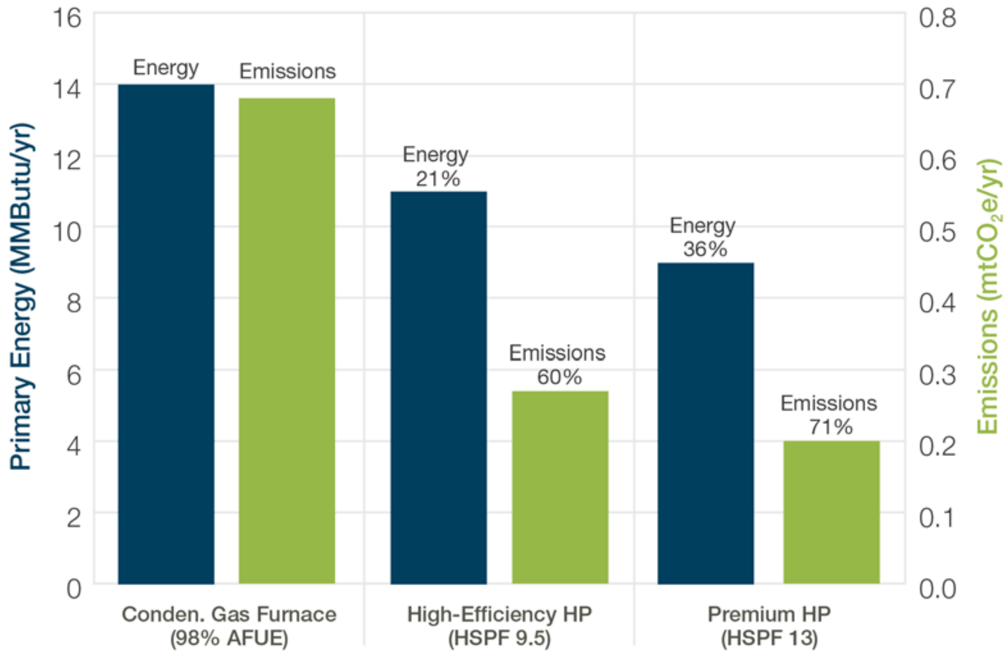
Source: See footnote 19 – Weighted by number of buildings



Heat pumps can deliver substantial energy savings from a gas heating baseline, even at the highest gas efficiency levels possible, because heat pumps can achieve efficiencies much greater than 100% (efficiencies of 300%-400% are typical) while combustion technologies cannot. The GHG emissions savings, without accounting for benefits from time-of-use control potential, in a one-to-one technology comparison can exceed 70%, as shown in Figure 5. These energy and emission savings can be even more dramatic in colder climates (e.g. where the weather frequently gets below freezing in the winter), where specific cold-climate heat pump models designed for performance at or below freezing should be selected to ensure good performance and efficiency in these applications. In California, the northeastern and central Sierras regions are the most suitable locations for this type of model.

FIGURE 5: AIR SOURCE HP ENERGY AND EMISSION SAVINGS COMPARED TO HIGH-EFFICIENCY GAS FURNACE: S. CA HOME

Source: NBI 2020. Based on 2018 data from EPRI



3.2. Technology Status

When it comes to electrifying space heating, heat pumps stand out due to their mature technology, high market awareness, and high efficiency. A heat pump transfers rather than generates heat from a variety of sources. A wide variety of technologies fall into the heat pump category—they use heat transfer from various sources such as outside air, water, the ground, refrigerant loops inside a building and waste heat. In the residential sector, air source heat pumps offer the most promise to displace gas-fueled forced-air furnaces. A premium-efficiency air source heat pump operating in a typical Southern California home uses 36% less energy and is responsible for 71% less GHG emissions compared to a high-efficiency condensing gas furnace.

Today's heat pumps rely on the vapor compression cycle, which necessarily uses refrigerants. Concerns around the use of refrigerants (see Section 7.1: Refrigerants) have spawned new technology concepts.[22] A good example is the combination (or Combi) heat pumps, which are designed to provide both space and water heat. Combi heat pumps are relatively uncommon in the U.S. but have been piloted in both new construction and retrofit programs abroad,

such as the Energiesprong program in the Netherlands and are a part of some demonstration programs in California where results are promising. [23]

An International Renewable Energy Association study from 2013 stated current research and development activities are expected to increase heat

[22] In 2014, DOE surveyed 17 proposed technologies and identified five promising candidates: thermoelastic, membrane, evaporative liquid dessicant, magnetocaloric, and Vuilleumier heat pumps.

[23] Rocky Mountain Institute's REALIZE initiative in California and the RetrofitNY program in New York are building on the Energiesprong model to scale zero energy retrofits across the U.S.

pump efficiency by 30-50% for heating services and to reduce costs by 20-30% by 2030.[24]

Starting in 2025, many space heating products sold in California will be required to use lower global warming potential (GWP) refrigerants.[25] This transition to mid-GWP refrigerants (<750 GWP) will affect a majority of space heating systems (indicated by † in Table 4). For more about refrigerants and upcoming changes to refrigerant regulations at the state and federal levels, see Section 7.1: Refrigerants.

Table 4 provides a summary of the status of electric space heating technologies and applicable building types. Following the table is a more in-depth explanation of the status of each space heating technology. Table 5 shows selected international products for space heating and combination space and water heating.

[24] IRENA 2013, Heat Pumps Technology Brief

[25] California Air Resources Board 2020, Prohibitions on High-GWP HFCs

TABLE 4: STATUS OF ELECTRIFICATION SPACE HEATING TECHNOLOGIES

SPACE HEATING TECHNOLOGY	MATRIX SCORES					BUILDING TYPE APPLICABILITY					VINTAGE APPLICABILITY	
	Technology Readiness	Product Availability	Ease of Application	Awareness	Scale of GHG Reductions	Single Family	Multifamily	Small Comm	Large Comm	Higher Ed/Inst	New Construction	Retrofit
240V ASHP, Split System†	High	High	Moderate	High	Moderate	✔	✔	✔	✔	✔	High	Moderate
Packaged Terminal Heat Pump†	High	High	Moderate	High	High		✔	✔		✔	High	High
240V ASHP Packaged RTU†	High	High	Moderate	High	High	✔	✔	✔	✔	✔	High	High
Heat Recovery Chiller	High	High	Low	High	Moderate				✔	✔	Moderate	Moderate
Mini-Split ASHP†	High	High	High	High	Moderate	✔	✔	✔	✔	✔	High	High
120V ASHP, Split System, <5 ton†	High	Moderate	High	Moderate	Moderate	✔	✔	✔			Low	High
Variable Refrigerant Flow††	High	High	Moderate	High	Moderate		✔	✔	✔	✔	High	Moderate
Electric Resistance Boiler	High	High	Moderate	High	Low		✔	✔	✔	✔	High	Moderate
Ground (and Water) Source Heat Pump	High	High	Low	High	Moderate	✔	✔	✔	✔	✔	Moderate	Low
Combo Small Packaged ASHP+DHW *emerging*	Moderate	Low	Low	Low	High	✔	✔	✔			High	High
Integrated Heat Pump Boiler and Domestic Water Heater *next gen*	Low	Low	Low	Low		✔	✔	✔	✔	✔		
Non-Vapor Compression Heat Pump *next gen*	Low	Low		Low		✔	✔	✔	✔	✔		

Refrigerant GWP must be below 750 (i.e. to be mid-GWP or low-GWP) in California beginning in 2025 for this product (†) and 2026 for this product (††). In general, HVAC products meeting this requirement are in development and are not available today.

High (3) Moderate (2) Low (1)

TABLE 5: LIST OF SELECTED INTERNATIONAL PRODUCTS FOR SPACE HEATING AND COMBINATION SPACE/WATER HEATING

End-Use	Technology Type	International Market Status	Domestic Status, Est. Availability	Manufacturers (Region)
Space Heating	Large natural refrigerant ASHP	Commercially available but under adopted	Commercially Available but Under adopted	Mayekawa, others (Japan)
Space Heating	120V packaged terminal heat pump	Prototypes and pilots	Not yet available	Innova (Italy)
Space Heating	120V mini-split heat pump	Commercially available but under adopted	Not yet available	LG, Samsung (Korea)
Space Heating	Window-mounted heat pump	Prototypes and pilots	Prototypes and pilots	Treaux (USA)
Space Heating	Hybrid/hydro VRF (water as distribution refrigerant)	Commercially available but under adopted	Add-on kit available now; integrated system est. 2020-2021	LG (Korea), Mitsubishi (Japan)
Space and Water Heating	Combined space and water heat pump (Combi)	Commercially available but under adopted	Not yet available	LG (Korea), Clivet (Italy), Factory Zero (Netherlands)
Space and Water Heating	Natural refrigerant (propane, CO_2, etc.) heat pump water heater	Widely commercially available	Few product options available	Alpha Innotec, Heliotherm, NIBE, Roth GmbH, Wolf GmbH, Vaillant (Germany), Denso (Netherlands), Hotjet (Czech), Enex, Enerblue (Italy), Daikin, Mitsubishi (Japan), Sanden (USA)

Status Summary

The status for each space heating electrification technology is described below. Various forms of heat pump systems are technically ready and available to address residential new construction, some retrofits, and commercial space heating needs. Historically, cold weather performance has been an issue for air source heat pumps: both energy efficiency and heating capacity have been significantly lower in colder conditions. However, in recent years, manufacturers have made great progress in advancing cold-climate heat pump technology. Today, product availability for key air source heat pump (ASHP) product types is relatively robust and both technology optimization and product diversity are expected to improve in the coming years.

Electric resistance boilers and electric reheat coils are technically ready and available to address niche space heating needs but do not offer the efficiency and GHG reduction benefits of heat pumps.

Space Heating Heat Pumps – Ready Now

(† subject to a CA requirement for <750 GWP refrigerants in 2025)

- **240V ASHP Split System†.** Suitable for all building types but more common in smaller buildings. Fully technically ready, grid-integrated control options available and advancing. Widely available and commonly installed, including cold-climate models. High GHG reductions when coupled with traditional equipment but lower GHG reductions compared to emerging low-GWP products.
- **Packaged Terminal Heat Pump†**. Suitable for small and large commercial, multifamily, and higher education/institutional buildings. Fully technically ready, many product options widely available. Less applicable for larger buildings because, as perimeter-sited systems, they cannot condition the interior core of the building. Retrofit-ready units can replace existing packaged terminal air conditioners, rendering a building’s gas or electric heating systems unnecessary. High GHG reductions when coupled with traditional equipment but lower GHG reductions compared to emerging low-GWP products.
- **240V ASHP Packaged Rooftop Unit (RTU)†**. Suitable for small and large commercial and higher education/institutional buildings. Packaged RTUs are common in both small and large buildings. Fully technically ready, grid-integrated control options available and advancing. Widely available, very common. High GHG reductions when coupled with traditional equipment but lower GHG reductions compared to emerging low-GWP products.
- **Heat Recovery Chiller.** Suitable for large commercial and higher education/institutional buildings. Fully technically ready, widely available, and relevant for specific applications such as central plants and large facilities. Typically installed as a site-customized measure. Requires a

waste heat source. In commercial settings, typically requires relatively significant simultaneous heating and cooling loads to be effective. High GHG reductions in the limited applications suitable for this technology.

- **Mini-Split ASHP**†. Suitable for single family, multifamily, and small commercial buildings. Fully technically ready. Widely available, with many product options including cold-climate models. Common in new construction, and a popular and useful option to retrofit existing gas heaters in homes and buildings where ducted ASHPs may not be ideal or suitable. High GHG reductions with traditional refrigerants, but less than emerging low-GWP products.
- **120V ASHP Split System, <5 ton**†. Suitable for single family, multifamily, and small commercial buildings. Fully technically ready and some products are available from major manufacturers but uncommon in the U.S. market. In particular, 120V outdoor unit availability can be low for splits and multi-splits. Retrofit-focused measure intended to work within site wiring limitations in existing buildings, specifically homes. Low voltage limits ability for resistance heating backup in cold conditions. Relative to other electric space heating technologies, GHG savings impacts are moderate to high. Low-GWP options are not available in the U.S. at this time but some products are available internationally.
- **Variable Refrigerant Flow (VRF) System.** Suitable for small and large commercial buildings, and some multifamily and institutional buildings. Fully technically ready, widely available, commonly used. Can attain high efficiencies in larger buildings in part by minimizing the overall energy demands associated with simultaneous heating and cooling from deep floor plates. Some “hybrid” (or “hydro”) VRF systems use water as the in-building heat transfer fluid, which is connected via heat exchangers to the heat pump’s refrigerant loop(s); this significantly reduces the amount of refrigerant in the system but comes at an efficiency penalty of up to 20%. Relative to other electric space heating technologies, GHG savings impacts are moderate to high. Energy savings are often substantial but GHG emissions and safety concerns associated with refrigerant leakage can be significant.[26] Current VRF systems use large volumes of conventional high-GWP refrigerants, which can significantly reduce the GHG savings relative to other electric options. Some mid-GWP options are currently being evaluated, and the industry will need to move to mid-GWP or low-GWP refrigerants by 2026 in California.
- **Water Source Heat Pump/Ground Source Heat Pump.** Suitable for all building types. Fully technically ready, widely available. Can achieve higher efficiency during cold weather conditions by using the ground or a water loop

† These technologies are required to use refrigerants with GWP <750 in California beginning in 2025.

[26] Because VRF systems require refrigerant lines to run throughout the building—including hundreds of joins and connections, often using field-built flared fittings—both the amount of refrigerant used and the opportunity for leakage is relatively high. Comprehensive research into refrigerant leakage rates in VRF systems is limited. The Northeast Energy Efficiency Partnership’s “[VRF Market Strategies Report](),” published in September 2019, states: ***“Although limited, additional reports have been cited by the U.K. Department of Energy & Climate Change, which identified a 3.5 percent leakage rate (8-10 percent of buildings leaking at a 40-50 percent rate) and another report by the U.S. Department of Defense identified leakage rates as high as 25 percent.”***

as the heat source, which can be much warmer than the ambient air. Significant site constraints. Requires establishing a nearby water source (tank, well, or local body of water), or drilling wells (vertical loops) or excavating land (horizontal and hybrid loops), which limits applicability especially for smaller buildings and in retrofit applications. Relative to other electric space heating technologies, GHG savings impacts are moderate to high. Current systems use conventional high-GWP refrigerants but low-GWP options are being researched.

Electric Resistance Heating Technologies – Ready Now

- **Electric Resistance Boiler and Electric Reheat Coil.** Suitable for all building types. Fully technically ready, widely available. Relatively low efficiency compared to heat pumps, which limits GHG impacts and ideal application cases due to high energy consumption. May be limited or prohibited by codes that restrict use of electric resistance heat. In general, low energy efficiency electric resistance heat should not be used where a heat pump could do the job. When installed in tandem with sufficient thermal energy storage, boilers can be well-suited where high penetrations of variable renewable resources result in over-production during certain hours, providing low-cost, clean electricity.

Combination Space and Water Heating Technologies – Emerging

- **Small Packaged Air Source Heat Pump and Hot Water Heat Pump.** Suitable for single family, multifamily, and small commercial buildings. Moderate technical readiness; no domestic availability. Component products are available domestically but no manufacturer yet offers a single packaged unit in the U.S. Available internationally and is a central component of the Energiesprong scalable home retrofit business model.
- **Integrated Heat Pump Boiler and Domestic Water Heater.** Suitable for all building types. Moderate technical readiness: the basic technology components are well-developed but not combined at the market level, so no packaged mainstream products are available in the U.S. GHG savings impacts may be high but are hard to estimate at this time.

Across the residential, commercial, and institutional sectors, heat pump technologies are fully mature and widely available. Some innovations, both recent and in progress, related to low-GWP refrigerant and cold-climate technologies are making progress. These technologies have the potential to significantly reduce GHG emissions. However, they generally have low market awareness and availability, with only a few products typically available to consumers. Efficiency programs should prioritize low-GWP refrigerant and cold-climate technologies to improve awareness and market penetration when such technologies become available.

Within the residential sector, 240V split and mini-split air source heat pumps using conventional (typically HFC) refrigerants are mature and widely available. In the residential retrofit market, 120V split systems are market-ready and available.

A large diversity of products is available for the commercial sector. Heat recovery chillers, split, and mini-split 240V ASHPs, VRF systems, PTHPs, and packaged 240V ASHP RTUs are all mature and readily available electric technologies that can be implemented in both new and retrofitted buildings.

Across all sectors there is often an inverse relationship between technology readiness, awareness, and availability, versus ease of application and scale of GHG reductions. In other words, **the most ready and available technologies still face some application barriers and/or are not yet fully optimized for emission reductions.** This speaks to the continued need to remove application barriers, both through product development and building design strategies.

Finally, a few products identified in this study are in the early phases of research and development. These include combination space and water heaters, which heat water for radiant heating and are often but not exclusively used in commercial buildings (heat pump boiler/water heater for HVAC + domestic hot water, DHW) as well as those employing other strategies ("Combi" small packaged ASHP+DHW). The latter exists as part of a package for residential retrofits in the Energiesprong program in the Netherlands that has gained popularity in other countries. Within California, combination space and water heaters and "Combi" systems are currently part of demonstration programs through the California Energy Commission's EPIC program.[27]

A variety of innovations within the category of non-vapor compression heat pumps are currently in the laboratory research and early product development stage—as discussed in the Technology Status section above.

3.3. Roadblocks and Recommendations

Two key technology barriers common to heat pumps of all types are cold-climate performance and the upcoming transition to mid- and low-GWP refrigerants. Manufacturers have made great strides in improving cold-climate heat pump performance, but there is room for improvement. Other roadblocks, and the ways to overcome them, vary both by building type and vintage (existing or new construction). In all sectors, electrifying existing gas-fired heating systems comes with unique retrofit barriers related to site considerations such as wiring, ducting, and building configuration. A full explanation of roadblocks and recommendations by technology and sector are described below. Recommendations are summarized in Table 6.

Roadblocks

Cold-climate performance and refrigerant transitions, which are roadblocks common to every heat pump technology, are discussed below.

- **Cold-climate performance**. Both the heating capacity and the efficiency of traditional heat pumps tend to suffer when the outside air temperature is

[27] Rocky Mountain Institute's REALIZE program

low. This has been identified as a heat pump application barrier for over a decade, and programs like the U.S. Department of Energy's Building Technologies Office Emerging Technologies program and the Northeast Energy Efficiency Partnership's High Performance Air Source Heat Pump Initiative have helped spur research, remove installation barriers, improve customer and installer knowledge, and widely publicize cold-climate products. Major manufacturers regularly release new models with improved low ambient temperature performance (generally defined as 100% capacity at 5°F and 75% capacity at -13°F).

- **Transition to lower-GWP refrigerants.** The anticipated phase-out of high-GWP refrigerants may reduce heat pump options available to consumers, requiring new products. HFCs, which are currently the most commonly used set of refrigerants in small-to-midsize HVAC (e.g. R-410A, R-134A), will be phased out in California starting in 2025 (for most heat pump types) and in Washington beginning in 2024. Other states are likely to follow. While major manufacturers are developing new refrigerants and products in anticipation of these rules (especially HFOs and refrigerant blends), few products are market-ready, especially for the small commercial or consumer sector. New refrigerants that *do* exist are sometimes proprietary to a particular HVAC manufacturer, raising concerns about future availability. For more information about refrigerants, see Section 7.1: Refrigerants.

Technology-specific roadblocks are discussed below.

- **240V Packaged and Split ASHP.** These heat pumps are workhorses of electrification and the key roadblocks are in implementation, not technology. Driving demand and accelerating retrofits away from gas furnaces and toward heat pumps should be a top priority of electrification programs. 240V ASHP units (that is, 208V, 230V, 240V, or 480V units), whether packaged or split, are well known, very common, and widely available. A wide range of products and options are available for every building type, application type, and climate. Compared to other heat pump types, cold-climate options are available for these ASHP. The supply chain is robust and designers, contractors, commercial building owners, and operators are familiar with the technology. While the transition to lower-GWP refrigerants will cause some changes in product specifications and performance, manufacturers are expected to navigate the transition successfully. Combustion furnaces can produce hotter air than heat pumps, requiring additional airflow. Therefore, in some retrofit applications, existing ductwork may need to be replaced. Customer education may be required for those accustomed to higher distribution air temperatures. In large commercial buildings, significant application barriers include design and installation challenges such as larger equipment capacities required than are available, limited outdoor or roof area for condensing equipment, or more complex load and usage patterns demanding sophisticated product operation.

- **Packaged Terminal Heat Pump.** This technology is mature, although manufacturers continue to improve and add new products. PTHPs are used in new buildings but are especially important as a retrofit technology and are most prevalent in hospitality, healthcare, and multifamily buildings. Typical retrofits will replace either a through-wall sleeve air conditioner (which does not provide heat) or a packaged terminal air conditioner (PTAC), which can provide heat through electric resistance strip heat, hot water, or steam coils fed by a central boiler. Electrical service upgrades may be necessary to accommodate electric resistance backup heat that might be desired for colder climates. The emerging window mounted heat pump meant to replace a window air conditioner has some similarities to the PTHP both technologically and in application and is anticipated to be an important electrification-enabling technology in certain retrofit applications.

- **Heat Recovery Chiller.** While impactful, fully mature, and well known, heat recovery chillers are limited in their applicability to large commercial, hospital, institutional, and district energy facilities with central plants and significant simultaneous heating and cooling loads. Retrofit applications often have site barriers such as piping, pumping, and controls system limitations as well as space/equipment configuration challenges in the mechanical room or central plant facility. Thermal energy storage can be an excellent site decarbonization strategy in combination with chillers when offsetting site natural gas use from boilers on the heating side but may face similar application challenges.[28]
- **Mini-Split ASHP.** Installation practices can substantially impact the system lifetime, performance, and efficiency of mini-split ASHP. Proper system sizing and air handler location are important. Because mini-split ASHPs do not require ducting, they are often considered the best retrofit electrification solution for homes and buildings served by gas furnaces whose ductwork is too small or otherwise not suitable for a ducted ASHP. Field-installed refrigerant lines can vary significantly in the quality of their connections, which can result in high leakage if poor installation practices are used (e.g. inferior flare connections).
- **120V ASHP Split System <5 Ton.** These systems are promising for retrofit applications and can address electrical service/wiring barriers in single-family homes and small commercial buildings. However, their lower voltage means less power is available for backup electric resistance heating.
- **Variable Refrigerant Flow.** While the technology is typically highly efficient and offers good performance, several barriers limit VRF applicability and market penetration. Market barriers common to many electrification technologies also exist for VRFs including lower installer experience and expertise, higher first costs, and lack of awareness. Two key technology barriers relate to refrigerants. First, VRF systems typically use high-GWP refrigerants and must transition to lower-GWP refrigerants (less than 750) by 2026 in California. Some manufacturers are developing lower-GWP options, but they are not currently available in the U.S. market. Second, the systems contain large volumes of refrigerant in typically long refrigerant lines, making them prone to poor installation practices (e.g. inferior flare

[28] McCracken, M. P.E., *ASHRAE Journal*, July 2020 [Electrification, Heat Pumps, and Thermal Energy Storage]

connections) that can result in substantial refrigerant leakage, which can have deleterious impacts on the environment, human health, system performance, and system components. Finally, building codes regarding refrigerant safety can also constrain the design and applicability of VRF systems, especially for institutional and multifamily settings.

- **Electric Resistance Boiler and Electric Reheat Coil.** These technologies are mature and well-established, with no significant market barriers. However, their relatively poor efficiency makes them less desirable than other options. Site and application barriers include a need for increased electrical infrastructure to support high peak electrical demand, which may limit retrofit applicability.
- **Ground Source Heat Pump.** GSHP barriers are similar to other heat pump barriers, including higher cost, lack of awareness, and a smaller group of experienced designers and installers. However, because GSHPs draw heat from the ground, they do not typically have the same cold-climate performance and efficiency issues as ASHPs. Conversely, this limits their applicability to particular sites, especially for retrofits. Similar barriers exist for water source heat pumps, which are similar to GSHPs but draw heat from a managed water source rather than the ground.
- **Combination Space and Water Heating Heat Pump.** Availability is the primary roadblock for this promising technology. It is in active demonstration in California but not otherwise widely available. International installations have taken off, notably as part of the Energiesprong program in the Netherlands.
- **Non-Vapor Compression Heat Pump.** These technologies are not yet ready but are gaining attention in active research and development investments through DOE and at universities. More years of research, development, pilots, and iterative design will likely be required.

Recommendations

This section first discusses specific recommendations for each space heating electrification technology, then summarizes these by solution channel, and lastly provides a summary recommendations table mapping the path to resolve the barriers. Cold-climate performance and refrigerant transition recommendations are presented first because they are common across all heat pump types.

- **Cold-climate performance**. Manufacturers have made great progress in this field and are still working to improve cold-climate heat pump performance and efficiency. In California, a relatively small number of homes and buildings are located in climates where this is a major issue. Programs should target the areas where heat pumps are perceived is in-effective due to low winter outdoor temperatures and raise industry and consumer awareness of cold-climate heat pump performance and availability.
- **Transition to lower-GWP refrigerants.** Manufacturers are aware of the pending transition to lower-GWP refrigerants and are generally expected to successfully navigate the transition. Many manufacturers are

developing and are expected to use proprietary refrigerants or blends, which may raise concerns about availability. Utility and market transformation programs should engage manufacturers to support the transition to mid-GWP products and eventually to low-GWP natural refrigerants such as CO_2 and propane.

BY TECHNOLOGY

Technology-specific recommendations are discussed below.

- **Heat Pump (Packaged ASHP, Split ASHP, Mini-Split ASHP, PTHP, GSHP).** Continued and expanded mass market support is needed to drive much higher market penetrations of these heat pumps. For single-family homes, continued and expanded mass market support is needed for split and mini-split heat pump heating products, both 240V and 120V, to replace conventional furnaces and wall heaters. For multifamily, small family, and some large commercial and institutional buildings, a similar set of highly efficient and mature products, including: 240V split ASHP, mini-split ASHP, 240V packaged ASHP (RTU), and PTHP, are widely available. Efficiency programs should continue to provide mass-market support for these heat pumps technologies in the immediate term. Split and mini-split technologies should be promoted within the retrofit market in particular, as their small refrigerant piping lines require significantly less space than packaged air-distribution technologies and can sidestep ducting-related barriers. For larger buildings, mass market program support must be combined with industry education to ensure that the design and construction industry is equipped to address the design and installation barriers associated with these technologies.
- **Heat Recovery Chiller.** Market support can help drive more retrofits and help make heat recovery one of the standard practice options considered for new construction projects, especially for large central plants and district systems. The expansion of incentives and other support to include thermal energy storage, which can dramatically scale up the energy and GHG benefits of many heat recovery chiller applications, could help drive higher market penetration of the heat recovery chiller.
- **Variable Refrigerant Flow Technology** Workforce training programs, often offered by VRF manufacturers, have helped to improve the design, installation, and maintenance of VRF systems and address quality and safety concerns. These should be continued. Mass market, customized, or whole-building incentive programs can continue to support the financial case for VRF where appropriate, especially for low-GWP products.
- **Combination Space and Water Heating Heat Pump.** Manufacturers should be encouraged to make these products available in the U.S. Efficiency programs can support deployment by including the technology in a whole-building multi-end-use retrofit program similar to

Energiesprong. The California REALIZE program is beginning to make progress on this front.[29]

BY CHANNEL

Recommendations for advancing space heating electrification technologies by channel are below. Recommendations are italicized.

TECHNOLOGY:

Upstream - *Increase Product Availability and Performance.* Encourage manufacturers to continue to drive innovation on system efficiency and accelerate work on low-voltage options for retrofit applications, both mid-GWP and low-GWP refrigerant systems, and cold-climate heat pumps across all heat pump types. Drive market demand to enhance manufacturer confidence in the future market for these products so that manufacturers are justified in making research and development and production investments in these products.

MARKET SOLUTIONS:

Midstream - *Support and Educate the Industry.* Support architects, engineers, builders, distributors, and installers by supplying them with good data and industry materials that can be used to deliver high-quality design and installation outcomes. Also address concerns around issues including installation best practices, important design considerations, relative first costs, system lifetimes, maintenance needs, configuration options, and resiliency.

Midstream - *Ensure Quality and Drive Retrofits.* Help installers and designers have confidence in switching from gas heating and provide high-quality installations by giving good guidance and education around sizing, and configuration. Support retrofits in existing buildings using new products such as 120V split system heat pumps as well as through program support focused on helping resolve application barriers such as wiring, ducting, and configuration challenges. Make the case for HVAC upgrades to strengthen the contractors' and facility managers' rationale framework.

Downstream - *Build demand.* Build consumer awareness of the technologies and their value as the cornerstone to building electrification. This should help increase product availability and price. Address customer concerns about backup heat and resiliency, clarifying that because almost all gas space heating systems require electricity to power fans or pumps, they cannot supply backup heat during power outages. *See Section 9.1: Commonalities.*

PROGRAM SOLUTIONS:

Efficiency Programs - *Increase Incentives based on GHG reductions and assure ENERGY STAR labels.* Provide incentives and financing options to both customers and midstream players (designers/installers) based on GHG reductions as well as simple site energy calculations. Expand incentives for retrofits to help installers address site barriers such as wiring and ducting.

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[29] See footnote 27

Assure new products are tested and labeled through ENERGY STAR as a way to raise consumer awareness.

POLICY SOLUTIONS:

Codes and Standards - ***Keep up With Low-GWP, Value Carbon and Grid Integration.*** Use continuous maintenance or other building performance standards to keep up with fast-changing refrigerant shifts, new options, and refrigerant safety. This should be done more frequently than the code cycle requires. Update regulations and policies to value GHG reductions alongside or instead of energy savings. Value grid interactivity and demand flexibility benefits based on both grid services and scale of GHG reductions.

Space Heating Roadmap Summary

Table 6 summarizes key roadblocks in advancing the electrification of space heating technologies, and the near-term recommendations for actions.

TABLE 6: SUMMARY OF SPACE HEATING ROADBLOCKS AND RECOMMENDATIONS[30]

Space Heating Electrification Technologies –
Roadmblocks and Recommendations for Energy Efficiency Programs: 2020-2025

Recommendation 1: Increase Product Availability and Performance

TECHNOLOGY CHANNEL	**Solution Target:** Upstream - Manufacturers	
ROADBLOCKS	**RECOMMENDATIONS**	
Low product availability (more limited cold-climate products, 120V <5 ton heat pumps, low-GWP systems in general) Cold-Climate Performance Issues (including re: pending refrigerant changes)[M] Few choices for affordable housing retrofits	• **Ensure Incentives.** Maintain incentives for low-GWP products and cold-climate products in general to encourage production. • **Optimize Cold-Climate Model Performance.** Assure cold-climate models performance meets specifications for locations in NE and the Sierras of California.	• **Retrofit Systems.** Increase production and availability of smaller low voltage systems for retrofits. • **Prime PTHP and Window-mounted Heat Pump.** Support product development, market, and program pathway for units that fit into affordable multifamily retrofits.

[30] "M" as a superscript means "Manufacturer Input" (see Appendix page A-6: Manufacturer Feedback on Space and Water Heating).

Recommendation 2: Support and Educate the Industry

MARKET CHANNEL	**Solution Target:** Midstream – Designers, Installers, Builders	
ROADBLOCKS	**RECOMMENDATIONS**	
Existing building wiring, ducting, and configuration constraints[M] Higher first cost, potentially higher energy cost, split incentive structural barrier[M] Risk aversion due to maintenance concerns (seeking to avoid callbacks) End-user preferences: lower supply air temperature vs gas furnace and particularly during startup/defrost cycles; noise during defrost switchover[M] Risk aversion to electrification for heating as a core service; fear of removing "gas back-up" during power outages, etc.	• **Site Assessment Best Practices.** Assure tools and materials are widely available regarding the selection and application of the best equipment, including proper sizing calculations. • **Create Technology Performance Materials.** Address concerns about backup heat, resiliency, and related considerations in customer-facing materials for use by installers.	• **Deliver Demos and Data.** Enhance and build industry materials on system installation, design considerations, system lifetimes, maintenance needs, and configuration options[M]

Recommendation 3: Ensure Quality and Drive Retrofits

MARKET CHANNEL	**Solution Target:** Midstream - Designers, Installers, Facility Managers	
ROADBLOCKS	**RECOMMENDATIONS**	
Designer and installer confidence for new product types and fundamental shift in heating designs (e.g. a move away from VAV and towards Heat Pumps), especially for retrofit applications[M] Absence of HVAC retrofit rationale	• **Make the Case.** Develop credible and compelling business and market trend case materials for moving to electrification technologies for heating systems.	• **Drive Retrofits.** Advance the benefits for proactive upgrades and assure small (<5 ton) 120V split system heat pumps are a retrofit target; enhance trade ally training and engagement on retrofit-specific topics[M]

Recommendation 4: Incentives and ENERGY STAR Labels

PROGRAM CHANNEL	**Solution Target:** Efficiency Programs | Federal ENERGY STAR Program	
ROADBLOCKS	**RECOMMENDATIONS**	
Program lists and incentives get outdated, need to reflect newest products on market (low-GWP refrigerant, cold-climate) and update incentives to increase adoption Program incentives lack carbon valuation ENERGY STAR testing and specs for new products	• **Incentives.** Maintain incentives for products, and designers/installers of novel systems (e.g. electrification incentives).[M] • **Value Carbon.** Establish programmatic value for emission reductions alongside energy benefit, including reductions from refrigerant leakage impacts.	• **ENERGY STAR Labels.** Assure partnership with ENERGY STAR on testing, specifications, and full product labeling to build consumer confidence.

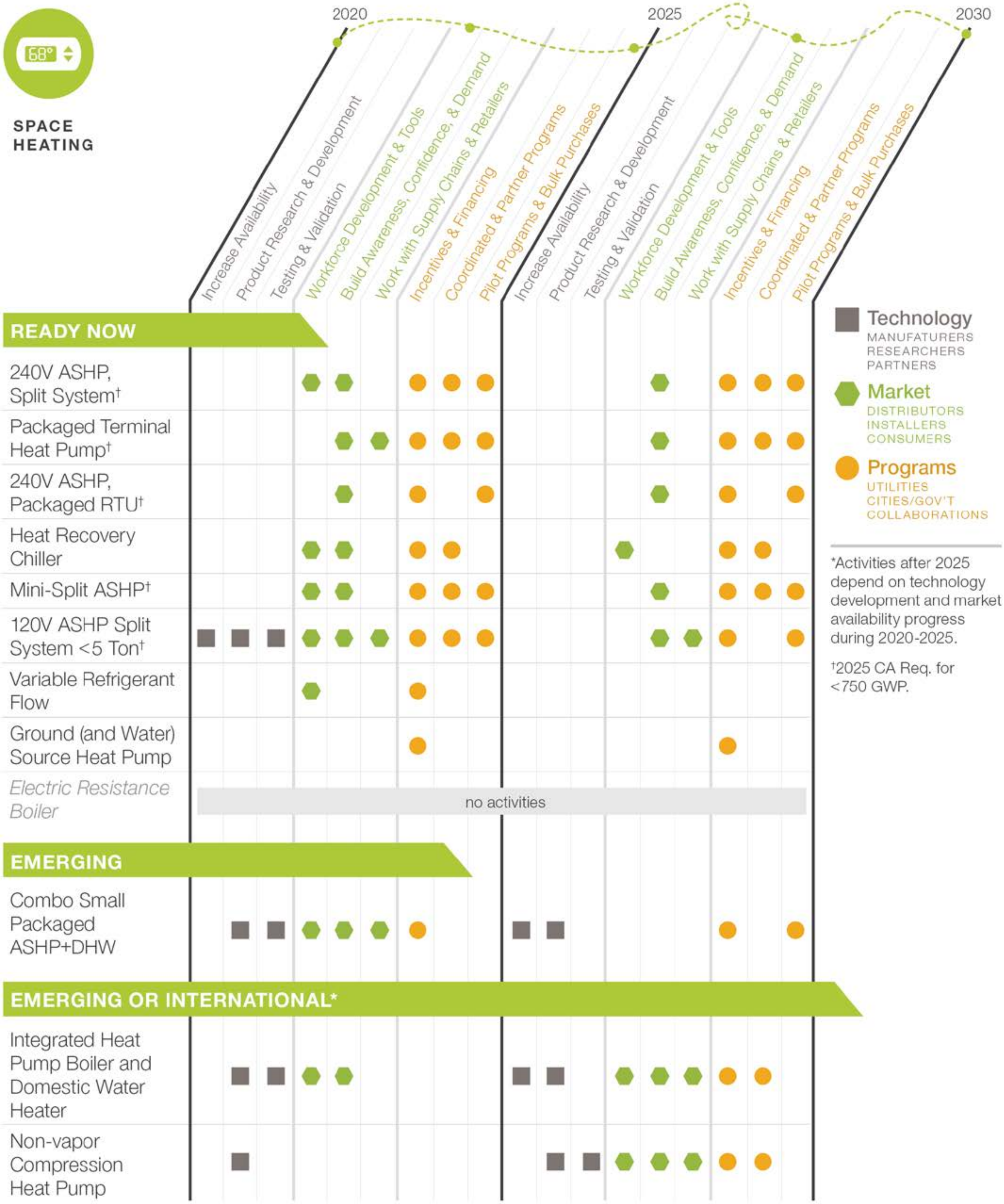
Recommendation 5: Keep up with Low-GWP, Value Carbon and Grid Integration

POLICY CHANNEL	Solution Target: State Government, Cities, Public Utility Commissions, Energy Efficiency Programs	
ROADBLOCKS	**RECOMMENDATIONS**	
Code guidance needs to keep up to date on newest low-GWP refrigerants and refrigerant safety[M] Lack of fuel and carbon price signals for electrification[M]	• **Standards Development/Integration.** Ensure codes and standards keep up with new refrigerants to assess safety and performance consistently across products[M]	• **Increase Electrification Value Signals.** Value emission reductions in addition to energy reductions. • **Value Grid Benefits.** Remove barriers to customized valuation based on grid integration benefits[M]

Space Heating Roadmap at a Glance

The Space Heating Electrification Roadmap at a Glance shows the activities for efficiency programs to advance these technologies over two time frames for the next 10 years in Figure 6. Within each time frame the activities occur in parallel to move the technologies toward much greater and more rapid adoption. The roadmap is organized by three of the Solution Channels introduced in Table 3. The fourth Solution Channel—Policy and Standards—are addressed above in Table 6 or covered across all technologies in the Collective Recommendations Summary in Table 20.

FIGURE 6: SPACE HEATING ELECTRIFICATION ROADMAP AT A GLANCE



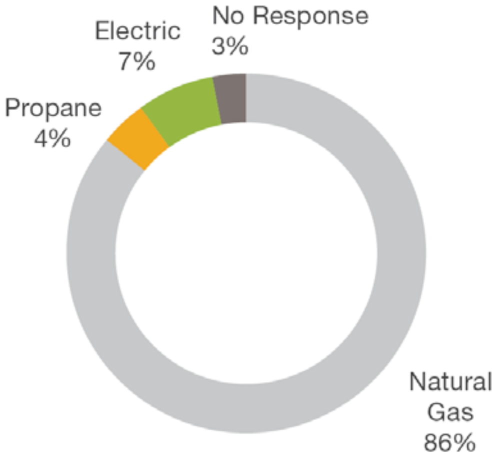
4. Water Heating

4.1. Impact and Importance

Nothing says comfort like hot water. But combustion water heaters burning gas or propane account for 90% of water heating equipment (Figure 7)—and 40% of natural gas use—in California homes.[31] For California to meet its climate goals, at least 30% of the state's residential gas water heaters must be electrified by 2030.[32]

FIGURE 7: CALIFORNIA SINGLE FAMILY AND MULTIFAMILY WATER HEATING STOCK

Source: Khanolkar, A. NBI 2020 – based on California water heating stock data from RASS 2009[33]



Combustion water heaters burning gas or propane account for 90% of water heating equipment in California homes.

In commercial buildings, hot water use varies widely by building type. In multifamily it can be the top energy use while it is minor use in offices for hand washing, dishwashing, and occasional on-site showers. Higher education facilities include dorms and food service with large hot water needs. Restaurants and commercial laundry also demand high quantities of hot water. Electrification technologies available support those uses as well.

[31] UC Davis for CEC 2019

[32] SCE 2019, Pathway 2045 | The Advanced Water Heating Initiative (AWHI), supported by many of the BETR funders, has a goal of 45% of California residential water heater stock to be HPWHs by 2030.

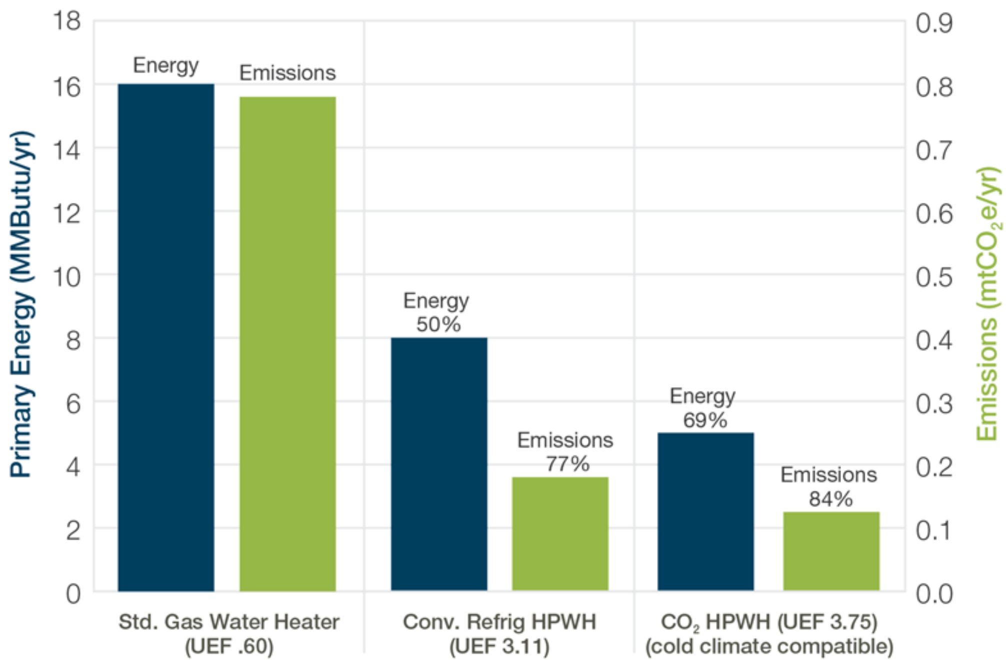
[33] Residential Appliance Saturation Survey 2009 *(RASS 2019 was delayed and anticipated in 2021)*

Water heating is on the front lines of electrifying and decarbonizing buildings, especially in the residential sector. Water heating electrification focuses on heat pump water heaters (HPWHs)—a decades-old, reliable technology now undergoing a renaissance in technological optimization. The technology is immediately ready for residential new construction and large multifamily applications. Emerging products will meet panel constraint retrofit applications and shift to lower global warming potential (GWP) refrigerants.

Heat pump water heaters offer dramatic energy and emission reduction compared to the ubiquitous standard gas water heater, as seen in Figure 8. A conventional refrigerant HPWH operating in a typical Southern California home uses half the energy and produces 77% fewer emissions compared to conventional gas-powered water tanks. A HPWH with CO_2-based refrigerants has negligible emissions.[34]

FIGURE 8: HPWH ENERGY AND EMISSION SAVINGS COMPARED WITH STANDARD GAS WATER HEATER: S. CA HOME

Source: NBI 2020 Based on 2018 data from the EPRI.



Primary source energy only, includes gas distribution losses and electric generation, transmission and distribution losses. Does not include emissions from gas delivery or refrigerant leakage.

There are three key components of beneficial electrification: energy efficiency, emissions reductions, and cost savings. Smart HPWHs hit all three criteria. They are super-efficient, they help keep utility bills low for occupants of all-electric buildings, and the new California demand management standard

[34] Currently there is only one HPWH product with CO_2 refrigerant available for the residential market, but more options are in development and anticipated in the near future. See Refrigerants section.

(JA13), ensures that they can be smart and flexible to optimize clean renewable generation, reducing electricity costs for all Californians.[35]

Off-the-shelf 240V heat pump water heaters are ready for both new construction and retrofit applications.

4.2. Technology Status

The readiness and GHG impact of HPWHs make them the clear leader for water heating electrification. HPWHs are technically ready and available to address residential new construction, some retrofits, and multifamily-

[35] JA13 Qualification Requirements for Heat Pump Water Heater Demand Management Systems is a performance compliance requirement for California to shift water heater loads to reduce peak load and enable renewable energy integration. A national requirement for this capability–CTA 2045–has been tested and is under consideration as a product requirement.

institutional hot water needs. HPWH products are generally either ‘unitary’ (50-100 gallon storage tank with integrated heat pump) or ‘central’ (one or multiple heat pumps serving a water heating plant, typically in multifamily or institutional buildings). Solar thermal and electric resistance water heaters are technically ready but have drawbacks.

Emerging products set the stage for retrofits and further emission reductions: The 120V unitary product, a game-changer for the residential retrofit market, is expected in 2021 but needs field validation. This plug-in unit will more easily fit locations of existing gas tanks without wiring upgrades. Its more modest rate of hot water supply can be offset by a slightly larger tank and mixing valve (the mixing valve allows the tank to heat water above typical delivery temperatures, storing more heat without introducing the risk of delivering scalding-hot water).

Table 7 summarizes the status of electric water heating technologies and applicable building types and vintages. Following the table is a more in-depth explanation of the status of each water heating technology. Table 8 shows selected international products for water heating and combination water and space heating.

TABLE 7: STATUS OF ELECTRIFICATION WATER HEATING TECHNOLOGIES

WATER HEATING TECHNOLOGY	MATRIX SCORES					BUILDING TYPE APPLICABILITY					VINTAGE APPLICABILITY	
	Technology Readiness	Product Availability	Ease of Application	Awareness	Scale of Ghg Reductions	Single Family	Multifamily	Small Comm	Large Comm	Higher Ed/Inst	New Construction	Retrofit
Unitary 240V HPWH, conventional refrigerant	High	High	Moderate	Moderate	Moderate	✔	✔				High	Moderate
Central HPWH, conventional refrigerant	High	High	Moderate	Moderate	Moderate		✔			✔	High	Moderate
Central HPWH, low-GWP refrigerant	Moderate	Moderate	Moderate	Moderate	High		✔			✔	High	Moderate
Unitary 240V HPWH, low-GWP refrigerant	Moderate	Low	Moderate	Low	High	✔	✔			✔	High	Moderate
Unitary 120V HPWH, conventional refrigerant *emerging*	Moderate		Low	Low	Moderate	✔	✔					Moderate
Unitary 120V HPWH, low-GWP refrigerant *emerging*	Low		Moderate	Low	High	✔	✔					Moderate
Solar Thermal Assisted WH	Moderate	Moderate	Low	Moderate	Moderate	✔	✔				High	Moderate
Electric Resistance WH: Point of Use Distributed, Tankless	High	High	Moderate	High	Low	✔	✔	✔	✔	✔	High	Moderate

High (3) Moderate (2) Low (1)

Notes: Most HPWH products today use conventional (high-GWP, usually HFC) refrigerants. HPWHs are not marked as “applicable” in Small and Large Commercial because water heating needs are minimal in most offices. However, higher hot water usage occurs in some commercial buildings such as restaurants, health care, and lodging. In such cases HPWHs are often applicable and valuable.

General Scoring Notes. Across single-family, multifamily, and commercial water heating technologies, both unitary 240V HPWHs and electric resistance tankless, or instantaneous, water heaters score high in terms of technology readiness, availability, and awareness, but the GHG emission reductions of HPWHs are much greater. Across commercial products, central HPWHs and small electric resistance point-of-use water heaters are also ready, available, and well known. Electric resistance water heaters are applicable primarily to small uses in large and small commercial restrooms.

In general, as with space heating heat pump technologies, HPWH technologies with high readiness, availability, and lower GHG reductions tend to face moderate-to-low construction industry and customer awareness and ease of application in retrofit applications. The inverse is also true: Products with the very highest GHG reductions tend to have low product readiness, availability, and consumer awareness. The latter category includes products that are still emerging, such as 120V unitary HPWH targeted to retrofit applications and low-GWP HPWHs where the heat transfer technology using novel fluids is still evolving. For cold-climate outdoor applications, the split HPWH is the only suitable model for two reasons: It uses CO_2 as the refrigerant, which is efficient in low temperatures and has negligible GWP, and the tank remains indoors while the condenser is a separate unit that can be located outdoors.

To advance water heating electrification, this study recommends prioritizing technologies that are both fully ready and available and deliver high GHG reductions compared to other measures.

TABLE 8: INTERNATIONAL PRODUCTS FOR WATER HEATING

END-USE	TECHNOLOGY TYPE	INTERNATIONAL MARKET STATUS	DOMESTIC STATUS, EST. AVAILABILITY	MANUFACTURERS (REGION)
Water Heating	240V CO_2 heat pump water heater (Sanden Ecocute products)	Commercially available but under adopted	Commercially available but under adopted	Daikin, Mayekawa, Hitachi, Mitsubishi, Sanyo, Panasonic (Japan)
Water Heating	120V split system HPWH	Prototypes and pilots	Not yet available	Nulite, OSB (China)
Water Heating	120V unitary HPWH	Prototypes and pilots	Not yet available	Ariston (Italy), Nyle (USA), Haier (China)
Water Heating	240V wall mounted heat pump water heater	Prototypes and pilots	Not yet available	LG (Korea), AO Smith (USA)

END-USE	TECHNOLOGY TYPE	INTERNATIONAL MARKET STATUS	DOMESTIC STATUS, EST. AVAILABILITY	MANUFACTURERS (REGION)
Water Heating	Large compressor / small tank HPWH	Commercially available but under adopted	Not yet available	Mitsubishi, Panasonic (Japan), Danfoss (Denmark)
Water Heating	Central HPWH	Prototypes and pilots	Available 2021 (estimated)	Sanden (USA), Mitsubishi (Japan)
Space and Water Heating	Combined space and water heat pump	Commercially available but under adopted	Not yet available	LG (Korea), Clivet (Italy), Factory Zero (Netherlands)
Space and Water Heating	Natural refrigerant (propane, CO_2, etc.) HPWH	Widely commercially available	Few-to-no product options available	Alpha Innotec, Heliotherm, NIBE, Roth GmbH, Wolf GmbH, Vaillant (Germany), Denso (Netherlands), Hotjet (Czech), Enex, Enerblue (Italy), Daikin (Japan)

Status Summary

The technology status for water heating electrification technologies is described below.

Heat Pump Water Heaters (HPWHs) – Ready Now

Heat Pump Water Heaters are technically ready and available to address residential new construction, some retrofits, and commercial hot water needs. The GHG reductions are dramatic compared to existing gas technologies, on the order of 50-70%, and the energy efficiency is 2-4 times that of electric resistance or gas-burning hot water heaters.[36] Emerging low-GWP products will improve the GHG reductions another 7-10% over conventional refrigerants. Efficiency programs should prioritize conventional refrigerant HPWH technologies, which are ready, available, and proven. They should work in parallel to advance emerging low-GWP and grid-connected systems for water heating.

- **Unitary 240V Conventional Refrigerant HPWH**. Refrigerant: R-410a or R-134a. Multiple product options are available and suitable for primarily single family residential homes with potential for individual multifamily units. Grid-integration control available. Fully technically ready, widely available with multiple product options. High GHG reductions compared to gas technologies but moderate GHG reductions compared to emerging low-GWP products.
- **Central Conventional Refrigerant HPWH.** Refrigerant: R-134a. Available and suitable for multifamily buildings and higher education/institutions. Grid-integration control available. Fully technically ready and widely available with multiple product options. High GHG reductions compared to gas technologies but moderate GHG reductions compared to emerging low-GWP products.
- **Central Low-GWP HPWH.** Refrigerant R-744 (CO_2). Suitable for multifamily and higher education. Grid-integration control available. Fully technically ready. Availability rated moderate as there is just one market-ready product with another in field demonstration and others in development. High GHG reductions compared to gas technologies and conventional refrigerant central HPWH.
- **Unitary 240V Low-GWP HPWH.** Refrigerant R-744 (CO_2). Suitable for residential and also used in a series (several intertied for greater production capacity) for multifamily. Grid-integration control available. Availability rated low, as there is just one market-ready, available product with a wide set of installations for both residential as well as multifamily applications used in series. High GHG reductions compared to other electrification measures.

[36] Oil-fired hydronic water heating, very common in the Northeast U.S., has higher baseline emissions, so HPWHs can deliver even greater GHG impact.

Heat Pump Water Heaters (HPWH) – Emerging

Major HPWH manufacturers are working on lower voltage products and have begun the transition to low-GWP refrigerant technologies. Developing new market products requires a multitude of equipment design and materials modifications, which may require new production lines. These changes have time and financial investment impacts on manufacturers who, in order to make them, need confidence in the potential market size, pricing, and ability for programs to increase product demand.

Performance must be highly reliable and verified. Lab and field testing are critical—by both the manufacturer and by independent third-parties through demonstrations and evaluation. Underwriters Laboratory requirements (UL listing) are a final step to market readiness. These products are far along on this path to market and are anticipated to be on the market in 2021–2023. Their progression must be strongly supported in parallel with increasing demand for HPWHs that can be immediately met with the conventional refrigerant products above.

- **Unitary 240V Low-GWP Refrigerant HPWH**. CO_2 or other low/zero GWP. Suitable for residential new construction and commercial buildings. There is one market-ready, available product with a wide set of installations for both residential as well as multifamily applications used in this series. This category remains in the “emerging” group due to the absence of multiple products. High GHG reductions compared to other electrification measures.
- **Unitary 120V Conventional Refrigerant Retrofit-Ready HPWH.** Refrigerant: R-134a. Suitable for residential retrofit. Grid-integrated control available. At least one 120V unit will be market ready by early 2021 with other products in development and planned for 2021 pilot tests in California, Because of their low-voltage and low-amperage needs they can ideally plug in to existing wall sockets or be hardwired into a dedicated 20-amp supply without requiring expensive panel upgrades and/or home rewiring. Their rate of hot water production is limited by the lower energy input. Technology strategies to address this include a larger storage tank with a higher tank temperature resulting in greater total stored BTUs available and the addition of a mixing valve to delivery at the set point. This last strategy has a minor efficiency penalty from greater standby losses. The technical design to address the retrofit market is evolving differently with various manufacturers and being field tested with the unit(s) ready for demonstration. The unitary 120V HPWH will be well suited to smaller homes, which have lower hot water demand. The unitary 120V HPWH is not recommended for new home construction, where higher voltage units can be installed at the time of construction. High GHG reductions compared to other electrification measures.
- **Unitary 120V Low-GWP Refrigerant Retrofit-Ready HPWH.** CO_2 or other low/zero GWP. Suitable for residential retrofits. No known available products. The low-GWP versions of the retrofit-ready 120V HPWH will be released after their conventional-refrigerant counterparts, which are

manufacturers' current priority. High GHG reductions compared to other electrification measures.

Other Technologies: Solar Thermal and Electric Resistance – Ready Now

The following technologies are all technically ready and available but are expensive, labor intensive, have higher maintenance requirements and/or their performance or GHG impacts make them a lower priority for decarbonizing buildings.

- **Solar Thermal Assisted Water Heater.** Solar rooftop thermal supplying a standard gas or electric water tank. For residential and commercial buildings. Solar thermal is an additional technology with a long history and a high capability of reducing emissions. When properly sited and operated solar thermal can offset 70-80% of the hot water needs of a California home from solar heating. However, it has limited site feasibility, higher maintenance requirements, and performance issues that continue to marginalize its potential.[37] For these reasons technical readiness is rated a 2 (moderate). Strong GHG impacts compared to gas due to the use of solar as the primary source but far less than the year round efficiencies of HPWHs so GHG reductions are rated moderate.
- **Electric Resistance Water Heater.** Water heating technologies that rely on electric resistance heat are inefficient compared to HPWHs (3-5 times more energy use) but meet a need for a small electric water heating solution for space-constrained installations, a remote site that is not connected to a more centralized gas supply, and/or has very low-use, such as a commercial restroom. While switching from gas to electric resistance heat with these technologies will certainly reduce site emissions, it will not have nearly as much impact as switching to heat-pump technologies, where the greater energy efficiency has a major corresponding emissions reduction.
  - » **Distributed Point of Use Water Heaters** Suitable for residential and commercial buildings. Fully technically ready, widely available, and commonly used as a small or secondary water heater for bathrooms, break rooms, and kitchens. Storage tanks are typically small (2.5-20 gallons).
  - » **Whole-House Electric Tankless (Instantaneous) Water Heater**. Suitable for residential and commercial buildings. Fully technically ready and available. Require high voltage and amperage, thus often limited to new construction. Grid peak demand impacts can be substantial. Relative to other electric water heating technologies, GHG reductions are low because resistance heating is much less efficient than heat pump water heating.

4.3. Roadblocks and Recommendations

Heat pump water heaters offer the best pathway for both residential and commercial decarbonization, yet they face challenges common to most building

[37] UC Davis for CEC 2019, Solar Water Heating Assessment Project (*For California Homes)*

electrification technologies as described above. Retrofit applications in all cases have lower ‘ease of application’ scores due to the site conditions and panel constraints. The characteristics of the existing and emerging systems are often in conflict. These limitations are driving the need for the 120V unitary product. The roadblocks and recommendations are described below by technology and sector and summarized with recommendations in Table 9.

Roadblocks

Unitary 240V – Residential. There is large availability across a wide range of 240V HPWHs products. Manufacturers and most plumbing contractors are aware of HPWHs, but few choose to promote them. In new construction single family there are no technical barriers to 240V HPWHs as the standard practice. Barriers exist in some new developments where there are requirements to connect to the natural gas system and there are consumption expectations per household in order to address gas infrastructure costs across a set of homes. For retrofits, panel size, 240V wiring, and potentially space constraints are potential barriers for the 240V HPWHs, which can be large.

Market roadblocks downstream at the customer end for the 240V HPWH are primarily low awareness and confidence leading to low demand. In the market midstream the supply chain stocking practices in response to the lack of demand are an issue that limits installer confidence of availability. Installer skills with the increased electronics of HPWHs, poor experiences with past models, and preferences for their current business approach built on familiarity and economics with gas water tanks are significant barriers. In addition, most gas water heaters can provide hot water during power outages, whereas HPWHs cannot unless the building has islanding capability and distributed energy resources.

There are also some technical information gaps. There is a lack of monitored field data around single-family water heaters (gas as well as electric) and thus a need for increased field data on performance and pre and post utility bill analysis to understand actual on-site performance. This will help reconcile bench and lab testing with proven site performance and create increased confidence in the energy and cost comparisons needed to grow demand. In addition, some modeling software does not model the water heating end-use with performance curves the way it does for HVAC systems, so design firms lack the tools for assessing the equipment.

Central – Commercial/Multifamily. The market default for commercial water heating plants is gas-fired tanks or in very few cases condensing gas tank water heaters driven by economics and market familiarity. Each commercial application, primarily multifamily, typically requires a time-intensive customized demand assessment, ground-up system design and product application configuration.

The design industry and contractors are unfamiliar with central heat pump products, which often leads to a default back to central gas-fired boiler equipment. Very few design firms are familiar with the system design requirements. Existing central HPWH application examples are available but there are few or no templates or design tools built from prior installations. This limits the number of potential future installations. Low-GWP central systems have the same hurdles but also the absence of market products. New emerging low-GWP systems are in testing and development for performance validation.

Unitary 240V Low-GWP – Residential. There is one ready and available product using CO_2 as the refrigerant with a wide set of installations for both residential as well as commercial multifamily applications, where the units are used in series. Because of the use of CO_2 this single product is also cold-climate compatible serving an important site and climate zone need. Roadblocks for this product are a high relative cost to other water heating options including non-CO_2 HPWHs, and market and contractor awareness of the product and the benefits.

There is a need for a greater number of products with low-GWP 240V systems beyond the one manufacturer to increase installation options and pricing range and to target cold climate applications. Manufacturing roadblocks exist as the current product line of conventional (high GWP) 240V HPWHs have yet to establish sufficient market adoption to warrant the attention and investment by manufacturers in another product. Low-GWP system production requires significant changes in product design and development to assure that the new refrigerant type and cycle meets performance specification. Manufacturers need proven market demand or regulatory requirements (less attractive) to make a rapid shift from current products.

Unitary 120V – Residential Retrofit Ready. There are numerous barriers to swapping out an electric resistance or gas water heating system with a new HPWH, the greatest of which are:

- **Space constraints.** HPWHs require adequate air circulation and exhaust access typically found only in larger indoor water heater locations (such as a garage, unconditioned basement, or large mechanical room or closet) or outdoor space if the location is temperate or the system is cold-climate compatible. And, because HPWHs are wider and taller than other water tanks, a 120V retrofit HPWH will very likely require a larger tank to deliver adequate hot water supply rates, which may create a sizing constraint.
- **Power constraints.** For retrofits, the only available equipment is the 240V unit which requires adequate panel ampacity, a dedicated circuit, and 240V wiring—items rarely found near existing gas tanks. The 120V product is a solution to this roadblock, as a plug-in or direct-wired unit requiring a more typical household outlet or 20-amp circuit.
- **Hot water recovery rate.** The 120V system will have slower hot water production due to the lower electrical supply and absence of electrical resistance element as supplemental heat. Therefore, manufacturers are designing solutions such as a larger tank for increased capacity and/or a mixing valve so the tank can be overheated. The most suited target market for reliable delivery is families of four or less with modest hot water needs. A few systems are currently in demonstration in California and more are planned for 2021 through AWHI. A recent effort to increase the exposure

and training of installers through a bulk purchase of 120V prototype units was sidelined due to the local efficiency program's hesitation to put incentives into a product that is not yet available on the market.

Solar Thermal Assisted Water Heating. Solar thermal remains promising but highly challenged in its ability to prove reliable performance and ease of installation. A 2019 UC Davis study notes several water heating and equipment problems with installations throughout California.[38] In addition, the roof site placement limits applicability. Customer acceptance of this large, highly visible equipment is considerably lower in the U.S. compared to other parts of the world where solar thermal is ubiquitous.

Electric Resistance Technologies. Electric resistance water heating technologies such as tankless or point-of-use distributed water heaters have few technical roadblocks within the new construction market. They are technically very reliable and are well known. However, their size makes them appropriate for small uses only, such as in office restrooms. In residential applications, the instantaneous system is not a good choice over a HPWH, as its energy use is much higher than the HPWH. In retrofits, these technologies require the appropriate electrical infrastructure, which can limit applicability and/or increase costs. The absence of significant GHG reductions compared to applications where HPWHs can meet the water heating needs makes electric resistance technologies a low priority for advancement.

Recommendations

This section first discusses specific recommendations for each water heating electrification technology, then summarizes these by solution channel, and lastly provides a summary recommendations table mapping the path to resolve the barriers.

BY TECHNOLOGY

Technology-specific recommendations are discussed below.

- **Unitary 240V - Residential.** Efficiency programs should prioritize 240V HPWHs for all residential new construction. They provide the greatest GHG reduction and lowest occupant operating cost when used with their full control capability during off-peak hours of a technically ready and widely available technology. The 240V product can also be a retrofit solution where there is sufficient panel ampacity and air volume to meet its power and air-exchange needs. Programs should leverage code requirements and customer interest in resiliency and distributed energy resources to enable optional HPWH operation during power outages by islanding the building from the grid and drawing on solar and storage resources.
- **Central System.** Efficiency programs should prioritize HPWHs for new multifamily and multifamily retrofits. This was the No. 1 market priority identified by manufacturers in a 2018 EPRI water and space heating

[38] UC Davis 2019, IBID

survey and workshop.[39] There are multiple conventional-refrigerant, large-capacity product options of 10 tons or greater. A new low-GWP product with a nominal 10-ton capacity is currently in demonstration and is likely to hit the market in 2021. The only unitary 240V water heater using CO_2, while sized for a single-family residential home, has been used in a wide range of existing multifamily projects with central systems[40]. Because this is a split-system HPWH (the compressor and heat exchanger are not integrated with the tank) multiple units can be combined to serve one or many tanks of various sizes to meet large water-heating load resulting in significant energy and emissions savings. The CO_2 refrigerant is cold-climate compatible and thus can be located outdoors if necessary, in almost any climate.

- **Unitary 240V – Multifamily.** Unitary 240V systems should be promoted for multifamily new buildings during early design stage. Applications include an individual tank per unit or clustered larger tanks serving multiple units. Multifamily systems require sufficient electrical supply, air supply, and exhaust, which is most easily done at new construction and in warmer California climates where the water heater closet may be on an exterior deck. Existing multifamily buildings with adequate space can swap out electric resistance water heaters for 240V HPWHs. Energy efficiency programs may consider the emerging unitary 120V system for multifamily applications.
- **Emerging 120V and Low-GWP Products**. 120V HPWH, and HPWHs of all voltages using low-GWP refrigerant, need continued development and technology validations. These technologies are actively in development and will continue to be over the next several years. They are critical technologies to address retrofit water heating applications and provide the highest GHG reducing-solution. The recommendations to support these must occur in parallel with existing products in order to increase market awareness and preparedness, which will spur greater production and availability from manufacturers and the supply chain.

BY CHANNEL

Recommendations for advancing HPWHs by channel are below. Recommendations are italicized.

TECHNOLOGY:

Upstream - *Resolve Product Readiness and Increase Mid-Stream Confidence.* The readiness and availability of HPWHs is a two-way street: Efficiency programs must build demand to help signal to manufacturers there will be a market. As demand grows so will product volume, availability, and features. Currently, the key recommendations include assure universal adoption and operational efficacy of the proposed national grid-integrated controls specification (CTA-2045) and the California-required demand management controls (JA13) in all current product lines. In addition,

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[39] See Appendix page A-6.

[40] Ecotope has been the leading design firm on the West Coast for this application.

technology development must continue to be on the optimization of 120V retrofit-ready systems. There are several 120V products anticipated in 2021 but these are not yet on the market. Ongoing research and development to obtain the best hot water response rate and most flexibility in terms of physical size and wiring requirements for retrofit applications is needed. Manufacturer and efficiency partnerships are working to set up an independent third-party field test in 2021 to assure both energy and supply performance. Finally, the efficiency industry must continue to make the case and develop the market for low-GWP products as a way to accelerate manufacturer progress for new low-GWP product availability.

MARKET SOLUTIONS:

Midstream - *Support the Supply Chain.* The supply chain has the greatest influence on consumer decisions and is therefore critical to increasing the adoption of HPWHs. The success of suppliers, contractors, and retailers relies on a model where they make money per sale and assure their reputation in order to make repeat sales, while minimizing call-backs. The solutions needed must function within their standard business model. It's important to understand their operational mode and margins when trying to gauge their interest in and willingness to be product advocates. The efficiency industry must support a healthy business model by proving a price point and value proposition where suppliers, contractors, and retailers can make the sale, assuring reliable availability from manufacturers, and increase confidence in the product performance both in terms of energy and reducing the frequency of warranty callbacks. In addition, they need collateral materials to educate consumers.

Mid-Stream - *Create Installation Guidance.* HPWHs require different physical and technical settings than gas or electric resistance water heating systems. For new construction these are more straightforward with the need for clear site installation parameters and training provided to builders and plumbers. For retrofit, guidance and training are also key to help installers specify the right products and assure the successful application of both unitary and central HPWHs in existing buildings. Clear technical guides and tools for retrofit HPWHs include equipment selection and sizing templates, space and air requirements, hot water supply rates and energy performance data in relation to use patterns.

The integration of grid controllability creates another learning step for installers and the site set up of the new JA13 time-of-use codes into the equipment and CTA-2045 controls capabilities is well beyond what is required for other water heating products. Phone apps and on-unit instructions will help both the installer and building owners if an issue arises. This was identified as a key need by manufacturers (see Appendix page A-7). Installers and builders also need the data on site performance that can inform their representations with consumers as well as tools for identifying the economics of HPWHs in various applications.

Downstream - *Build demand.* Create consumer awareness of the technologies and their value as the cornerstone to building electrification. This will also increase product availability and reduce prices. See Section 9.1: Commonalities.

PROGRAM SOLUTIONS

Efficiency Programs: *Establish Data and Value* | *Align with Federal and Statewide Programs*. Efficiency programs of utilities, consumer choice aggregators (CCAs), local cross-regional jurisdictions, and cities and states have a significant role to play in the effort to move the HPWH market. Their technical and market knowledge, interests, community role, and investments have a long history of shifting the built environment to more efficient technologies that offer multiple benefits.

First, there remains a need for continued field research by implementation programs that share outcomes. They need to provide product validation of energy use, hot water supply rates, controls, installation practices, and other key information. Efficiency programs must lead in gathering utilities, energy professionals, manufacturers, and industry collaborations (like the Advanced Water Heating Initiative[41]) to identify what data already exists and what data are missing in order to validate field performance and technology readiness. This includes but is not limited to: monitored field data for water heaters (gas as well as electric), pre- and post-installation utility bill analysis for annual energy savings, and data about software issues connected to properly modeling water heating performance. The demand-response benefit to both the utility and the statewide grid must be part of program valuation that in turn influences the incentive levels.

At the Federal program level, ENERGY STAR has been attentive to California's and the Northwest's progress with HPWHs through AWHI and is exploring how to engage as a partner to increase adoption. ENERGY STAR testing, connectivity criteria, control specifications, and labeling of new products must keep pace with the ambitious level of planned electrification activities on the West Coast, and likely nationally, to assure consistent product representation to consumers.

Finally, efficiency programs must work with city, county, and state governments to coordinate statewide programs, financing, and information so that midstream and downstream parties can make informed buying decisions. The TECH and BUILD programs, created by California SB 1477, share these objectives, but success will depend on the statewide coordination of energy efficiency programs with selected contractors.

POLICY-STANDARDS SOLUTIONS

Federal Controls Standard. *National Standard for CTA-2045 Controls.* A federal standard remains an important credential to unify the market and these technologies through the national adoption of CTA-2045 and DOE efficiency standards. At the state level, California has already adopted JA13, becoming a decisive national leader in decarbonization policies that support building electrification. Yet the water heating market remains underwhelmed by the pace and activity resulting from these standards to date.[42]

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[41] Advanced Water Heating Initiative (AWHI)

[42] Author's personal notes from manufacturer feedback through various forums

Water Heating Roadmap Summary

Table 9 summarizes key roadblocks in advancing the electrification of water heating technologies, and the near-term recommendations for actions.

Where a recommendation is distinct to a specific technology within the HPWH category, it is noted. Most areas represent the larger topics and activities needed across water heating electrification technology to drive high adoption of high-efficiency, reliable, low-emission technologies for residential and commercial water heating within five years.

TABLE 9: SUMMARY OF HPWH ROADBLOCKS AND RECOMMENDATIONS[43]

Heat Pump Water Heaters (Unitary and Central) - Roadblocks and Recommendations for Energy Efficiency Programs: 2020-2025

Recommendation 1: Resolve Product Readiness and Increase Mid-Stream Confidence[M]

TECHNOLOGY CHANNEL	**Solution Target:** Upstream and Midstream - Manufacturers and Supply chain	
ROADBLOCKS	**RECOMMENDATIONS**	
Low product availability (120V and low-GWP) Absence of universal adoption of OEM DR/TOU controls (CTA-2045) Reluctance to displace existing electric resistance and gas product lines High price point partly due to low volumes of production	• **Development and Field Testing.** Refine and test products to meet retrofit applications constraints and capacity needs and low-zero GWP refrigerants. • **Grid-integrated Controls.** Finalize agreed-upon national specification (CTA-2045) for inclusion on all systems. Establish date of universal product integration at manufacturer.	• **Lead with HPWHs**. Establish the pricing, incentives and product availability that make HPWHs attractive to mid-stream supply and installer chain. Assure extensive training and product incentives to prompt adoption[M]

Recommendation 2: Create Installation Guidance

MARKET CHANNEL	**Solution Target:** Midstream – Installers and Contractors	
ROADBLOCKS	**RECOMMENDATIONS**	
Space and air needs[M] Power availability[M] Grid integrated controls set up Condensate drain location[M] Resiliency Concerns	• **Demos and Data.** Create industry materials on the 240V vs 120V units including the set up and commissioning of grid-integration controls. • **Installer Training and Tools**[M] Provide training, guidance and resources to installers on space configurations. • **Retrofit Unit.** Advance the 120V unit and make bulk purchases to train installers on site conditions and installing methods.	• **Site and Product Assessment Guides.** Assure the selection and application of the best equipment to match the site constraints and consumer capacity needs. • **Enhance Resiliency.** Leverage technology advances and interest in grid islanding, solar, and energy storage to enable operability during power outages.

[43] "M" as a superscript means "Manufacturer Input" (see Appendix page A-6: Manufacturer Feedback on Space and Water Heating).

Recommendation 3: Establish Data and Value | Federal Specification Program Alignment and Statewide Programs

PROGRAM CHANNEL	Solution Target: Efficiency Programs | Federal ENERGY STAR Program	
ROADBLOCKS	**RECOMMENDATIONS**	
Gaps in field data, and underestimation of demand response value in program models[M] Misaligned federal ENERGY STAR testing, connectivity criteria, validation, and labeling Lack of statewide program consistency to transform the market	• **Data:** Identify current data gaps and establish the field research to fill gaps. Data is needed on both the actual performance of gas and electric technology, and on operating costs under various rate scenarios based on field performance data. Standardize segmented data gathering across California for HPWH sales. • **Evaluate value of HPWH demand response**[M] Alter current program models to include the potential value of the grid-integrated controls from HPWHs.	• **Specification and Testing.** Update the ENERGY STAR specification and testing criteria to align with the NEEA Advanced Water Heating Specification, to support nationwide alignment and adoption. • **Participate in collaborative and universal program approaches.** Support the emerging efforts of the TECH program in 2021 and ongoing efforts of Advanced Water Heating Initiative (AWHI) for collective approaches and centralized places for market and industry to work together. • **Put money and financing up front.** Efficiency programs must invest to get the market primed for HPWH and make the cost difference negligible.

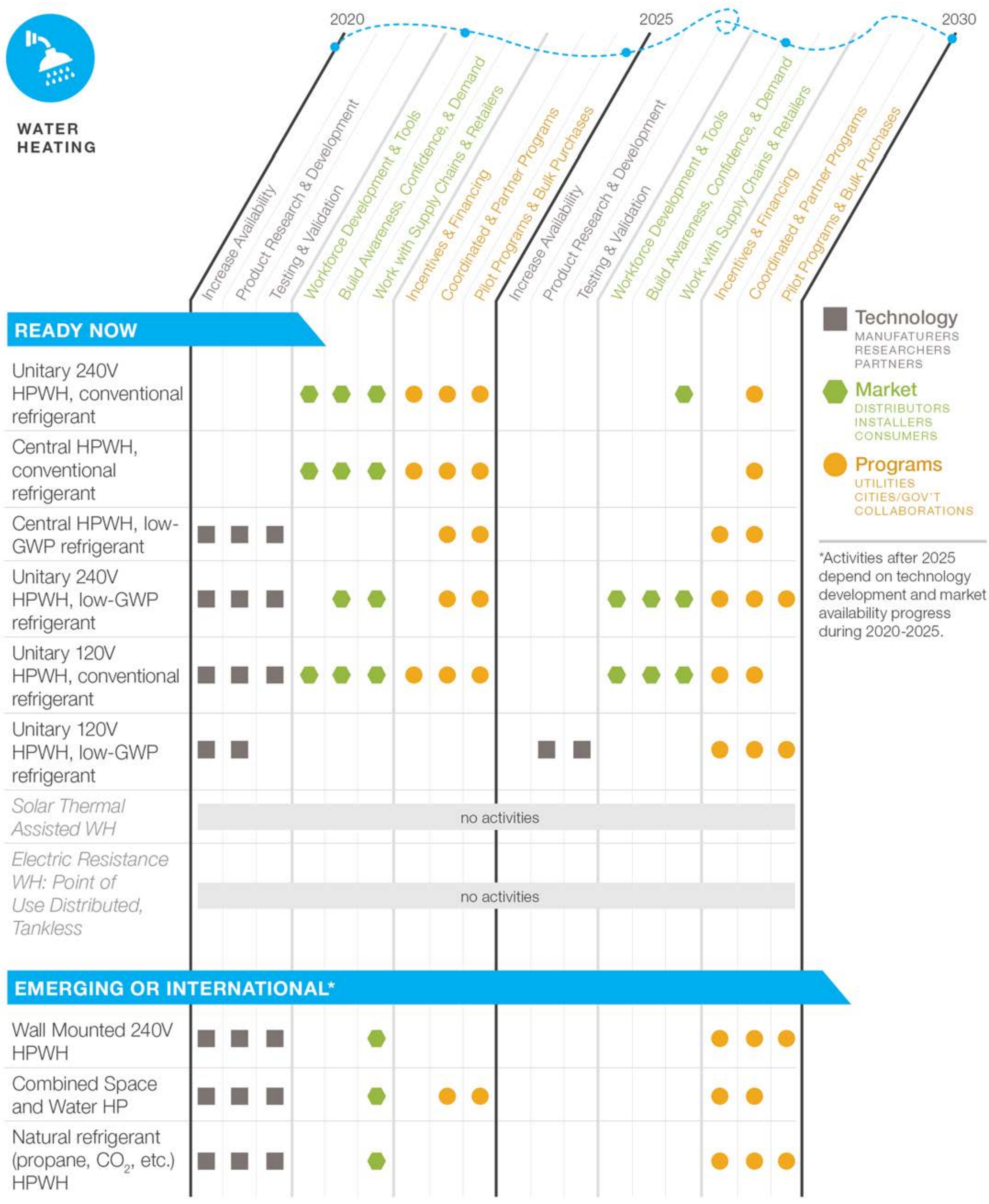
Recommendation 4: Title 24 Updates and National Standard for CTA-2045 Controls

POLICIES-STANDARDS CHANNEL	Solution Target: Federal Government	
ROADBLOCK	**RECOMMENDATIONS**	
Absence of full performance credit in T24 and lack of federal standard for CTA-2045 for water heater grid connectivity	• **Update T24 Compliance Software.** Integrate unitary as well as central HPWHs system modeling in order for designers to get full performance credit.	• **National Standard for CTA-2045 Controls.** Need for federal adoption of updated efficiency standards, testing procedures, and connectivity criteria, which aligns with universal CTA-2045 port for grid-integrated controls.

Water Heating Roadmap at a Glance

The Water Heating Electrification Roadmap at a Glance shows the activities for efficiency programs to advance these technologies over two time frames for the next 10 years in Figure 9. Within each time frame the activities occur in parallel to move the technologies toward much greater and more rapid adoption. The roadmap is organized by three of the Solution Channels introduced in Table 3. The fourth Solution Channel - Policy and Standards – are addressed above in Table 9 or covered across all technologies in the Collective Recommendations Summary in Table 20.

FIGURE 9: WATER HEATING ELECTRIFICATION ROADMAP AT A GLANCE



5. Cooking

5.1. Impact and Importance

After sanitation and shelter, cooking is the single-most important function of any building type whether commercial, institutional, or residential. Cooking represents a small proportion of total statewide residential energy and gas use: about 5% of energy and 7% of gas use.[44] Cooking with gas-fired appliances is associated with adverse indoor health effects in California homes, including elevated risk of asthma, cardiovascular disease, and cancer.[45] In the commercial sector, cooking represents a great opportunity for reducing energy use (buildings dedicated to commercial cooking use 5-7 times more energy per square foot than other types of commercial buildings) while cutting emissions and improving performance, indoor air quality, and workplace comfort.[46]

The relatively low cost of natural gas as a fuel source and the simple infrastructure requirements of gas equipment created an economic and technical advantage for gas cooking over the last 20 years that led to most residential and commercial kitchens operating with a hybrid of gas and electric appliances. In mixed-fuel commercial kitchens, most of the heavier duty cooking appliances—ranges, ovens, fryers, griddles, grills and broilers—are gas while the lighter duty equipment such as microwaves, toasters, hot food holding, panini grills, and steamers are all electric.[47]

Cooking is not only a core function of many built environments; it is also a difficult task and an act that elicits strong opinions and deep emotions. Residential and commercial cooking cannot be ignored in getting to carbon neutrality. However, unlike other more utilitarian applications such as space and water heating, replacing gas cooking appliances in buildings with electric

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[44] CEC 2015, References for Calculating Energy End-Use, Electricity Demand and GHG Emissions

[45] LBNL 2015, Results of the California Healthy Homes…: *Impact of Natural Gas Appliances on Air Pollutant Concentrations* found the use of natural gas cooking burners substantially increases the risk of elevated CO, NOX and NO2 consistent with prior studies.

[46] EPA ENERGYSTAR 2015, [Guide for Cafes, Restaurants and Kitchens]

[47] Frontier Energy Food Service Technology Center field-research and site-audit experience 1989 to 2020

equipment will require a much deeper education and outreach campaign. Efforts must target technology, economics, opinions, habit, and biases.

5.2. Technology Status

Currently available off-the-shelf electrification equipment can replace almost every piece of gas equipment in both residential and commercial kitchens, providing the same or better performance.[48] Even quick-serve restaurant chains recognize they can fully operate with either fuel (natural gas or electric) and typically have a dual-fuel prototype and an all-electric prototype for applications in different areas of the U.S. and international markets. All technologies for the electrification of residential and commercial cooking score high for technology readiness and high or moderate for product availability, as shown in Table 10.

Most of the gas appliances in a home or commercial kitchen, including ovens, fryers, griddles, and steamers, could be replaced with electric equivalents and the cooks would not notice the difference. However, the gas range top and gas wok range (widely used in restaurants), are two appliances that are deeply embraced by many cooks both due to tradition and habit as well as the strong visual-feedback component.

Fortunately, induction technology has the potential to replace traditional gas cooking appliances with equipment that is safer and better performing. Other electric cooking technologies based on electric resistance (ranges as well as appliances such as ovens, broilers, warmers, fryers, etc.) have been available for many years as alternatives to gas combustion in residential and commercial kitchens.

Table 10 summarizes the status of electric cooking technologies and applicable building types and vintages. Following the table is a more in-depth explanation of the status of each cooking technology.

The commercial full-sized induction wok range is widely available from a variety of manufacturers in China and Japan, but only one product is currently available in the U.S. and distribution is limited.

[48] The underfired open gas broiler is the one piece of commercial cooking equipment that does not currently have a true electric equivalent from a taste and cooking performance standpoint; however, there are electric chain broilers as well as other process changes that can facilitate the replacement of a gas broiler with electric equipment.

TABLE 10: STATUS OF ELECTRIFICATION COOKING TECHNOLOGIES

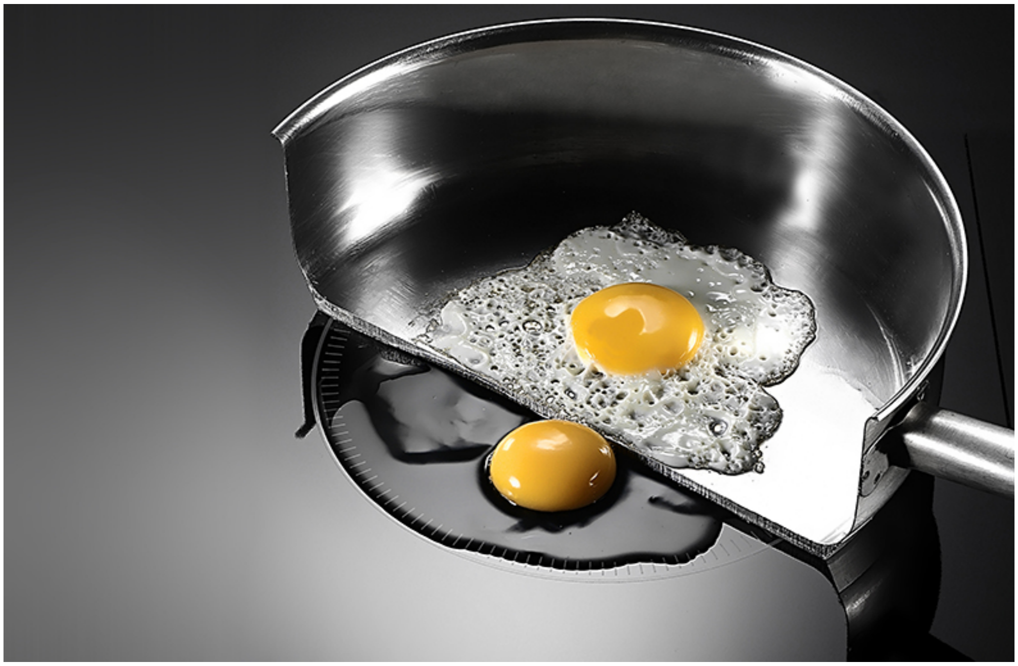
COOKING TECHNOLOGY	MATRIX SCORES					BUILDING TYPE APPLICABILITY		VINTAGE APPLICABILITY	
	Technology Readiness	Product Availability	Ease of Application	Awareness	Scale of GHG Reductions	Residential Kitchens	Commercial Kitchens	New Construction	Retrofit
Commercial Electric Cooking Equipment: Oven, Fryer, etc.	High	High	High	High	High		✔	High	Moderate
Commercial Induction Range	High	Moderate	Moderate	Moderate	High		✔	High	Moderate
Commercial Electric Cooking Equipment: Combination Oven	High	High	High	High	High		✔	High	Moderate
Residential Drop-In/Slide-in/Stand-Alone Induction Range	High	High	Moderate	Moderate	High	✔		High	Moderate
Commercial Induction Full Size Wok Range	High	Low	Moderate	Moderate	High		✔	High	Moderate
Commercial Electric Cooking Equipment: Chain Broiler	High	High	High	Moderate	High		✔	High	Moderate
Commercial Countertop Induction Hob/Wok	High	High	High	Moderate	Moderate		✔	High	High
Residential Countertop Induction Hob	High	High	High	Moderate	Moderate	✔		High	High
Commercial Electric Resistance Range	High	High	Moderate	High	Moderate		✔	High	Moderate
Residential Electric Resistance Range	High	High	Moderate	High	Moderate	✔		High	Moderate

High (3) Moderate (2) Low (1)

Introducing Induction

Residential and commercial induction cooktops are crucial gateways to the strategic electrification of homes and commercial food service operations. However, acceptance and implementation of this technology is moving slowly due to the lack of knowledge as to the performance and safety benefits of induction cooktops in comparison to natural gas or propane burner cooktops.

The perception that gas cooktops are superior in performance to electric cooktops has been prevalent for decades. Gas cooktops offer users the ability to adjust the heat to the pan based on a visual reference to the height of the flame. Many home cooks prefer the immediate response of flame adjustment to the delayed response associated with electric resistance coils.



Induction technology, however, has recently revolutionized electric cooktop cooking by changing the way heat is transferred to cookware. Using a magnetic field, induction cooktops excite the molecules in a pot or pan, generating heat for cooking. Induction technology results in a near complete energy transfer to the cooking vessel, making induction cooktops incredibly energy efficient relative to other modes of cooking. Other benefits of induction cooktops, in comparison to gas burners and traditional resistance heating elements, include faster cook times, more precise temperature control, and improved safety. When a pot or pan is removed from the stovetop on a gas burner, the heat needs to be manually turned off. But, when a pot or pan is removed from an induction stovetop, the magnetic coil immediately stops consuming energy, providing the most effective energy control of any range top design. And, since there is no open flame or hot element on an induction range top, there is no chance of a burn injury or igniting a stray potholder or paper towel that might be on or near the range top.

Induction range tops for both residential and commercial applications are now available to consumers in single-hob, multi-hob, and traditional “6-burner” configurations. (A hob is the generic term for a stovetop burner or element.) These induction ranges outperform the equivalent gas and electric resistance range tops in energy efficiency, heat up and boil tests, and simmer tests.[49, 50] Because induction ranges use electronic controls, they also provide a level of repeatable temperature control that is not available in gas range burners, which generally utilize continuous gas valve controls.

[49] D. Livchak, R. Hendick, R. Young, Frontier Energy prepared for SMUD, July 2019, *Residential Cooktop Performance and Energy Comparison Study* Report # 501318071-R0

[50] E. Ruan, Frontier Energy prepared for the California Energy Commission, January 2020, *Induction Cooktop Analysis*

Induction wok ranges have been available in Asia for many years and are utilized in a variety of forms, from the smaller countertop units up to the full-sized commercial induction wok ranges. The smaller commercial countertop induction woks have been available in the U.S. for more than 20 years but have very limited acceptance. The full-sized commercial induction wok ranges became available in the U.S. in late 2019 through one small distributor. Residential induction woks are available in the U.S.

Status Summary

Moving from a mixed-fuel residential kitchen to an all-electric kitchen is fully achievable in new construction today with available induction range tops and electric resistance ovens. Moving from a mixed-fuel commercial kitchen to an all-electric kitchen is also achievable with available technologies, including induction, but this transition requires an integrated system approach to the kitchen design that is not currently being employed in most cases.

All technologies for the electrification of residential and commercial cooking with the exception of one commercial item as noted in footnote 49, score high for ‘technology readiness’ and high or moderate for ‘product availability.’ Residential electric-resistance cooktops are technically ready and widely available but lack good applications, performance experience, and GHG impacts.

Induction Cooktops

- **Residential-grade induction range**. Suitable for single family, multifamily, non-restaurant commercial kitchens (e.g. office kitchens, break rooms). Fully technically ready with many product options, including drop-in ranges, slide-in ranges, and oven-range combination units. GHG reductions are high compared to other cooking technologies.
- **Restaurant-grade induction range**. Suitable for restaurant and institutional kitchens. Fully technically ready, somewhat common internationally and becoming more common in the U.S. Traditional flat-topped induction ranges are available in multiple configurations; only one full-sized induction wok range is available in the U.S. at this time. These higher kW appliances offer performance that matches standard commercial gas equipment and typically require 208V and higher power sources. GHG reductions are high compared to other cooking technologies.
- **Countertop induction hob/wok**. Suitable for all building types, including restaurants; products are typically either consumer-grade (residential, small commercial) or restaurant-grade. Restaurant applications are fully technically ready with many product options ranging from lower kW light-duty units to the higher kW full-production equipment. Can be considered a transitional electrification technology due to the impermanent status of plug-in countertop appliances. GHG reductions are moderate to high compared to other cooking technologies.

Electric Foodservice Appliances

- **Electric oven, fryer, griddle, chain broiler, food warmer, etc.** Suitable for restaurants and institutional kitchens. Fully technically ready, widely available, common. Typically well known by cooks and distributors alike. Some electric cooking appliances offer faster, more efficient heat delivery than gas equipment. Certain equipment may require retraining or minor cooking process changes due to variability in performance characteristics compared to similar gas equipment. Retrofits replacing gas equipment in existing kitchens will require rewiring and may require circuit-breaker/electrical-panel upgrades. GHG reductions are high compared to other cooking technologies.

Electric Resistance Cooktops

- **Radiant (resistance element) range**. Suitable for all building types, including residential and commercial buildings, and restaurants. Fully technically ready, widely available, very common in residential but not common in commercial applications. Poor responsiveness, long cool-down time after turning off heat, and other issues make this a technology of last resort. While the energy efficiency of resistance elements is lower than induction, the efficiency is high enough to produce moderate GHG reductions.

5.3. Roadblocks and Recommendations

Roadblocks

The end-user is one of the major roadblocks to a fully electrified kitchen. When comparing electric-resistance coil and glass top radiant cooktops with gas cooktops, consumer surveys indicate that people tend to prefer the familiarity and quick response time of gas burners. Some also like having the option to charbroil on the flame. Consumer awareness efforts, such as product demonstrations, promotions by celebrity chefs, and regional case studies, are ways to demystify the induction technology and contrast the high performance of induction with the poor performance of electric resistance elements.

Induction cooktops are faster and provide more temperature control than gas or radiant electric stoves. However, a significant barrier is that induction remains more expensive and requires ferrous pots and pans: potentially a separate investment. There is also less market familiarity, leading people to stick with the tried-and-true gas stove. The efficiency or utility industry may unintentionally introduce an additional roadblock by promoting electric-resistance coil and glass-top cooktops as an option to electrify homes. Because electric-resistance cooktops deliver such poor performance, they might turn consumers off of any electric cooking solutions.

Site conditions, primarily existing wiring limitations, are a potentially significant barrier to the electrification of other kitchen equipment such as ovens, griddles, broilers, and fryers.

Recommendations

Drop-in/slide-in induction and countertop induction options are recommended for low-production retrofit applications in both residential and commercial settings given the ease of installation. These are also less expensive compared to multi-hob induction stovetops and can build trust and familiarity with the product. As noted above, the solution to all-electric cooking is to leapfrog over available low- performance electric-resistance technologies and go straight to a high-performing induction.

Commercial electric cooking equipment (oven, fryer, etc.) scores highly in all parameters evaluated in the Matrix, indicating that it is a mature and effective technology, primed for immediate program support. Retrofit programs should consider site-specific design and installation barriers, in particular wiring limitations, and consider ways to drive higher participation by addressing these barriers.

Cooking Roadmap Summary

Table 11 and Table 12 summarize key roadblocks and recommendations to electrify kitchens and the near-term recommendations for actions. Because the products, solution channels, end-user priorities, and economic paradigms are so different, the tables are separate for residential (Table 11) and commercial (Table 12) cooking technologies.

TABLE 11: SUMMARY OF RESIDENTIAL COOKING ROADBLOCKS AND RECOMMENDATIONS[51]

Residential Induction Cooking Roadblocks and Recommendations for Energy Efficiency Programs: 2020-2025

Recommendation 1: Increase Awareness and Desire

MARKET CHANNEL	**Solution Target:** Consumers, Builders, Retailers
ROADBLOCKS	**RECOMMENDATIONS**
Low consumer awareness of induction cooking products Lack of consumer confidence in induction cooking products Wiring constraints in some existing building retrofit projects Higher product cost and alternative cookware required	• **Campaigns.** Multi-channel awareness and promotional campaigns featuring ease and indoor air quality and safety benefits of induction cooking, celebrity chefs focusing on superior control and speed. Demystify the cookware needed. • **Contractor Awareness.** For remodels contractors need to be advocates for the product and the steps to make the stovetop fit with existing infrastructure. For new construction, builders need to make these the default for new homes. • **Cost.** Significant education and outreach dollars will be needed to influence the consumer market in any real and appreciable way. Education programs will need to provide hands-on learning and will need to also cover bigger picture concerns such as "resiliency" and "life-cycle costing". Equipment buy downs will be necessary in the initial years (see Program Channels).

Recommendation 2: Create Retrofit Models

TECHNOLOGY CHANNEL	**Solution Target:** Manufacturers
ROADBLOCKS	**RECOMMENDATIONS**
Existing locations with gas ranges may lack the available power to serve the induction stove top	• **Retrofit Models.** Partner with manufacturer to increase the products applicable for gas retrofits, smaller homes, and affordable housing. Make induction models that are not just for the wealthy.

Recommendation 3: ENERGY STAR Testing and Label

PROGRAM CHANNEL	**Solution Target:** ENERGY STAR federal program
ROADBLOCKS	**RECOMMENDATIONS**
Lack of ENERGY STAR product labeling for induction ranges	• **Testing – Labeling.** ENERGY STAR does not label residential induction ranges or standalone hobs. A new label category should be created for residential induction cooktops. This helps consumer confidence and product consistency.

[51] Additional recommendations for addressing consumer demand, mid-stream supply chain, efficiency programs and policies common to all electrification technologies are in Table 15.

TABLE 12: SUMMARY OF COMMERCIAL COOKING ROADBLOCKS AND RECOMMENDATIONS[52]

Commercial Cooking Electrification Technologies – Roadblocks and Recommendations for Energy Efficiency Programs: 2020-2025

Recommendation 1: Increase Awareness and Confidence

MARKET CHANNEL	**Solution Target:** Commercial and Institutional Users, Building Owners, Distributors, Builders, Designers
ROADBLOCKS	**RECOMMENDATIONS**
Low consumer awareness of induction cooking products Lack of consumer confidence in induction cooking products Higher product cost and alternative cookware required Existing electrical capacity and plugs limit potential for 1:1 retrofits of commercial kitchen equipment (ovens, fryers, broilers, etc.)	• **Campaigns.** Multi-channel awareness and promotional campaigns featuring celebrity chefs focusing on superior control, speed, and safety of induction cooking as well as demonstrations, online classes, case studies, and field demonstration projects. • **Economics.** Utilization of research on annual and life-cycle costs to establish credible economic information. • **Materials.** Development of clear and compelling collateral materials for presentation to chefs and restaurant owners demonstrating the benefits of induction cooking. • **Design Models.** Create various commercial kitchen templates and design layouts into existing modeling tools showing integration between all-electric products, power requirements and specs for designers. • **Advocacy.** Advocacy for codes and policies that further the ability to make the case for this technology due to pending regulatory requirements. Allows messaging to 'get ahead of the requirement and/or avoid the penalty/cost.' • **Cost.** Program incentives will be necessary in the initial years (see Program Channel). Expand rebate value for gas-to-electric kitchen conversions to help offset costs of rewiring, upgrading panel, and potentially upgrading service.

Recommendation 2: ENERGY STAR Label and Incentives

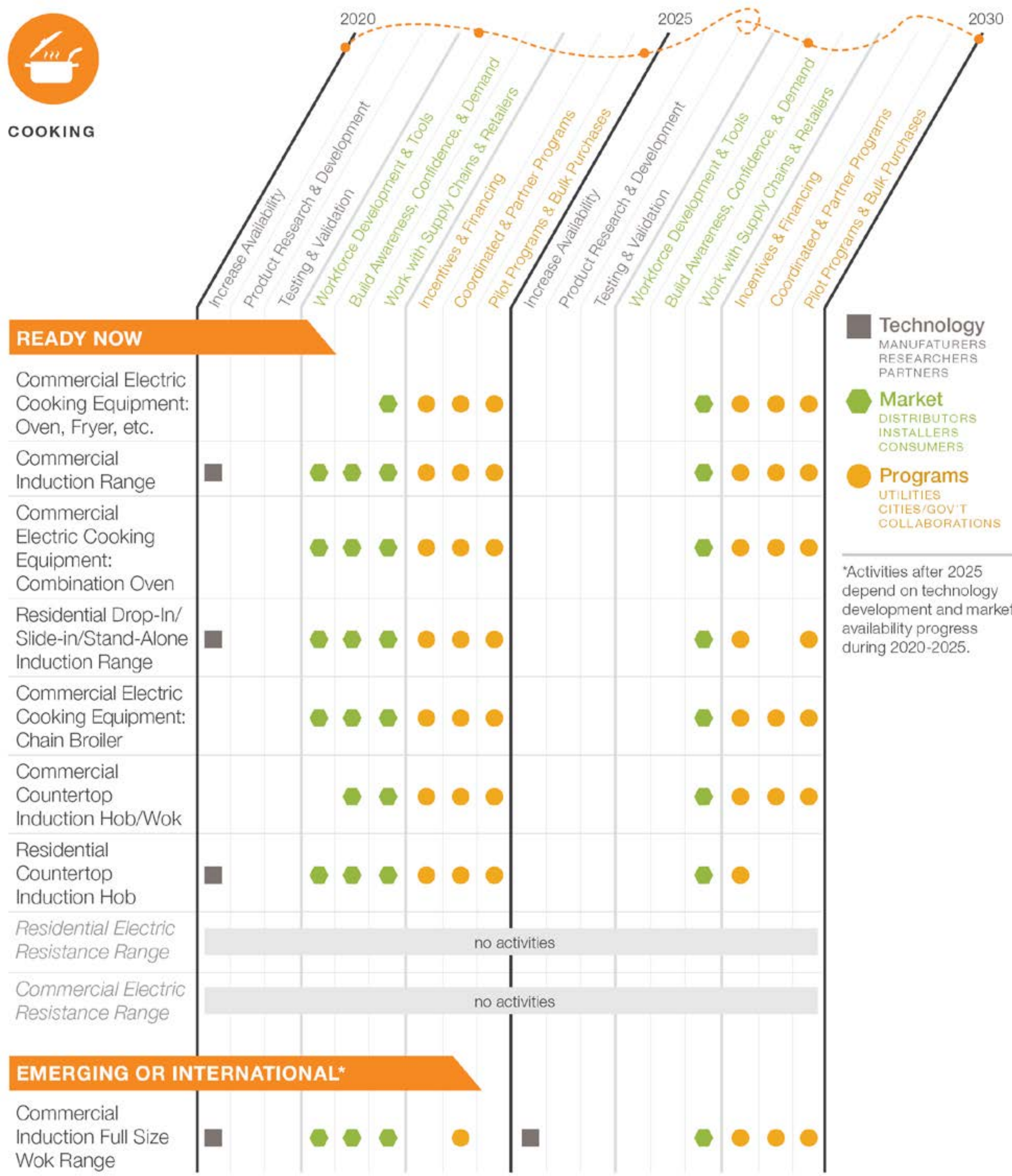
PROGRAM CHANNEL	**Solution Target:** ENERGY STAR federal program
ROADBLOCKS	**RECOMMENDATIONS**
Lack of ENERGY STAR product labeling for commercial electric equipment High price Lack of incentives for ENERGY STAR products	• **Testing – Labeling.** ENERGY STAR does not label commercial induction ranges or hobs and only labels certain other commercial kitchen equipment. Induction ranges, induction wok ranges, standalone induction hobs, chain broilers, and combination ovens could be added to the ENERGY STAR program.

[52] Additional recommendations for addressing consumer demand, mid-stream supply chain, efficiency programs and policies common to all electrification technologies are in Table 15.

Cooking Roadmap at a Glance

The Cooking Electrification Roadmap at a Glance shows the activities for efficiency programs to advance these technologies over two time frames for the next 10 years in Figure 10. Within each time frame the activities occur in parallel to move the technologies toward much greater and more rapid adoption. The roadmap is organized by three of the Solution Channels introduced in Table 3. The fourth Solution Channel - Policy and Standards – is covered in the Collective Recommendations Summary in Table 20.

FIGURE 10: COOKING ELECTRIFICATION ROADMAP AT A GLANCE



6. Clothes Drying and Laundry

6.1. Impact and Importance

Clothes drying and laundry represent a small proportion of residential gas use in California (approximately 4%).[53] Yet in some commercial and multifamily buildings, laundry systems can be the greatest energy hog. Large clothes dryers use huge amounts of energy to remove water from heavy, wet clothing—a process that represents up to 81% of the total energy used to complete an average load of laundry.[54]

For this study, the baseline is the standard gas dryer. However, many buildings have already installed electric resistance dryers as the standard. Of the electric clothes drying technologies analyzed, the electric resistance dryer is the least efficient, representing a big opportunity for energy and emission reduction efforts. The 30-amp resistance element puts stress on the electrical grid, as it runs far longer than most other appliances, as well as taking up precious capacity in lower amp panels.

6.2. Technology Status

For this study, we looked at four electric clothes dryer types and one integrated laundry system, as shown in the table below. All but one of the technologies included in this study are technically ready but not widely adopted in the U.S. The focus is on clothes drying rather than washing because gas use in clothes washing is associated with water heating, which is covered elsewhere in this study. The exception is the institutional/industrial laundry sector: the system considered entirely displaces the need for laundry-dedicated water heating.

Table 13 summarizes the status of electric clothes drying and laundry technologies and applicable building types and vintages. Following the table is a more in-depth explanation of the status of each clothes drying and laundry technology.

[53] CEC 2015, References for Calculating Energy End-Use, Electricity Demand and GHG Emissions *(enter title to access pdf – not linkable)*

[54] Redwood Energy 2019, Electric Multifamily Guide

TABLE 13: STATUS OF ELECTRIFICATION CLOTHES DRYING AND LAUNDRY TECHNOLOGIES

CLOTHES DRYING AND LAUNDRY TECHNOLOGY	MATRIX SCORES					BUILDING TYPE APPLICABILITY				VINTAGE APPLICABILITY	
	Technology Readiness	Product Availability	Ease of Application	Awareness	Scale of GHG Reductions	Single Family	Multifamily	Institutional	Laundry	New Construction	Retrofit
Heat Pump Dryer	●	●	◒	◒	●	✓	✓			●	●
Combo Washer-Dryer (Condenser Dryer)	●	●	◒	◒	◒	✓	✓			●	●
CO_2 Laundry System	●	●	◒	○	◒			✓	✓	●	●
Electric Resistance Dryer	●	●	●	●	○	✓	✓	✓	✓	●	◒
Ultrasonic Dryer	○	○	●	●	●	✓	✓			●	●

● High (3) ◒ Moderate (2) ○ Low (1)

Status Summary

Although clothes drying comprises a more modest energy use compared with space and water heating, switching to more efficient technologies is an important strategy for achieving California's carbon neutrality goal. The electric resistance dryer, which requires both 240V electrical connections and venting, scores lower for 'ease of application' for existing buildings and has lower GHG reductions compared to heat pump dryers and combo washer/dryers.

Clothes Dryers

- **Heat Pump Dryers.** Suitable for single family, multifamily, and small commercial buildings. Fully technically ready but still improving, newly available in the U.S. Heat pump dryers are somewhat more efficient than condensing dryers, and much more efficient than resistance dryers (about 60% less energy use than a standard resistance dryer and 30-40% less electricity than efficient ENERGY STAR-rated electric resistance clothes dryers[55]). Like resistance dryers, they are 240V and require no ductwork. However, currently available models (mainly imported from Europe) are smaller than U.S. customer expectations for most residential units, and much too small for institutional or industrial applications.
- **Combo Washer/Dryer (typically uses a Condenser Dryer).** Suitable for single family, multifamily, and small commercial buildings. Fully technically ready and available yet uncommon in the U.S. These units typically combine washing and drying functions in the same appliance. They are popular worldwide due to their space- and work-savings. They also use 120V and can be plugged into any outlet without retrofit. There is no ductwork required. The great majority of today's combo washer/dryer units include condenser dryers. Combo units with heat pump dryers are also available but rare. Condensing dryers use a compressor but do not have active heat recovery from the condenser, instead letting vapor condense passively using a water-cooled heat exchanger. The warm water is then discarded down the drain. These dryers use roughly half the energy of resistance dryers, while water usage is somewhat higher due to the use of domestic cold water to drive condensation in the heat exchanger.
  Today's condenser dryer models (mainly imported from Europe) are smaller than U.S. customer expectations for residential units, and too small for industrial applications. One model is large enough (4.5 cubic feet) to match many Americans' habits. Smaller units (2-3 cubic feet) are appropriately sized for small rental retrofits.
- **Standard Electric Resistance Dryers.** Suitable for all building types. Fully technically ready, widely available since the 1950s, very common. Requires venting to the outdoors and 240V service. ENERGY STAR electric resistance dryers, which use humidity sensors to prevent over-drying, deliver 20% energy savings over standard electric resistance dryers

[55] CPUC 2018, *Energy Efficiency Potential and Goals Study for 2018 and Beyond* and Martin, E. et. al. ACEEE Summer Study 2016 *Measured Performance of Heat Pump Clothes Dryers*

due to shorter run times.[56] These dryers generally became available in the last decade. Relative to other electric clothes drying technologies, GHG savings impacts are low.

- **Ultrasonic Dryers.** Suitable for all building types. Early stage (laboratory) research and development.[57] Technology relies on using piezoelectric transducers–a device that converts electricity to vibration—to evaporate water out of clothes. Once this technology is developed and available on the market, it has the potential for high GHG savings. However, this may be 10+ years in the future.

Integrated Laundry System

- **CO_2 Laundry System.** Suitable for industrial and institutional facilities. Technologically ready but still emerging (recently commercially available from one manufacturer). Liquid CO_2 displaces water, eliminating the need for water heating (typically supplied by a dedicated gas boiler) altogether. These large-scale systems are optimized for dry cleaners, industrial, and institutional laundry use; in these applications the energy and GHG reductions are high compared to other electrification measures.

6.3. Roadblocks and Recommendations

Roadblocks

The main roadblocks for clothes drying technology are research and development of larger commercial-grade systems, and a need for further growth in the U.S. market. U.S. consumer expectations for large-capacity clothes dryers have impeded market growth for comparatively smaller combination condensing clothes washer/dryers and heat pump clothes dryers, both of which are more common in Europe. Typically, U.S. clothes dryers are 7 cubic feet while condensing dryers range from 2-4 cubic feet.

From an application perspective, the main roadblock for clothes drying technologies is in retrofit scenarios where a new electric resistance dryer is replacing a gas dryer: it will need a 240V electrical outlet.

Recommendations

For residential buildings, heat pump clothes dryers and combo washer/dryers (condensing dryers) are the recommended technologies. Neither require venting, which increases installation flexibility. The great majority of combo washer/dryers use condenser dryers, but heat pump dryers are more efficient, and this technology option should be expanded in the market.

Efficiency programs should focus efforts on growing the heat pump and combo washer/dryer (condensing dryer) market in the U.S. using the suggestions in Table 14.

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[56] ENERGY STAR Clothes Dryers

[57] DOE and GE product development

The electric resistance dryer is widely available and is the only electric dryer technically ready for commercial applications. While it is less efficient and produces more GHG emissions than both heat pump dryers and combo washer/dryers, when compared to gas systems, it has lower GHG emissions. Therefore, it should be prioritized over gas systems for now.

Looking ahead, ultrasonic dryers have high potential for commercial applications due to their high GHG reductions and applicability and as such are a prime candidate for a pilot program. Heat pump dryers and condensing dryers should continue to be developed for wider application to make them suitable for all building types. At the industrial/institutional scale, CO_2 laundry systems represent a promising and under-adopted technology that merits programmatic support.

Clothes Drying and Laundry Roadmap Summary

Table 14 summarizes key roadblocks and recommendations to electrify laundry and clothes drying and the near term recommendations for actions.

TABLE 14: SUMMARY OF CLOTHES DRYING AND LAUNDRY ROADBLOCKS AND RECOMMENDATIONS[58]

Clothes Drying and Laundry Electrification Technologies – Roadblocks and Recommendations for Energy Efficiency Programs: 2020-2025

Recommendation 1: Increase US Sized Equipment and Availability

TECHNOLOGY CHANNEL	**Solution Target:** Manufacturers	
ROADBLOCKS	**RECOMMENDATIONS**	
Current condenser and heat pump dryers are smaller than typical in the US market Drying cycles are relatively long	• **Make Larger Products.** Encourage manufacturers to offer larger-capacity clothes dryers in line with typical US consumer expectations.	• **Heat Pump Combo Units**. Encourage manufacturers to produce washer/dryer combo units with heat pump dryers.

[58] See Table 22 for additional recommendations for addressing consumer demand, midstream supply chain, efficiency programs, and policies common to all electrification technologies.

Recommendation 2: Build Demand

MARKET CHANNEL	Solution Target: Consumers, Building Owners, Distributors, Builders, Designers, Retailers	
ROADBLOCKS	**RECOMMENDATIONS**	
Low consumer awareness of alternatives to gas and electric resistance dryers Consumer impatience with longer clothes drying cycle times Higher product cost	• **Campaigns.** Multi-channel awareness and promotional campaigns to focus on environmental, economic, and clothing protection (from lower temperature operation) benefits of heat pump and condenser clothes dryers and "set-it-and-forget-it" convenience of washer/dryer combo units. • **Economics.** Document superior economics of high-efficiency electric clothes drying technology.	• **Advocacy.** Advocacy for codes and standards that further the ability to make the case for this technology due to pending regulatory requirements. Allows messaging to "get ahead of the requirement and/or avoid the penalty/cost." • **Cost.** Buy downs will be necessary in the initial years (see Program Channel). • **Get new Products into the Supply Chain.** Most consumers have never seen a combo unit. Work with retailers as products come to market to promote.

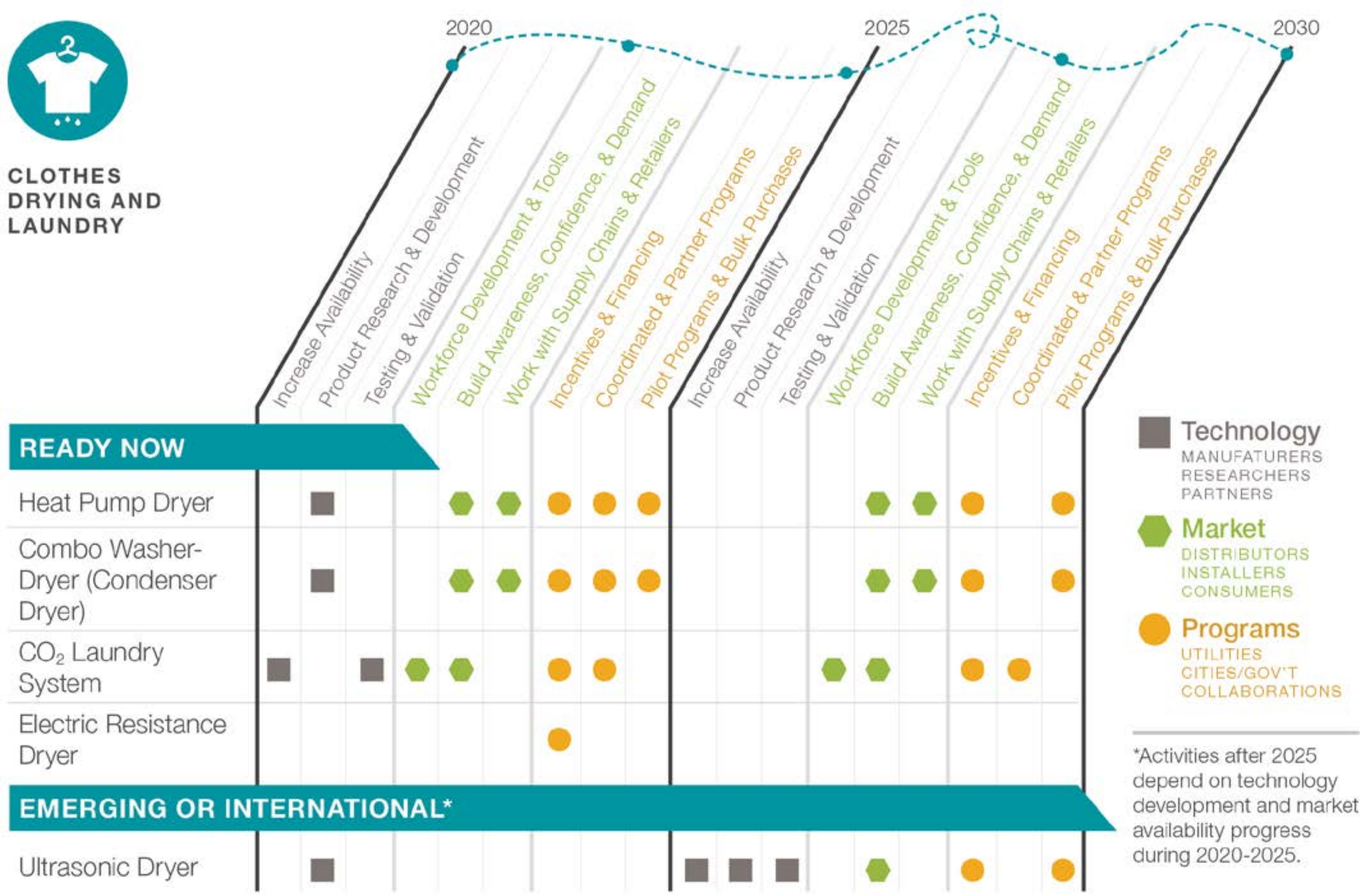
Recommendation 3: ENERGY STAR Label for Condenser Dryers

PROGRAM CHANNEL	Solution Target: ENERGY STAR federal program, efficiency prorgrams, mid-stream supplier and at retailers	
ROADBLOCKS	**RECOMMENDATIONS**	
Lack of ENERGY STAR product labeling for condenser dryers	• **Testing – Labeling.** ENERGY STAR labels electric resistance dryers with moisture sensors and heat pump dryers, but not condenser dryers. These could be added as "washer/dryers" or in a standalone manner but because most units sold are combination washer/dryers this may be a better option.	• **Product Incentives.** Reduce initial price at the supply chain and retailer to grow adoption and awareness.

Clothes Drying and Laundry Roadmap at a Glance

The Clothes Drying and Laundry Electrification Roadmap at a Glance shows the activities for efficiency programs to advance these technologies over two time frames for the next 10 years in Figure 11. Within each time frame the activities occur in parallel to move the technologies toward much greater and more rapid adoption. The roadmap is organized by three of the Solution Channels introduced in Table 3. The fourth Solution Channel—Policy and Standards—is covered across all technologies in the Collective Recommendations Summary in Table 20.

FIGURE 11: CLOTHES DRYING AND LAUNDRY ELECTRIFICATION ROADMAP AT A GLANCE



7. Refrigerant and Grid Factors

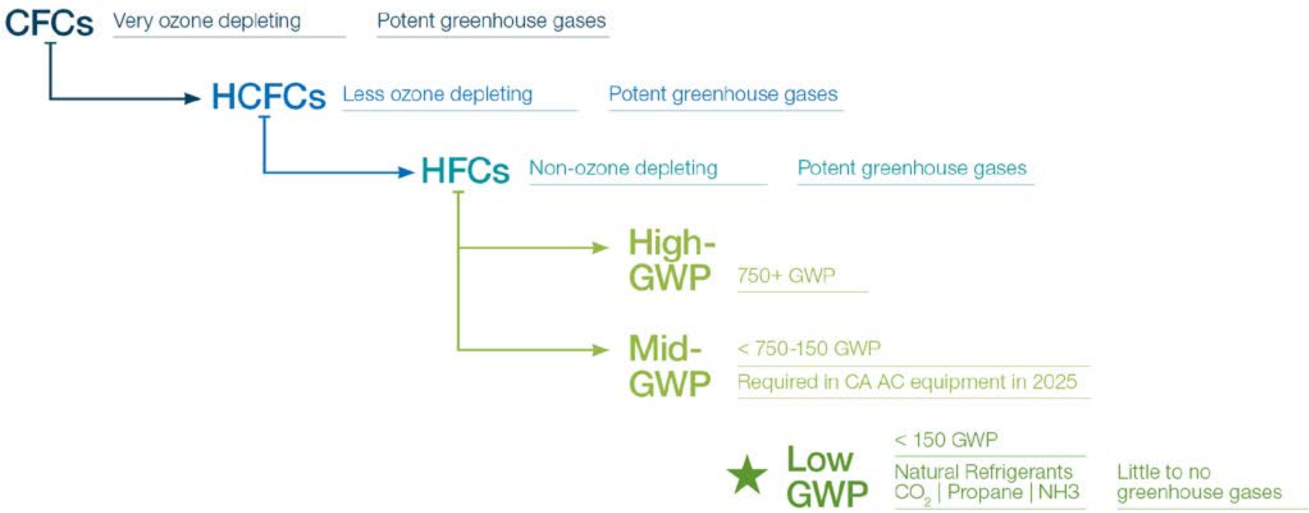
The opportunity and benefits of many of the electrification technologies—predominantly the heat pump technologies—are affected by changes in refrigerant types and by the integration of grid-connected controls. This section provides an overview of these factors.

7.1. Refrigerants: A Major Player in Emissions Reductions

Heat pump technologies rely on refrigerants to transfer heat. Refrigerants, with the exception of natural refrigerants, are very potent greenhouse gases (GHG) and are actively regulated (see Figure 12). Hydrofluorocarbons (HFCs), today's "third-generation" refrigerants, are an improvement over first- and second-generation chlorofluorocarbon (CFC) refrigerants in reducing the ozone depletion. Yet there is still concern about managing leaks and the disposal of HFCs.

FIGURE 12: EVOLUTION OF REFRIGERANTS TO LOW GLOBAL WARMING POTENTIAL

Source: Higgins, C. NBI Based on CARB



Refrigerants are measured by their global warming potential (GWP). While today's HFC refrigerants have come down from historic levels of over 4,000 GWP to near or below 2,000 GWP, they remain in the category of 'high-GWP' because of their significant GHG emissions. Many available and emerging technologies have significantly lower GWP as seen in Table 15. Refrigerants 150-750 are considered 'mid-GWP' while those less than 150 GWP have 'low-GWP'. Natural refrigerants such as propane, CO_2 and ammonia (NH3), fall into the low-GWP category.

TABLE 15: COMMON REFRIGERANTS AND ASSOCIATED GLOBAL WARMING POTENTIAL

Global Warming Potential Category	Refrigerant	Global Warming Potential	Equipment Use
High-GWP (750+)	HFC-410a	2088	US Air Conditioners (many units required to go to < 750 GWP in California in 2025)
	HFC-134a	1430	Heat Pump Water Heaters
Mid-GWP (150-750)	HFC-32	675	International AC – emerging in US
Low-GWP | Natural Refrigerants (<150)	R-744 CO_2	1	Present in some HPWHs products and emerging in other heat pumps
	R-1234-yf	4	Emerging
	R-290 Propane R-717 Ammonia	4	Not common due to safety regulations

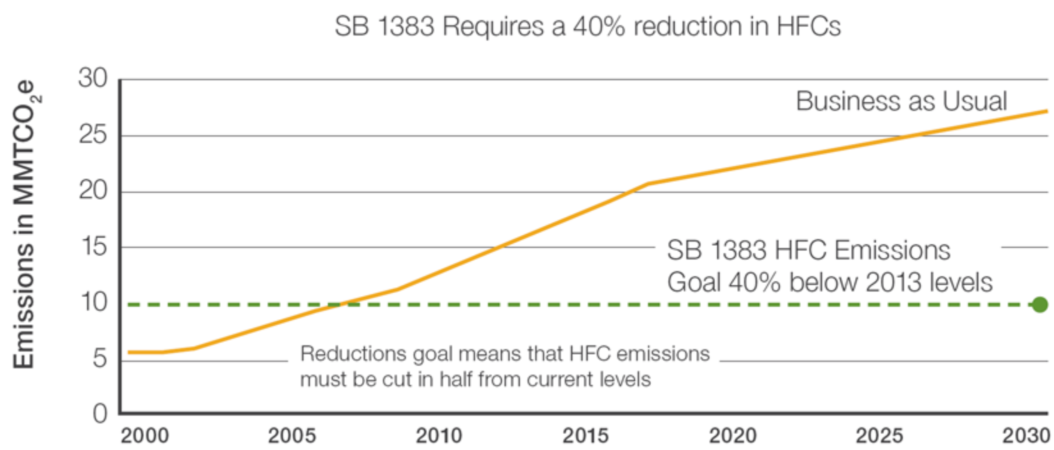
Leakage of high-GWP refrigerants remains a concern, particularly at end-of-life disposal. The U.S. Environmental Protection Agency is planning a national phase-out of HCFCs by 2030. In December 2020, the US passed legislation that brings the nation in line with the Kigali amendment to the Montreal Protocol: to cut the production and import of HFCs by 85% by 2035 and giving EPA the power to regulate manufacturers and importers to do so. Also, in December 2020, the California Air Resources Board adopted a ban on the use of high-GWP refrigerants, which impacts most new and replacement stationary heating and air-conditioning equipment starting January 1, 2025.

Senate Bill (SB) 1383 sets a target of 40% reduction in HFCs, which supports California's 2045 carbon neutrality goal.[59] Figure 13 shows that without reductions HFC emissions are on a trajectory to greatly exceed the California requirement for 40% reductions by 2030.

[59] CARB 2018, Hydrofluorocarbon (HFC) Prohibitions in California

FIGURE 13: HRC REFRIGERANT EMISSIONS TREND IN CALIFORNIA

Source: CARB



Emissions from stationary air-conditioning equipment alone were responsible for over a third of California's HFC-related emissions in 2018. Increased temperatures in California as well as wildfires are driving increased use of air conditioning throughout the state. To meet SB 1383's 40% reduction in HFC emissions target, the industry must rapidly shift to mid- and to low-GWP refrigerants.

Figure 14 provides examples of air conditioners (AC) and heat pump (HP) equipment that is required to be mid-GWP in California starting in 2025 (2023 for room equipment and dehumidifiers).[60] This trend follows similar requirements in Europe and Asia. These laws will help advance low-GWP product development, availability, and lower prices.

FIGURE 14: EXAMPLES OF EQUIPMENT REQUIRED TO BE <750 GWP BY 2025 IN CALIFORNIA

Source: CARB

AC/HP Equipment used in Residences	AC/HP Equipment used in Commercial/Non-residential Buildings	AC/HP Room Equipment + Dehumidifiers

What about heat pumps? Heat pumps with today's conventional HFC reduce emissions by 60-80% for space and water heating respectively compared to standard gas systems, as shown in Figure 5 and Figure 8 in the Space and Water Heating sections respectively. While they rely on refrigerants, heat pump product designs are improving to address refrigerant loss. For example,

[60] CARB December 2020, Proposed Amendments to HFC Regulations

unitary and central HPWHs have factory-sealed refrigerant systems, so leakage during installation and use is drastically reduced. Some split-system heat pumps are designed to be "plug and play" where the installer simply connects couplers between the indoor unit, the refrigerant line, and the outdoor unit in a pre-charged system. As heat pump technology evolves to reduce refrigerant GWPs and leakage, they will provide an increasingly clear pathway to near-zero emissions buildings.[61]

As electrification accelerates in both new and existing buildings, it's important to consider the GHG emissions of baseline technologies compared to replacements.

Mid and low-GWP products, with a few exceptions, remain rare in U.S. heat pump equipment. Manufacturers and the California efficiency industry are collaborating on the production and market paths for new refrigerant products. The few products that are available with mid-to-low-GWP refrigerants are gaining early attention and market presence to meet the pending requirements and align with program and policy decarbonization goals. But low-GWP refrigerants must be prioritized over the next 10 years in order to meet California's 2045 carbon neutrality goal.

Despite these challenges, moving from gas technology to heat pumps containing HFC refrigerants remains a smart and critical step toward building electrification and decarbonization. As more mid-to-low-GWP products become available, heat pumps will become even more attractive.

7.2. Building-Grid Integration and Controls: A Decarbonization Enabler

The decarbonization of the electricity sector or shifting away from fossil fuel-burning power plants and toward renewable energy, is a critical component of meeting California's 2045 carbon neutrality goal. Using renewable energy to power buildings is already an effective way to reduce carbon emissions in the state of California, where renewables reached more than 32% of energy production in 2018. By 2045, 100% of the state's retail electricity sales are targeted to be met by renewables.[62]

Achieving this goal will require far more wind and solar to be added to the California electric grid. Wind and solar are variable resources, generating electricity only when the wind is blowing or the sun is shining, creating big technical challenges for grid operators. Already, the difference in California's grid carbon intensity varies dramatically throughout the year, from well over 12,000 $mTCO_2$/hr[63] at peak times all the way down to less than 1,000 $mTCO_2$/hr in some hours.

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[61] Delforge, P. NRDC, September 2020, correspondence

[62] www.energy.ca.gov/sb100

[63] Metric tons of CO_2 per hour | CAISO Outlook: Emissions

The grid is fundamentally built to serve buildings, as 75% of all U.S. electricity, and 80% during peak times, is consumed in buildings. The relationship between buildings and the grid is a critical part of the picture as we seek to build carbon-neutral economies. When and how buildings use electricity is of primary importance to achieving grid decarbonization goals. Following are some ways buildings can support the grid and lower the GHG emissions resulting from their electricity use.

- Take a whole-building integrated approach to design that maximizes passive systems, load reduction, and energy efficiency.
  - » Example: Measures like advanced insulation and air sealing reduce energy demand—including during high-carbon and peak hours.
- Deploy time-of-use energy-efficiency strategies that save energy during times of higher grid peak demand and higher carbon.
  - » Example: West-facing shading helps manage afternoon solar heat gain, which reduces cooling loads during high-carbon, expensive summer afternoons and evening peak times. Added thermal mass can help buildings spread cooling and heating loads over longer periods, allowing efficient equipment like heat pumps to serve loads during non-peak hours.
- Maximize demand flexibility through smart, grid-connected controls, equipment, and devices.
  - » Example: The CTA-2045 and JA13 specifications help ensure that HPWHs are capable of two-way grid communication and can act on signals from the grid to adjust operations.
- Optimize the deployment of distributed energy resources such as solar photovoltaics (PV), batteries, and electric vehicles.
  - » Example: Orienting solar panels to the west instead of the south better aligns their energy production hours with grid demand (more evening production). Smart PV inverters help grid operators integrate more PV onto the grid.
- The GridOptimal Buildings Initiative is already making progress in this area.[64] This collaborative, multi-stakeholder effort is driving better building-grid integration through the development and deployment of new building-grid integration metrics. These metrics form the basis for the updated LEED v4.1 Grid Harmonization credit, worth up to three points. Utility program criteria, structurally aligned with the LEED credit framework, are under development.

[64] https://newbuildings.org/gridoptimal/

8. Residential Packages and Impacts

Electrifying homes is a natural starting place for building electrification programs. In new construction this is an easy lift technically and results in lifecycle occupant benefits in almost all scenarios. For single-family and low-rise multifamily the variety of technologies and the building type variations are less than in the commercial sector, which eases the selection and application learning curve. Residential electrification can also serve to inform small and medium commercial sector designers and contractors. All-electric developments already exist in parts of California in both market-rate and affordable housing projects, where developers recognized that *not* installing gas infrastructure freed up capital for higher efficiency strategies and appliances.

To provide a lens into a whole-building electrification strategy and estimate typical energy and emission savings over an all-gas-fired baseline, the research team created packages of technologies appropriate to each residential building type. The packages were developed to perform a 3-tiered analysis of energy and emission savings for different combinations. The packages are not in all cases the ideal recommendation, as that is dependent on site and economic considerations. The packages for the two residential building types—single-family homes and multifamily units—include the following:

- Baseline gas-powered baseline package,
- ‘Better’ all-electric package with moderate-efficiency equipment, representing immediately available and mature technologies, and
- ‘Best’ all-electric package with high-efficiency equipment, representing a max-tech combination.

Recommended packages are the same for new construction and existing buildings with minor variations in applicability. These packages were modeled by EPRI for residential buildings (single family and multifamily) using the

Building Energy Optimization Tool (BEopt).[65] Nonresidential building packages were not modeled as part of this project due to time and capacity constraints.

This section describes the all-electric packages for single-family homes and multifamily buildings. The energy and GHG reductions of moving from an all-gas baseline to the following all-electric packages are shown in the following three California climate zones:

- Climate Zone 3 (temperate coastal areas around San Francisco)
- Climate Zone 9 (Southern California inland valley climate around Los Angeles)
- Climate Zone 12 (Northern California Central Valley around Sacramento)

The team modeled other California climate zones as well. Results are mostly consistent across climate zone in terms of percentage reductions, but the higher baselines in certain climates, such as Climate Zone 16 (NE California and high Sierras), result in substantially higher energy and emission impacts per home.

8.1. Single-Family Homes

In single-family homes, both space heating and water heating account for a high proportion of total home energy use and GHG emissions. Many California utilities are advancing electrification of this sector through programs such as:

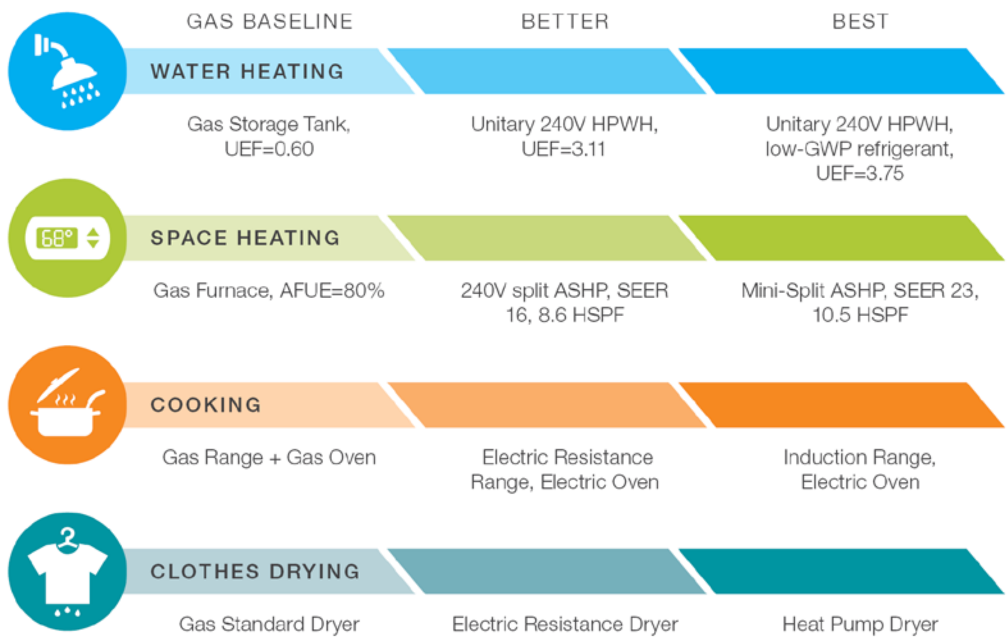
- Pacific Gas & Electric's All-Electric Climate Smart Homes webinar series
- Sacramento Municipal Utility District's All-Electric Smart Homes program
- Southern California Edison's Benefits of an Electric Home program
- Los Angeles Department of Water & Power's partnership in the E3 "Residential Building Electrification Study" to help designers, builders and owners understand the benefits (see footnote 62).

The gas baseline, all-electric 'better,' and all-electric 'best' packages are described in Figure 15 below.[66]

[65] U.S. Department of Energy BEopt

[66] Electric Resistance range was modeled because it has 'Better' emission reductions compared to a gas range. But it is ineffective at cooking compared to gas and to induction. We do not recommend introducing an inferior product to homeowners that may result in a return to gas technologies for cooking but rather advocate for the high satisfaction of induction stove tops.

FIGURE 15: SINGLE FAMILY TECHNOLOGY PACKAGE FOR ENERGY AND EMISSION ANALYSIS MODELING



Electrifying these systems yields high savings in terms of energy and GHG emissions, as shown in the charts below. In all cases modeled, the 'better' all-electric package cuts baseline energy use roughly in half and cuts emissions by more than 75%, while the 'best' case cuts energy use by nearly 2/3 and emissions more than 80% as seen in Table 16.[67]

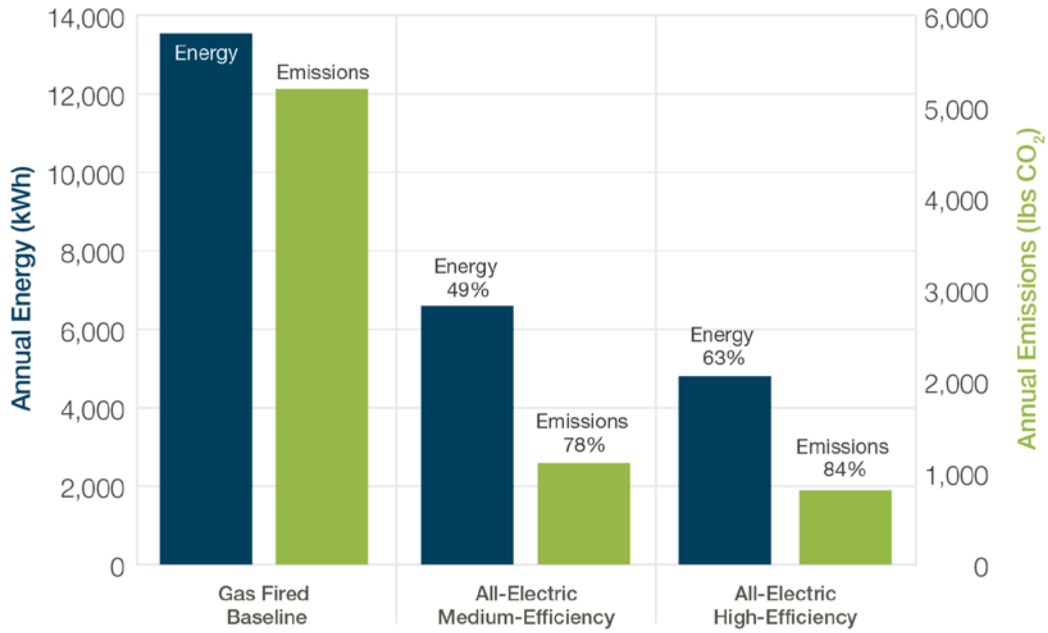
TABLE 16: SINGLE FAMILY ENERGY AND EMISSION SAVINGS FOR ELECTRIFICATION OF THE FOUR END-USES

		Single Family – Gas Base vs Better Package				Single Family – Gas Base vs Best Package			
		Site Energy Savings		Emissions Savings		Site Energy Savings		Emissions Savings	
City	**CA CZ**	**kWh**	**%**	**Lbs CO_2**	**%**	**kWh**	**%**	**Lbs CO_2**	**%**
San Francisco	3	6,852	49%	4,249	78%	8,711	63%	4,553	84%
Los Angeles	9	4,049	43%	2,804	76%	5,895	62%	3,103	84%
Sacramento	12	7,931	51%	4,775	79%	9,981	65%	5,124	85%
Lake Tahoe	16	18,357	65%	9,402	85%	18,674	66%	9,469	85%

In the San Francisco bay area, the cooler winter climate drives higher space heating loads, but the temperate climate is perfectly suited to heat pumps, resulting in high energy savings and GHG emissions reductions for 'better' and 'best' all-electric packages as shown in Figure 16.

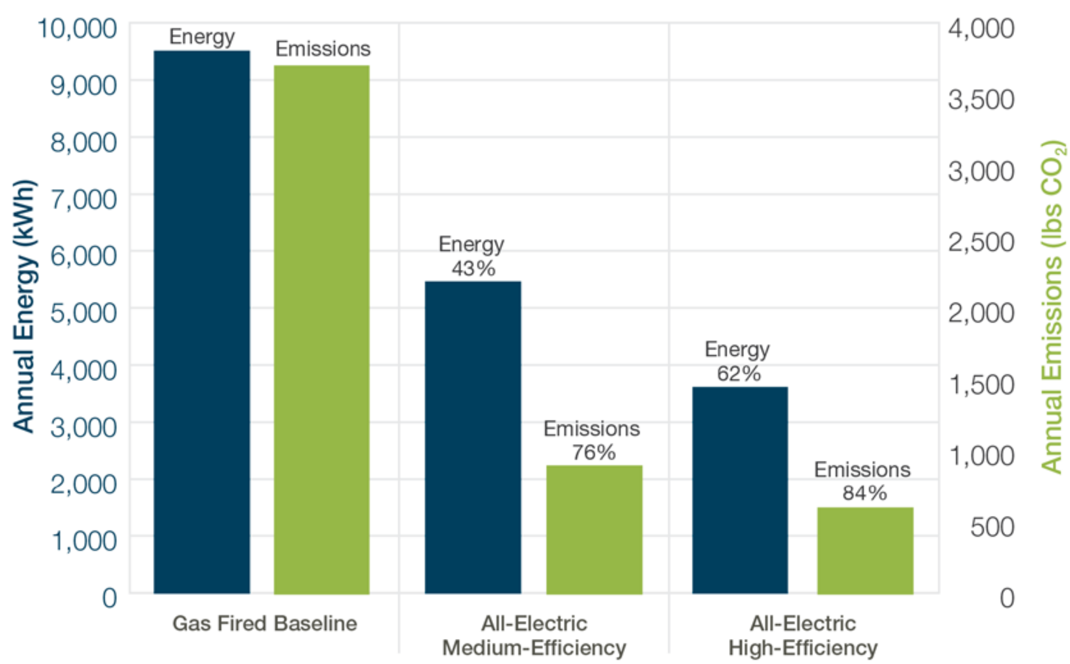
[67] Energy and CO_2 reductions represent the change from baseline to all-electric package for the sum of the four end-uses, not the whole building. Energy and CO_2 emissions associated with end-uses that are unchanged between baseline and all-electric packages, such as plug loads or lighting, is not represented.

FIGURE 16: SAN FRANCISCO HOME ENERGY AND EMISSION SAVINGS FROM ELECTRIFICATION OF THE FOUR END-USES



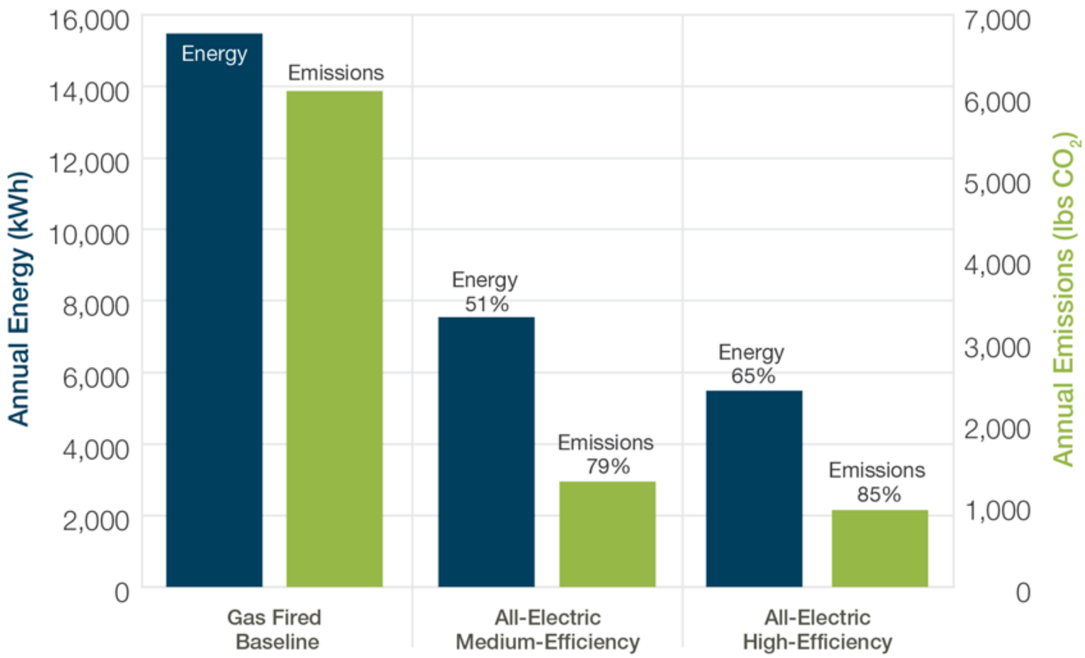
In the Los Angeles basin, warmer weather in the winter reduces the need for space heating, resulting in somewhat lower energy savings and CO_2 emissions reductions compared to San Francisco for both baseline and both of the all-electric cases as shown in Figure 17.

FIGURE 17: LOS ANGLES HOME ENERGY AND EMISSION SAVINGS FROM ELECTRIFICATION OF THE FOUR END-USES



In the Central Valley, the climate is more extreme (hotter in summer and colder in winter) than San Francisco and Los Angeles. This drives higher energy consumption across all cases modeled in Sacramento as shown in Figure 18.

FIGURE 18: SACRAMENTO HOME ENERGY AND EMISSION SAVINGS FROM ELECTRIFICATION OF THE FOUR END-USES



When reviewed as a group and with the addition of the colder region of Lake Tahoe, the energy and CO_2 savings per home is impressive. Total CO_2 emissions reductions increase significantly in colder climates due to the higher space-heating load. Individual efficiency programs should analyze the market share of various building types to determine their priority for absolute, not just relative, savings. A large and increasing number of heat pump models specifically designed to perform in cold climates are able to deliver 100% of rated capacity at 5°F and up to 75% of capacity at -13 °F[68].

[68] Mitsubishi Electric Trane HVAC Performance Construction Team, Zero Energy Project, 2020, [Achieve Reliable Comfort and Reliable Performance With Cold-Climate Heat Pumps]

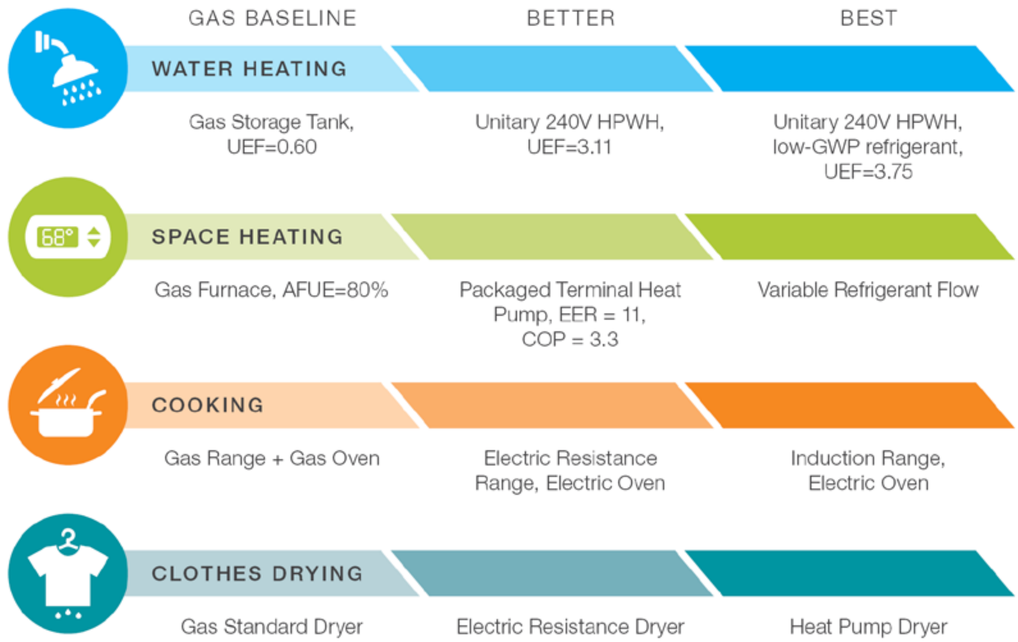
8.2. Multifamily Housing Units

For most multifamily buildings hot water use represents the No.1 energy demand, often followed by space heating. Tenant energy burden must be considered in tandem with upfront electrification costs, especially in low-income and affordable multifamily buildings. The variability in size and design of multifamily buildings greatly affects the technology options available to them. For example, low-rise multifamily buildings are more like single-family homes in many ways; whereas high-rise apartment/condo buildings are often designed and built more like commercial buildings. End uses such as water heating are addressed differently based on the size of the building: a larger multifamily building will more likely have a central water heating plant served by gas boilers, while townhomes and low-rises are more likely to use unitary water heaters.

The modeling package represents a typical scenario for low-rise multifamily (e.g. the laundry equipment and the water heating tank is present in each unit). The gas baseline, all-electric ‘better’, and all-electric ‘best’ packages are described in Figure 19 below.[69]

[69] See Footnote 66

FIGURE 19: LOW-RISE MULTIFAMILY TECHNOLOGY PACKAGE FOR ENERGY AND EMISSION ANALYSIS MODELING



Electrifying these systems yields high savings both in terms of energy and emissions. In all cases modeled, the 'better' all-electric package cuts baseline energy use roughly in half and cuts emissions by more than 75%, while the 'best' case cuts energy use by nearly 2/3 and emissions by more than 80% as shown in Table 17 below.[70]

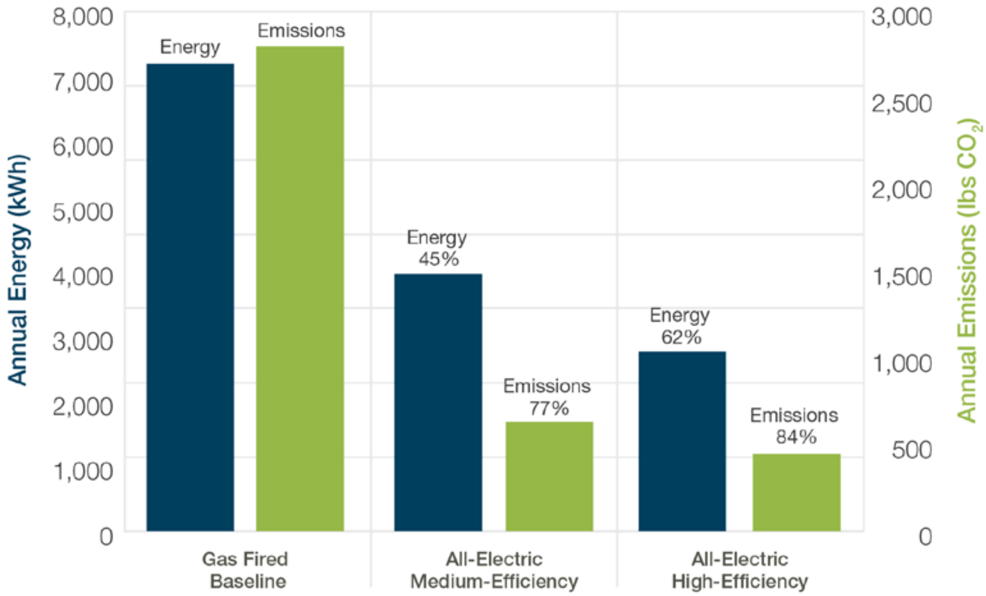
TABLE 17: LOW-RISE MULTIFAMILY ENERGY AND EMISSION SAVINGS FOR ELECTRIFICATION OF THE FOUR END-USES

		Multifamily – Gas Base vs Better Package				Multifamily – Gas Base vs Best Package			
		Site Energy Savings		Emissions Savings		Site Energy Savings		Emissions Savings	
City	**CA CZ**	**kWh**	**%**	**Lbs CO_2**	**%**	**kWh**	**%**	**Lbs CO_2**	**%**
San Francisco	3	3,236	45%	2,166	77%	4,434	62%	2,352	84%
Los Angeles	9	2,324	40%	3,153	85%	3,587	61%	3,353	90%
Sacramento	12	4,206	51%	2,563	80%	5,316	64%	2,733	85%
Lake Tahoe	16	7,445	57%	4,147	82%	8,433	65%	4,308	85%

San Francisco's temperate climate drives energy savings of more than 45% and CO_2 emission reductions of 77% for the 'better' package; the 'best' package provides greater savings as shown in Figure 20.

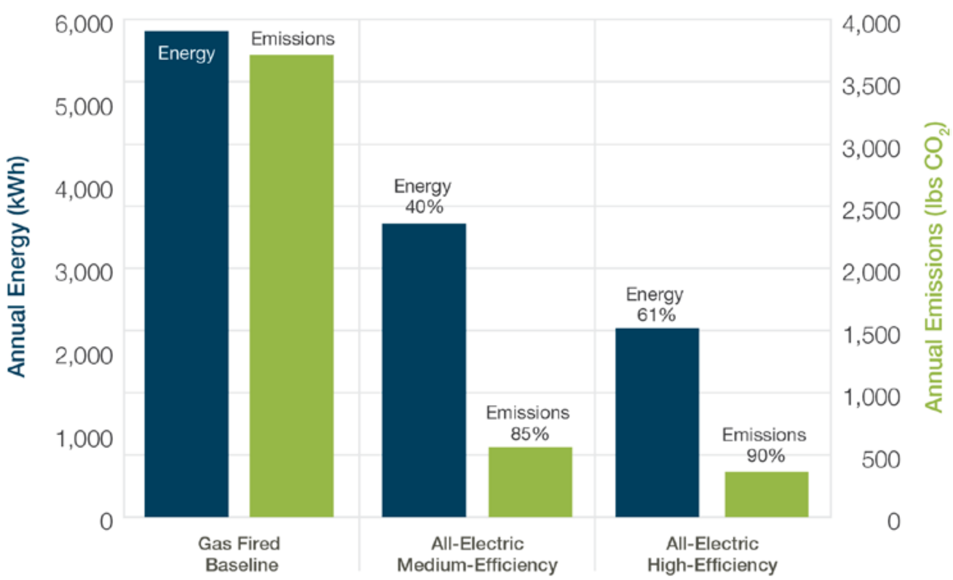
[70] See Footnote 67.

FIGURE 20: SAN FRANCISCO MULTIFAMILY ENERGY AND EMISSION SAVINGS FROM ELECTRIFICATION OF THE FOUR END-USES



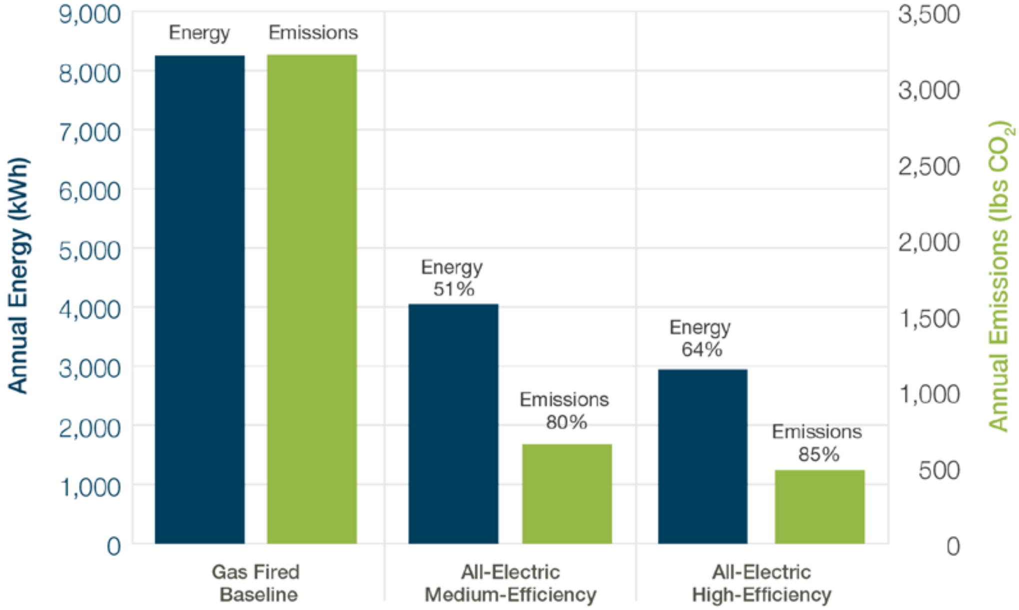
In Los Angeles, both the 'best' and 'better' packages have lower energy savings compared to San Francisco; yet because of the timing of those savings (i.e. occurring largely during times when relatively higher carbon generation is on the grid during summer evenings and winter mornings) the emission reduction is greater than in San Francisco as shown in Figure 21.

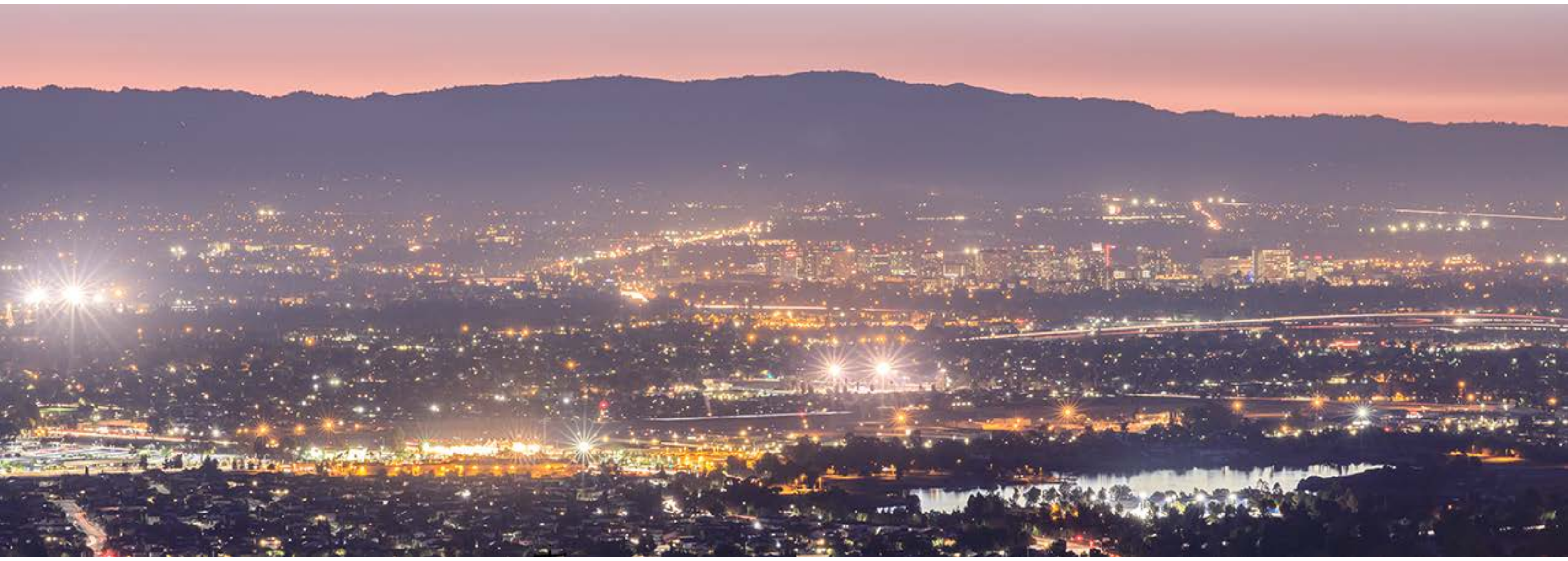
FIGURE 21: LOS ANGELES MULTIFAMILY ENERGY AND EMISSION SAVINGS FROM ELECTRIFICATION OF THE FOUR END-USES



In Sacramento, the colder winter climate drives higher heating loads, enabling the higher-efficiency equipment in both the 'better' and 'best' all-electric packages to provide greater energy and emission savings than either San Francisco or Los Angeles as shown in Figure 22.

FIGURE 22: SACRAMENTO MULTIFAMILY ENERGY AND EMISSION SAVINGS FROM ELECTRIFICATION OF THE FOUR END-USES





9. Conclusions and Commonalities

California efficiency programs and organizations have a 40-year history of transforming markets for the reduction of energy use in buildings. The industry is now widening the focus to include GHG emission reductions and energy use, both of which benefit community and public health. We can leverage our history to develop a new generation of programs that catalyze a larger set of societal and economic benefits. The findings in the BETR are fundamental as well as monumental, clearly describing California's technology path to building electrification.

While the focus of the BETR is on end-uses and technology status, the energy and emission reductions are compelling and serve as critical data drivers for the recommendations laid out in the Roadmap. Specifically, the BETR took a deeper dive analyzing residential impacts of building electrification compared to other building types, due to available modeling resources. Table 18 provides a summary of the energy savings and emission reductions from residential building electrification.

TABLE 18: BETR ANALYSIS ON RESIDENTIAL ENERGY AND EMISSIONS IMPACTS FROM BUILDING ELECTRIFICATION

Topic	Residential Findings	Reference
Space Heating	A high performance heat pump saves 36% energy and 71% emissions compared to a condensing gas furnace.	Figure 5
Water Heating	A conventional refrigerant HPWH saves 50% energy and 77% emissions compared to a standard gas water heater.	Figure 8
End-Use Packages	Electrifying the four main gas-using technologies of space and water heating, cooking and clothes drying in homes or multifamily buildings cuts energy use by over 40% and carbon emissions by over 75% for those four end-uses in all cases in multiple California climate zones.	Figure 16 - Figure 22

The BETR study found there are sufficient proven and market available technologies available today to fully electrify the studied set of building types and vintages: new and existing homes, multifamily, small and large commercial buildings (primarily offices), and higher education buildings as shown in Table 19.

TABLE 19: READY AND AVAILABLE ELECTRIFICATION TECHNOLOGIES BY SECTOR

WATER HEATING

SINGLE FAMILY	MULTIFAMILY	SMALL COMMERCIAL	LARGE COMMERCIAL	HIGHER ED/ INSTITUTIONAL
240V HPWH	240V HPWH	Point of use, distributed tankless	Point of use, distributed tankless	240V HPWH
240V HPWH low-GWP	240V HPWH low-GWP	*Offices were the commercial building type assessed. However, higher hot water usage occurs in other commercial buildings such as restaurants, health care, and lodging. In such cases HPWHs are often applicable and valuable.*		240V HPWH low-GWP
120V HPWH	Central HPWH			Central HPWH
	Central HPWH low-GWP			Central HPWH low-GWP
	120V HPWH			Point of use, distributed tankless
				120V HPWH

emerging due in the near future

SPACE HEATING

SINGLE FAMILY	MULTIFAMILY	SMALL COMMERCIAL	LARGE COMMERCIAL	HIGHER ED/ INSTITUTIONAL
240V AWHP Split System	240V AWHP Split System	240V AWHP Split System	240V AWHP Split System	240V AWHP Split System
240V ASHP Packaged RTU	240V ASHP Packaged RTU	240V ASHP Packaged RTU	240V ASHP Packaged RTU	240V ASHP Packaged RTU
Mini-Split ASHP	Mini-Split ASHP	Mini-Split ASHP	Mini-Split ASHP	Mini-Split ASHP
Ground Source Heat Pump	Ground Source Heat Pump	Ground Source Heat Pump	Ground Source Heat Pump	Ground Source Heat Pump
120V ASHP Split System < 5 tons	120V ASHP Split System < 5 tons	120V ASHP Split System < 5 tons	Variable Refrigerant Flow	Variable Refrigerant Flow
	Variable Refrigerant Flow	Variable Refrigerant Flow	Heat Recovery Chiller	Packaged Terminal Heat Pump
	Packaged Terminal Heat Pump	Packaged Terminal Heat Pump		Heat Recovery Chiller

COOKING

RESIDENTIAL KITCHEN	COMMERCIAL KITCHEN
Drop-In/Slide-in/Stand-Alone Induction Range	Induction Range
Countertop Induction Hob	Countertop Induction Hob/Wok
	Electric Oven, Fryer, etc.
	Combination Oven
	Chain Broiler

CLOTHES DRYING AND LAUNDRY

SINGLE FAMILY	MULTIFAMILY	INDUSTRIAL / COMMERCIAL
Heat Pump Dryer	Heat Pump Dryer	CO_2 Laundry System
Combo Washer-Dryer (Condenser Dryer)	Combo Washer-Dryer (Condenser Dryer)	

9.1. Commonalities

The BETR provides details about each technology within its end-use application. However, the technologies share commonalities, including roadblocks and recommended activities for rapidly advancing them together in the market. The five collective strategies to advance all the technologies are seen in Figure 23 with colors matching the channel of activity.[71]

FIGURE 23: FIVE COLLECTIVE STRATEGIES TO ADVANCE ELECTRIFICATION TECHNOLOGIES

These five collective strategies focus on the recommended top priorities for utilities and organizations working to advance building electrification programs and decarbonization policies in the state of California. This includes efficiency program administrators, jurisdictions, nonprofits, and decarbonization advocates. Explanations of the collective strategies are in Table 20.

TABLE 20: FIVE COLLECTIVE ROADBLOCKS AND RECOMMENDATIONS FOR BUILDING ELECTRIFICATION TECHNOLOGIES[72]

Strategy 1: Build Demand[M] | Create Compelling Value[M]

MARKET CHANNEL	**Solution Target:** Downstream - Consumers, Building Owners, Builders, Designers	
ROADBLOCKS	**RECOMMENDATIONS**	
Low consumer awareness and demand[M] Low consumer value proposition[M] Higher product cost	• **Campaigns**[M] Multi-channel awareness and promotional campaigns targeting benefits of electrification, impacts from fossil fuel use etc. • **Economics**[M] Utilization of research on annual and life-cycle costs to establish credible economic information. • **Materials**[M] Development of clear and compelling collateral materials for presentation to consumers by installers, system designers and retailers.	• **Advocacy.** Advocacy for codes and policies that further the ability to make the case for this technology due to pending regulatory requirements. Allows messaging to 'get ahead of the requirement and/or avoid the penalty/cost.' • **Cost**[M] Program incentives and financing will be necessary in the initial years (see Program Channel).

[71] See Table 3 for explanation of the channels.

[72] "M" as a superscript means "Manufacturer Input" (see Appendix page A-6: Manufacturer Feedback on Space and Water Heating).

Strategy 2: Support Supply Chain[M] | Make the Business Case Work

MARKET CHANNEL — **Solution Target:** Midstream - Installers, Suppliers, Distributors, Retailers

ROADBLOCKS	RECOMMENDATIONS
Low installer and builder value proposition[M] Lack of confidence in system reliability and knowledge Lack of sufficient warranty to address labor for call backs/returns – i.e.: Controls Supply chain and installer resistance to change existing models	• **Business Proposition.** Establish a business pro-forma for increased sales. Develop market adoption projections and gross/net margin by product line that speaks to the mid-stream players to get in the driver's seat to accelerate these products. • **Create Capability**[M] Provide training for plumbers and HVAC technical installation, controls, commissioning and marketing. • **Supporting Materials**[M] Provide sales materials including case studies and project/customer testimonials. • **Ensure Product Pipeline**[M] Stabilize the product pipeline and increase product knowledge with suppliers and big box retailers. Equipment must be readily available for installers and consumers.

Strategy 3: Partner with Production – Manufacturers are Motivated

TECHNOLOGY CHANNEL — **Solution Target:** Manufacturers

ROADBLOCKS	RECOMMENDATIONS
Need for retrofit market units Gaps in performance optimization and validation Slow growth in low-GWP models Historic inconsistencies in efficiency program commitments Availability variability[M]	• **Design for Retrofit.** Models with different size configurations and lower amperage requirements are needed (see specifics by technology and end-use). • **Product Reliability.** Assure both products and labor are fully covered for an extended warranty period. Continue product refinements, particularly electronics and controls, to increase reliability and overcome contractor experiences with product failures. • **Trust.** Set clear outcomes and timelines for increasing product demand that manufacturers can trust. • **Partnerships**[M] Create collaborations with manufacturers with realistic goals and consequences. Integrate specialist from the various technology groups and business development into efficiency programs. • **Mass Markets**[M] Establish early large buys from major market parties. • **Money.** Understand the production model and invest in supporting transitions to new products.

Strategy 4: Close the Cost Gap – Invest Heavily Now

PROGRAM CHANNEL — **Solution Target:** Efficiency Programs

ROADBLOCKS	RECOMMENDATIONS
Lack of credible economics on total cost of technology ownership Insufficient program incentives and consistency Technology and installation costs Absence of easy to access finance products	• **Economics**[M] Establish accurate and easy to convey total cost of ownership and societal costs. • **Incentives**[M] Incorporate a wider-range of utility and societal values into the benefits side of product and program cost-effectiveness assessments. Advocate to regulators regarding parameters for establishing rate-payer based incentives. Target incentives mid-stream as a method to reduce consumer cost. • **Layering.** Utilize allied programs to layer incentives and benefits to end-users and mid-stream entities. • **Funding/Financing**[M] Assure easy access to low cost financing and repayment, On Bill Payment, integration with building improvement mechanisms to get the market primed with electrification technologies and make the cost difference negligible.

Strategy 5: Align Program and Policy Signals – Make the Path Easy

POLICIES AND STANDARDS CHANNEL	**Solution Target:** State Gov't, Cities, PUCs
ROADBLOCKS	**RECOMMENDATIONS**
Misaligned policies Program constraints on measure incentives Lack of Fuel and Carbon price signals[M]	• **Market Transformation Leadership.** Establish a statewide strategy, funding and entity to lead a coordinated approach to building electrification[M] • **GHG Policies.** Drive advancement through significant Federal, State and City goals for GHG reductions, low-GWP refrigerants and clear timelines. • **City Reach Codes.** Provide resources and templates to cities for the adoption of electric-preferred and/or mandated reach codes. • **Cost-effectiveness Tests.** Value GHG in addition to energy reductions. Remove barriers to customized valuation based on grid integration benefits. • **Fuel and CO_2 Pricing.** Adopt fuel pricing regulations that incorporate GHG impacts of extraction, transport, and generation to reduce the disparity in fuel costs. Continue to work within the Cap and Trade program with expansion to building/home-level carbon caps.[73] • **Set electrification rates.** Support Time of Use and electrification rates that will reward electrification and address energy cost burden and equitable electrification. • **Title 24.** Set prescriptive and performance pathways in T24 for all electric commercial buildings to use high-efficiency electric appliances for all regulated and non-regulated end-uses.

The Sooner the BETR

In residential the current levels of adoption of high efficiency electric heat pumps for both space and water heating are abysmal—with only around 2% adoption as seen in Table 21. While the current numbers are less available for induction cooking and high efficiency laundry, they also have very low current adoption.

TABLE 21: FUEL SHARE FOR RESIDENTIAL SPACE AND WATER HEATING APPLIANCES IN CALIFORNIA [74]

Fuel	Space Heating	Water Heating
Natural Gas	82%	86%
Propane	2%	4%
Electric Resistance	11%	5%
Electric Heat Pumps	2%	2%
Unknown or not used	3%	3%

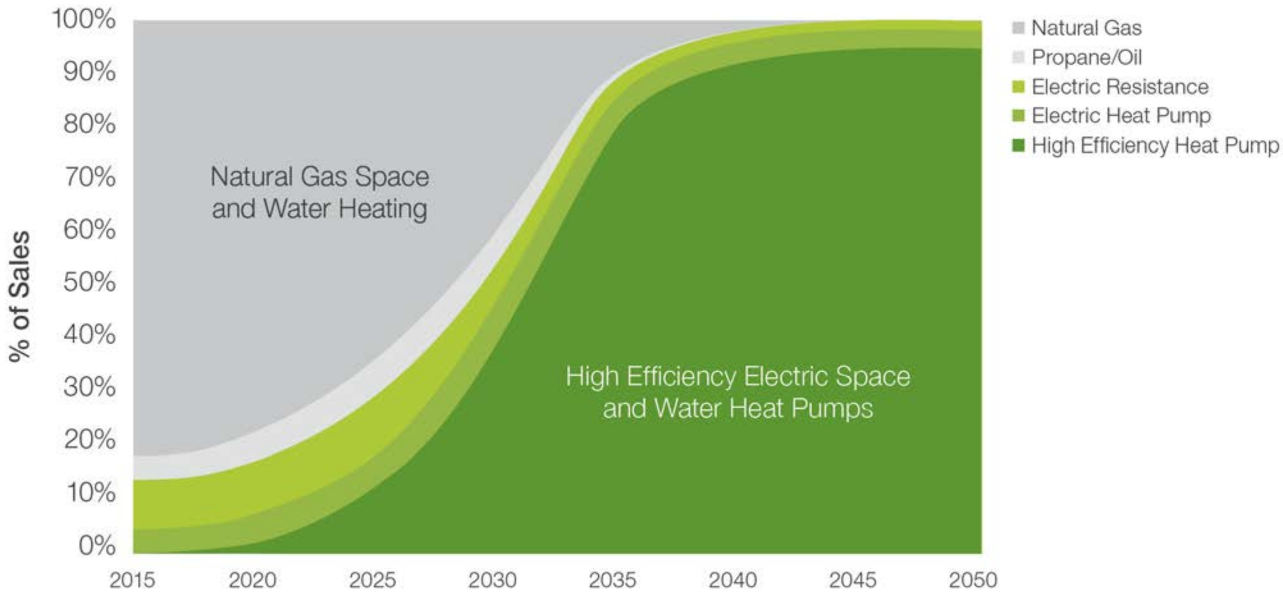
Figure 24 shows a conceptual adoption curve for these technologies to support decarbonization goals based on the current fuel proportion for space

[73] New York City is the first city in the U.S. to implement a building-level carbon cap system in their building performance standard under [Local Law 97](). This study recommends California look at this model and continue to make carbon a commodity that drives building owner decisions in support of electrification.

[74] Data derived from: EIA RECS 2015 table CE3.5 | Calmac 2012 California Lighting and Appliance Study | RASS 2009 *(RASS 2019 was delayed and anticipated in 2021)*.

and water heating. As programs support increased high efficiency space and water heat technologies it creates the classic 'tipping point' where sufficient adoption will establish building electrification. The next ten years are critical if we want building electrification to be the new norm in 2030 and beyond.

FIGURE 24: CONCEPTUAL MARKET ADOPTION TO MEET CALIFORNIA CLIMATE TARGETS[75]



The next ten years are critical if we want building electrification to be the new norm in 2030 and beyond.

9.2. Summary

The extent of research and findings in BETR is extensive. For this reason, the authors and advisors suggested a BETR Summary document as an accompanying document. The BETR Summary represents key takeaways and the technology status and recommendation graphics to provide the information at a glance. This full BETR has the detail and layered information on each technology, market channel, and recommendation.

The funders of this study are committed to helping the state of California meet its 2045 carbon neutrality goal. If one thing is clear from this Roadmap, it's that we must act with greater urgency to accelerate building electrification technologies. By working together to take the recommendations into concrete actions, we can make great progress toward reducing the energy use and GHG emissions of all buildings across the state of California over the next 10 years.

[75] Penetration data from Table 18, curve based on a figure in E3 2019, Residential Building Electrification in California

Appendices

The Matrix and Technology Assessment Graphics (TAG) Tool

The term “Matrix” refers to the large Excel-based spreadsheet created by the BETR research team to organize and assess the qualitative characterizations of electrification technology status. The Matrix contains the scores for all technologies in all sectors across all five first-priority parameters (see Section 2.0: Roadmap Methodology) for new construction and retrofit applications. The second-priority parameters, of interest but less directly relevant for comparison, are included for additional information. The project team included a “Thoughts” column for each parameter, which contains notes explaining the rationale behind each rating. There are also columns that include the sources used to justify the scoring.

Below is an image of the Matrix (Figure 3).

The Technology Assessment Graphics (TAG) tool, which is in the same spreadsheet, automatically pulls data from the Matrix. The TAG includes a dynamic PivotChart tool that allowed the project team, and will allow other users, to easily visualize how technologies rate across the five first-priority parameters and compare scores across technologies. A drop-down menu allows customized groupings of technologies.

In an example below, the TAG tool compares cooking technologies for commercial building applications. 'Commercial Electric Cooking Equipment' scores a 3 across all first-priority parameters, indicating a mature and effective technology, while 'Commercial Countertop Induction Hobs/Wok's receives mainly scores of 2, indicating the existence of some remaining challenges to full deployment and maturation.

FIGURE 25: AN EXAMPLE OF A CUSTOMIZED TAG CHART

By delivering customized data visualizations based on the Matrix, the TAG tool enabled the BETR project team to gain simple, straightforward characterizations of technologies across specific end-uses, sectors, and vintages without having to filter through a spreadsheet containing more than 1,000 characterizations. When presenting their findings in the BETR, the project team elected to establish the core technology level scores and represent them in the Status Tables within each end-use section. The scores are shown through the use of "Harvey Balls" (fully shaded, half shaded, or empty) reflecting whether the technology received a 'high,' 'moderate,' or 'low' score.

The Matrix and TAG tools were delivered to BETR project funders as a standalone deliverable, separate from this Roadmap. They are not available for wider distribution. However, they could be leveraged to create other regional technology assessments.

Resources on Electrification and Decarbonization

The research team used a variety of resources on building electrification and decarbonization to complete this study. The first resource lists the literature sources used by the project team to inform the scoring of each technology in the BETR. The second is a comprehensive list of additional resources gathered by NBI on building electrification and decarbonization.

Literature Review Used in the BETR Scoring Assessment

Literature Review Used in the BETR Scoring Assessment			
Entity	**Hyperlink**	**Name**	**Year**
ASHRAE	ASHRAE Non Vapor Compression 2014	Alternatives to Vapor-Compression HVAC Technology	2014
California Energy Commission (CEC)	CEC Research Gaps 2019	Research Gap Analysis for Zero-Net Energy Buildings	2019
Daikin	Daikin Heat Pump Products	Air To Water Heat Pump Systems	2020
Energy and Buildings	Energy and Buildings VRF vs VAV 2009	Simulation comparison of VAV and VRF air conditioning systems in an existing building for the cooling season	2009
Energy Reports, Elsevier	Energy Reports VRF vs VAV 2017	Evaluation of energy savings potential of variable refrigerant flow (VRF) from variable air volume (VAV) in the U.S. climate locations	2017
Energy+Environmental Economics (E3)	EEE Electrification 2019	Residential Building Electrification in California	2019
Lawrence Berkeley National Laboratory (LBNL)	LBL Electrification 2018	Electrification of buildings and industry in the United States	2018
Northeast Energy Efficiency Partnerships (NEEP)	NEEP ASHP 2016	Northeast/Mid-Atlantic Air-Source Heat Pump Market Strategies Report 2016 Update	2016
NEEP	NEEP VRF 2019	Variable Refrigerant Flow (VRF) Market Strategies Report	2019

Literature Review Used in the BETR Scoring Assessment			
Entity	**Hyperlink**	**Name**	**Year**
National Renewable Energy Laboratory (NREL)	NREL Water Heating 2013	Comparison of Advanced Residential Water Heating Technologies in the United States	2013
NREL	NREL 71500 2018	Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States	2018
NREL	NREL 70485 2017	Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections through 2050	2017
Redwood Energy	Redwood Energy Electrification 2019	A Zero Emissions All-Electric Multifamily Construction Guide	2019
Rocky Mountain Institute (RMI)	RMI Mechanical Systems 2018	Next-Generation Building Mechanical Systems	2018
Synapse	Synapse Heating 2018	Decarbonization of Heating Energy Use in California Buildings	2018
U.S. DOE EERE	EERE Dryers 2017	The Ultrasonic Dryer	2017
U.S. Environmental Protection Agency (EPA) Energy Star	Energy Star Dryers 2011	ENERGY STAR Market & Industry Scoping Report Residential Clothes Dryers	2011
U.S. EPA Energy Star	Energy Star Products	Energy Efficient Products	2020
U.S. EPA Energy Star	Energy Star Dryers	Clothes Dryers	2020
U.S. EPA Energy Star	Energy Star Geothermal HP	Geothermal Heat Pumps	2020
U.S. Department of Energy (DOE) EERE	EERE Water Heating 2012	Test Procedures: Residential water heaters: Guidance	2012
U.S. DOE	DOE Non Vapor Compression 2014	Energy Savings Potential and RD&D Opportunities for Non Vapor-Compression HVAC Technologies	2014
U.S. Department of Energy (DOE) EERE	EERE Water Heating	Rulemaking: Commercial Water Heating Equipment	2020
Washington State University (WSU)	WSU Washers 2020	Emerging Technologies	2020

Additional Electrification and Decarbonization Resources

Additional Electrification and Decarbonization Resources			
Entity	**Hyperlink**	**Name**	**Year**
American Public Power Association	Article	From the ground up: Building electrification	2019
Building Decarbonization Coalition	Fact sheet	A Journalist's Guide to Building Electrification in California. Cleaner, Safer and More Affordable: Why California Cities are Moving Toward Zero-Emission Buildings	
Edison International	Link to web page	All-electric homes and buildings	web
Emerald Cities Collaborative	Report	The Building Electrification Equity Project	2020
Energy+Environmental Economics (E3) for the California energy Commission	Report on need for gas transition strategy in CA	The Challenge of Retail Gas in California's Low-Carbon Future	2020
Forbes	Article	As Cities Begin Banning Natural Gas, States Must Embrace Building Electrification Via Smart Policy	2019
The Greenlining Institute	Report	Equitable Building Electrification. A Framework for Powering Resilient Communities	2019
Greentech Media (GTM)	Article: Guidance for electrifying homes	Electrify Everything! A Practical Guide to Ditching Your Gas Meter	2018
New Buildings Institute	Blog	Electrification Nation: Policies and Technologies	2020
Rocky Mountain Institute (RMI)	Report/paper	The Economics of Electrifying Buildings	2018
RMI	Web page with report links; info	Building Electrification	2020
Sierra Club	Building Electrification Action Plan	Building Electrification Action Plan for Climate Leaders	2019

Manufacturer Feedback on Space and Water Heating[76]

In 2018 Electric Power Research Institute (EPRI) led two in-person workshops on behalf of Southern California Edison (SCE) with major manufacturers of space and water heating equipment. There are no formal published results of those meetings, but the aggregated responses were used to inform the BETR and other work on behalf of SCE. Both organizations provided New Buildings Institute (NBI) with permission to share the list of attending companies and the questions asked.

Responses to the questions below are indicated by a M in the Roadblocks and Recommendations sections of both the space heating and water heating end-use sections (see Section 183: Space Heating and Section 4: Water Heating) and in the 5 Collective Strategies table (see Table 20).

[76] This is part of information gathered by EPRI in 2017 to inform SCE's electrification direction. It is not published but is provided here by permission from SCE to further support the BETR study.

Space Heating

Space Heating Manufacturer Workshop Participants

- Daikin
- Rheem
- Carrier
- Fujitsu
- Mitsubishi Electric

Manufacturers Survey Questions:

1. What are the top 3 to 5 challenges to getting broader acceptance and greater number of installations of high-efficiency electric heat pumps (particularly as Southern California is ~90% natural gas space heating)?
2. What are the top 3 or 4 major advances (e.g., technology, communications, etc.) which must be met in the next 5 years to further push residential/light commercial electric heat pumps into the marketplace?

Responses

Space Heating Challenges

Challenges for High Efficiency Space Conditioning	
Category	Challenges
Policy Changes	• Natural Gas Emission Tax (NOx, some starting in Southern CA) • Remove Fuel-switching Barriers • Zero Net Carbon • Change Minimum Efficiency for Variable-capacity Heat Pump (CEC)
Cost	• Equipment First Cost – Rebates to Appropriate Stakeholder • Equipment First Cost – Financing • Utility Acceptance – Appropriate Credit for both EE and DR
Product Performance	• Supply Air Temperature during Startup and Defrost • Supply Air Temperature versus Gas Furnace • Noise During Defrost Switchover • Remote Monitoring (FDD, Energy Performance)
Consumer Education	• Better customer awareness of costs, benefits, and equipment performance • For heating-only home, benefit of electric heat pump providing cooling as well • Clearly define customer cost effectiveness of electric heat pump over natural gas
Supply Chain Development	• Attracting and training technicians who can install and commission, especially inverter-driven equipment • Early equipment retirement programs
Building Infrastructure Limitations	• Electric panel undersized for heat pump application

Space Heating Technology Advancements Needed:

Technology Advancements Needed for Space Heating	
Category	**Technology Advancements**
Communication Improvements	• Expand data available to utilities, aggregators • More reliable, lower costs • Unify communication protocol for DR with expected goal (target) • Large data may slow down business network, use separate network for data
Lower Costs	• First cost reduction • Cost effective technology to allow heat pump sizing for full heating load, with little-or-no electric strip supplemental • Improve cost for electric resistance on OD coil, hot gas bypass, multiple heat exchangers and thermal storage for applicability to residential applications • Lower cost for power electronics that will allow for greater adoption of inverter driven compression
Cold Temperature Operation and Defrost	• Don't allow electric strip heat activation based solely on outdoor temperature or for all heating conditions • Minimize frost buildup (e.g., coil coatings) • Improve cold climate heat pump performance
Improved Installation and Commissioning	• Ease of installation • Update installation methods, avoid cold blow (proper supply air diffuser placement) • Improved software for unit commission, and continuous monitoring to maintain high performance
Fault Detection and Diagnostics	• Improvements to on-board fault detection and diagnostics • Improved diagnostics to notify customer when compressor fails and electric strip is solely meeting the heating load
Alternative Refrigerants	• Refrigerant replacement (R-410A phase-out)
Improved Equipment Sizing Methods	• Proper equipment sizing. If oversized for heating, then select multi- or variable-capacity system to retain part-load cooling performance

Water Heating

Water Heating Manufacturer Workshop Participants

- Daikin
- Rheem
- AO Smith
- Bradford White
- Sanden
- Steffes

Manufacturers Survey Questions

1. What are the top 4 or 5 challenges to getting broader customer acceptance of high-efficiency electric water heating (i.e. HPWHs)?
2. What are the top 3 or 4 major technology advances that must be met in the next 5 years to further push HPWHs into the marketplace?

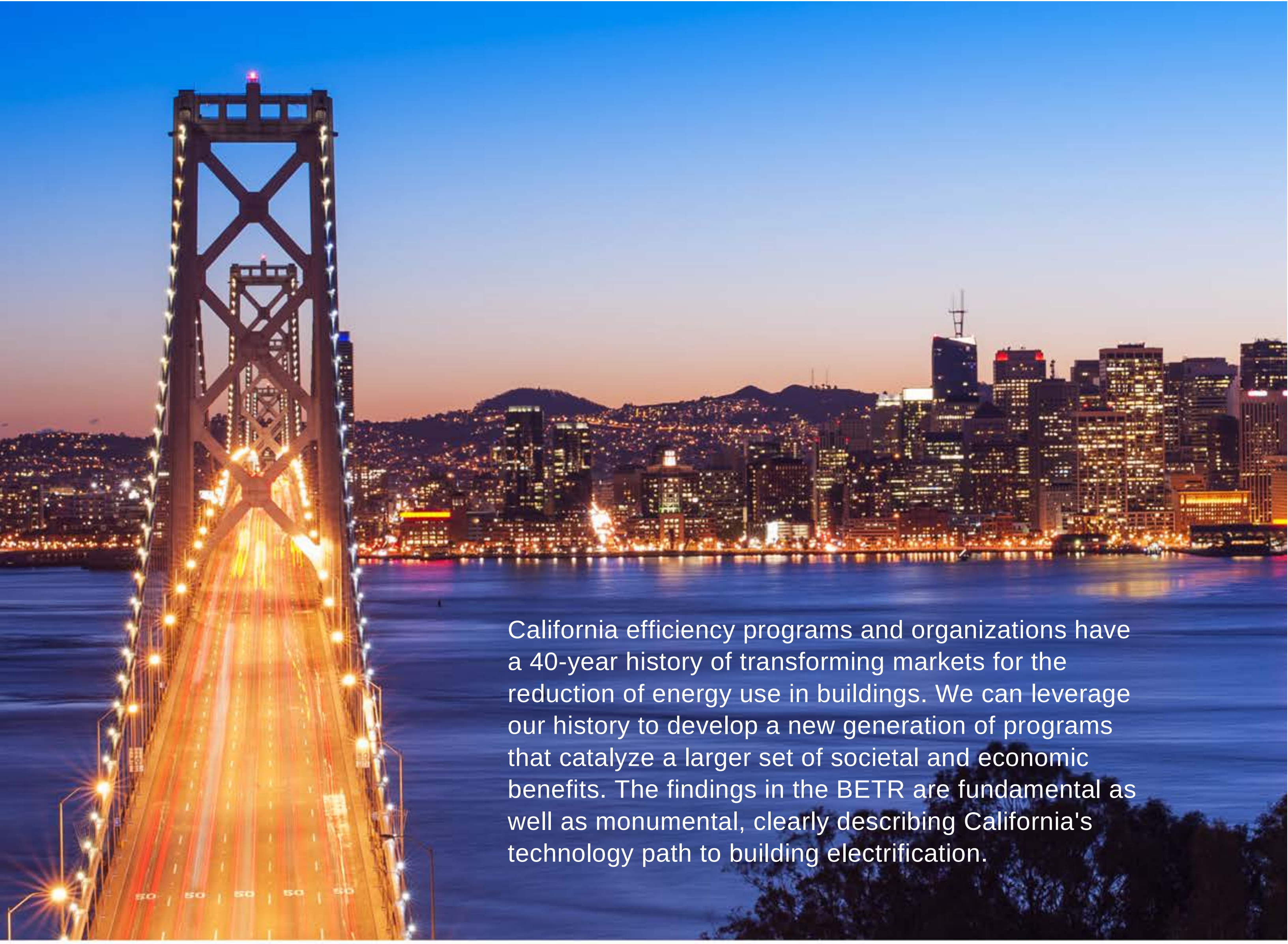
Manufacturers Responses

HPWH Challenges

Challenges for High Efficiency Water Heating	
Category	Challenges
Contractor / Rep Education	• HVAC + Plumbing Capabilities • Sales – Contractor / Rep • Application – Contractor / Rep • Installation – Contractor • Commissioning – Contractor
Customer Education	• Education of Gas-to-HPWH Conversion (Benefit; Use-Case) • Utility Program Involvement • Simplified, Clear Messaging
Cost	• Fuel Cost – Traditional Low Cost of Natural Gas • Equipment First Cost – Rebates to Appropriate Stakeholder • Equipment First Cost – Financing
Product Availability	• Emergency Installation (On-truck or Warehouse) • Availability at Big-Box Stores • Full Manufacturer Buy-In • Distribution Channel Improvements
Building Infrastructure Limitations	• 240V Availability • Condensate Drain • Physical Space too Small for HPWH Conversion
Grid Resource Adoption	• HPWH Limited Market Share

HPWH Technology Advancements Needed

Technology Advancements Needed for HPWH
Category
Multi-Family Product Series
Smart Control Integration / Improved Communication
HPWH for California Specification (e.g., 115 VAC, 15A, High Storage Temp
Grid-Service Expansion / Development
Time-of-Use Implementation – Contractor and/or Customer Training
Large Commercial Product Series
Tank Lining for Higher Storage Temperature



California efficiency programs and organizations have a 40-year history of transforming markets for the reduction of energy use in buildings. We can leverage our history to develop a new generation of programs that catalyze a larger set of societal and economic benefits. The findings in the BETR are fundamental as well as monumental, clearly describing California's technology path to building electrification.

New Buildings Institute (NBI) is a nonprofit organization driving better energy performance in buildings to make them better for people and the environment. We work collaboratively with industry market players—governments, utilities, energy efficiency advocates, and building professionals—to promote advanced design practices, innovative technologies, public policies, and programs that improve energy efficiency. The Getting to Zero website houses over 300 curated resources including guidance, educational webinars, policy models, research, case studies, and more to help all buildings achieve zero energy. Visit gettingtozeroleadership.org to learn more.

The Building Decarbonization Coalition (BDC) unites building industry stakeholders with energy providers, environmental organizations, and local governments to help electrify California's homes and workspaces with clean energy. Through research, policy development, and consumer inspiration, the BDC is pursuing fast, fair action to accelerate the development of zero-emission homes and buildings that will help California cut one of its largest sources of climate pollution, while creating safe, healthy and affordable communities.