Beneficial Electrification of Water Heating

By David Farnsworth, Jim Lazar, and Jessica Shipley

Part of the *Electrification in the Public Interest* Series

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Responsibility for the information and views set out in this paper lies entirely with the authors.

Abbreviations

ACEEE	American Council for an Energy-Efficient Economy
BE	beneficial electrification
Btu	British thermal unit(s)
CO_2	carbon dioxide
COP	coefficient of performance
EERS	energy efficiency resource standards
EPA	Environmental Protection Agency
ER	electric resistance
HP	heat pump
kWh	kilowatt-hour
NREL	National Renewable Energy Laboratory

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About This Series

For electrification to be considered beneficial, it must meet one or more of the following conditions without adversely affecting the other two:

1. Saves consumers money over the long run;
2. Enables better grid management; and
3. Reduces negative environmental impacts.

The first paper in this series, *Beneficial Electrification: Ensuring Electrification in the Public Interest*, explores policy and regulatory decisions that need to be made to accommodate innovations across the power sector that make it possible to electrify many energy uses currently fueled by oil, propane, and natural gas. The paper makes the case for what RAP calls beneficial electrification—in other words, electrification in the public interest.

The authors offer six principles that will help policymakers and regulators formulate and evaluate their electrification strategies to broadly secure the benefits. Finally, the paper looks at operational elements that states may want to consider as they move ahead with electrification.

This companion paper and two others feature pathways and no-regrets options for regulators to apply these principles specifically to space heating, water heating, and electric vehicles. Each paper lays out initial steps for regulators to establish programs, including standards and metrics to measure success. More specifically, these papers explore issues such as rate design to enable beneficial electrification; program design and implementation; relationships between beneficial electrification and energy efficiency and demand response programs; screening tests for beneficial electrification; and impacts on wholesale markets and vice versa.

Learn more and download the full series at www.raponline.org/BE.

Executive Summary

Today it can take far less energy to heat a gallon of water with electricity than directly with fossil fuel.

Technological advances, both in the efficiency of electricity generation and the end uses it fuels, have opened up opportunities for beneficial electrification (BE). Water heating, like space heating, is one of these opportunities. Water heating accounts for almost 20 percent of residential energy bills—and, put simply, today it can take far less energy to heat a gallon of water with electricity than directly with fossil fuel.

In this paper, we explore strategies available to make the electrification of water heating beneficial, meaning it will meet at least one of our BE conditions without adversely affecting the other two:

1. Saves consumers money over the long run;
2. Enables better grid management; and
3. Reduces negative environmental impacts.

We conclude that electric water heating can save a consumer money, serve as a resource for power grid operators, and reduce air pollutant emissions.

Matching Technology to Water Heating Needs

This paper examines two technology options for electrification of water heating: electric resistance (ER) water heaters and air source heat pump (HP) water heaters. Conventional ER heaters are essentially tanks containing one or more submerged electric heating elements. HP water heaters are tanks with heat pumps attached directly to them. Although they have different cost and operating characteristics, each is likely to have a place in a future that includes increased electrification.

Currently, electric water heating is not uniformly distributed around the United States. It is dominant in the Southeast and less popular but still common in the West, the Midwest, and New England. Within these regions there are also variations among states and between rural and urban areas.

As with space heating, factors such as housing type (single family, apartment, or manufactured housing), number of units served, and age of a dwelling affect which water heating option works best. For example, in apartment buildings where each unit has an individual ER water heater, the best choice may be to make those units controllable via the grid. For multi-family units with central water heating, an HP system can be efficient. New construction offers the opportunity to outfit homes for all-electric service, including HP water heaters, avoiding the cost of extending natural gas service.

Meeting the Conditions for Beneficial Electrification

Consumer Economics

Determining whether electrification will bring consumers economic benefits, the first condition of BE, is a situation-specific calculation affected by several factors. These include:

- Building type;
- The installed cost of the water heater (specifically the incremental cost above that of the alternatives);
- The cost of energy to run the water heater; and
- Potential co-benefits of installing water heating at the same time as space heating and cooling.

In 2018, the American Council for an Energy-Efficient Economy published a study analyzing the life cycle costs of replacing oil and propane water heaters when they fail. The study concluded that HP water heaters have lower costs relative to both oil and propane alternatives.

In this paper, we conduct a simple calculation of the consumer benefits today from replacing a failed natural gas water heater with a heat pump model. RAP found that current estimates of installation costs for an HP water heater exceed those for a gas version by about $50 to $1,000. Relying on a flat electricity rate, the simple payback period for switching would be between one and 22 years. Under a time-varying rate, however, the switch to a heat pump model would have a simple payback period of zero to six years.

A 2018 study concluded that heat pump water heaters have lower life cycle costs relative to both oil and propane alternatives.

The National Renewable Energy Laboratory conducted a study in 2017 in which it projected various electrification scenarios based on existing literature and cost data. Even under its least favorable scenario, residential HP water heaters are cost-competitive with gas versions in 2020.

This suggests that heat pump water heater efficiencies can be expected to improve in the relatively near term. It also demonstrates that the capital costs of residential HP water heaters, although higher, can be offset by long-run fuel savings. Converting to controlled heat pump models can be expected to produce the highest economic return, but controlled electric resistance water heaters can also provide substantial savings in housing types where they are easier to install.

Grid Management

Enabling better grid management is the second condition of beneficial electrification. Both electric resistance and heat pump water heaters can be integrated into the grid with the use of control systems that allow the end user, grid operator, aggregator, or another party to monitor the state of "charge" (that is, the water temperature) and control the charging. This can enable, for example, demand response and load shifting. Because electric water heating load is controllable, it can add flexibility to the grid and serve as a tool for grid operators. Despite this potential, just 2 percent of electric water heaters are currently participating in utility demand response programs, though utility interest in tapping this resource continues to grow.

Electric water heating can make significant contributions to solving grid management challenges that utilities face.

1. **Shifting demand:** The growing share of variable renewable energy resources on the grid means that system operators increasingly need to focus on meeting net load—the difference between forecast load and the amount of load met by intermittent resources. Controlled water heating load can be shifted away from system peaks to cheaper hours. It can also be moved to times when variable energy resources are available. This reduces the need for curtailment and saves consumers money while still ensuring they have hot water when they need it.
2. **Ancillary services:** Smart electronics and improved communications are creating a new category of responsive appliances that can help grid operators by providing ancillary services. Electric resistance water heaters are especially suited to fast-response types of controls, making them especially suited to providing, for example, voltage support and frequency response.
3. **Direct partnerships with variable energy resources such as rooftop photovoltaics:** In some areas of the United States, installers are beginning to deploy photovoltaic solar water heaters, where direct current solar panels are coupled to an ER water heater without an intervening inverter (which can add cost and reduce delivered electricity). Coordinating these resources with grid control programs is an opportunity for utilities, especially in areas where solar demand is strong.

Energy and Emissions Efficiency

Reducing negative environmental impacts is the third condition of beneficial electrification. The continued use of fossil fuels throughout much of the economy—no matter how efficient that use—cannot reduce greenhouse gas emissions enough to meet climate goals. These goals are attainable, however, by saving as much energy as possible through efficiency, decarbonizing the power sector, increasing the electrification of end uses, and relying on a cleaner grid to fuel them.

Because electrical end uses replace on-site combustion of fossil fuels, electrification avoids emissions at the point of customer use. Although electrification still causes emissions associated with power generation, total emissions are often reduced by employing efficient end uses and relying on energy from cleaner generation sources.

More energy-efficient electric end uses, in combination with the greening of the generation fleet, create the potential for increased emissions efficiency. In other words, due to the electric sector's declining emissions, consumers can now produce fewer pounds of pollution per gallon of water heated, despite consuming more electricity. The thermodynamic efficiency and emissions efficiency of water heaters vary among technologies and across regions and depend on the characteristics of the utility grid to which they are connected.

By ascertaining the efficiency of a water heater and considering the carbon content of its energy supply, we can estimate the emissions per delivered unit of hot water. RAP has determined that heat pumps can result in higher carbon emissions than fossil-fueled alternatives if an electricity system has more than 50 percent coal generation. However, if the electric system is no more carbon-intensive than combined cycle natural gas, heat pumps become less carbon-intensive than propane and natural gas water heaters. And when the electric system becomes low-carbon (no more carbon-intensive than 50 percent gas/50 percent non-carbon), all the electric strategies result in equal or lower carbon emissions than natural gas and propane. Some parts of the United States meet this standard today; many more will in the future.

Putting Beneficial Electrification Into Action for Water Heating

This paper illustrates the potential for significant consumer, grid, and environmental benefits associated with changing the way we heat water. In the final section, we discuss ways to encourage greater deployment of electric water heating.

Standards for New Buildings

For existing housing, the conversion to more efficient electrified water heating will be a long-term task requiring significant investment. The transition for new construction, however, can occur much more rapidly. In this context, the entire cost of a water heating system is incremental. Capital costs of more efficient alternatives, in many instances, are competitive with conventional electric or fossil-fueled water heating. Building energy codes and other rules should be reviewed to ensure they do not create barriers or obstacles to electrification.

Appliance Standards

The current appliance standards for residential water heaters were adopted in 2010 and took effect in April 2015. The US Department of Energy and Environmental Protection Agency have been in discussions with stakeholders about the future potential of grid-connected water heating.

It is not clear how and when the department will recommend new water heater appliance standards, or how the agency will articulate voluntary Energy Star standards. It is clear, however, that water heaters with built-in control systems offer substantial benefits. Including Wi-Fi or another utility interface to ensure water heaters receive a grid signal would support load shifting and demand response, practices that can improve grid reliability and the economics of electric water heating.

Additionally, there is the question of fuel-neutral appliance standards. As standards are reviewed, it would be worthwhile, for example, to consider the energy use associated with standards for natural gas water heaters compared with standards for other types. In other words, in establishing standards that truly capture efficiencies available to the US market, experts should compare the relative efficiency of all water heaters, not simply those using the same fuel—for example, gas vs. gas or electric vs. electric.

State Energy Policy

Because state policies can help or hinder BE, states will need to ensure that policies reflect opportunities associated with current innovations in technology. For example, states need to consider integrated resource plans that recognize the potential of electrification and its many effects on the future development of both electric and gas utilities. Currently, an electric-only integrated resource plan may not fully explore the effects of system trends and investments, especially their effects on in-state gas companies. Likewise, a plan addressing only natural gas might fail to recognize potentially cleaner and lower-cost electric alternatives, to the detriment of consumers and the environment.

Squaring utility infrastructure investment and acquisition with new realities is just as important as adjusting utility planning practices. For example, utility practice varies as to how expanded natural gas infrastructure is paid for, whether by individual new customers paying to connect or as a socialized cost all ratepayers bear. If regulators are comparing the costs of electrification versus continued development of natural gas infrastructure, it will be important to recognize any implicit subsidies.

The metrics used in state energy efficiency resource standards also are worth another look. Consumption reductions that these standards require are often denominated in kilowatt-hours (kWhs). Yet, while electrification can decrease total energy use, it may increase kWh consumption. States could address this conflict by reformulating their metrics or including an electrification carve-out in their standards. New York state, for example, recently adopted a statewide cumulative annual site energy savings target that is delineated in British thermal units and will incentivize the most cost-effective efficiency measures across all fuels. States can also consider including a classification or “tier” in their renewable portfolio standards (as Vermont has done) requiring utilities to meet part of their portfolio obligation by pursuing programs or activities that meet criteria for beneficial electrification.

Many traditional energy efficiency programs also have blanket prohibitions on switching customers between electric and natural gas service, or prohibitions against utility programs that increase load. We encourage states to apply the three BE conditions to consider whether electrification programs, fuel switching, and associated load growth are indeed in the public interest, and how these prohibitions may need to be altered.

Finally, as with all energy policies, affordability affects the ability of all customer classes to share equitably the benefits of electric water heating. As states identify electrification goals and make plans for its deployment, they will need to ensure that low-income customers are not left behind. Low-income households typically have older and less efficient appliances and less thermally efficient housing, which could, in turn, hinder appliance efficiency. State programs can recognize these circumstances and help address the gap in affordability.

Due to the electric sector’s declining emissions, consumers can now produce fewer pounds of pollution per gallon of water heated.

Rate Design

Customers are willing to shift their electricity consumption to cheaper hours of the day when the financial incentive is meaningful. To enable them to do so, time-varying pricing can communicate cost differences at different times of the day. This type of pricing provides an economic incentive to commercialize technologies that provide demand flexibility, thereby enabling load shifting and the economical provision of ancillary services.

Rates shape the way consumers use the grid. Grid managers can use rates—especially in combination with technology that can automate many decisions—to motivate customers and enlist their help in making more efficient use of existing grid investments and avoiding unnecessary new investments.

Incentives and Other Programs

Financial incentives—including rebates, loans, or tax incentives offered by utilities, third parties, or government programs—can drive electrification. Some utilities are experimenting with incentives for builders, which can promote electrification in new construction. Others are offering discounts to ratepayers to enroll their water heaters in grid control programs.

Early appliance retirement programs can also help customers make more reasoned decisions about water heater replacement. Rather than having to make purchase decisions under the duress that often accompanies an appliance breakdown, customers can consider replacing aged appliances in a more thoughtful and reasoned manner. Early retirement programs can identify appliances that are nearing the end of their useful lives, then work with customers to replace them before an emergency purchase is required.

Financial incentives—including rebates, loans, or tax incentives offered by utilities, third parties, or government programs—can drive electrification.

The beneficial electrification of water heating constitutes an economical and practical path forward for saving consumers money, better managing the power grid, and reducing greenhouse gas emissions. In this paper, the authors apply RAP's three BE conditions to illustrate electric water heating opportunities available today and in the near future. With a closer look, state and local decision-makers are likely to appreciate these opportunities and the economic and consumer benefits they will bring.

Opportunities in a Changing Energy Sector

Reversing the current reliance on direct use of fossil fuels for water heating can benefit consumers, the grid, and the environment.

Today there is an opportunity to replace fossil-fueled equipment with more efficient electrically fueled equipment, enabling consumers to better control and reduce the cost of their energy use. Put simply, today it can take far less energy to heat a gallon of water electrically than with fossil fuel. This is due to the improved efficiency of both electricity generation and end-use appliances.

The consumer economics of switching to electricity may not be compelling in all situations at current fuel prices, but as electric technologies continue to improve in efficiency and decline in cost, potential benefits for consumers can be expected to increase.

In 2015, residential and commercial buildings in the United States accounted for about 40 percent of primary, or total, energy consumption—the single largest share.[1] Residential and commercial buildings also accounted for a significant share of energy consumption at the point of customer use. Water heating is about 18 percent of residential energy use.[2]

In this paper, we explore strategies available to electrify water heating loads—electric resistance (ER) and heat pump (HP) water heaters—as a means of contributing to the transition to a low-carbon economy. Water heating is an example of an electrical end use that can reduce reliance on fossil fuels and make energy use cleaner and more efficient.

In our paper *Beneficial Electrification: Ensuring Electrification in the Public Interest,* we established that for electrification to be considered beneficial, it must meet at least one of three conditions without adversely affecting the other two.[3] These conditions are:

1. Saves consumers money over the long run;
2. Enables better grid management; and
3. Reduces negative environmental impacts.

As an illustration of beneficial electrification (BE), consider a homeowner's replacement of a propane-fired water heater that failed with a more efficient heat pump model. Instead of paying $25 a month for propane water heating and $50 a month for the home's general electricity use, the homeowner might pay a $60 monthly electricity bill while no longer having a propane bill. The $15 difference in her combined monthly energy spending would reflect an overall reduction in energy cost despite the increase in kilowatt-hour (kWh) consumption. This illustrates how electrification can be a more economic investment and save consumers money over the long run. The consumer economics of fuel switching may not be compelling for all applications or every region of the country at current fuel prices, but as electric technologies continue to improve in efficiency and decline in cost, potential benefits for consumers can be expected to increase.[4]

Electric water heaters also enable improved grid management through control of their energy use, or "charging."[5] Electrification load is often relatively flexible in when it draws power from the grid. As long as customers can take a hot

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[1] Jadun, P., McMillan, C., Steinberg, D., Muratori, M., Vimmerstedt, L., and Mai, T. (2017). *Electrification futures study: End-use electric technology cost and performance projections through 2050* (NREL/TP-6A20-70485). Golden, CO: National Renewable Energy Laboratory. Retrieved from https://www.nrel.gov/docs/fy18osti/70485.pdf

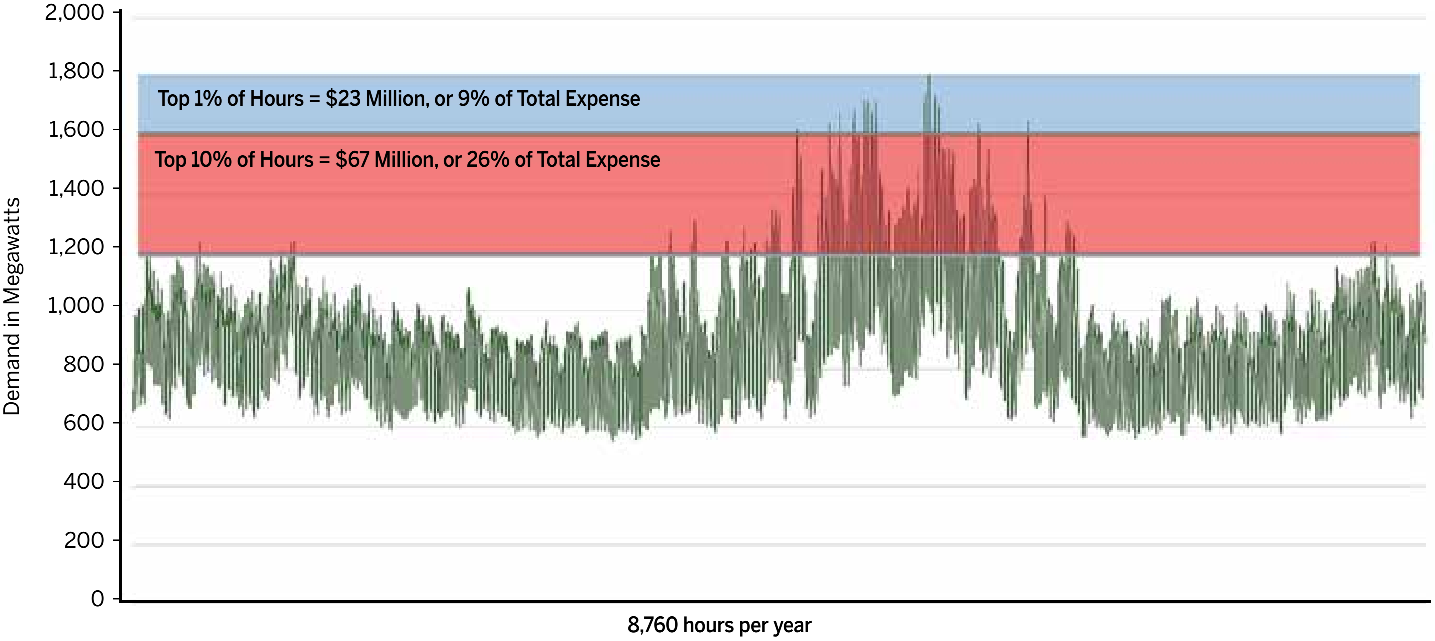
[2] US Department of Energy, Office of Energy Efficiency & Renewable Energy. *Water heating* [Webpage]. Retrieved from https://www.energy.gov/energysaver/heat-and-cool/water-heating. See also Walker, A. (2016, November 16). Solar water heating. *Whole Building Design Guide* [Webpage]. National Institute of Building Sciences. Retrieved from https://www.wbdg.org/resources/solar-water-heating

[3] Farnsworth, D., Shipley, J., Lazar, J., and Seidman, N. (2018, June). *Beneficial electrification: Ensuring electrification in the public interest.* Montpelier, VT: Regulatory Assistance Project. Retrieved from https://www.raponline.org/knowledge-center/beneficial-electrification-ensuring-electrification-public-interest/

[4] Although this paper focuses on electrification, we acknowledge there is room for improved efficiency of currently electrified end uses and that this will contribute to reducing the costs of electrification.

[5] Like other demand response resources, managed electrification load has the potential to help utilities keep their systems stable and efficient; to defer upgrades to generation, transmission and distribution systems; and to deliver economic benefits to consumers. See Alstone, P., Potter, J., Piette, M.A., Schwartz, P., Berger, M., Dunn, L.N., et al. (2017). *2025 California demand response potential study—Charting California's demand response future: Final report on Phase 2 results.*. Berkeley, CA: Lawrence Berkeley National Laboratory. Retrieved from http://eta-publications.lbl.gov/sites/default/files/lbnl-2001113.pdf

Figure 1. Peak Energy Demand and Spending in Rhode Island, 2016



Source: Rhode Island Division of Public Utilities & Carriers, Office of Energy Resources, and Public Utilities Commission. (2017). *Rhode Island Power Sector Transformation: Phase One Report to Governor Gina M. Raimondo.*

shower when desired, they don't care about when their water heater is drawing power. As a result, water heaters can serve as thermal storage of energy supplied at other times of the day.

Because of this flexibility, water heating load can be valuable to grid operators or others like aggregators who can control and manage it. For example, it can help move load away from more expensive peak usage periods to times when there is less demand for electricity and it costs less.

Figure 1 illustrates the costs borne by Rhode Island ratepayers—millions of dollars—that might be avoided by shifting this flexible load.[6] In 2016, the top 1 percent of peak load hours cost 9 percent of the total amount spent on electricity; the top 10 percent of peak load hours cost more than a quarter of what was spent that year on electricity. The capability to move load away from peaks is of high value to utilities and when shared could be a source of savings for consumers.

Furthermore, being able to move water heating load can also help grid managers avoid the curtailment of variable renewable resources. For example, if the wind is blowing in the middle of the night when other loads are small, flexible electric demand can make use of wind generation that would otherwise be wasted.

The savings from these and other management strategies can be shared with customers through time-varying rate designs that encourage them to take advantage of cost-cutting opportunities and discourage them from adding electric load at times that could raise system costs, affecting all consumers.

The electrification in the homeowner example on the previous page can also be beneficial because it can reduce emissions of air pollutants. First, the replacement of a relatively less efficient propane water heater with an HP unit immediately avoids propane-related emissions. Second, as the emissions from generating the electricity that fuels the heat pump decrease over time, the appliance is positioned to produce fewer emissions.

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[6] Rhode Island Division of Public Utilities & Carriers, Office of Energy Resources, and Public Utilities Commission. (2017). *Rhode Island power sector transformation: Phase One report to Governor Gina M. Raimondo*. Retrieved from http://www.ripuc.org/utilityinfo/electric/PST%20Report_Nov_8.pdf

Matching Technology to Water Heating Needs

The optimal choice of electrified water heating technology depends on factors such as housing type and region.

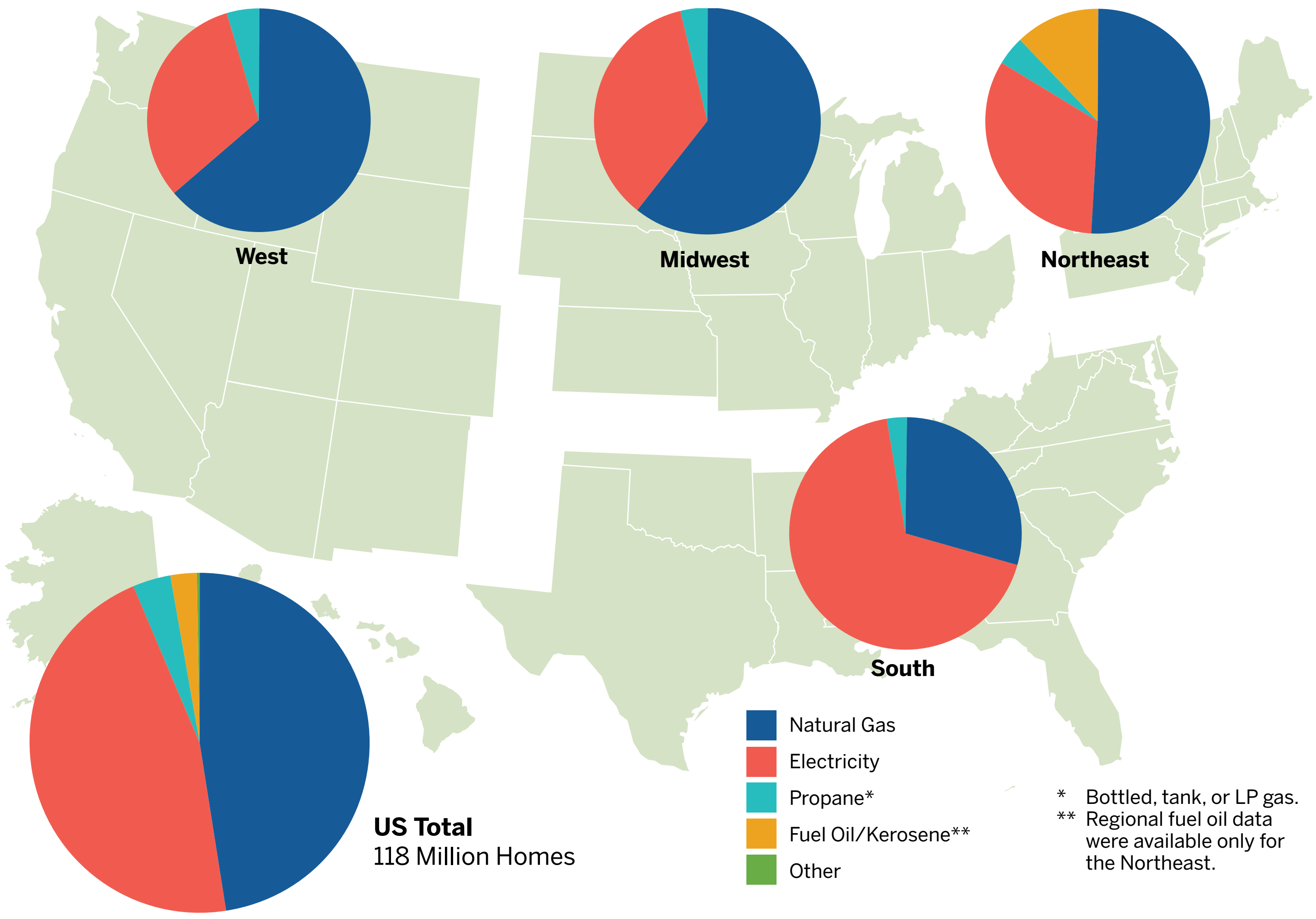
Beneficial electrification is a collection of strategies designed to identify and overcome barriers and take advantage of technology trends to benefit consumers, grid operations, and the environment. In the case of water heating, this means analyzing the suitability of replacing fossil-fueled technologies with electrical technologies. To better understand opportunities for electric water heating, the following discussion will first identify technology options, then consider how they might vary by factors that include region and housing type.

Technology Overview

For purposes of illustrating BE opportunities, we examine two technology options for electrification of water heating: electric resistance water heaters and air source heat pump water heaters. Although they have different cost and operating characteristics, each is likely to have a place in a future that includes increased electrification.[7]

Currently, electric water heating is not uniformly distributed around the country. It is dominant in the Southeast and less popular but still common in the West, the Midwest,

Figure 2. Fuels Used for Water Heating in Primary Residences



Source: US Energy Information Administration. (2018, May). *2015 Residential Energy Consumption Survey.*

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[7] There are also emerging water heating technologies that we do not describe in detail but are still worth noting. One is a thermal exchange water and space heating system that draws heat from wastewater discharged from buildings. Another is a carbon dioxide-based heat pump water heater for multi-family residences, with a single water heater serving multiple units. Another is a single heat pump outdoor unit that provides space heating, space cooling, and water heating. Observations based on Jim Lazar conversation with Fred Fletcher, former assistant general manager of Burbank Water and Power.

and New England, as Figure 2 on the previous page illustrates.[8]

Electric water heating is also largely concentrated in single-family homes. Table 1 shows the distribution of different types of water heating in the US by housing type.[9]

There are also differences among states and between urban and rural areas within these regions. Averaged across the country, water heating accounts for about 18 percent of residential energy use (see Figure 3).[10]

Conventional electric resistance water heaters are essentially tanks containing one or more submerged electric heating elements. Their efficiency is often expressed as an energy factor representing the percentage of input energy that is ultimately delivered to the end use. The greater the energy factor, the more efficient the appliance.[11] Energy factors for ER water heaters are generally higher than 0.9—denoting 90 percent efficiency—and often close to 1.0.[12]

HP water heaters are tanks with heat pumps attached to them. Although in warmer climates heat pump compressors may be located outside, they typically take heat from indoor ambient air and use it to heat water.[13] Heat pump water

Table 1. Water Heating in Primary US Homes by Housing Type

	Total US	Single-family detached	Single-family attached	Apartment (two- to four-unit building)	Apartment (five- or more unit building)	Mobile home
All homes	118.2	73.9	7.0	9.4	21.1	6.8
Fuel used by main water heater						
Natural gas	56.3	37.4	4.0	5.0	9.0	0.9
Electricity	54.6	31.2	2.9	3.9	11.2	5.3
Propane	4.2	3.2	N	N	N	0.5
Fuel oil/kerosene	2.8	1.8	N	N	0.7	N
Other	0.3	0.2	N	N	N	N
Size of main water heater						
Small *(30 gallons or less)*	15.3	7.2	0.8	1.9	3.1	2.3
Medium *(31 to 49 gallons)*	51.8	37.3	4.2	2.0	4.9	3.5
Large *(50 gallons or more)*	31.8	26.9	1.8	1.0	1.2	1.0
Tankless	3.0	2.6	0.2	N	N	N
Central unit in an apartment building	16.3	N	N	4.4	11.8	N

N=No data available.

Source: US Energy Information Administration. (2018, May). *2015 Residential Energy Consumption Survey.*

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[8] US Energy Information Administration. (2018, May). *2015 Residential energy consumption survey,* Tables HC8.7 and HC8.8. Retrieved from https://www.eia.gov/consumption/residential/data/2015/hc/php/hc8.7.php and https://www.eia.gov/consumption/residential/data/2015/hc/php/hc8.8.php

[9] US Energy Information Administration, 2018, Table HC8.1. Retrieved from https://www.eia.gov/consumption/residential/data/2015/hc/php/hc8.1.php

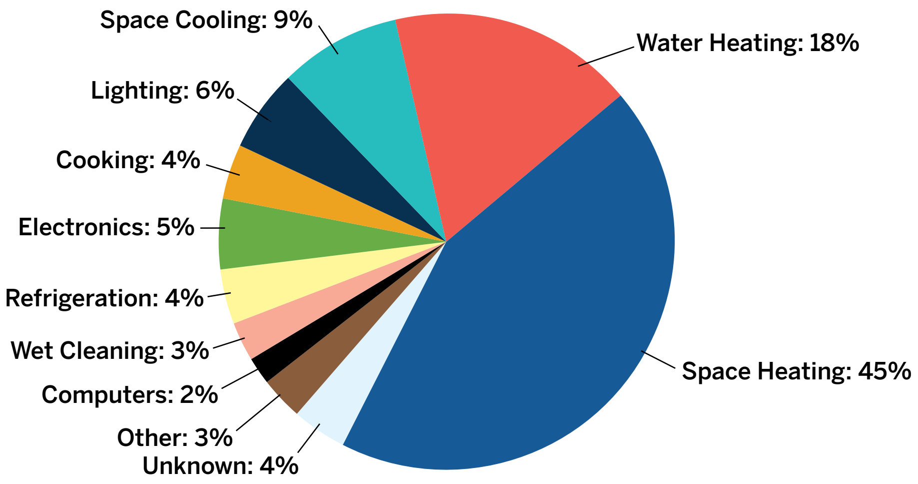
[10] US Department of Energy, Office of Energy Efficiency & Renewable Energy. (2012, March). *2011 Buildings energy data book.* Washington, DC: Author. Retrieved from https://openei.org/doe-opendata/dataset/6aaf0248-bc4e-4a33-9735-2babe4aef2a5/resource/3edf59d2-32be-458b-bd4c-796b3e14bc65/download/2011bedb.pdf

[11] Furnace Compare. *Energy factor and water heaters* [Webpage]. Retrieved from https://www.furnacecompare.com/faq/definitions/energy-factor.html

[12] Shapiro, C., Puttagunta, S., and Owens, D. (2012, February). *Measure guideline: Heat pump water heaters in new and existing homes.* Washington, DC: US Department of Energy, Office of Energy Efficiency & Renewable Energy. Retrieved from https://www1.eere.energy.gov/buildings/publications/pdfs/building_america/measure_guide_hpwh.pdf

[13] For a more complete description of the capabilities of various types of heat pumps in different climates, see the Technology Overview section of Shipley, J., Lazar, J., Farnsworth, D., and Kadoch, C. (2018, November). *Beneficial electrification of space heating.* Montpelier, VT: Regulatory Assistance Project. Retrieved from https://www.raponline.org/knowledge-center/beneficial-electrification-of-space-heating

Figure 3. Water Heating is the Second Largest Component of Home Energy Use



"Wet cleaning" includes clothes washers and dryers and dishwashers.

Source: US Department of Energy. (2012, March). *2011 Buildings Energy Data Book*.

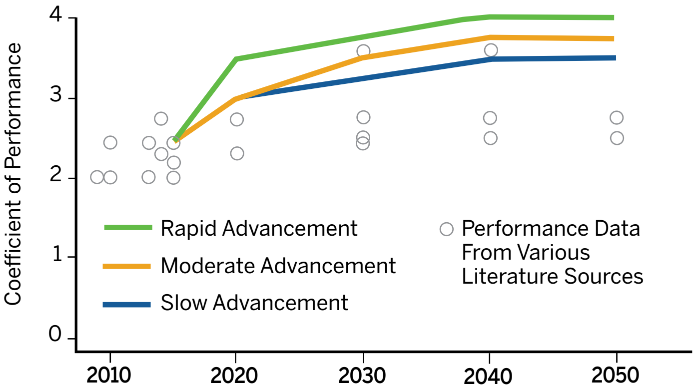
heater efficiency is expressed as a coefficient of performance (COP).[14] As of 2016, 12 manufacturers offered Energy Star-qualified HP water heaters. As newer technologies, they currently represent a very small share of installed electric water heaters.[15]

Based on performance data from a suite of literature sources, a National Renewable Energy Laboratory (NREL) analysis identified three scenarios for future HP water heater performance, illustrated in Figure 4.[16] They start with a COP of 2.5 today but increase in efficiency to a COP of 3.0 in 2020 even under NREL's least favorable development case, the "slow advancement" scenario. This suggests that heat pump water heater efficiencies can be expected to improve in the relatively near term.

Table 2 on the next page provides a summary of water heating technologies and their capabilities.

Although ER water heaters can operate independently of ambient air temperature and be used year-round without concern for climatic conditions, climate can affect the suitability of heat pump alternatives. Figure 5 on Page 21 is a climate zone map[17] that US Department of Energy

Figure 4. Heat Pump Water Heater Performance Projections



Source: Jadun, P., McMillan, C., Steinberg, D., Muratori, M., Vimmerstedt, L., and Mai, T. (2017). *Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections Through 2050.*

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[14] COP represents the same information as energy factor. For a brief further explanation of COPs and energy factors, see the Appendix.

[15] Jadun et al., 2017, p. 44. A list of Energy Star-certified water heaters can be found at https://data.energystar.gov/Active-Specifications/ENERGY-STAR-Certified-Water-Heaters/3gp2-af4x/data.

[16] Jadun et al., 2017, p. 44.

[17] Baechler, M., Williamson, J., Gilbride, T., Cole, P., Hefty, M., and Love, P. (2010, August). *High-performance home technologies: Guide to determining climate regions by county* (PNNL-17211). Washington, DC: US Department of Energy, Office of Energy Efficiency & Renewable Energy. Retrieved from https://www1.eere.energy.gov/buildings/publications/pdfs/building_america/ba_climateguide_7_1.pdf

Table 2. Summary of Electric Water Heating Technologies

Electric resistance water heaters
An ER water heater is a tank containing one or more submerged heating elements. Ways of making a completely passive water heater “smarter” include putting it on a timer that can limit usage to utility off-peak periods. Millions of smart electric resistance water heaters are in service today at utilities with time-varying rates or water heat-specific rates. Other smart controls are discussed below.
Heat pump water heaters
HP water heaters are tanks with heat pumps attached directly to them. They, too, can be smart, responding to grid needs and price signals, as discussed below.[18]
Grid-integrated water heaters
Both electric resistance and heat pump water heaters can be integrated into the grid with the use of control systems that allow the end user, grid operator, aggregator, or another party to monitor the state of “charge” (that is, the water temperature) and control charging to enable, for example, demand response and load shifting. Water heaters may have built-in timers, Wi-Fi,[19] or another utility interface (e.g., open standard for connecting to the internet) so they can receive a grid signal.[20] Passive water heaters can be retrofitted to turn them into signal-receiving smart appliances.[21]

researchers developed based on the average annual number of heating and cooling degree days.[22] States throughout the Southern tier in the red, orange, yellow, and even green areas have limited heating needs due to their relative warmth. With generally higher ambient air temperatures, these are areas where heat pumps are especially effective at meeting water heating needs.

Conversely, if one were to consider only cooling degree days, one would see the areas where HP water heaters are most efficient corresponding to areas where there is high demand for air conditioning.[23] Heat pump water heaters expel cool and dehumidified air. This can be used to positive effect in a home already trying to cool itself during warm weather.

Heat pump water heaters expel cool and dehumidified air. This can be used to positive effect in a home already trying to cool itself.

Because residential HP water heaters are often located indoors and draw heat from that space, they are less likely to

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[18] Although not discussed in detail in this paper, split system HP water heaters are larger units currently available in the commercial sector but with promising applications in multi-family housing. They receive an incoming stream of potable water, extract heat from either the ambient air or the incoming water, and transfer this heat into the water output stream. The resulting chilled air or water can be used for air conditioning or other purposes. Hotels, restaurants, and others currently using separate systems for heating water and chilling air are the primary market for this technology now, but residential applications are emerging.

[19] For example, products by Rheem with EcoNet, for both electric resistance and heat pump water heaters. See https://www.rheem.com/econet/.

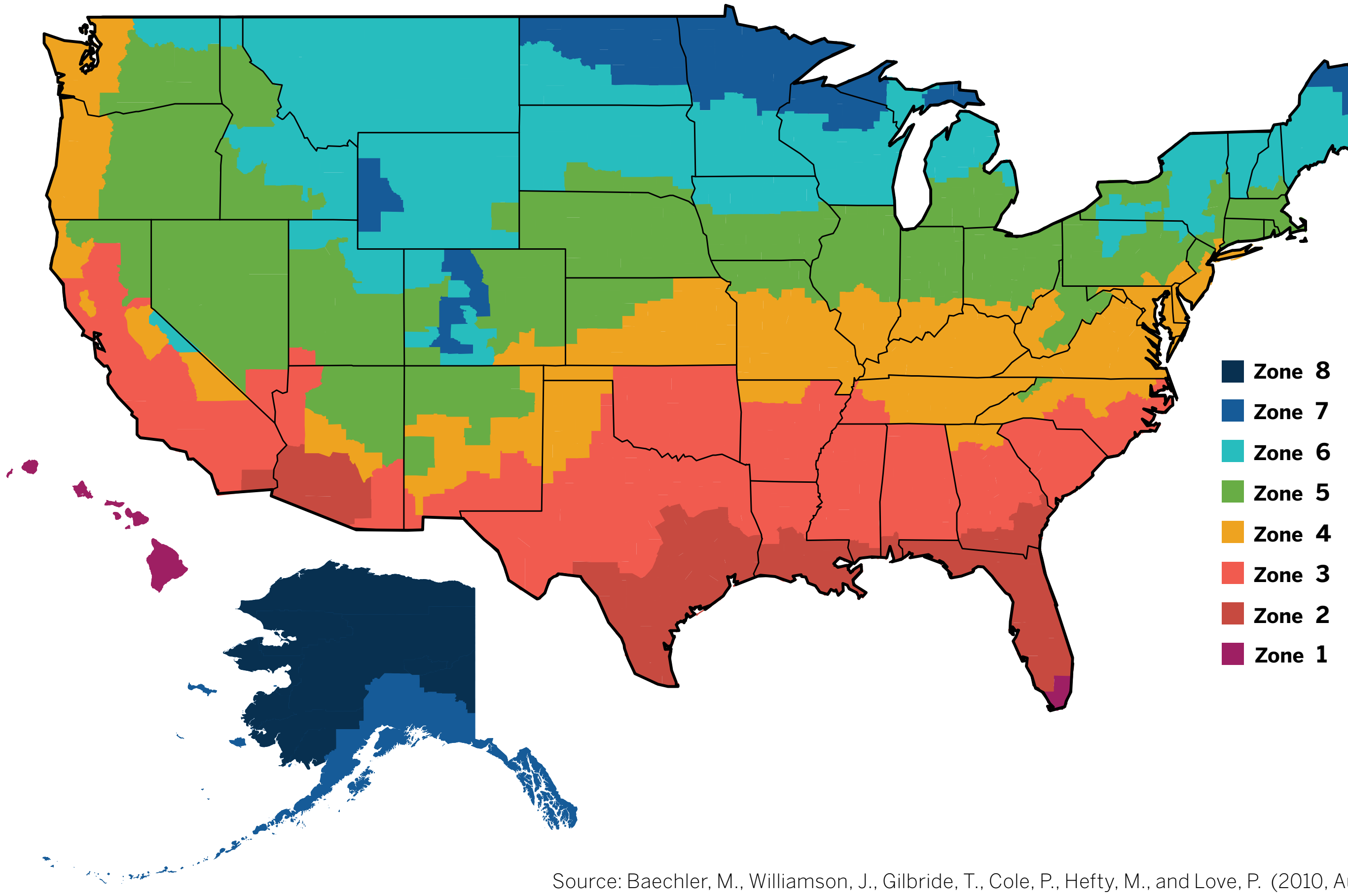
[20] For example, a CTA-2045 port. See A.O. Smith Corp. and SkyCentrics. *Grid connected water heater solution with CTA-2045* [Video]. Retrieved from https://www.youtube.com/watch?v=baPmqPgQhDE. See also Energy and Environmental Economics Inc. (2014, January). *Investigating a higher renewables portfolio standard in California*. San Francisco, CA: Author. Retrieved from https://www.ethree.com/wp-content/uploads/2017/01/E3_Final_RPS_Report_2014_01_06_ExecutiveSummary-1.pdf

[21] The Center for Energy and the Environment has been conducting a “Field Study of Intelligent, Networked, Retrofittable Water Heater Controller.” See https://www.mncee.org/resources/events-webinars/2018/field-study-of-an-intelligent,-networked,-retrofit/. See also Aquanta Inc. product information at https://aquanta.io/ and CarinaTechnology Inc. product information at http://www.carinatek.com/products.html.

[22] The National Weather Service characterizes heating and cooling degree days as based on an assumption that when the outdoor temperature is 65 degrees, there is no need for either cooling or heating in order to be comfortable. “Degree days are the difference between the daily temperature mean, (high temperature plus low temperature divided by two) and 65°F. If the temperature mean is above 65°F, we subtract 65 from the mean and the result is Cooling Degree Days. If the temperature mean is below 65°F, we subtract the mean from 65 and the result is Heating Degree Days.” See National Weather Service. *What are heating and cooling degree days* [Webpage]. Retrieved from https://www.weather.gov/key/climate_heat_cool

[23] See, for example, El Dorado Weather. *Mean total cooling degree days* [Webpage]. Retrieved from https://eldoradoweather.com/climate/US%20Climate%20Maps/Lower%2048%20States/Temperature/Mean%20Total%20Cooling%20Degree%20Days/Gallery/mean-total-cooling-degree-days.html

Figure 5. Climate Zones by Number of Heating and Cooling Degree Days



Source: Baechler, M., Williamson, J., Gilbride, T., Cole, P., Hefty, M., and Love, P. (2010, August). *High-Performance Home Technologies: Guide to Determining Climate Regions by County.*

experience a performance decline in colder climates than air source heat pumps for space heating, which rely on outside air.

Actual field-tested HP water heater ratings may differ from standard reported ratings for reasons besides climate. For example, improper installation can result in insufficient airflow. The temperature of incoming water may also reduce efficiency. Oversizing relative to need can result in overconsumption and increased standby losses (that is, cooling that occurs when the tank is idle). It is also important in colder climates to account for the cooling of indoor air as the heat pump extracts warmth to heat water.[24]

Recognizing these caveats, in this paper we assume a COP of 3.0 for HP water heaters. Due to climatic conditions, homes in half the country can expect to experience better efficiencies than that. We also find the implications of NREL's "slow" and "moderate" advancement scenarios compelling. Both cases project HP water heater COPs of 3.0 by 2020. In other words, it is reasonable to expect efficiency and performance to improve in the near term, increasing their suitability in parts of the country with higher-than-average heating degree days.

Optimal Water Heating Options Vary by Housing Type

Different types of housing are amenable to different water heating options, reflecting another issue to consider when electrifying water heating. Factors such as housing type (single family, apartment, or manufactured home), number of units served, and age of the dwelling all help determine what option works best. Table 3 on the next page provides greater detail about water heating options for major housing types.

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[24] Harris, J., Neme, C., and Calwell, C. (2005, November). *Residential heat pump water heaters: Energy efficiency potential and industry status.* New York, NY: Natural Resources Defense Council.

Table 3. Electric Water Heating Options for Various Housing Types

Existing apartments

Most low-rise apartments in the US that heat water electrically have individual electric resistance water heaters. These dwellings are typically built with only cold-water service to each unit, meaning that retrofit to solar or central hot water systems could be difficult and expensive. For these buildings, controlled ER water heaters may be suitable.[25] Several utilities are implementing this strategy, including Portland General Electric[26] and Hawaiian Electric Co.[27] In existing apartments, the economical choice may be to install controlled ER water heaters when existing appliances fail or to retrofit existing water heaters with control devices.

Although space and other constraints in some multi-family buildings will pose a challenge to installing heat pump water heaters, that is not universally the case. Where these aren't concerns, HP models are also well-suited for this housing type.

New apartments

Newly constructed apartments are good candidates for shared heat pump water heating. Changes to building codes are needed in many areas to enable the use of shared water heaters.

Large multi-family buildings with central water heat

In this housing type, where gas boilers are a common source of both hot water and heating energy, a commercial-type HP water heater may be an appropriate choice, providing both hot water and chilled water that can be used for air conditioning.

Existing single-family homes

Homeowners desiring electric water heating will need to consider a number of factors—for example, available space and the suitability of existing plumbing and electric service installation. Owners may need to enlist contractors or other specialists to ensure proper installation of whatever water heating appliance they choose. For example, because HP water heaters expel cool air and can be as loud as a dehumidifier, they are often installed in a basement or a part of the house where these factors are not an issue. HP water heaters require air circulation and space around the unit. In addition to these points, it is important for homeowners to ensure proper sizing of the appliance itself.

Houses with existing natural gas service will be the least cost-effective to convert to electric water heating. Conversion will be more attractive where a dwelling can also switch to heat pumps for space heating and thereby potentially eliminate monthly fixed charges for natural gas service, typically $10 to $20. Converting space heating and cooling and water heating simultaneously could also reduce the incremental cost of electric water heat installation. Because converting from natural gas represents a major investment, it is less likely without support or incentive programs.

Houses that heat with oil or propane may be good candidates for conversion to electric water heating when the existing furnace or boiler needs to be replaced. Homes that heat with these fuels tend to be in colder climates, so the performance of cold climate heat pumps may be a factor in the economic calculation. These homes may be more rural and may not have natural gas service available, further improving the economics of switching.

New single-family homes

Newly constructed homes are excellent candidates for installation of heat pump water heating in combination with HP space conditioning. Developers can avoid the cost of extending natural gas service and pass those savings on to homebuyers. Houses can be configured to put the water heater in a carport, garage, or basement, where any sound impacts are negligible.

Existing manufactured homes

Manufactured homes typically have electric resistance water heaters. Many of these homes are constructed in a way that will not accommodate larger HP water heaters due to size or airflow. For these homes, grid-integrated ER water heaters may be the logical option. Coupled with time-varying rates, the economic savings could justify the additional expense.

New manufactured homes

Newly constructed manufactured homes may be capable of designs that accommodate HP water heaters. If not, grid-integrated ER units may be a reasonable option. Coupled with time-varying rates, the economic savings could justify the additional expense.

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[25] This example of moving from less efficient to more efficient electrical water heating, although a form of optimization, is not electrification (i.e., moving from a fossil-fueled end use to an electrical end use) as we have defined it in this paper. It is important, however, to recognize that electrification-related activities can still produce greater efficiencies and that complementary efficiency policies can improve the effects of electrification.

[26] Personal communication with Conrad Eustis, Portland General Electric.

[27] Personal communication with Rich Barone, Hawaiian Electric Co.

Meeting the Conditions for Beneficial Electrification

Electrified water heating has the ability to save consumers money, make the grid more flexible, and reduce carbon emissions.

As noted previously, electrification is beneficial only if it satisfies at least one of the following criteria, without adversely affecting the other two:

1. Saves consumers money over the long run;
2. Enables better grid management; and
3. Reduces negative environmental impacts.

In this section we look at several types of electric water heating and whether they satisfy this test.

New construction can avoid the costs of connecting to the natural gas supply network, making heat pumps comparatively more economical.

Consumer Economics

The first condition of BE is that it benefits consumers economically. This means end-use consumers will save money over the lifetime of an electric water heating technology as compared with the fossil-fueled alternative that would otherwise be used. Determining whether electrification will be cost-effective for consumers is a situation-specific calculation affected by several factors.

Factors Affecting Economics

Although heat pump water heaters may be the most cost-effective option available for most applications, they will not be suitable for all situations. Controlled electric resistance water heaters can be cost-effective for consumers under certain conditions, primarily where low-cost electricity is available at certain times of the day, or where there are constraints on HP installation. Below we describe some of the factors affecting the economics of consumer decisions to switch from fossil-fueled technologies to electric water heating or to have it installed during building construction.

1. **Building type** may affect which technologies can be installed. For example, the space in existing apartments may be limited and constrain the choices of water heating technology. New construction can avoid the costs of connecting to the natural gas supply network, making HP water heaters comparatively more economical. To explore the economics of water heating, we focus primarily on existing single-family homes.
2. **Installed cost of the electric appliances** themselves, and specifically the incremental cost above that of an alternative, strongly influences whether consumers adopt a technology. If electric options cost more than fossil-fueled alternatives, consumers able to pay the incremental cost will need to save money on operation and maintenance over the lifetime of the appliance to make the economics work. The incremental difference in cost between an electric appliance and the alternative will also affect the reasonableness and ability of utility programs to provide incentives to overcome price differentials.
3. **The cost of energy** also affects whether electrification makes sense for consumers. This requires comparing fuel costs (natural gas, propane, or fuel oil) with electricity costs for supplying an equivalent amount of useful heat. These costs will vary significantly by region. Areas like the Pacific Northwest, Midwest and Southeast with generally low electricity prices[28] will be more favorable for electrification than higher-cost regions like California and the Northeast. In addition to the cost of energy at the time of installation, projected changes in fuel costs over the life of the appliance should be considered when analyzing the total costs of ownership.
4. Whether **space heating and cooling** is being installed simultaneously or being added could affect the economics of electric water heating. Installing the technologies together may reduce their incremental upfront costs—for example, through labor savings or discounts on equipment purchases. Additionally, contractor familiarity with these complementary technologies could mean more effective installation, operation, and maintenance.

Current Economics

According to the US Energy Information Administration, out of approximately 118 million primary residences, 56 million homes use natural gas for their main source of water heating.[29] About 55 million use electricity, and about 7 million use

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[28] US Energy Information Administration. (2018, January 25). *State electricity profiles* [Webpage]. Retrieved from https://www.eia.gov/electricity/state/

[29] US Energy Information Administration, 2018, May, Table HC8.1.

propane or fuel oil. Although natural gas water heating is most common, the relatively high cost of propane and fuel oil makes them more economically attractive options for electrification. The following discussion considers each of these in turn.

Economics generally favor converting oil and propane water heaters to heat pumps. In 2018, the American Council for an Energy-Efficient Economy (ACEEE) published a study of the energy, financial, and emissions impacts of replacing failed oil and propane furnaces, boilers, and water heaters with high-efficiency heat pumps.[30] With regard to water heating, ACEEE found that HP water heaters "often have lower initial costs than oil water heaters in addition to their lower operating costs." Even though HP alternatives are more expensive than propane water heaters, their "lower operating costs typically pay back to consumers in less than five years."[31]

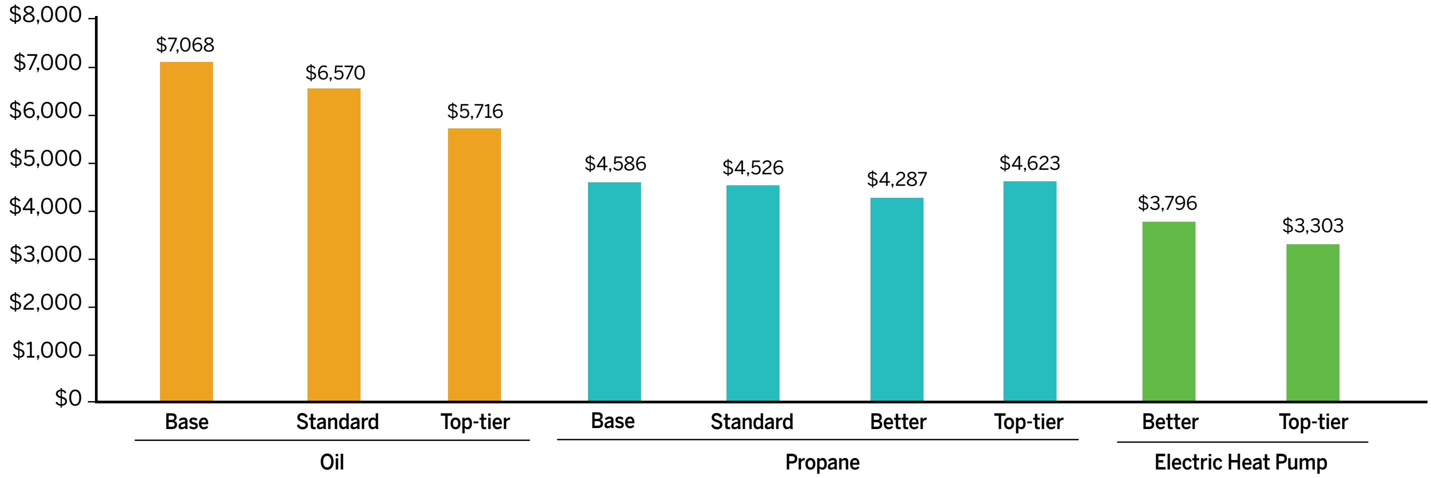
The ACEEE study concluded that HP water heaters offer substantial life cycle savings relative to oil and modest savings by comparison to propane water heaters (see Figure 6).[32]

ACEEE generally concluded that HP water heaters "cost less to purchase and install than oil water heaters" and that the "simple payback relative to oil water heaters is immediate."[33]

Regarding the replacement of propane water heaters, ACEEE found that heat pump alternatives "typically pay back in about 3-4 years at reference case prices, 2-3 years at high prices, and 5-8 years at low prices."[34] Figure 7 on the next page illustrates these conclusions.[35]

The economics of replacing natural gas water heaters with HP models produce different results. While the ACEEE analysis is limited to switching from oil and propane, the simple calculation in Table 4 on the next page illustrates the annual costs and savings of switching from natural gas when a water heater fails.[36] Assuming average electricity rates, the annual cost savings, $45, are modest. However, with an illustrative time-of-use electricity rate, the annual

Figure 6. Life Cycle Cost of Water Heaters



Source: Based on Nadel, S. (2018). *Energy Savings, Consumer Economics, and Greenhouse Gas Emissions Reductions From Replacing Oil and Propane Furnaces, Boilers, and Water Heaters With Air-Source Heat Pumps.*

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[30] Nadel, S. (2018). *Energy savings, consumer economics, and greenhouse gas emissions reductions from replacing oil and propane furnaces, boilers, and water heaters with air-source heat pumps* (Report A1803). Washington, DC: American Council for an Energy-Efficient Economy. Retrieved from http://aceee.org/research-report/a1803

[31] ACEEE's analysis focused nationally because it found that water heater energy use does not vary dramatically around the country.

[32] ACEEE assumes a 21-year equipment life and a 5 percent real discount rate. See Nadel, 2018, pp. 14-15. The discount rate is used to determine the present value of future cash flows, taking into consideration inflation and risk. For more information, see Investopedia's explanation at https://www.investopedia.com/terms/d/discountrate.asp.

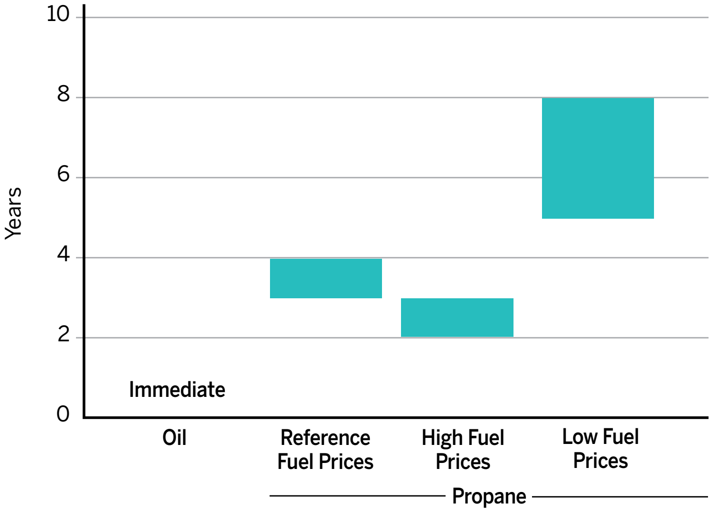
[33] ACEEE recognized that an exception would be where an installation would require a service or circuit upgrade that could raise the cost of conversion. Nadel, 2018, p. 27.

[34] The study analyzed economics for heat pump conversions at the time an existing oil or propane system needs to be replaced. For new construction, the results might be different, as the cost of oil and propane access and oil storage can be avoided.

[35] Nadel, 2018.

[36] The most efficient conventional gas water heaters are Energy Star with a minimum energy factor of 0.67 (which we round to 0.7 for our calculations). This corresponds to estimated gas use of about 230 therms per year, assuming a tank smaller than 55 gallons. US Department of Energy and US Environmental Protection Agency. *Water heaters* [Webpage]. Retrieved from https://www.energystar.gov/products/water_heaters

Figure 7. Payback Periods for Replacing Failed Oil or Propane Water Heater With Heat Pump



Source: Based on Nadel, S. (2018). *Energy Savings, Consumer Economics, and Greenhouse Gas Emissions Reductions From Replacing Oil and Propane Furnaces, Boilers, and Water Heaters With Air-Source Heat Pumps.*

savings more than triple to $157.[37]

Combining these savings with data on installation cost allows us to estimate payback periods. NREL's electrification study characterizes the installed cost (that is, capital and installation) of an HP water heater as ranging from $1,400 to $2,630, depending on the tank volume and efficiency.[38] NREL assumes an average installed cost of $1,990.

Relying on US Energy Information Administration and Sacramento Municipal Utility District data, the authors of another 2017 study found similar installed costs.[39] Additionally, they assume that natural gas water heaters have installed costs of $1,350. Combining these two sets of assumptions, one can expect that the incremental cost of an HP water heater over a gas model is $50 to $1,010.

Assuming this range of incremental costs, a simple payback period for switching to an HP water heater would range from one to 22 years where the yearly savings are $45 on a flat electric rate. On a time-varying rate where the yearly savings are $157, the switch would produce a simple payback period of zero to six years (see Figure 8).

The simple calculation in Table 4 illustrates that the annual cost savings of an HP water heater compared with a natural gas version can be modest. In cases where natural gas service has yet to be extended to a site, however, the installation of a heat pump model can avoid those additional costs. In addition to the cost of energy at the time of installation, projected changes in costs of various fuels over the life of the appliance are also important when assessing total costs of ownership. The next section discusses this and other aspects of the future economics of water heating.

Future Economics

The NREL analysis discussed above examined the consumer economics of electrification, including residential water

Table 4. Annual Cost Savings of Switching From Natural Gas Water Heater to Heat Pump

	Natural gas	Heat pump with standard electric rates	Heat pump with time-of-use electric rates
Amount of fuel	230 therms	1,600 kWh	1,600 kWh
Fuel cost	$1.10/therm	$0.13/kWh	$0.06/kWh (off-peak)
Annual cost of operation	$253	$208	$96
Annual savings by switching	--	$45	$157

Calculations based on gas water heater with energy factor of 0.7 and heat pump with coefficient of performance of 3.0. Fuel prices based on 2017 national averages.

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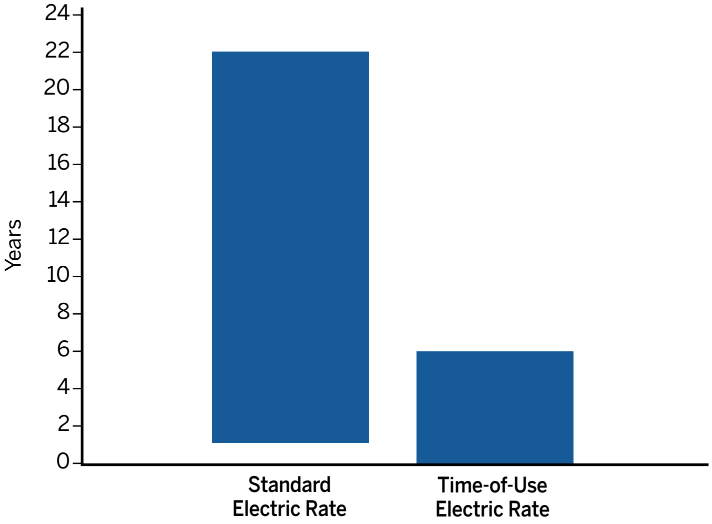
[37] Due to its flexibility, electric water heating load can be managed through a time-of-use rate, and the savings associated with lower-cost off-peak electricity can be shared with consumers. See the section on rate design beginning on Page 47 for further discussion of flexible load and rates.

[38] Jadun et al., 2017.

[39] Raghavana, S.V., Weib, M., and Kammena, D.M. (2017, October). Scenarios to decarbonize residential water heating in California. *Energy Policy, 109,* 441-451, citing US Energy Information Administration. (2015, April). *Updated buildings sector appliance and equipment costs and efficiency,* Appendix A, and ICF International. (2012, January). *Report on societal carbon reduction potential through electrification.* Sacramento Municipal Utility District. Retrieved from https://rael.berkeley.edu/wp-content/uploads/2017/07/Raghavan-Wei-Kammen-WaterHeating-_-ENergyPolicy-2017.pdf

heating, at current and forecast energy prices.[40] The results of the study are not regionally differentiated, in that it used national averages for fuel prices. Regions with lower electricity costs or higher natural gas prices would see more favorable economics than NREL's results, and vice versa for the opposite fuel price conditions.

Figure 8. Payback Periods for Replacing Failed Natural Gas Water Heater With Heat Pump

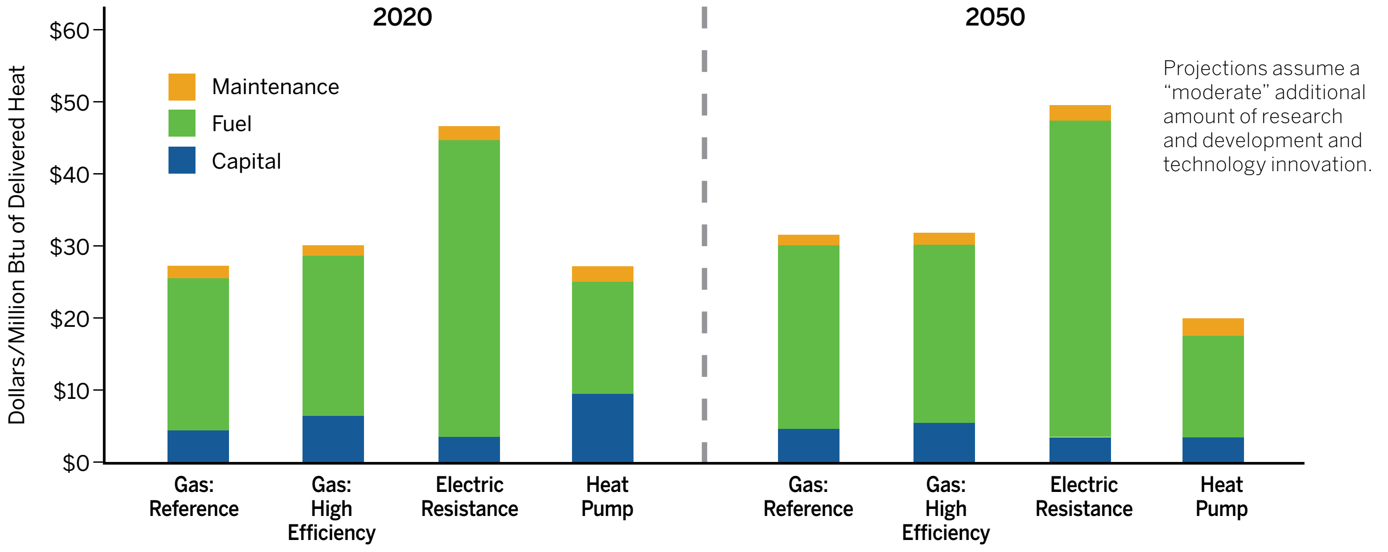


Source: Based on available literature and authors' analysis.

Figure 9 shows that, in NREL's "moderate advancement" scenario, residential HP water heaters are competitive with gas water heaters based on projected 2020 costs and will then begin to provide a cost advantage.[41] In this analysis, a heat pump water heater in 2020 with a levelized cost of service of $27.60 per million British thermal units (Btu) of delivered heat is more economical than a high-efficiency natural gas water heater with a levelized cost of service of $30.60 per million Btu.[42] In regions with electricity costs near or below the national average, it could be economical for new water heaters to be heat pump models. Of course, this observation would also depend on regional gas prices. NREL's findings demonstrate that, at current (or soon expected) installed cost and performance levels, HP water heaters are approaching cost parity with natural gas models.

NREL makes several other findings. Although the capital

Figure 9. Projected Consumer Economics for Water Heaters



Projections assume a "moderate" additional amount of research and development and technology innovation.

Source: Based on Jadun, P., McMillan, C., Steinberg, D., Muratori, M., Vimmerstedt, L., and Mai, T. (2017). *Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections Through 2050.*

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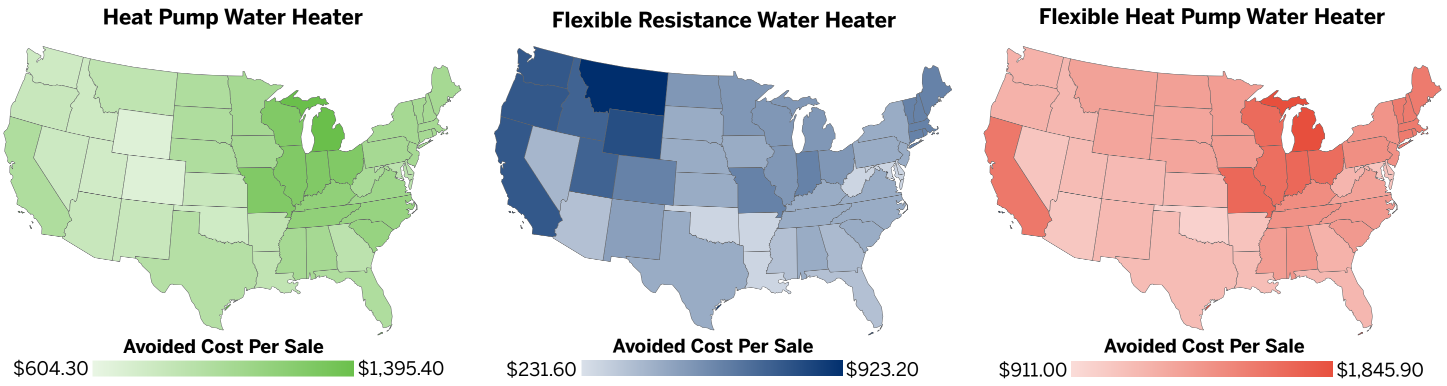
[40] Jadun et al., 2017.

[41] The study analyzed consumer economics at three discount rates (7, 10, and 13 percent) to calculate net present value under various scenarios. The discount rate is used to determine the present value of future cash flows, taking into consideration inflation and risk. We show the results for a 7 percent discount rate. These results reflect the "moderate advancement" scenario, meaning they assume a moderate amount of additional research and development and technology innovation, beyond what is assumed in the "slow advancement" case, will occur. The core components of NREL's analysis include the capital cost, efficiency, and lifetime of an appliance; fuel and maintenance costs; the discount rate associated with the individual adopter; and an assumed usage pattern or capacity factor. Increasing a discount rate makes technologies like water heaters, which have higher upfront capital costs, less cost-competitive. Lowering the discount rate has the opposite effect.

[42] Levelized cost illustrates the net cost to install a water heater system divided by its expected lifetime output. It is an economic assessment of the cost of an investment over its lifetime: initial investment, operations and maintenance, fuel, and cost of capital. See National Renewable Energy Laboratory. *Simple levelized cost of energy (LCOE) calculator documentation* [Webpage]. Retrieved from https://www.nrel.gov/analysis/tech-lcoe-documentation.html

Figure 10. Economic Benefits of Alternatives to Electric Resistance Water Heating



Heat Pump Water Heater

Flexible Resistance Water Heater

Flexible Heat Pump Water Heater

Avoided costs are represented as net present value.

Source: Based on Agan, J., Boyd, E., and Jones, R. (2018). *Energy Efficiency & Flexible Load in Buildings: Integrating Demand-Side Technology Assessments*.

costs for residential HP water heaters make up a larger portion of the levelized costs than for natural gas and ER models, these are offset by long-run fuel savings. Due to their high efficiency, HP water heaters, for example, have lower electricity costs than their electric resistance counterparts.

> At current (or soon expected) installed cost and performance levels, HP water heaters are approaching cost parity with natural gas models.

A recent US Department of Energy presentation identified the net present value[43] of 24 demand-side technologies, including heat pump water heaters (see Figure 10).[44] It found capacity and energy benefits nationwide from residential HP water heaters, but especially capacity benefits concentrated in the West and Northeast, and energy benefits in the Midwest and South. Warmer climate zones are more favorable to electrification due to greater heat pump efficiency. States with low electricity prices are more favorable to electrification due to lower energy costs relative to natural gas. Regions with high differentials between daytime and nighttime electricity rates will also be more favorable for flexible (controlled) electrified water heating.

Figure 10 illustrates that converting to controlled HP water heating produces the highest economic return, but also that controlled electric resistance technology can provide substantial savings.[45] The latter is important, because in cases where space is limited (such as apartments or small manufactured homes), ER water heating may prove more suitable.

Before moving to the next section, where we consider grid management opportunities for water heating, we note that additional benefits may come from having a smart or controlled water heater that can be flexibly managed. For instance, parents with young children are admonished to limit water temperature to reduce the risk of scalding. This is something that can be readily controlled by a smart water heater.[46] Smart water heaters can also employ learning techniques, similar to a smart thermostat, to optimize water heating. This includes, for example, saving energy by not reheating water in the middle of the day when families are at work or school, or enabling deeper temperature setbacks, saving money for homeowners on vacation.

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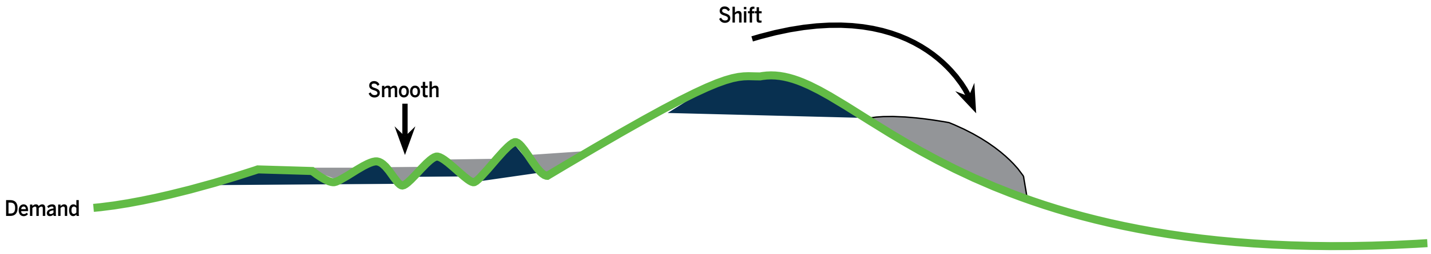
[43] "Net present value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period of time." See Investopedia. *Net present value* [Webpage]. Retrieved from https://www.investopedia.com/terms/n/npv.asp

[44] Agan, J., Boyd, E., and Jones, R. (2018, April). *Energy efficiency & flexible load in buildings: Integrating demand-side technology assessments* [Presentation]. US Department of Energy, Office of Policy. Retrieved from https://docs.wixstatic.com/ugd/a35761_2064b7e5b28c416fb3141752790f5296.pdf

[45] We discuss controlling water heaters in the next section, on grid management.

[46] Mayo Clinic. Burn safety: Protect your child from burns. *Healthy Lifestyle: Infant and Toddler Health* [Webpage]. Retrieved from https://www.mayoclinic.org/healthy-lifestyle/infant-and-toddler-health/in-depth/child-safety/art-20044027

Figure 11. Shifting Electricity Demand



Source: © E Source, adapted from Integral Analytics Inc.

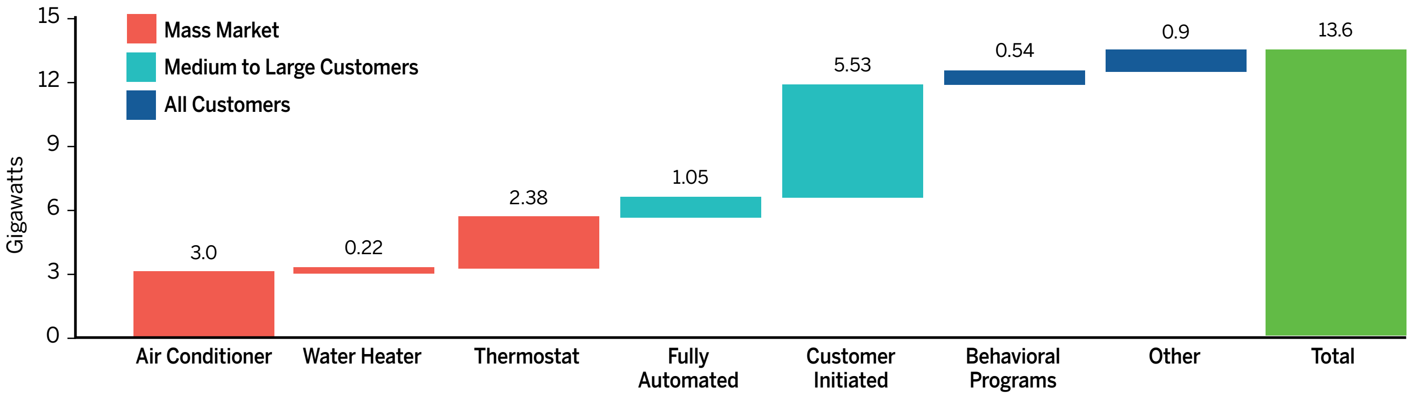
Grid Management

The second BE condition is that electrification can help in managing the grid. Because electric water heating load is controllable, it constitutes a promising opportunity to add flexibility to the grid and serve as a tool for grid operators.[47] Figure 11 characterizes how flexible load can be controlled to shave peaks and smooth out valleys.[48]

For example, water can be heated in the middle of the night and used for showers six hours later. For this reason, The Brattle Group characterizes electric water heaters as “essentially pre-installed thermal batteries that are sitting idle in more than 50 million homes” across the US.[49] Happily, not all are sitting idle. According to a 2017 survey by the Smart Electric Power Alliance, about 2 percent of electric water heaters are participating in utility demand response programs (see Figure 12).[50]

Electricity grids utilize various flexibility tools to ensure the electric power system can respond to variations in load. Electric resistance and heat pump water heaters can be included on that list. The Smart Electric Power Alliance reports that despite being one of the smallest reported categories of demand response, controlling water heaters is “non-disruptive to customers” and is called upon more frequently than other devices.[51] The organization also says that nearly 70 percent

Figure 12. Total 2016 Enrolled Demand Response Capacity



Source: Chew, B., Feldman, B., Esch, N., and Lynch, M. (2017, October). *2017 Utility Demand Response Market Snapshot.*

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[47] Like other demand response resources, managed electrification load has the potential to help utilities keep their systems stable and efficient; to defer upgrades to generation, transmission and distribution systems; and to deliver economic benefits to consumers. See Alstone et al., 2017. According to the Smart Electric Power Alliance, demand response is defined as a distributed energy resource “that is available to control the operability, reliability, and resiliency of grid operations.” See Chew, B., Feldman, B., Esch, N., and Lynch, M. (2017, October). *2017 Utility demand response market snapshot.* Washington, DC: Smart Electric Power Alliance. Retrieved from https://sepapower.org/resource/2017-utility-demand-response-market-snapshot/

[48] Podorson, D. (2014, September). *Battery killers: How water heaters have evolved into grid-scale energy-storage devices*. E Source. Retrieved from https://www.esource.com/ES-WP-18/GIWHs

[49] Hledik, R., Chang, J., and Leuken, R. (2016). *The hidden battery: Opportunities in electric water heating*, p. 1. Cambridge, MA: The Brattle Group. Retrieved from http://www.electric.coop/wp-content/uploads/2016/07/The-Hidden-Battery-01-25-2016.pdf

[50] Chew et al., 2017.

[51] They also note that utilities are using fewer water heaters with one-way controls and shifting to “faster-responding, grid-interactive water heaters that use two-way communications and can provide ancillary services.” Chew et al., 2017.

of utility survey respondents indicated they are planning, researching, or considering using demand response to manage greater adoption of variable energy resources; nearly 30 percent have already done so. Figure 13 illustrates these responses.[52]

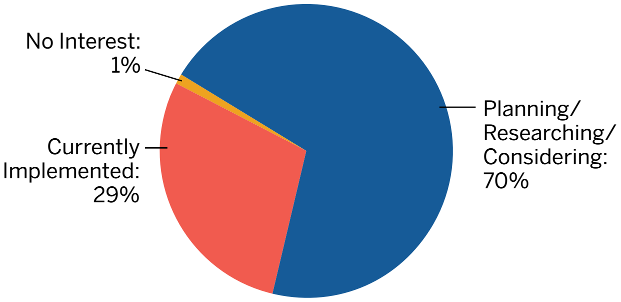
Water heating load is flexible in when it needs to draw power, so it can serve as a flexible resource for grid operators to call upon to ensure stability.

The electric grid has always needed a certain amount of flexibility because demand varies on a daily and seasonal basis. The integration of increasing amounts of variable energy resources requires even greater flexibility. Here we look at the contributions that electric water heating can make for the following categories of grid management: shifting demand; ancillary services; and direct partnerships with variable energy resources like rooftop photovoltaics.

Shifting Demand

Because of the growing availability of low-cost and non-emitting variable energy resources, a key grid management requirement for system operators today is meeting net load—the difference between forecast load and the amount met by intermittent resources.[53] Grid operators now recognize that active efforts on the demand side can help meet today's balancing challenges.[54] As we have noted, water heating load is flexible in when it needs to draw power, so it can serve as a resource for grid operators to call upon to ensure stability. In fact, these end uses can become resources themselves if system operators want to use them as such.

Figure 13. Utility Interest in Using Demand Response to Integrate Renewable Energy



Source: Based on Smart Electric Power Alliance. (2017, October). *2017 Utility Demand Response Market Snapshot.*

The two figures on the next page depict uncontrolled water heating loads, one at the regional level (Figure 14) and the other at the individual homeowner level (Figure 15).[55] Both illustrate the opportunity for greater flexibility.

Figure 14 illustrates residential water heater electricity usage in a cooler climate, by month and hour of the day.[56] The heavier red line reflects the median and shows there is a sharp demand increase between 6 and 9 a.m. and a smaller increase between 4 and 8 p.m. throughout the year. Left uncontrolled, this consumption profile falls heavily into expensive morning and evening utility peak load periods.

Figure 15 depicts 24 hours of electricity consumption on a winter day by a household in the Pacific Northwest.[57] The green line is the mid-day output of a solar system (very limited in January); the red line shows gross power consumed by the household. The four distinct spikes in demand reflect uncontrolled electric water heater cycling.[58] For this house on this day, hot water consumption was greatest between 5 and 7 p.m., again consistent with the peak demand period for most utilities.

Figures 14 and 15 illustrate the opportunity to shift demand—that is, to manage water heating load away from system peaks. Using controlled technologies, it is possible to

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[52] Chew et al., 2017.

[53] Colburn, K. (2017, January 24). Beneficial electrification: A key to better grid management [Blog post]. Regulatory Assistance Project. Retrieved from https://www.raponline.org/blog/beneficial-electrification-a-key-to-better-grid-management/

[54] Colburn, K. (2017, February 1). Beneficial electrification: A growth opportunity [Blog post]. Regulatory Assistance Project. Retrieved from https://www.raponline.org/blog/beneficial-electrification-a-growth-opportunity/

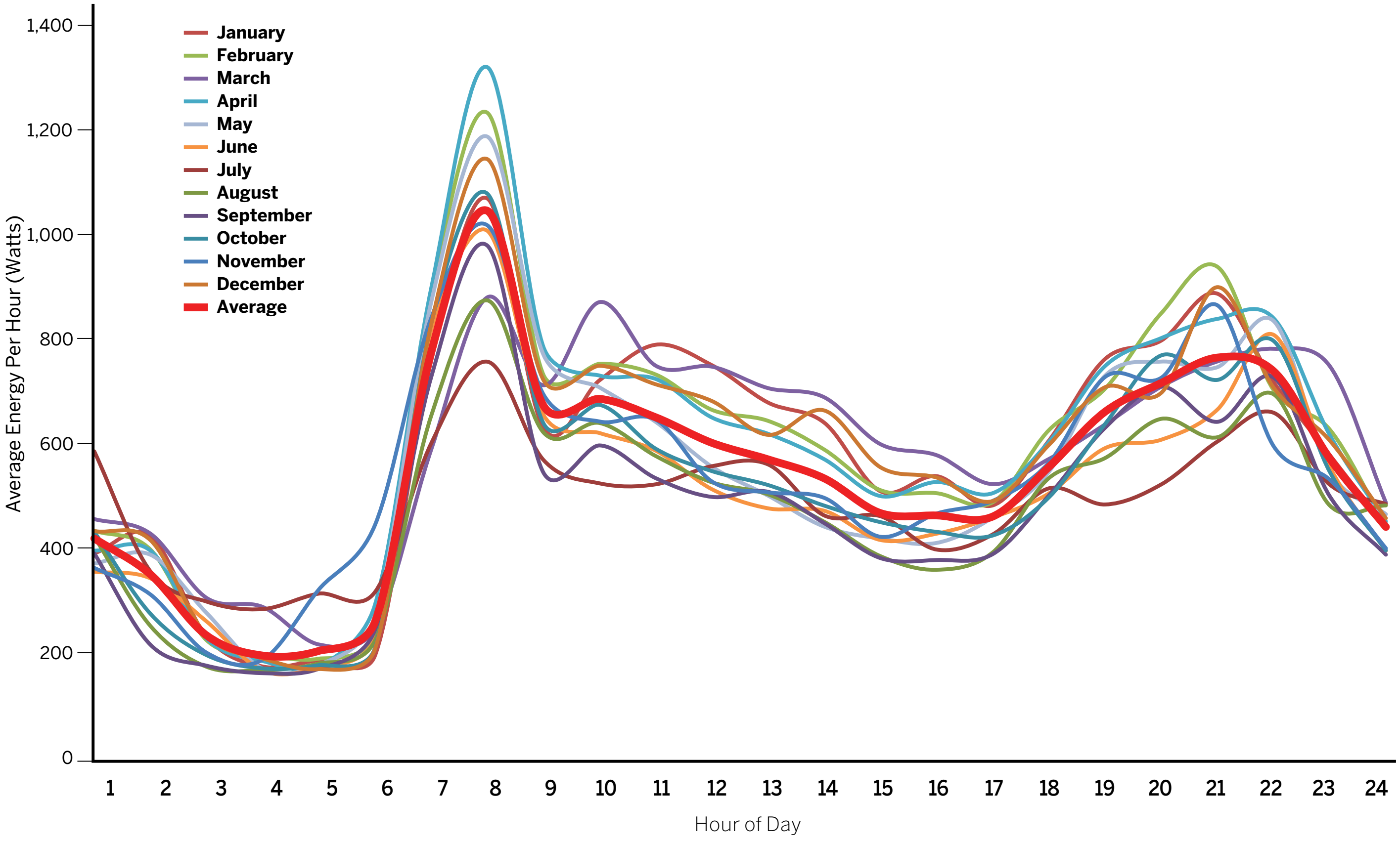
[55] We emphasize that this is a depiction. In some parts of the country, such as California, this morning ramp would be replaced by a more pronounced evening ramp.

[56] Based on a figure provided by Steffes.

[57] Based on personal communication with Convergence Research, 2005.

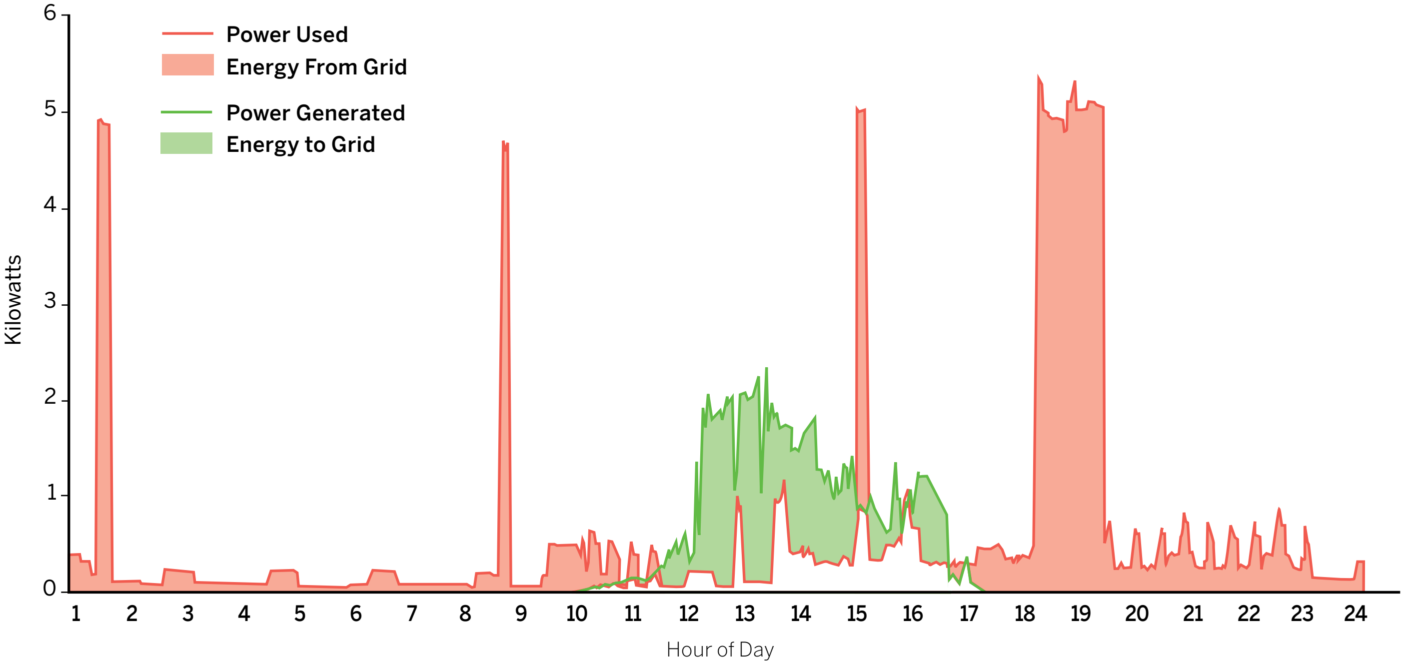
[58] Most electric resistance water heaters have heating elements that draw 4.5 kilowatts when they are on. This compares with average electricity demand for a typical household of 1 to 2 kilowatts over the course of a day. With daily water heat consumption of 8 to 12 kWhs, the water heater typically runs only two to three hours a day.

Figure 14. Water Heater Usage Profile



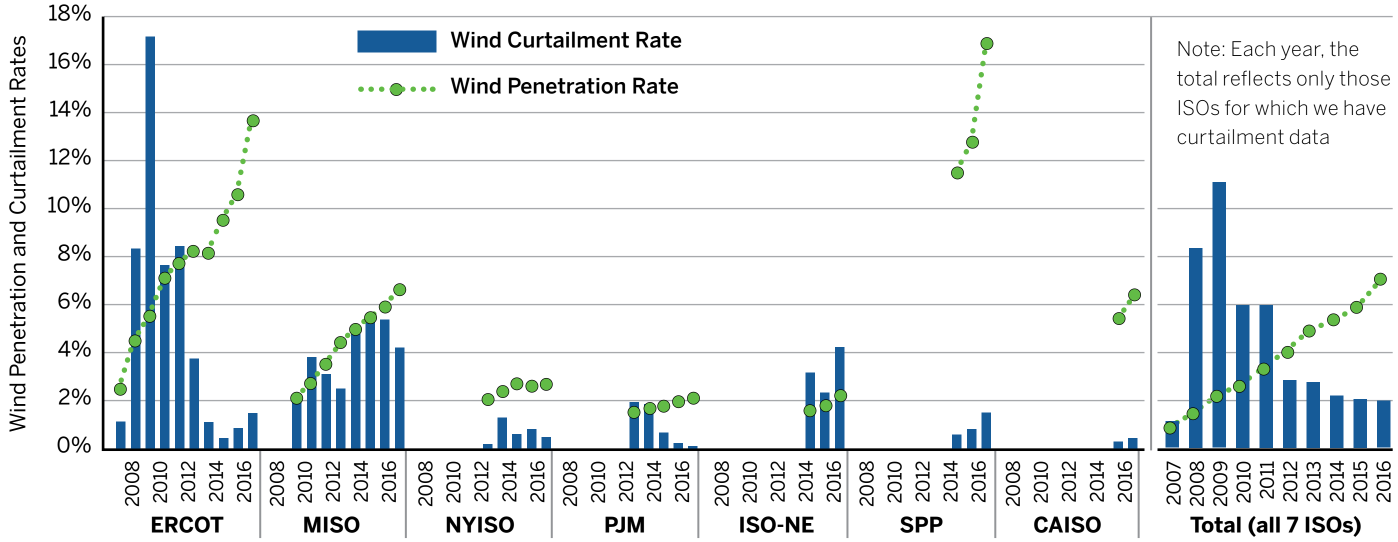
Source: Based on figure from Steffes.

Figure 15. Illustrative Electricity Production and Consumption for a Seattle Residence



Source: Based on personal communication from Convergence Research.

Figure 16. Wind Penetration and Curtailment



Note: Each year, the total reflects only those ISOs for which we have curtailment data

Note: All curtailment percentages shown represent both forced and economic curtailment.
PJM's 2012 curtailment estimate is for June through December only.

Source: Wiser, R., and Bolinger, M. (2017). *2016 Wind Technologies Market Report.*

heat water when power is cheaper and cleaner or, in the case of Figure 15, shift load into the mid-day when an on-site photovoltaic array is producing power.

Flexible water heater load constitutes a valuable resource for grid managers, renewable energy developers, and consumers not only in shifting load but also in avoiding curtailment of variable energy resources. As illustrated in Figure 16, increased amounts of renewable energy are being produced across the country, but are too often curtailed.[59]

In 2016, the Electric Reliability Council of Texas curtailed more than 800 gigawatt-hours of wind energy, or about 1.6 percent of its total wind generation. In the same year, the Midcontinent Independent System Operator curtailed more than 2,000 gigawatt-hours of wind power, or about 4.3 percent of its total wind energy.[60]

Figure 17 illustrates a trend toward increasingly frequent periods when lack of demand for energy leads to negative five-minute prices on the California wholesale energy market.[61] In 2015 and 2017, a majority of negative prices occurred during mid-day hours, consistent with increased solar generation. This further illustrates the opportunity for more proactive grid management to coordinate flexible water heating load with the availability of low-cost and renewable energy resources.

Figures 16 and 17 reveal an opportunity for shifting demand. Reducing curtailment with flexible load can help couple clean resources with incremental electrification demand. Likewise, flexible water heating load can be used to take advantage of available electricity during times of negative prices, saving consumers money and making use of power for which there is otherwise no demand.

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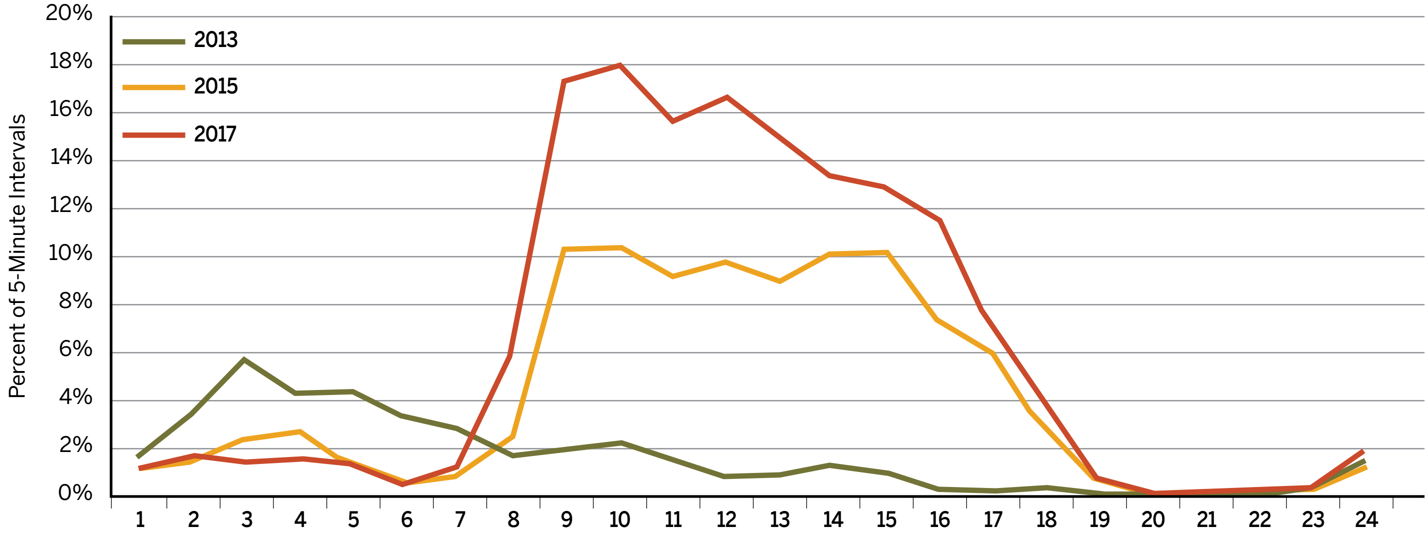
[59] "Curtailment of wind project output happens because of transmission inadequacy and other forms of grid and generator inflexibility. For example, over-generation can occur when wind generation is high, but transmission capacity is insufficient to move excess generation to other load centers, or thermal generators cannot feasibly ramp down any further or quickly enough." Wiser, R., and Bolinger, M. (2017). *2016 Wind technologies market report*, p. 37. Washington, DC: US Department of Energy, Office of Energy Efficiency & Renewable Energy. Retrieved from https://energy.gov/sites/prod/files/2017/10/f37/2016_Wind_Technologies_Market_Report_101317.pdf

[60] Wiser and Bolinger, 2017. See also US Department of Energy, Office of Energy Efficiency & Renewable Energy. (2015). *EERE 2014 wind technologies market report finds wind power at record low prices.* Washington, DC: Author. Retrieved from https://www.energy.gov/eere/articles/eere-2014-wind-technologies-market-report-findswind-power-record-low-prices. Wind is not the only renewable resource affected: In 2016, the California Independent System Operator curtailed more than 308,000 megawatt-hours of wind and solar generation combined. California Independent System Operator. (2017). *Impacts of renewable energy on grid operations*. Folsom, CA: Author. Retrieved from https://www.caiso.com/Documents/CurtailmentFastFacts.pdf

[61] California Independent System Operator Corp. (2018, June). Figure 3.6 Hourly frequency of negative 5-minute prices by year (ISO LAP areas). *2017 Annual report on market issues & performance*, p. 86. Folsom, CA: Author. Retrieved from http://www.caiso.com/Documents/2017AnnualReportonMarketIssuesandPerformance.pdf

Figure 17. Hourly Frequency of Periods With Negative Market Prices, Creating Opportunities for Demand Response



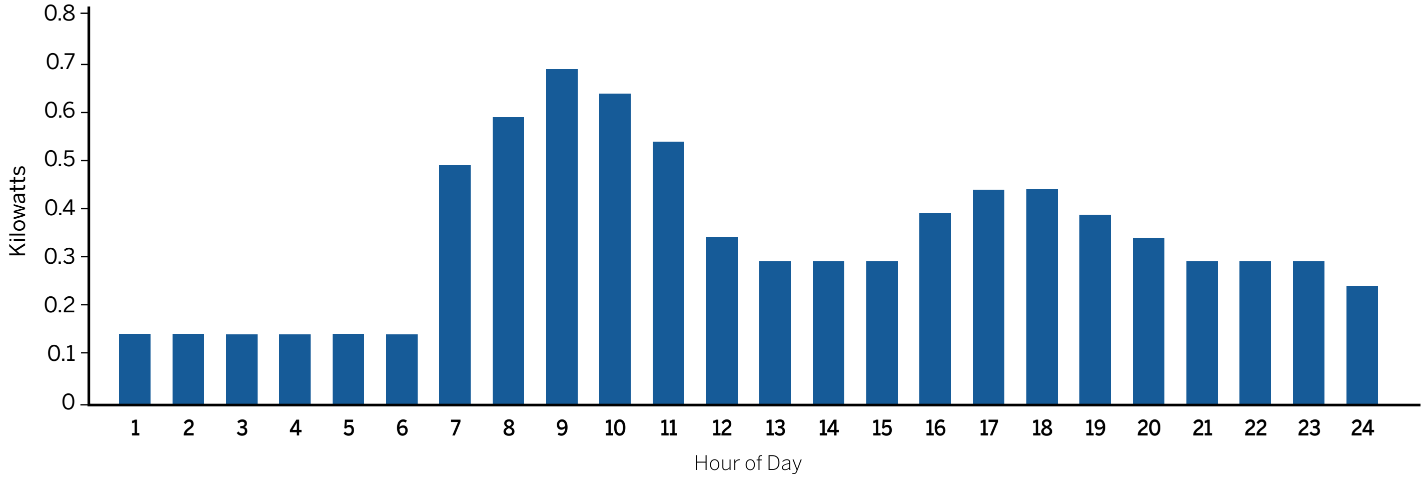
Source: California Independent System Operator. (2018, June). *2017 Annual Report on Market Issues & Performance. Licensed with permission from the California ISO. Any statements, conclusions, summaries, or other commentaries expressed herein do not reflect the opinions or endorsement of the California ISO.*

While Figure 15 on Page 31 provides a useful picture of a single home, it is important to remember—for purposes of utility resource planning, rate design, and environmental analysis—that hundreds of customers are on each distribution circuit, and thousands or millions on each utility system. The diversity among different customers' electricity use will tend to smooth out total demand. In the following four figures we illustrate average per-customer hourly water heating load for an electric utility to show how it might be better managed.

Here, we assume that water heating load adds approximately 8 kWh a day, or 3,000 kWh a year, as would be typical of a mix of single-family, mobile home, and apartment households. In Figure 18, morning hot water use runs from 7 to 11 a.m. and totals about 3 kWh per household. Evening use runs from 4 to 8 p.m. (after solar production declines but before wind power becomes surplus) and totals about 2 kWh.

We also assume that residential electric water heaters used in the United States typically have a minimum storage capacity of about 40 gallons of hot water, or about 5 kWh of useful energy storage.[62] Few houses use that much water in either the

Figure 18. Uncontrolled Electric Resistance Water Heating in Illustrative Household



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[62] Delivering the water at about 100 to 105 degrees presumes preheating to 150 to 155 degrees. This would require the use of a thermostatic mixing valve to protect users from scalding.

morning or evening, so it is possible to shift some of this load into other hours of the day, with little risk of running out of hot water.

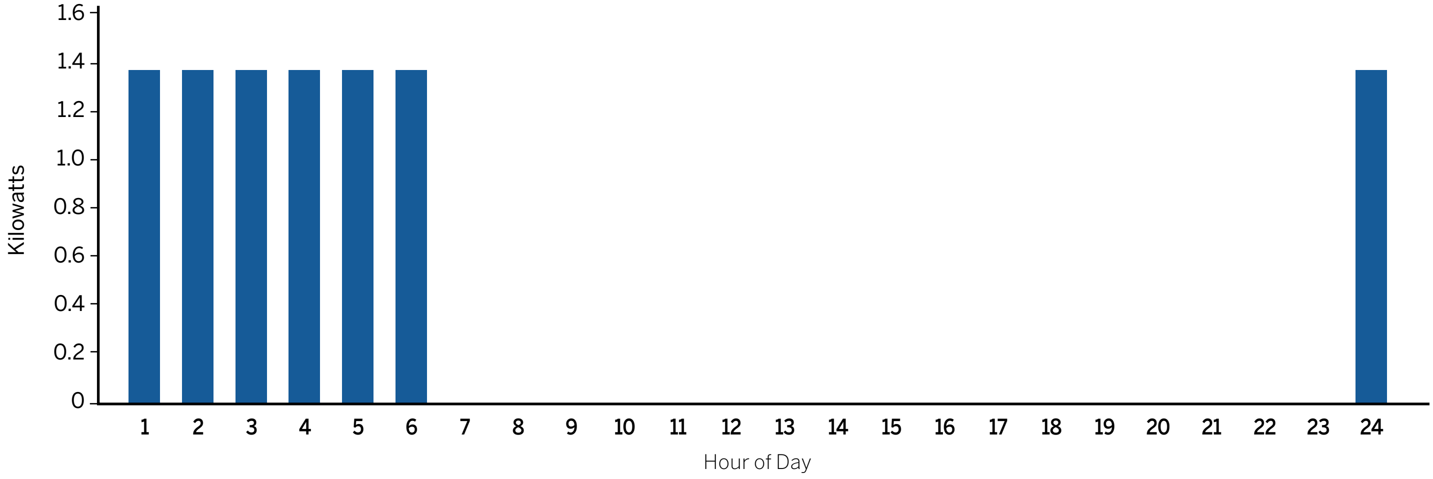
Using radio-controlled electric resistance water heaters, electric cooperatives and some investor-owned utilities have managed residential water heating service for decades.[63] These systems were originally installed to reduce system peak demands and to provide a market for low-cost off-peak power. Consumers participating in these programs typically installed tanks that hold more than a full day's supply, heat water overnight when electricity demand is low, and then use that preheated water throughout the day.[64] Although this provides more grid flexibility, it also has some potential to increase electricity consumption to the degree that standby losses increase.

These programs are gradually being converted to active grid-integrated controls, with the ability to use excess wind energy when it is available, provide ancillary services to the grid, and offer other benefits. Figure 19 shows an illustrative electricity use profile with controlled charging to take advantage of low-cost power at night.[65]

Today, water heaters on a timer or connected to the internet continue this approach, but it requires the customer to have more hot water storage than usual. At 7 a.m., the tank must hold enough to last the entire day. Utilities operating such programs often install 80- to 100-gallon water heaters or store water at hotter temperatures and use a blending valve to deliver it safely. Charging—that is, heating a tank of water—once a day enables greater shifts of load. Most of these systems operate without utility control and simply rely on timers. A water heater timer costs less than $50 and is easy to install when connecting the electricity to the appliance.[66]

Controlled water heater electricity use throughout the day can take advantage of low-cost power whenever it is available, while ensuring consumers have hot water when they need it. Controlled water heaters can also work with smaller tanks, such as those found in apartments, because there are periods during the day (which may vary from day to day) when low-cost power is available.[67]

Figure 19. Illustrative Controlled Resistance Water Heating Using Low-Cost Power at Night



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[63] Tweed, K. (2013, May 15). *Hot water heaters: When energy efficiency fights demand response.* Greentech Media. Retrieved from https://www.greentechmedia.com/articles/read/hot-water-heaters-when-energy-efficiency-fights-demand-response

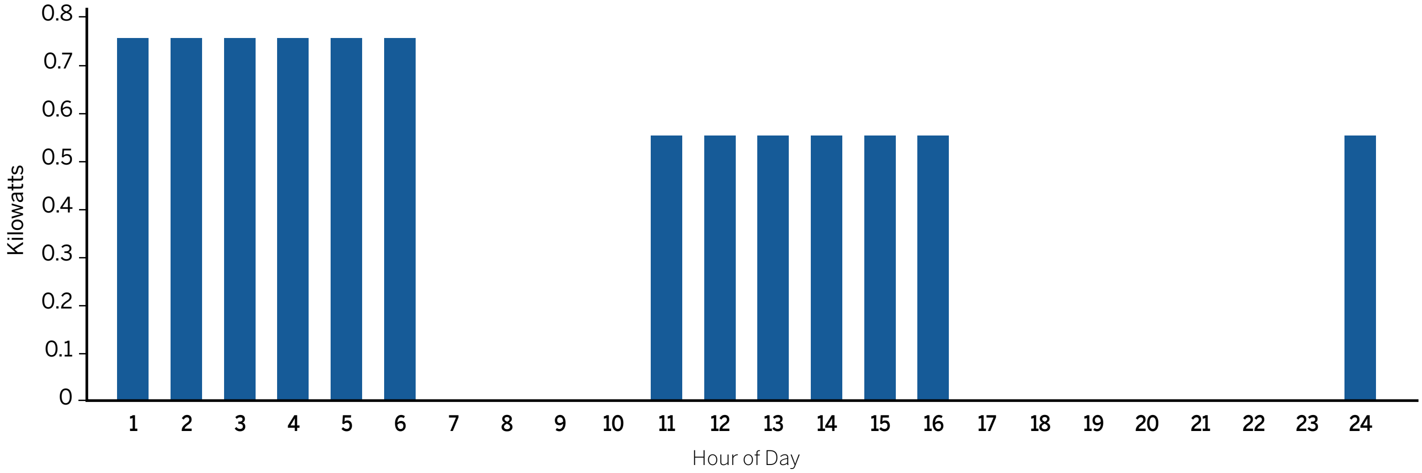
[64] Holly, D. (2017, November 17). *Unique partnership, modern energy savings: Co-ops, home builder team up to bring grid-interactive water heaters to new homes in Minnesota.* National Rural Electric Cooperative Association. Retrieved from https://www.electric.coop/minnesota-grid-interactive-water-heaters/. Great River Energy estimates that, with 50 water heaters enrolled in a load control program, the utility has the potential to manage 200 kilowatts for purposes of load shifting.

[65] It is low-cost for the utility, but with the appropriate rate design, this cost advantage can be shared with electricity ratepayers.

[66] For example, The Home Depot and Amazon.com sell Intermatic timers for less than $50 that work with high-amperage loads like water heaters. They require only a few minutes to install between the power circuit and water heater.

[67] Either timers can control water heating into predicted low-cost hours, or sensors on the water tank that are connected to the utility or aggregator can communicate the level of hot water storage and the rate of hot water use. Podorson, D. (2016). *Grid interactive water heaters—How water heaters have evolved into a grid scale energy storage medium.* Washington, DC: American Council for an Energy-Efficient Economy. Retrieved from aceee.org/files/proceedings/2016/data/papers/6_336.pdf

Figure 20. Illustrative Controlled Resistance Water Heating Using Wind Power at Night and Solar Mid-Day



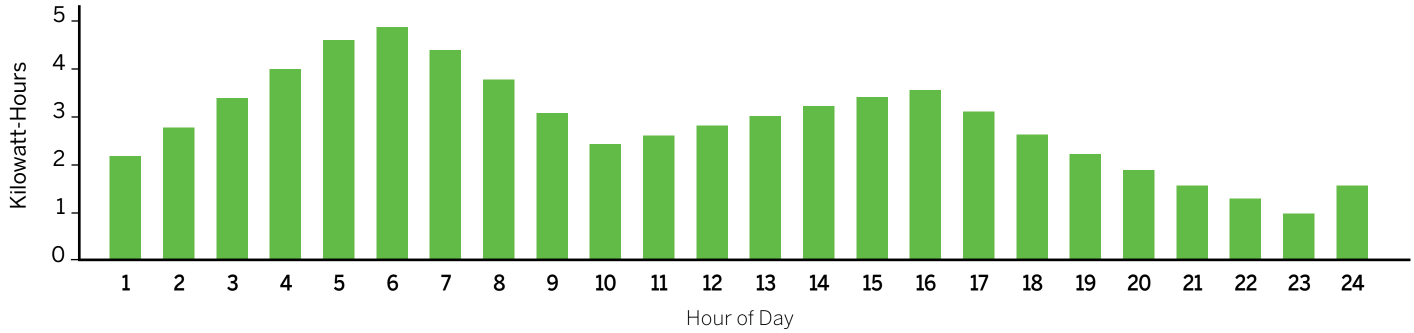
With grid connectivity, the end user, utility, or aggregator can ascertain and manage the level of hot water storage and the rate of hot water use.[68] The utility or aggregator can then dispatch the heating elements to take advantage of low-cost electricity[69] while still providing reliable hot water service.[70]

For instance, water could be heated overnight rather than during the morning peak. Water could then be heated again at mid-day, avoiding electricity use during the evening peak hours. This could result in an electricity consumption pattern, as illustrated in Figure 20, that is very different from that depicted above for uncontrolled water heating, but with no impact on the availability of hot water for the household.

The ability to control water heaters also lets grid operators use wind power (at night) and solar power (during the day) to meet residential hot water needs with low-cost renewable energy that might otherwise be curtailed. In this situation, even a coal-dominated utility might be able to serve water heating load with low-emissions electricity.[71] The level of hot water in the storage tank, with the typical hot water demands shown above in Figure 18, is illustrated in Figure 21.

Controlling water heaters also allows for more efficient use of water heating capacity. For example, 8 kWh a day[72] of hot water energy needs can be met with a typical 40-gallon[73] residential ER water heater tank—which holds only 5 kWh of

Figure 21. Energy Storage in Illustrative Managed Electric Resistance Water Heater



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[68] See various approaches, including integrated connectivity, retrofit controllers, or CTA-2045 enabling, described in Table 2 and accompanying notes.

[69] As noted above at note 65, it is low-cost for the utility, but with the appropriate rate design, ratepayers can share in this benefit.

[70] Systems performing this have been introduced by Steffes, Shifted Energy, Mosaic Power, and Power Over Time into utility pilot and demonstration programs. Not all water heaters need to be controlled in order to shape water heating load.

[71] See the discussion of emissions efficiency beginning on Page 40.

[72] See Figure 15 and accompanying text.

[73] This tank size is typical of smaller multi-family residences or smaller households.

working storage—if some of the hot water is used in the morning and then recharged mid-day for later use.

As the grid accommodates greater amounts of variable resources, the power system will exhibit greater price differentials, making load shifting more valuable.

Because some consumers have higher hot water demand than others, sensors and controllers can operate to provide power—even at higher-cost times if necessary—so that hot water will always be available. However, it is possible to preheat the vast bulk of water heating load. According to one expert, less than 1 percent of total water heating energy must be supplied at high-cost hours, despite 70 percent of hot water consumption occurring during these hours.[74] The key is to have a fleet of water heaters capable of providing users a "state of charge" in order for the appliances to be controlled effectively to ensure sufficient hot water is available.

The discussion of load shifting to this point has focused on ER water heaters. As discussed above, HP water heaters use much less energy, typically have 50 to 80 gallons of storage capacity, and can also be used for load shifting.

Because HP water heaters typically draw about 1 to 1.5 kilowatts on average—one-third to one-fourth the power of a resistance model—potential load savings by shifting HP water heater usage are much smaller. Therefore, the cost of installing control technology needs to be evaluated against smaller peak demand savings and smaller load shifting to hours when costs and emissions are lower. Consequently, the grid management economics for individual HP water heaters may be less robust than they are for ER alternatives.

The economics of grid-integrated HPs may still be attractive, however. Despite producing smaller load savings, HP units remain good candidates for demand response programs whereby a utility can reduce the electric load of a group of water heaters by an individually small amount that cumulatively provides the grid with meaningful load shifting and peak load reduction.[75]

As noted by Lawrence Berkeley National Laboratory, a "future grid system with more electrified end uses, coupled with greater control and automation of end-use operation, can provide grid operators and utilities with greater control over load shapes and aggregated end uses."[76] It should also be noted that the value of this load shifting will increase as the daily price differential in electricity production and delivery grows. In other words, as the grid accommodates greater amounts of variable resources, the power system will exhibit greater price differentials, making load shifting more valuable even in smaller quantities.

GE Appliances has conducted research illustrating the effectiveness of water heating as a grid management strategy, reinforcing the value of HP water heaters despite their smaller load savings. GE's research demonstrates the capability of HP water heaters to control and smooth electricity demand with as little as 10 percent penetration in the market.[77] Figure 22 depicts the water heating-related demand of 1,000 homes before any intervention and the effects of managing demand from 100 HP water heaters distributed among those homes.[78]

The green highlighted areas on the demand curves earlier and later in the day reflect when the controlled water heaters are turned off and peaks are reduced. The yellow shaded area in the middle of the day illustrates when controlled water heating is deployed to take advantage of solar resources running

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[74] Personal conversation with Kelly Murphy of Steffes. Alternatives for customers with higher hot water demand than others would be to control the water heaters for fewer hours, rely on bigger tanks or higher temperatures, or employ better algorithms to reflect their usage.

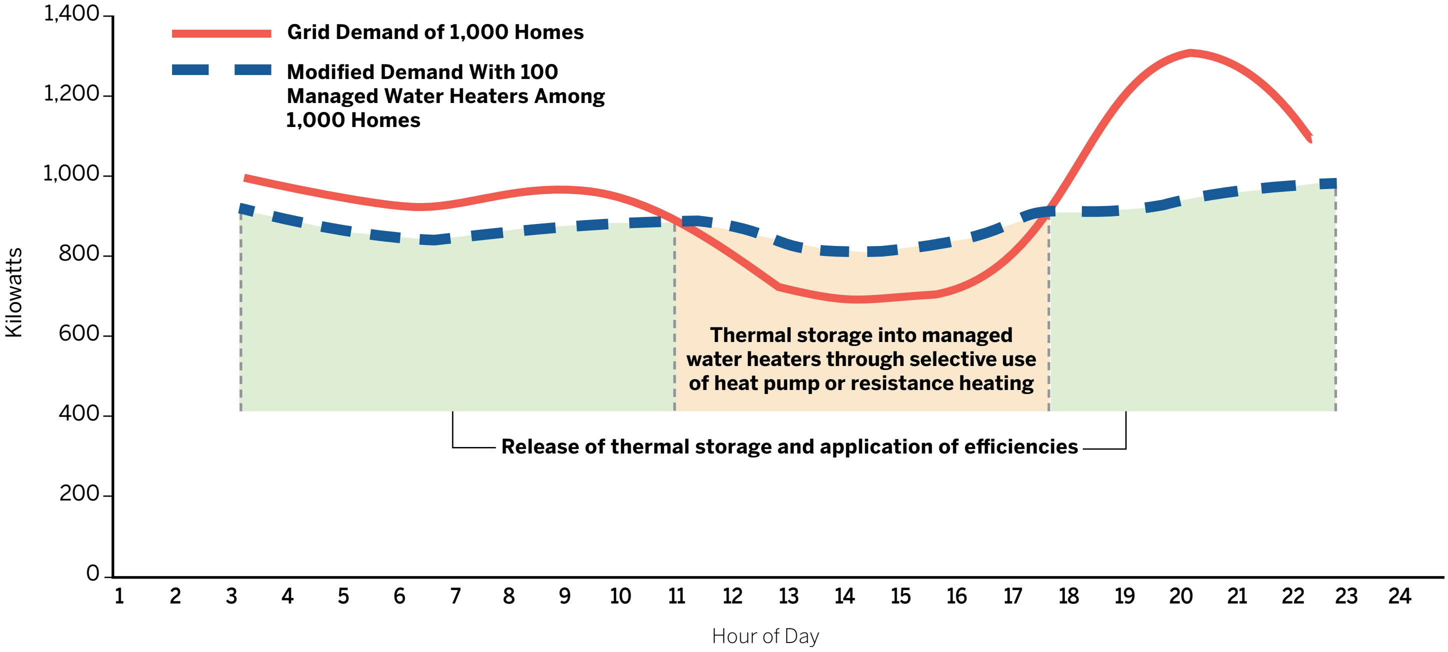
[75] "A future grid system with more electrified end uses, coupled with greater control and automation of end-use operation, can provide grid operators and utilities with greater control over load shapes and aggregated end uses." Deason, J., Wei, M., Leventis, G., Smith, S., and Schwartz, L.C. (2018). *Electrification of buildings and industry in the United States: Drivers, barriers, prospects, and policy approaches* (LBNL-2001133). Berkeley, CA: Lawrence Berkeley National Laboratory. Retrieved from http://etapublications.lbl.gov/sites/default/files/electrification_of_buildings_and_industry_final_0.pdf. See also Nadel, S. (2016). *Comparative energy use of residential furnaces and heat pumps* (Report A1602). Washington, DC: American Council for an Energy-Efficient Economy. Retrieved from https://aceee.org/comparative-energy-use-residential-furnaces-and

[76] Deason et al., 2018.

[77] DuPlessis, S. (2016, February). *Grid responsive GeoSpring HPWH* [Presentation to ACEEE 2016 Hot Water Forum]. GE Appliances.

[78] DuPlessis, 2016.

Figure 22. Managing as Few as 10 Percent of Water Heaters Can Significantly Smooth Demand



Source: Based on DuPlessis, S. (2016, February). *Grid Responsive GeoSpring HPWH.*

mid-day. This relatively modest water heating intervention both shaves peaks and fills valleys, producing a flatter, lower-cost demand curve.

Enabling water heaters to provide ancillary services such as voltage support and frequency response can help ensure power system reliability.

Ancillary Services

As noted above, smart electronics and improved communications are creating a new category of responsive appliances that can, through the provision of ancillary services, help grid managers meet operational requirements.[79] The Federal Energy Regulatory Commission defines ancillary services as those "necessary to support the transmission of electric power from seller to purchaser, given the obligations of control areas and transmitting utilities within those control areas, to maintain reliable operations of the interconnected transmission system."[80] Enabling water heaters to provide ancillary services such as voltage support and frequency response can help ensure power system reliability.[81]

In addition to controlling electric resistance water heaters to contribute to load shifting as discussed above, it is possible to control the heating elements of these appliances in very short increments to help meet different grid management needs. This flexibility enables a utility or aggregator to control load in ways that can provide frequency regulation (a transmission-level service)[82] or voltage support

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[79] Lazar, J. (2016, July). *Electricity regulation in the US: A guide* (2nd edition), p. 177. Montpelier, VT: Regulatory Assistance Project. Retrieved from http://www.raponline.org/wp-content/uploads/2016/07/rap-lazar-electricity-regulation-US-june-2016.pdf

[80] Federal Energy Regulatory Commission. *Guide to market oversight: Glossary* [Webpage]. Retrieved from https://www.ferc.gov/market-oversight/guide/glossary.asp?csrt=17095980229329892926

[81] This is a subset of those ancillary services supplied with generation that include reactive power voltage regulation, system protective services, loss compensation service, system control, load dispatch services, and energy imbalance services. DuPlessis, 2016.

[82] Frequency regulation involves a water heater responding to a signal and quickly increasing or decreasing its load. See the discussion of various frequency regulation pilots in Hledik et al., 2016, p. 6. See also Upadhye, H., Domitrovic, R., and Amarnath, A. (2012). *Evaluating peak load shifting abilities and regulation service potential of a grid connected residential water heater.* Washington, DC: American Council for an Energy-Efficient Economy. Retrieved from https://aceee.org/files/proceedings/2012/data/papers/0193-000008.pdf

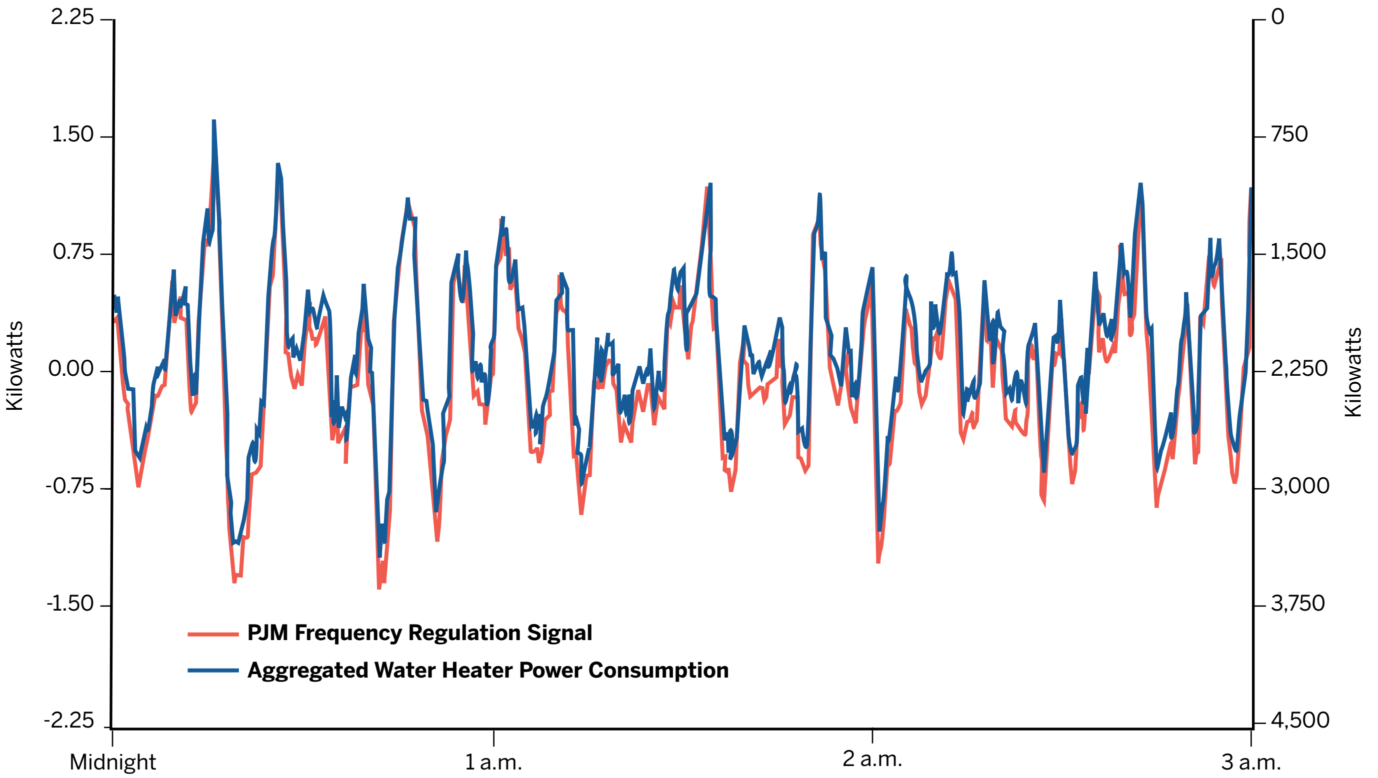
(a distribution-level service).[83]

Using controlled water heaters, Mosaic Power is providing frequency regulation service to PJM Interconnection today.[84] Figure 23 illustrates how its aggregated ER water heating load follows PJM's frequency regulation signal very closely—more closely, in fact, than the generating units traditionally used to provide frequency regulation.[85]

In its 2017 *Hidden Battery* study,[86] The Brattle Group found, for example, that ancillary services could provide an annual economic value of up to $195 per customer with a 50-gallon ER water heater (or about $2,000 over the life of a water heater), and more for an 80-gallon model.[87]

The Brattle Group found that ancillary services could provide an annual economic value of $195 or more per customer.

Figure 23. Water Heater Frequency Regulation Signal Following



Source: Based on figure from PJM Interconnection.

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[83] Voltage support, historically provided by generation resources, is used to ensure that grid system voltage is maintained or, when necessary, restored. "New technologies (e.g., modular energy storage, modular generation, power electronics, and communications and control systems) make new alternatives for voltage support increasingly viable." Eyer, J., and Corey, G. (2010, February). *Energy storage for the electricity grid: Benefits and market potential assessment guide* (SAND2010-0815), p. 33. Albuquerque, NM, and Livermore, CA: Sandia National Laboratories. Retrieved from https://www.sandia.gov/ess-ssl/publications/SAND2010-0815.pdf

[84] Mosaic Power. *About frequency regulation* [Webpage]. Retrieved from https://mosaicpower.com/the-frequency-regulation-market/. However, some utilities believe they will obtain all the grid services that controlled water heaters can provide via batteries installed at various points on their system. Personal communication with Conrad Eustis, Portland General Electric.

[85] Ott, A. (2011, February 13). *Energy storage and frequency regulation* [Presentation to FERC/NARUC Smart Response Collaborative]. PJM Interconnection. Retrieved from https://www.smartgrid.gov/files/Energy_Storage_Frequency_Regulation_201106.pdf

[86] Hledik et al., 2016.

[87] The difference in net benefits for the 50-gallon and 80-gallon cases considered is due to the cost of the control equipment to enable peak shaving. Given the available cost data at the time and the study's capacity cost assumptions, as well as the low level of heat pump water heater load during peak hours, the cost of installing the control equipment for an HP water heater outweighed the benefits. Based on conversation with Ryan Hledik, The Brattle Group.

Table 5. Annual Net Per-Customer Benefits of Ancillary Services Provided by Electric Resistance Water Heaters

	PJM East (2014)	MISO (2014)	MISO (2028)
50-gallon	$162	$39	$195
80-gallon	$172	$46	$216

Source: Hledik, R., Chang, J., and Leuken, R. (2016). *The Hidden Battery: Opportunities in Electric Water Heating.*

Table 5 illustrates the value of these benefits.[88]

The costs of installing controls and communications to enable grid-integrated water heating are not insignificant.[89] If included when a water heater is manufactured, the cost would be less than $100, but retrofits are much more expensive.[90] If the customer has internet service, the cost of the communication technology may be negligible, but without it, the utility or grid aggregator may also need to install cellular or other controls at higher costs.[91]

Unlike ER water heaters, heat pump compressors are mechanical devices that could suffer unacceptable wear if controlled into the sub-minute periods required for fast-response ancillary services. We therefore do not assume they are capable of providing ancillary services benefits comparable to those ER water heaters can.[92] Both technologies, however, can be sufficiently controlled to shift load and reduce curtailment of variable energy resources.

Electric Resistance Water Heaters and Solar Photovoltaics

Advanced electrification technology may also present opportunities in partnership with solar water heating. In many places in the US, direct solar water heating is an attractive option.[93] In some areas, installers are beginning to deploy photovoltaic solar water heaters, where the direct current solar panels are directly coupled to an electric resistance water heater, without an intervening inverter (which adds cost and reduces delivered kWhs).[94] With solar water heaters, the traditional approach has been to provide electric resistance backup so that once the sun goes down, the customer's hot water needs can be ensured with the electric water heater.

A combination of controlled ER technology and solar technology may be appropriate here. Smart home management systems can learn household hot water use patterns and deploy the electric backup only when there is an anticipated need for hot water, and to do so considering current and anticipated electricity prices. For example, if a solar water heater produces enough hot water to carry the customer from 5 to 8 p.m., but not enough to fill the tank, the home energy management system might delay backup operation until later in the evening, when electricity loads are lower and wind energy may be available.[95]

All the necessary technology components for effectively combining solar generation and water heating exist in today's solar and grid-integrated water heating industries. We are not

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[88] Hledik et al., 2016, p. 26.

[89] Implementing federal appliance standards that require manufacturers to fit new electric resistance water heaters with control technology would enable greater water heating load management and do so at a lower cost. See the discussion of appliance standards beginning on Page 44.

[90] Hledik et al., 2016, identifies retrofit costs of up to $400 per unit for sensors and communication.

[91] Hawaiian Electric Co. has targeted buildings with existing internet service to control cost. Personal conversation with Rich Barone, Hawaiian Electric Co.

[92] Northwest Energy Efficiency Alliance. (2015, March). *Heat pump water heater model validation study* (Report No. E15-306). Portland, OR: Author. Retrieved from https://neea.org/img/uploads/heat-pump-water-heater-saving-validation-study.pdf

[93] HI Revised Statutes 196-6.5, originally adopted in 2008, amended in 2009, 2010, and 2011.

[94] Personal conversation with J. Carl Freedman, Haiku Design and Analysis.

[95] The storage capability of the 50-gallon tank allows for curtailments of up to four hours a day; longer curtailments would either lead to an unacceptable risk of hot water shortages or require that the water in the tank be preheated to unacceptable levels. Alternatively, the larger storage capability of the 80-gallon tank allows it to be curtailed up to 16 hours a day without violating the constraints described above. Note that in some cases customers would need a roughly 100-gallon tank to achieve the full 16 hours of curtailment with minimal risk of hot water shortages. Tanks being used in this manner would also require a mixing valve, which allows the maximum temperature of the water to be increased, reducing the possibility of hot water shortages when curtailing load on a daily basis. Hledik et al., 2016, p. 16.

yet aware of the coordination of these technologies. This may present an attractive pilot opportunity for utilities in areas where solar water heating is common, such as California, Hawaii, and Florida.

Climate goals are attainable by saving energy through efficiency, decarbonizing the power sector, increasing the electrification of end uses, and relying on a cleaner grid.

Energy and Emissions Efficiency

The third condition for determining whether an electric water heating application is beneficial is that it reduces environmental impacts. Here we use carbon emissions as a proxy for broader emissions impacts. In pursuit of their climate change goals, US states and others have conducted studies to identify transition pathways to a low-carbon economy.[96] These studies share many common conclusions, including the key role that electrification must play.[97]

The continued use of fossil fuels throughout much of the economy—no matter how efficient that use—cannot reduce emissions enough to meet climate goals.[98] Studies argue that climate goals are attainable, however, by saving as much energy as possible through efficiency, decarbonizing the power sector, increasing the electrification of end uses, and relying on a cleaner grid to fuel them.[99]

Because electrical end uses replace on-site combustion of fossil fuels, electrification avoids emissions at the point of customer use.[100] Although electrification still causes emissions associated with power generation, total emissions are often reduced by using efficient electrical end uses and relying on energy from cleaner generation sources.[101]

More energy-efficient electric end uses, in combination with the greening of the generation fleet, improve emissions efficiency, meaning fewer pounds of pollution are emitted per gallon of hot water produced despite greater kWh consumption. The thermodynamic efficiency and emissions efficiency of electric water heaters vary among technologies and across regions depending on the characteristics of the utility grid to which they are connected.[102]

To determine when electrification of water heating is beneficial, we need to analyze each technology's emissions efficiency. By combining the efficiency of the end-use appliances with the carbon content of their energy supply, we can compare the emissions efficiency of electrification with fossil-fueled alternatives. The tables in this section summarize the three steps in a simple calculation, illustrated in Figure 24, of the emissions per million Btu of delivered water heat for various technologies.

Table 6 compares the thermodynamic efficiency of several

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[96] See, for example, European Climate Foundation. (2010, April). *Roadmap 2050: A practical guide to a prosperous, low-carbon Europe—Policy recommendations.* The Hague, Netherlands: Author. Retrieved from www.roadmap2050.eu/attachments/files/Volume2_Policy.pdf. See also Energy and Environmental Economics. *Summary of the California state agencies' PATHWAYS project: Long-term GHG reduction* [Webpage]. Retrieved from https://www.ethree.com/public_proceedings/summary-california-state-agencies-pathways-project-long-term-greenhouse-gas-reduction-scenarios/

[97] Mahone, A., Hart, E., Haley, B., Williams, J., Borgeson, S., Ryan, N., and Price, S. (2015, April). *California PATHWAYS: GHG scenario results.* San Francisco, CA: Energy and Environmental Economics. Retrieved from www.ethree.com/wp-content/uploads/2017/02/E3_PATHWAYS_GHG_Scenarios_Updated_April2015.pdf

[98] Van der Slot, A., Schlick, T., Pfeiffer, W., and Baum, M. (2016, April). *Integrated fuels and vehicle roadmap to 2030+.* Munich, Germany: Roland Berger GmbH. Retrieved from https://www.rolandberger.com/en/Publications/Integrated-Fuels-and-Vehicles-Roadmap-2030.html

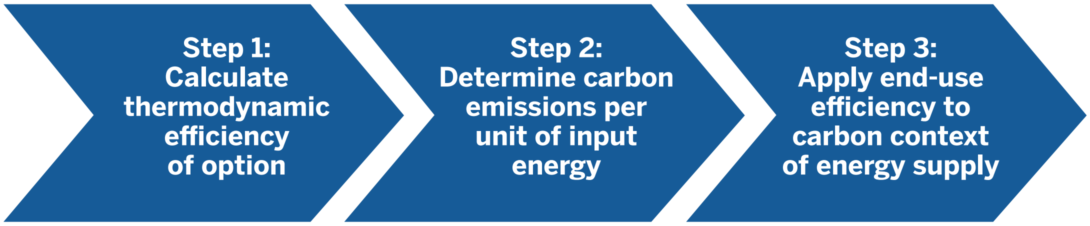
[99] Nelson, J., Mileva, A., Johnston, J., Kammen, D., Wei, M., and Greenblatt, J. (2013, February). *Scenarios for deep carbon emission reductions from electricity by 2025 in Western North America using the SWITCH electric power sector planning model* (Publication No. CEC-500-2014-109). Sacramento, CA: California Energy Commission. Retrieved from www.energy.ca.gov/2014publications/CEC-500-2014-109/CEC-500-2014-109.pdf

[100] See Dennis, K., Colburn, K., and Lazar, J. (2016, July). Environmentally beneficial electrification: The dawn of "emissions efficiency." *The Electricity Journal, 29*(6), 52-58. Retrieved from https://www.sciencedirect.com/science/article/pii/S1040619016301075

[101] Wei, M., Nelson, J., Greenblatt, J., Mileva, A., Johnston, J., Ting, M., et al. (2013). Deep carbon reductions in California require electrification and integration across economic sectors. *Environmental Research Letters, 8*(1). Retrieved from http://iopscience.iop.org/article/10.1088/1748-9326/8/1/014038/meta. See also Williams, J.H., DeBenedictis, A., Ghanadan, R., Mahone, A., Moore, J., and Morrow III, W.R., et al. (2012, January). The technology path to deep greenhouse gas emissions cuts by 2050: The pivotal role of electricity. *Science,* 335(6064), 53-59. Retrieved from https://doi.org/10.1126/science.1208365

[102] Dennis et al., 2016, and US Energy Information Administration, 2018, January 25.

Figure 24. Determining Emissions Efficiency of a Water Heating Technology



types of water heaters[103]—including electric depending on the fuel used to generate the power.

Emissions efficiency is different, incorporating not only the thermodynamic efficiency of equipment, but also the carbon dioxide (CO_2) emissions associated with fueling it. Electric generation options are set out in Table 7,[104] including mixes of non-carbon resources such as wind and solar,[105] illustrating the pounds of CO_2 emitted per million Btu of delivered electricity.[106, 107]

By ascertaining the efficiency of the end-use appliances and considering the carbon content of their energy supply, we can estimate the emissions per delivered unit of hot water. For these calculations, we assume that the typical household uses about 20 million Btu of hot water a year. First, we calculate the emissions associated with natural gas and propane water heaters at today's best efficiency ratings. Emissions range

Table 6. Comparative Efficiency of Water Heating Technologies

	Energy factor, coefficient of performance, or efficiency	Coal or nuclear generation efficiency (35%)	Gas combined cycle generation efficiency (50%)
		Net thermodynamic efficiency of electric technologies	
Electric resistance	0.95	33%	48%
Heat pump	3.00	105%	150%
Standard propane	70%	N/A	
Standard gas	70%		
On-demand propane	90%		
On-demand gas	90%		

Table 7. Illustrative Electric Sector Carbon Emissions

	100% coal	50% coal/ 50% gas	100% gas combined cycle	50% gas/ 50% non-carbon	100% non-carbon
Fuel source CO_2 (pounds/million Btu)	214		117		
Conversion efficiency	0.35		0.5		
Generated electricity CO_2 (pounds/million Btu)	611		234		
Line losses	10%		10%		
Delivered electricity CO_2 (pounds/million Btu)	679	470	260	130	0

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103 For on-demand fossil-fueled models, we use the Energy Star minimum energy factors. See US Department of Energy and US Environmental Protection Agency. *Water heater key product criteria.* Retrieved from https://www.energystar.gov/products/water_heaters/residential_water_heaters_key_product_criteria

104 Fuel emissions factors are from the US Energy Information Administration.

105 Some analysts attribute a carbon impact to nuclear, based on the carbon inputs to the nuclear fuel cycle. We do not in this paper.

106 The term "illustrating" should be emphasized. Because electrification involves adding new load, knowing a system's marginal emissions (the emissions that would be added with the use of one more kWh or reduced if a kWh is avoided) is one key to understanding the emissions associated with electrification. Capacity expansion modeling will also be important to characterize the emissions associated with significant amounts of additional electrification load.

107 System average line losses are in the range of 6 to 10 percent on most US utility grids, but they increase exponentially as power lines become heavily loaded. Avoiding a small amount of electricity demand in the highest peak hours can reduce line losses by as much as 20 percent. See Lazar, J., and Baldwin, X. (2011, August). *Valuing the contribution of energy efficiency to avoided marginal line losses and reserve requirements.* Montpelier, VT: Regulatory Assistance Project. Retrieved from https://www.raponline.org/knowledge-center/valuing-the-contribution-of-energy-efficiency-to-avoided-marginal-line-losses-and-reserve-requirements

Table 8. Carbon Emissions of Fossil-Fueled Water Heaters

	Energy factor	Fuel source CO_2 (pounds/ million Btu)	Water heat CO_2 (pounds/ million Btu)
Standard propane	0.7	139	199
Standard gas	0.7	117	167
On-demand propane	0.9	139	154
On-demand gas	0.9	117	130

from 130 (for an on-demand gas water heater) to 199 (for a standard propane water heater) pounds of CO_2 per million Btu of delivered hot water (see Table 8).

To compare, Table 9 illustrates the emissions associated with electric water heaters, which vary dramatically depending on the source of the electricity. The numbers in the green cells show the circumstances in which the electric option is more emissions-efficient than fossil-fueled water heating options, based on average emissions of the grid. Numbers in the red cells illustrate cases in which electrification would not produce lower emissions, and yellow cells denote similar emissions.

Table 9 shows that even heat pumps can result in higher carbon emissions if an electricity system has more than 50 percent coal generation.[108] However, if the electric system is no more carbon-intensive than combined cycle natural gas, heat pump water heaters become less carbon-intensive than propane and natural gas alternatives. And when the electric system becomes low-carbon (no more carbon-intensive than 50 percent gas/50 percent non-carbon), all of the electric options result in equal or lower carbon emissions than natural gas and propane. Some parts of the United States meet this standard today; many more will in the future.[109]

Table 9. Emissions Efficiency of Electric Water Heating Options in Various Power System Mixes

	Water heat CO_2 (pounds/million Btu)				
	100% coal	50% coal/ 50% gas	100% gas combined cycle	50% gas/ 50% non-carbon	100% non-carbon
Electric resistance	715	495	274	137	0
Heat pump	226	157	87	43	0

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[108] In the near term, electrification can be expected to increase emissions associated with the marginal electric generating units called on to serve that load. For the longer term, there may be other approaches to characterizing expected emissions effects that reflect longer-term averages or capture the potential coordination between electrification load and variable renewable resources that might otherwise be curtailed. For a further discussion of this issue, see Farnsworth et al., 2018.

[109] California and the Pacific Northwest, for example, currently have low-carbon power systems. As solar and wind become a larger part of the resource mix for hours when hot water load is experienced, we anticipate that Arizona, Nevada, Texas, Iowa, and other states will achieve this.

Putting Beneficial Electrification Into Action for Water Heating

Policymakers, regulators, and utilities should consider complementary approaches that address the barriers to investment in new technology.

This paper has illustrated the potential for significant consumer, grid, and environmental benefits from electrifying water heating. In this section, we discuss ways to encourage greater deployment of electric water heating. These fall into several categories: building codes, appliance standards, state energy and climate policy, rate design, and incentives and other programs.

Energy codes and other rules should be reviewed to ensure they do not create barriers or obstacles to electrification.

Standards for New Buildings

Improving the efficiency of our water heating practices will require a thoughtful and long-term effort. The transition can be much quicker, however, in new construction. In this context, the entire cost of a water heating system is incremental. Capital costs of more efficient alternatives, in many instances, are competitive with conventional electric or fossil-fueled water heating. Energy codes for buildings and other rules should be reviewed to ensure they do not create barriers or obstacles to electrification—for example, by precluding electric water heating, including grid-integrated ER water heating that can take advantage of low-cost energy and provide electric system flexibility.[110]

Appliance Standards

The current appliance standards for residential water heaters were adopted in 2010 and took effect in April 2015.[111] Their efficiency requirements vary depending on the type of water heater and its rated storage volume.[112] According to the Appliance Standards Awareness Project, “for storage water heaters with a volume greater than 55 gallons, the standards require a heat pump efficiency level for electric products and condensing efficiency level for gas products.”[113]

Although HP water heaters are the only products that meet these standards for tanks larger than 55 gallons, and thus the new norm for electric water heaters, evidence suggests these requirements can be circumvented. A 2016 Northwest Energy Efficiency Alliance report found that consumers and installers pursued “workaround solutions,” including “some overstocking of large ERWHs prior to the April 2015 update.”[114] There is also anecdotal evidence of the substitution of residential water heaters with commercial water heaters or residential water heaters with storage tanks smaller than 55 gallons.[115]

At the federal level, potential changes to appliance standards are in process. The Appliance Standards Awareness Project issued a study in 2016 indicating that updating federal standards for water heaters could capture significant savings.[116] The US Department of Energy in September 2018 issued a request for information “to better understand market trends and issues in the emerging market for appliances and commercial equipment that incorporate smart technology.”[117]

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[110] Deason et al., 2018, p. 43.

[111] See US Department of Energy, Energy Conservation Program: Energy Conservation Standards for Residential Water Heaters, Direct Heating Equipment, and Pool Heaters, 75 Federal Register 73,20112 (final rule June 15, 2010) (to be codified at 10 C.F.R. § 430). Retrieved from https://www.gpo.gov/fdsys/pkg/FR-2010-04-16/pdf/2010-7611.pdf

[112] Northwest Energy Efficiency Alliance. *Changes to residential electric water heater federal standards*. Retrieved from https://hotwatersolutionsnw.org/assets/documents/uploads/HWS_Federal-Standards-Guide_FNL_REF.pdf

[113] Appliance Standards Awareness Project. *Water heaters* [Webpage]. Retrieved from https://appliance-standards.org/product/water-heaters

[114] Evergreen Economics. (2016, August). *Northwest Heat Pump Water Heater Initiative market progress evaluation report #2* (Report No. E16-339). Portland, OR: Northwest Energy Efficiency Alliance. Retrieved from https://neea.org/img/uploads/northwest-heat-pump-water-heater-initiative-market-progress-evaluation-report-2.pdf. The report’s authors noted: “The findings and recommendations in this report that are associated with distributors and large retailers are not based on a representative sample of the four-state region—Idaho, Montana, Oregon and Washington.”

[115] Professional Plumbing, Heating, Cooling, and Piping Community. (2017). *Water heater regulations*. Retrieved from https://www.phcppros.com/articles/5312-water-heater-regulations

[116] DeLaski, A., Mauer, J., Amann, J., McGaraghan, M., Kundu, B., Kwatra, S., and McMahon, J.E. (2016, August). *Next generation standards: How the national energy efficiency standards program can continue to drive energy, economic, and environmental benefits* (Report A1604). Washington, DC: Appliance Standards Awareness Project and American Council for an Energy-Efficient Economy. Retrieved from https://appliance-standards.org/sites/default/files/Next%20Gen%20Report%20Final_1.pdf

[117] US Department of Energy. (2018, September 17). *Energy conservation program: Request for information on the emerging smart technology appliance and equipment market* (Document 83 FR 46886). Retrieved from https://www.federalregister.gov/documents/2018/09/17/2018-20131/energy-conservation-program-request-for-information-on-the-emerging-smart-technology-appliance-and. The Department of Energy is authorized to update existing and propose new appliance standards pursuant to the National Appliance Energy Conservation Act. US Department of Energy, Office of Energy Efficiency & Renewable Energy. *History and impacts* [Webpage]. Retrieved from https://www.energy.gov/eere/buildings/history-and-impacts

Ensuring water heaters receive a grid signal would support economical demand response, load shifting, and potential ancillary services.

At the ACEEE Hot Water Forum in March 2018, a US Environmental Protection Agency (EPA) Energy Star program manager held discussions with stakeholders regarding the future of grid-connected water heaters. They addressed topics that included the potential of heat pump water heaters for load shifting and the comparison between current specifications for grid-connected water heaters and the EPA's customary connected criteria, as expressed in other product categories.[118]

It is not clear how and when the Department of Energy will institute new water heater appliance standards or how the EPA will articulate voluntary Energy Star standards. What is clear, however, is that water heaters with built-in control systems offer potential benefits. This capability could enable end users, grid operators, aggregators, or other parties to monitor a water heater's state of charge (that is, water temperature) and control the manner in which it charges. Including Wi-Fi or another utility interface (for example, an open standard for connecting to the internet) to ensure that water heaters receive a grid signal would, in turn, support economical demand response, load shifting, and potential ancillary services.

Additionally, in establishing standards, experts should compare the efficiency of all water heaters, not simply those using the same fuel type—for example, not just looking at gas vs. gas, propane vs. propane, etc.

State Energy Policy

Because their policies can help or hinder beneficial electrification, states will need to ensure that policies reflect opportunities associated with current innovations in technology. For example, states could require both electricity and natural gas utilities to prepare integrated resource plans—long-term plans guiding generation, transmission, distribution, and energy efficiency investments—in a way that explores electrification growth scenarios and their potential effects on the development of both types of utilities. Currently, an electric-only integrated resource plan may not fully explore the effects of electric system trends and investments, especially electrification's effects on local gas distribution companies. Likewise, a natural gas-only resource plan might fail to recognize potentially cleaner and lower-cost electric alternatives, to the detriment of consumers, the environment, and a state's economy.[119]

Squaring utility infrastructure investment and acquisition with new realities is just as important as adjusting utility planning practices. Utility practice varies around the country regarding how new natural gas infrastructure is paid for. For example, new customers may cover all the costs of extending natural gas connections; the utility may socialize these costs so all customers pay for extensions; or there may be some combination of both approaches.[120] As regulators compare the costs and risks of electrification versus continued expansion of natural gas infrastructure, it will be important to recognize any implicit subsidies to determine the actual costs consumers will pay for their hot water.

Energy efficiency resource standards (EERS) offer another example of state policies that may warrant revision in light of electrification.[121] EERS and performance incentives often

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[118] US Department of Energy and US Environmental Protection Agency. *ENERGY STAR and connected water heaters—Evaluating market benefit discussion* [Webpage]. Retrieved from https://www.energystar.gov/products/energy_star_and_connected_water_heaters_%E2%80%93_evaluating_market_benefit_discussion

[119] The utility commission or siting board process of granting a certificate of public convenience and necessity involves similar analysis to that conducted in the context of an integrated resource plan. This would be another venue in which a state could engage in the analysis of reasonable alternatives to a proposed electrification or gas infrastructure project. Dworkin, M., Farnsworth, D., and Rich, J. (2001, June). The environmental duties of public utility commissions. *Pace Environmental Law Review,* 18(2), 325-382. Retrieved from https://digitalcommons.pace.edu/cgi/viewcontent.cgi?article=1564&context=pelr

[120] See, for example, Mississippi's "supplemental growth rider" for Atmos Energy Corp. authorizing a 12 percent return on equity for ten years to extend gas service to projects previously viewed as economically infeasible. Mississippi Public Service Commission, Docket No. 2013-UN-023, Order on July 11, 2013. Retrieved from http://www.psc.state.ms.us/InsiteConnect/InSiteView.aspx?model=INSITE_CONNECT&queue=CTS_ARCHIVEQ&docid=310900

[121] Levin, E. (2018, August). *Getting from here to there: How efficiency programs can go beyond MWh savings to next-generation goals.* Washington, DC: American Council for an Energy-Efficient Economy. Retrieved from https://aceee.org/files/proceedings/2018/node_modules/pdfjs-dist-viewer-min/build/minified/web/viewer.html?file=../../../../../assets/attachments/0194_0286_000100.pdf

measure energy savings in kWhs or therms, rather than in terms of primary energy like Btu or joules. Structured this way, EERS and related programs may discourage electrification because efficiency, as typically defined, requires decreases in kWh sales rather than reductions in primary energy consumption. States could address this obvious barrier readily, by including an electrification component (a carve-out) in their EERS or reformulating their metrics for measuring reductions to reflect primary energy use or greenhouse gas emissions. New York state recently adopted a statewide cumulative annual site energy savings target that is delineated in Btu and will incentivize the most cost-effective efficiency measures across all fuels.[122] In the Wisconsin Quadrennial Review process, the Public Service Commission set energy savings goals for 2019-2022 in terms of kilowatts, kWhs, therms, and million Btu.[123] Additionally, the commission set fuel-specific minimum performance standards.[124]

> Prohibiting or discouraging fuel switching is a policy that states would be wise to revisit with electrification in mind.

Natural gas efficiency programs should also consider the cost-effectiveness of choices beyond those typically available from gas distribution companies. If savings goals in gas programs encourage utilities to replace older, inefficient gas equipment with only new, more efficient gas appliances, any lower-cost and less carbon-intensive electrification opportunities will be lost for the life of the new natural gas appliance or equipment.

Prohibiting or discouraging fuel switching is another policy that states would be wise to revisit with electrification in mind.[125] Instead of setting out clear criteria for when fuel switching might be appropriate, many energy efficiency programs include blanket prohibitions against utility efforts to switch customers between electricity and natural gas, or they simply do not accommodate such switching.[126] Where electrifcation is beneficial—that is, consistent with RAP's three conditions—these prohibitions could be revisited. At the very least, regulators should specify principles articulating the conditions under which fuel switching would be allowed.

Some states also have prohibitions against utility programs to increase load, which can be expected to occur as electrification increases. Originally intended to prevent utility featherbedding, such provisions are unnecessary if electrification is beneficial, because it doesn't increase costs and environmental impacts for all ratepayers. This is why we encourage states to apply the three BE conditions to determine whether electrification programs and associated load growth are indeed in the public interest.[127]

To encourage electrification of water heating, states could also revisit their renewable portfolio standards and require utilities to meet part of their portfolio obligation by pursuing BE programs or activities. For example, Vermont recognizes cold climate heat pump installation as one way to meet utility obligations under its renewable energy standard.[128] Tier III of

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[122] New York State Energy Research and Development Authority and Department of Public Service. (2018). *New efficiency: New York*. Retrieved from https://www.nyserda.ny.gov/-/media/Files/Publications/New-Efficiency-New-York.pdf

[123] Public Service Commission of Wisconsin, Quadrennial Planning Process III, Docket No. 5-FE-101, Final Decision of June 6, 2018, p. 13. Retrieved from http://apps.psc.wi.gov/vs2015/ERF_view/viewdoc.aspx?docid=343909

[124] Public Service Commission of Wisconsin, 2018.

[125] In its policy on fuel switching, the Energy Trust of Oregon, for example, states that while fuel switching is a consumer choice and the Energy Trust offers "incentives for consumers to use high-efficiency equipment for the fuel consumers choose," the Energy Trust "does not intend its incentives to affect fuel choice." The Energy Trust also notes its intent to revisit the policy periodically to assess whether it "is missing compelling opportunities." See Energy Trust of Oregon, 4.03.000-P Fuel-switching Policy. Retrieved from https://www.energytrust.org/wp-content/uploads/2016/11/4.03.000.pdf

[126] For example, the Massachusetts Early Replacement Program allows neither fuel switching nor distribution system switching. Efficiency change-outs are supported by rebates of up to $3,250, but only to the extent that, for example, a less efficient propane water heater could be replaced with a more efficient propane water heater. See Mass Save. *Early heating and cooling equipment replacement* [Webpage]. Retrieved from https://www.masssave.com/en/saving/residential-rebates/early-heating-and-cooling/

[127] Farnsworth et al., 2018, p. 9.

[128] Under Tier III of Vermont's renewable energy standard, distribution utilities must acquire other renewable resources described under other parts of the program or "acquire fossil-fuel savings through energy transformation projects." These are defined as projects that "reduce the fossil-fuel consumption of a DU's customers and the greenhouse gas emissions associated with that consumption." The standard is set at 2 percent of annual retail sales in 2017, "increasing by two-thirds of a percent each year" until reaching 12 percent in 2032. State of Vermont, Public Utility Commission. *Renewable energy standard* [Webpage]. Retrieved from https://puc.vermont.gov/electric/renewable-energy-standard. See also VT Statutes Annotated, Chapter 30, §§ 8002-8005. Retrieved from https://legislature.vermont.gov/statutes/chapter/30/089

the standard provides for "energy transformation projects"—those that reduce fossil fuel consumption and greenhouse gas emissions.

Finally, as with all energy policies, affordability affects the ability of all customer classes to share equitably the benefits of electric water heating. As states identify electrification goals and formulate plans for its deployment, they will need to ensure that low-income customers are not left behind in this transition. Low-income households typically have older and less efficient appliances and often face fundamental challenges associated with the basic soundness of their homes. These households often lack the flexibility and resources to improve the efficiency of essential home energy uses such as water heating. As a result, they may have less ability than moderate- and higher-income customers to participate in electrification programs. We encourage states to recognize these circumstances and help address affordability gaps to ensure that the most effective water heating programs are available to all energy consumers.

Rate Design

Customers are willing to shift their consumption to cheaper hours of the day when the financial incentive is meaningful.[129] Using rates to signal value to consumers is not new, and, as noted earlier, many electric technologies can be scheduled or programmed to draw power when costs are low. However, for customers to have the incentive to take advantage of low-cost power—and enable them and the utility to reap the economic benefits—time-varying pricing is necessary to communicate cost differences.[130]

Rate designs that reflect the long-run marginal cost to produce electricity—that is, the cost to produce, transmit, and deliver the next unit of power over the long term—will tend to produce outcomes in the public interest over the long run.[131] Time-of-use pricing, which includes these long-run costs in time-varying energy charges, will tend to encourage customers to adjust their behavior and move their electricity use to times when it is cheaper for the utility to serve. This pricing provides an economic incentive to commercialize technologies that enable such demand flexibility, as well as services that can come from it like peak shaving and ancillary services.

If the cost of heating water electrically is sufficiently lower, customers may move their charging to off-peak periods that enhance grid management or reduce emissions. Rates shape the way consumers use electricity. Grid managers can use rates to motivate customers and enlist their help in making more efficient use of existing grid investments and avoiding unnecessary new investments.[132] As shown by the illustrative smart rate design in Table 10, there is a strong economic incentive for customers to shift their usage away from higher-cost critical-peak, on-peak, and mid-peak times and to take advantage of low-cost off-peak electricity.[133] The off-peak rate in this illustration is half the peak rate. Results from utility pilot programs and actual time-varying rates around the country show that customers do respond, moving some of their use to

Table 10. Illustrative Smart Rate Design

Rate element	Based on the cost of:	Illustrative rate
Customer charge	Service drop, billing, and collection only	$4.00/month
Transformer charge	Final line transformer	$1.00/kilovolt-ampere/month
Off-peak energy	Baseload resources plus transmission and distribution	$0.07/kWh
Mid-peak energy	Baseload plus intermediate resources plus T&D	$0.09/kWh
On-peak energy	Baseload, intermediate, and peaking resources plus T&D	$0.14/kWh
Critical peak energy	Demand response resources	$0.74/kWh

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[129] See Faruqui, A., Hledik, R., and Palmer, J. (2012, July). *Time-varying and dynamic rate design*, p. 38. Montpelier, VT: Regulatory Assistance Project. Retrieved from https://www.raponline.org/knowledge-center/time-varying-and-dynamic-rate-design/

[130] Time-of-use rates produce very small or indiscernible changes in bills for customers who make no change in usage but can provide a significant reward for those who do.

[131] Lazar, 2016.

[132] Ellerbrok, C. (2014). Potentials of demand side management using heat pumps with building mass as a thermal storage. *Energy Procedia, 46*, 214-219. Retrieved from https://ac.els-cdn.com/S187661021400191X/1-s2.0-S187661021400191X-main.pdf?_tid=0866a42f-74c1-4663-9641-8a6bfdf02418&acdnat=1531757467_b741f22bc53e7eb1035300429a6a8902

[133] Lazar, J., and Gonzalez, W. (2015). *Smart rate design for a smart future.* Montpelier, VT: Regulatory Assistance Project. Retrieved from http://www.raponline.org/document/download/id/7680

off-peak hours. Results also show that when paired with smart technology, like automated water heater controls, time-varying rates can be even more effective at shifting usage to reduce peak demand.[134]

In a scenario analysis looking at four regions of the country, Rocky Mountain Institute found that managing both water and space heating HP usage for peak load shaving and load shifting to optimize the cost-saving benefits of time-varying rates could save individual customers $2,000 to $4,000 over the lifetime of the device.[135] With time-varying rates, the storage associated with controlled HP and electric resistance water heaters can carry customers through critical peak periods cost-effectively in most locations. In addition, the lower off-peak rate will help enable controlled water heating, making it cost-competitive with fossil-fueled alternatives.

Incentives and Other Programs

Financial incentives for purchasing electric technologies can drive electrification, particularly during early deployment stages when costs are declining but have not reached parity with alternative technologies. Incentives can be offered by utilities (typically through rebates), third-party energy efficiency providers, or government agencies or programs through rebates, loans, or tax incentives.

Electric utilities have provided incentives to spur innovative technology deployment for more than 30 years. The Super Efficient Refrigerator Program brought huge improvements in refrigerator efficiency.[136] Window replacement incentives spurred the glazing industry to produce superior products that save energy and improve comfort.[137] Minimum efficiency standards for lighting have also been highly successful and used by states and the federal government to save energy.[138] Millions of smart thermostats are being deployed with utility financial support.[139] These programs tend to transform the market over time, so that continued incentives are not necessary. Some utilities are also experimenting with incentives for builders, which can be an effective way to promote electrification in new construction.[140]

Great River Energy and the Minnesota Rural Electric Association are members of the Community Storage Initiative, a collection of utility-sponsored programs that aggregate electric storage resources, such as water heaters and electric vehicles, to improve the efficiency of electric energy services for consumers.[141] Steele-Waseca Cooperative Electric has a program that combines community solar with controlled water heating.[142] Participants in the co-op's storage water heating program are eligible to receive a free water heater and to subscribe to solar power at a substantial discount.

Early retirement programs are another way consumers can get information and access to more efficient and economical appliances, including electric water heaters. This is especially important with water heaters because otherwise they are

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[134] Faruqui et al., 2012.

[135] These results are 15-year discounted values. Savings of this magnitude require time-of-use rates with significant cost differentials (e.g., a 3-1 ratio of peak to off-peak pricing). For more see Billimoria, S., Guccione, L., Henchen, M., and Louis-Prescott, L. (2018). *The economics of electrifying buildings*. Boulder, CO: Rocky Mountain Institute. Retrieved from https://www.rmi.org/insights/reports/economics-electrifying-buildings/

[136] Eckert, J. (1995). *The Super Efficient Refrigerator Program: Case study of a golden carrot program* (NREL/TP-461-7281). Golden, CO: National Renewable Energy Laboratory. Retrieved from https://www.nrel.gov/docs/legosti/old/7281.pdf

[137] Jones, J. (2015, July 21). Efficient window technologies: A history. *EcoBuilding Pulse*. Retrieved from http://www.ecobuildingpulse.com/products/efficient-window-technologies-a-history_s

[138] York, D., Bastian, H., Relf, G., and Amann, A. (2017, December). *Transforming energy efficiency markets: Lessons learned and next steps* (Report U1715), p. 8. Washington, DC: American Council for an Energy-Efficient Economy. Retrieved from http://ipu.msu.edu/wp-content/uploads/2018/01/ACEEE-Energy-Efficiency-Markets-2017.pdf

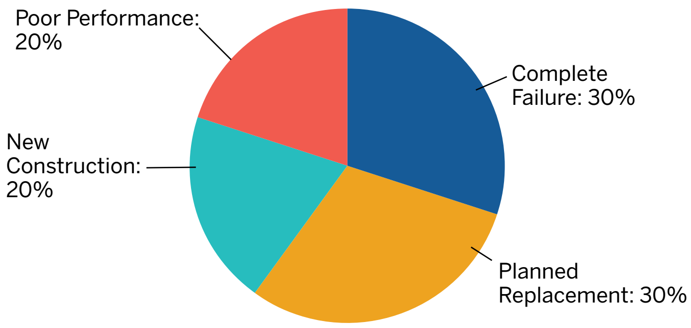
[139] Wilczynski, E. (2017, March 9). Turning up the heat: The rapid surge in smart thermostat programs [Blog post]. Retrieved from https://www.esource.com/Blog/ESource/ES-Blog-3-6-17-Smart-Thermostats

[140] Deason et al., 2018, citing Mullen-Trento, S., Narayanamurthy, R., Johnson, B., and Zhao, P. (2016, May). *SMUD all-electric homes deep dive.* Presented at the CA Building Decarbonization Research + Resources Synthesis.

[141] Western Area Power Administration. (2016, May). Great River Energy helps to launch community storage initiative. *Energy Services Bulletin*. Retrieved from https://www.wapa.gov/EnergyServices/Documents/ESBMay16.pdf. For a detailed description of community storage programs, see Grant, C., Keegan, P., and Wheeless, A. (2016, June). *Implementing community storage programs*. Arlington, VA: National Rural Electric Cooperative Association. Retrieved from http://www.communitystorageinitiative.com/wp-content/uploads/2016/05/tscommunitystoragejune2016.pdf

[142] Details of the programs are on the co-op's website at https://swce.coop/swce-field-services/renewables/.

Figure 25. Reasons for Purchasing a Water Heater



Source: US Department of Energy. (2009). *New Technologies New Savings: Water Heater Market Profile.*

typically purchased in emergency circumstances when an existing unit has failed. As a result, the purchase of a water heater rarely includes thoughtful planning or sufficient time for a consumer to weigh alternatives. As illustrated in Figure 25, according to the US Department of Energy there are three reasons homeowners replace water heaters: The unit fails; its performance becomes unacceptable; or the homeowner plans the replacement.[143] Assuming that the trends continue today, half of all water heater purchases are unplanned.

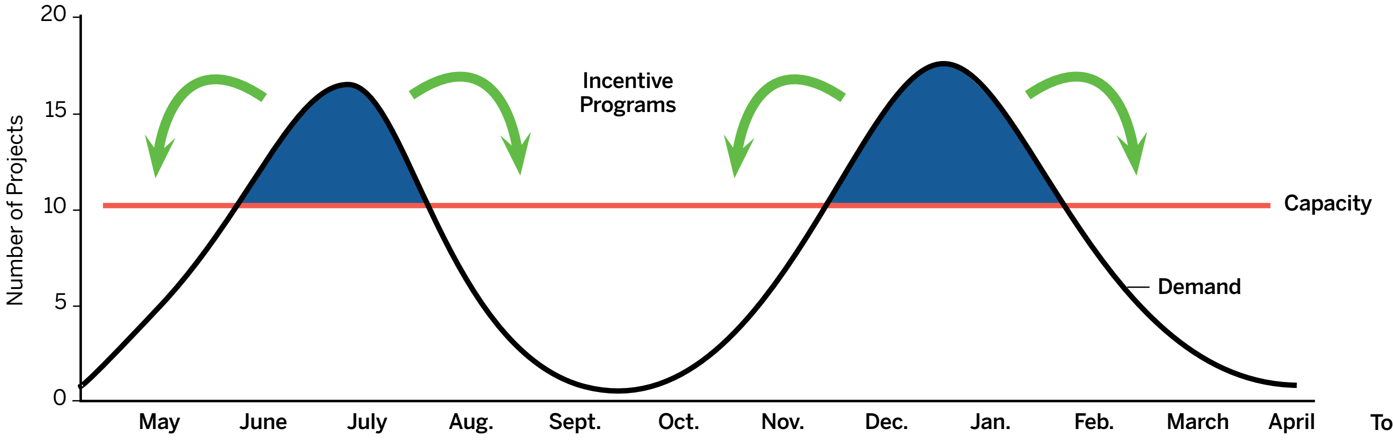
According to the director of utilities and performance construction for Mitsubishi Electric Trane HVAC US, in fact, “a large percent of all HVAC replacements are done in *emergency mode,* affording the contractor little to no opportunity to do anything in the home but replace what was already there.[144] ACEEE reports an even more troubling statistic: “Ninety-five percent of [water heater] sales are emergency replacements . . .”[145]

These insights strongly suggest the need for policy interventions to ensure better education and opportunity for consumers to take advantage of innovative economical and environmentally responsible electrification technologies for water heating.

Early retirement programs are one approach policymakers should consider. The goal, and related challenge, of an early retirement program is to identify older appliances and give homeowners the chance to replace them before they fail. This lets customers avoid emergencies and choose among more appliances and related program incentives for superior models.

Early retirement programs, as characterized in Figure 26,

Figure 26. Appliance Early Retirement Incentives Can Maximize Contractors’ Capacity



	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	Total
Current	5	10	10	5	1	2	8	10	10	8	3	1	73
With Programs	10	10	10	10	10	10	10	10	10	10	10	10	120

Source: Based on Dubin, E. (2018, October 3). *NEEP Annual Summit—A Manufacturer Perspective.*

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143 US Department of Energy. (2009). *New technologies new savings: Water heater market profile.* Washington, DC: Author. Retrieved from https://www.energystar.gov/ia/partners/prod_development/new_specs/downloads/water_heaters/Water_Heater_Market_Profile_Sept2009.pdf

144 Dubin, E. (2018, October 3). *NEEP annual summit—A manufacturer perspective* [Presentation]. Mitsubishi Electric Trane HVAC USA. Retrieved from https://neep.org/sites/default/files/4%20-%20Eric%20Dubin%20Power%20Talk.pdf

145 Merson, H.C., Barnacle, B., Cornejo, D., Burmester, C., Terborgh, J., and Huessy, F. (2018). *Five years and beyond with supply chain engagement: What’s next with upstream and midstream?* Washington, DC: American Council for an Energy-Efficient Economy. Retrieved from https://aceee.org/files/proceedings/2018/node_modules/pdfjs-dist-viewer-min/build/minified/web/viewer.html?file=../../../../../assets/attachments/0194_0286_000244.pdf

can also help contractors by leveling out the demand for their services over the year and drawing some of their capacity-constrained work from the busy spring and fall into the shoulder seasons when they are less busy.[146] In doing so, these programs not only provide more information and choices to consumers, they may also enable installers to be more responsive.

Midstream and upstream programs are another way to promote market transformation by engaging throughout the supply chain. Such programs help ensure that efficient water heating equipment is stocked and sold—even in emergency situations. According to ACEEE, this approach sets out a "clear value proposition for supply chain market actors."[147] The organization encourages program designers to recognize the value of "market intelligence" throughout the supply chain—from manufacturer to customer—and its key role in identifying and quantifying market barriers to most effectively target program interventions. Failure in the supply chain at any point—regarding building permits, adequate training for installers, or the availability of contractors or equipment—will hinder market development.

Conclusion

The beneficial electrification of water heating constitutes an economical and practical path forward for saving consumers money, managing the power grid, and reducing related greenhouse gas emissions. In this paper the authors have applied RAP's three beneficial electrification conditions to illustrate electric water heating opportunities available today and in the near future. With a closer look, decision-makers will see these opportunities and appreciate the benefits they can bring to every state's economy and consumers.

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[146] Dubin, 2018.

[147] Merson et al., 2018.

Appendix: Measuring and Characterizing Water Heater Performance

To ensure the adoption of appropriate water heating technologies, it is important to be able to rely on performance metrics. We consider two approaches used to characterize the performance of water heaters. One is the heating coefficient of performance (COP), typically used for heat pump water heaters. The other is an energy factor, used to characterize electric resistance water heater performance.

A standard definition of COP would be the net heat delivered by the water heater to the domestic water load divided by the total electrical energy consumed over a period of time:[148]

$$\frac{\text{Total heating capacity delivered (Btu)}}{\text{Total electric power consumption (watt-hours)}}$$

The energy factor represents the efficiency of the electric heating elements and tank losses under a 24-hour test procedure.[149] The energy factor for a typical electric resistance water heater would be 1.0. But due to heat loss from pipes and water tank walls (i.e., standby losses), it is lower. Testing procedure and calculations to determine energy factor are standardized among manufacturers.

Heat pump water heater performance can vary depending on a number of factors, as described in this paper. If a heat pump water heater operates with a COP of 3.0, for example, this means it will heat more than three times as much water as an electric resistance unit with the same electrical energy input.

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[148] Shapiro, C., and Puttagunta, S. (2016, February). *Field performance of heat pump water heaters in the Northeast.* Washington, DC: US Department of Energy, Office of Energy Efficiency & Renewable Energy. Retrieved from https://www1.eere.energy.gov/buildings/publications/pdfs/building_america/64904.pdf.

[149] Steven Winter Associates. (2012, June). *Heat pump water heaters: Evaluation of field installed performance.* Massachusetts Energy Efficiency Advisory Council. Retrieved from http://ma-eeac.org/wordpress/wp-content/uploads/Heat-Pump-Water-heaters-Evaluation-of-Field-INstalled-Performance.pdf

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