Realizing the Residential Electrification Opportunity: One Heat Pump at a Time

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ABSTRACT

Space and water heating in residential buildings is a major contributor of greenhouse gas (GHG) emissions in the United States. Advanced electric heat pumps (HP) and heat pump water heaters (HPWH) are poised to provide a low carbon alternative to traditional fossil-based space and water heating. Widespread deployment of heat pumps could help address the significant portion of building emissions and primary energy used in American households; however, much work needs to be done to close the knowledge gap between like-for-like fossil equipment replacement and switching to HPs for the average contractor. The Pacific Northwest National Laboratory (PNNL) has been working on closing this knowledge gap through the development of decision tools and resources targeted towards contractors and installers. Developed in coordination with stakeholders and experienced contractors from a variety of geographic regions, these tools help streamline the process of sizing and selecting residential HPs and HPWHs for key use cases. Along with the complementary Retrofit Decision Tool developed by PNNL, the decision tools will help contractors understand the importance of whole building considerations when choosing HPs including envelope upgrades, duct assessments, and electrical assessments to ensure optimal selection and performance of the HP or HPWH. They also provide direct links to resources and best practices developed by PNNL as well as external entities to further help contractor education and training. This paper describes the development of these tools, and their role in moving the existing space and water heating market towards HPs to help realize the country's decarbonization goals.

Introduction

Energy usage from residential buildings accounts for nearly 19% of U.S. energy-related greenhouse gas emissions (EIA 2023a). The largest typical end-uses for residential buildings are space-conditioning and water heating, respectively making up 52% and 18% of residential site energy usage (EIA 2022). Emissions can be reduced by decarbonizing these end-uses. The process of decarbonization in this regard involves shifting fossil fuel end-uses to electricity, which is increasingly produced by low-carbon generation methods. In 2022, electric power industry emissions were estimated at 858 lbs. of CO_2 per Megawatt-hour (MWh), down from roughly 1,400 lbs. of CO_2/MWh in 1990 (EIA 2023b). This is a result of cleaner electricity generation sources being brought online in the U.S. New, more efficient technologies and construction practices have also helped to decrease emissions from these end-uses in newly constructed residences. However, the U.S. has a significant number of aging buildings in its residential building stock. Decreasing and decarbonizing space-conditioning and water heating energy in these homes presents a challenge as well as a significant opportunity.

Existing residences may have higher energy use for several reasons. The first is old or inefficient equipment installed in the residence. Equipment may be original from the time of construction, when efficiency standards were lower, or it may have been replaced with equipment that marginally improved efficiency. An example could be a 25-year-old fuel oil boiler used for water and space heating, a standard electric resistance water heater, or an original duct system that leaks and is uninsulated. All represent opportunities to increase efficiency and/or decarbonize an end-use.

The second reason for higher energy use in existing residences is due to the construction of the residence itself. Even if a house has a brand new, efficient heating, ventilation, and air conditioning (HVAC) system, it may consume more energy to operate because the house is leaky or lacks insulation. Homes built before the standardization of energy codes in 1980 may have less insulation, resulting in higher heating and cooling loads for the HVAC system to handle. Newly-constructed homes are not immune to these problems, especially those built in states or municipalities with outdated codes, but generally have more insulation and lower energy use intensity (EIA 2022).

Both reasons are important to consider in the process of decarbonizing and increasing efficiency in existing residential buildings. A third reason for higher energy use is that although efficient technology may be selected for a well-insulated house, the efficiency of the equipment may not be realized if it is designed or installed incorrectly. Currently installed central air conditioners and air-source heat pumps waste 9% of their energy usage due to installation faults (Winkler et al. 2020). This factor brings the installation workforce into the equation for efficiency and decarbonization, and ties multiple pieces together. A well-trained workforce can consider these three reasons for higher residential emissions and work to tackle them. The workforce needs to promote high efficiency decarbonization technologies, consider those technologies in the context of the whole home, and install equipment properly. Two of the tools described in this paper were developed with the goal of training the workforce to understand these challenges. The third tool links the first two together and adds the homeowner to the equation.

For the purposes of this paper, we focus primarily on decarbonization technologies such as heat pump water heaters (HPWH), air-source heat pumps (ASHP) for space conditioning with a focus on cold-climate heat pumps (CCHP) using variable-speed compressors, and home envelope improvements.

Department of Energy Perspective

U.S. Secretary of Energy Jennifer M. Granholm said, “Exploring new ways to build and operate America’s buildings is key to cutting harmful emissions and combatting the climate crisis.” To this end, DOE’s Office of Energy Efficiency and Renewable Energy is deploying solutions to support President Biden’s plan to transition America to net-zero greenhouse gas emissions by 2050 (DOE 2023). DOE efforts take many shapes, including laboratory research on emerging technologies, workforce development, codes and standards work, and technical support to significant expenditures like the energy efficiency incentives found in the Inflation Reduction Act and the Bipartisan Infrastructure Law.

Typical Replacement vs. Decarbonization Retrofit

It is important to make the distinction between the "typical" scenario that occurs after a customer calls a contractor to replace or add new equipment and the scenario that occurs in a retrofit focused on decarbonization (and efficiency, to a lesser extent). In a typical call for a new water heater or HVAC system, the most common solution is a like-for-like replacement. The existing equipment is swapped out for the most similar equipment offered by the installer. This approach benefits both consumers and the installers by simplifying the sales and installation processes. The customer was likely happy with the performance of the equipment before failure, and few modifications are needed to accommodate the new equipment. Installers may use this opportunity to upsell the customer with more efficient or advanced technology, particularly if they were not satisfied with their previous equipment's performance. However, if the existing equipment in the home uses fossil fuels, the upsell will not usually include decarbonization technology.

For a decarbonization retrofit, and even some retrofits involving electric-to-electric replacements, a more in-depth design process must occur. Because the characteristics of the fossil fuel and electric equipment are significantly different, the installer or designer must work to determine the best system for the project. There may be significant changes required to supporting systems of the home, such as ducting, electrical wiring, and plumbing. Depending on the company, these design processes may require subcontractors to join the project. A thorough HVAC system redesign may include changes to the envelope of the home, including adding insulation, installing new windows, and air sealing. The timeline may also be extended if equipment needs to be specially ordered. While some customers may start the project with the goal of decarbonizing their home or a piece of equipment, others will need to be convinced by the contractor that it is a feasible, attractive, and reliable option. This adds a complicated layer with equity implications, as the options for decarbonization often include a higher first cost that may or may not be offset by incentives.

Closely tied to the differences between these scenarios is the timing and urgency of the project. Customers are typically motivated to replace a system only when it fails or begins to perform poorly. In the case of water heaters, as many as 85-90% of replacements occur in an "emergency" scenario, where the equipment has failed, and the customer has no hot water (NEEA 2016). HVAC system replacements may occur more proactively, though equipment failure is still a large driver for replacement.

For customers to consider a decarbonization retrofit over a typical replacement, proactive replacements need to become more commonplace and emergency replacements need to utilize streamlined design and installation processes. For those scenarios that occur proactively (i.e., while the existing equipment is still functional) there is an easier opportunity for decarbonization because the customer can continue using the equipment during a longer design and installation process.

For example, consider a home with a gas furnace and central air conditioning (AC). A customer calls at the beginning of the summer when they notice their AC isn't working as well as it did last year. They're interested in replacing their whole system with an all-electric heat pump. The contractor may say that this job has a lead time of two weeks, during which they can keep using their existing system. The customer does so and ends up with exactly the equipment they want, which will save them energy and money.

Consider the same scenario, but the customer waited until the middle of summer when the AC fails. They're interested in replacing their whole system with an all-electric heat pump. The contractor may say that this job has a lead time of two weeks, but now the customer has no AC and it's hot outside. The contractor says that they can get a replacement AC in by the end of the week. The customer chooses the project with the shortest timeline, but doesn't get the equipment that will save them energy and money.

To alleviate the second scenario, contractors need robust supply of equipment, creative solutions (such as loaner equipment), and training to quickly and efficiently overcome barriers they may encounter. On the other hand, increasing proactive replacement will require higher consumer awareness, attractive financial propositions, and effective marketing by contractors. This paper will mainly focus on overcoming barriers for contractors and consumer awareness.

Tools Overview

PNNL has developed three tools to support DOE goals on decarbonization and efficiency: Heat Pump Water Heater Installation Tool, Cold Climate Heat Pump Decision Tool, and the Retrofit Decision Tool. All three tools are found on the Building America Solution Center (BASC), a DOE site operated by PNNL focusing on high performance construction topics. The first two tools focus mainly on contractors and are intended to be used as part of the training process for a contractor learning how to design and/or install these systems. Contractors can use these tools to learn about the decision-making processes of designing the equipment and addressing key hurdles in the process by walking through a real project chosen by the user.

The Retrofit Decision tool is geared towards homeowners interested in the most effective ways to decarbonize their homes. It provides data-driven suggestions for decarbonization measures, including equipment and envelope options, based on simple information about the home. In cases where a HPWH or ASHP are recommended, links will connect the user to the relevant tool.

Tool Design Process: Prototypes, Stakeholders, and Reviews

The tools underwent a collaborative design process involving many PNNL staff, stakeholder committees comprised of external subject matter experts (SME), software engineers, user experience experts, and installers/contractors. Initial versions of the tools were created in Excel to allow for easy editing and sharing with stakeholders. Reviews for the Excel prototype were focused on technical accuracy and the high-level workflow of the tools. The tools were then moved to the web, where increased functionality and usability features could be implemented.

The tools underwent further review by contractors in the relevant industries. HVAC experts reviewed the CCHP Decision Tool, providing useful feedback on technical topics as well as usability issues. Contractors with plumbing, pipefitting, and electrical experience reviewed the HPWH Installation Tool. Reviewers had varying levels of knowledge and experience with HPWHs, which allowed for feedback from experts and the target audience of the tool. These reviews also focused on technical accuracy along with usability. Some users performed guided walkthroughs of the tools, while others reviewed the tools without assistance from the PNNL team. The latter reviews revealed aspects of the tools that could be potentially confusing to users. The tools continue to undergo review by industry experts for improvements of usability, additions, and technical fixes.

Addressing Technical and Workforce Challenges with Heat Pump Installations

The goal of these tools is to help contractors become more familiar with heat pump systems, especially those using variable-speed technology. By using these tools, contractors can learn about the best practices for these systems and how to navigate common barriers faced during retrofit scenarios, all through the lens of a potential real-world project. If they can understand how these systems can be successfully implemented, even in challenging scenarios, they can address the technical challenges posed by installing heat pumps in older housing stock. A well-trained HVAC workforce will be able to speak confidently to customers and help them on their electrification journeys.

Cold Climate Heat Pump Decision Tool

The Cold Climate Heat Pump Decision Tool was created to help guide contractors through the decision-making process for heat pump sizing and selection, with a focus on retrofit applications in cold climates. However, it can be used in all areas of the U.S. and for new construction projects of homes. It is built on the premise that contractors are most familiar with like-for-like replacement projects and may need resources to guide them through a new design/installation process with unfamiliar technology. HVAC contractors have noted that projects can quickly become complicated due to a home's unique characteristics, especially if the project involves installing a technology that differs significantly from the existing equipment in the home. For this reason, it was necessary to simplify the tool. Simplification not only reduces the burden on the user, but also makes the outputs and guidance more generalizable across different projects.

The main structure of the tool involves collecting information about a real or hypothetical residence from users across four sequential input screens and providing output on a final screen. The first input screen collects high-level project information about the house and existing equipment. The second screen provides guidance on performing a residential load calculation and collects the values from that calculation, which are integral to the sizing process of heat pump systems. The third screen collects information about the existing duct system, if there is one. For heat pump retrofits, the duct system can often be a barrier to installing a correctly sized system. The tool estimates airflow requirements for a potential system and compares them with existing airflow capacity. Calculations based on the inputs to this page help the contractor consider options for utilizing the existing ducts, adding more duct capacity, or bypassing the duct system entirely with ductless equipment. The fourth screen helps users determine if there is sufficient electrical capacity for a new heat pump system by using an add-on tool to evaluate electrical panels. The output screen summarizes the action items to ensure a successful project, describes several options for system sizes and configurations to meet the project goals, and links with an external product database for real-life equipment suggestions. We describe each input screen in detail below.

Enter project information. This page collects inputs such as zip code, existing heating fuel type, presence of ducts, presence of air conditioning equipment, and the project objective. The project objective is used to shape the guidance and outputs provided. Customers may be interested in installing a heat pump for a variety of reasons. The three reasons most relevant to the tool are:

- Replacement of an existing heat system
- New system or replacement of an existing cooling system
- Displace heating from the existing system

Residential load calculation. On this page, users can enter the design heating and cooling loads after conducting a load calculation. The Air Conditioning Contractors of America has established a methodology called Manual J 8th Edition (MJ8), which is recognized as an industry standard for calculating heating and cooling loads of a structure. The tool does not feature a method for performing MJ8 but does provide rationale for performing the calculation and further resources for contractors unfamiliar with the process. Many contractors do not perform MJ8 or a similar load calculation for every job, though they are often required to do so depending on their local codes. Rules of thumb are common for determining heating and cooling loads, especially those based on square footage. Other contractors may rely on previous installations in similar homes to determine the loads. Having reasonable levels of confidence in the heating and cooling requirements of a building is key to choosing equipment that will perform efficiently and keep the customer comfortable. This information can be obtained by performing a proper MJ8 calculation.

Duct system assessment. On this page, users enter information about the existing duct system, if there is one. There are many heat pump systems that do not require ducts, so an important consideration in any heat pump project is to consider the condition and size of the ducts to determine if a ducted or ductless system is more appropriate. If a duct system can be reused, it may lower the installation costs. However, if the system is replacing a centrally ducted furnace, the duct system could have several issues that might impact heat pump operation thus making the home less energy efficient.

If the furnace and existing duct system are sized correctly to the home, the duct system may have inadequate airflow capacity to accommodate a heat pump. This is due to the lower delivery temperature of the air from a heat pump system compared to a furnace. The heat pump may be able to overcome this constraint with longer run times, but it's important to make these considerations when designing the system.

The duct system may also have issues with air leakage into unconditioned parts of the home, which can lower the efficiency of the equipment by as much as 20% (ENERGY STAR 2024). The duct system may not run to every desired room of the house, especially if there have been additions to the house, or provide adequate heating and cooling in every room.

Users can input airflow measurements through the system, if available. Otherwise, they can enter dimensions of the main supply and return trunks, as well as qualitative assessments of the duct condition. This page helps contractors to consider the importance of the duct system to a heat pump installation and will result in guidance if modifications are necessary.

Electrical panel information. On this page, users are asked to determine if there is physical space for the breaker required for a heat pump as well as available ampacity in the electrical panel. A pop-up Electrical Panel Estimator allows users to estimate the ampacity of the existing panel based on the National Electric Code (NEC) 220.83 calculation. This estimator tool uses assumptions and default values for equipment unless provided with exact wattage values for larger appliances, so it does not constitute a fully compliant NEC calculation. However, it can give the user an idea of the likelihood of a panel upgrade or some other intervention to allow the heat pump circuit.

In some areas of the country, electrical panel and service upgrades can cost between $2,000-$30,000 (Pena et al. 2022). If an expensive upgrade can be avoided, electrification projects become more accessible and affordable. As households move away from fossil fuels to electricity, contractors are going to need to become more familiar with these calculations and how to perform them. They should rightfully be conservative when it comes to safety around electricity, but should also know that in general many homes do not come close to reaching the capacity of their panels (Walker 2023). In the Clean TECH California Program, panel upgrades were most often triggered by solar photovoltaics (PV) and electric vehicle (EV) chargers (Walker 2023). This estimator can help start contractors on that path to familiarity and understanding.

Outputs. On this page, the user can view their inputs and see the guidance and recommendations based on their inputs. Guidance is often based on major action items that may exist, such as upgrading the duct system or electrical panel. There are also options presented that allow the project to continue forward without these upgrades, though in some cases they may be unavoidable. In these cases, guidance on these upgrades is given such that the project can still be completed. System configurations such as centrally ducted and multi-split are discussed, along with guidance on sizing based on the project objective and the design loads entered.

By utilizing an API connection to the Northeast Energy Efficiency Partnerships' (NEEP) Cold Climate Air Source Heat Pump List, the tool presents equipment options that fit the user's project objectives. This database is a powerful repository of performance data collected by NEEP that allows for metrics to be calculated based on the home's location and design load. The following data is calculated for each potential system in the NEEP List and is used to sort and filter through the list based on the inputs to the CCHP Decision Tool:

- Percent of design heating load served
- Percent of design cooling load served
- Percent of heating hours served while modulating
- Percent of cooling hours served while modulating

These outputs combine general guidance with specific equipment to provide a powerful learning opportunity for users.

Methodology. The tool logic most resembles a decision tree, wherein certain choices create branching paths that guide the user to the output. The major decision points are listed below:

- Project objective
- Presence of ducts or willingness to install new ducts

- Existing fuel type
- Whether the system should be designed to heating or cooling load

These inputs will determine the configuration of systems recommended, sizing approach, and backup heating approach, as well as major action items before the installation.

Addressing Technical and Workforce Challenges with Heat Pump Water Heater Installations

To make HPWHs a widespread technology for decarbonization, installations need to be made easier for contractors and more contractors need to gain familiarity with and confidence in the equipment. The HPWH Installation Tool can be an important component of both these factors.

Installation is made easier through a guided approach, where the most common hurdles are addressed in detail and common plumbing knowledge is cut out to keep the guidance short and sweet. One goal of the tool is to give contractors few, if any, good reasons to avoid a HPWH for an installation project. It can be used by people at any step in the process, from the homeowner, to call center agents, to the installer on the jobsite.

Furthermore, this tool can be used by all those who fall somewhere in between on the scale from homeowners to licensed installers. It is unclear how many water heaters are installed without a permit or by an unlicensed individual. However, it will be important to bring this part of the workforce along in the decarbonization journey as well. Not only do handypersons need to understand how to successfully install a HPWH, but they also need to be members of their communities that are spreading the benefits of the technology to their friends, neighbors, and customers.

After using this tool on several jobs, on real or hypothetical projects, a contractor might feel comfortable addressing most of the issues that can arise during a HPWH installation. In this case, they will no longer need to use the tool on every job. Perhaps they return to it for guidance on a new or unique situation that they encounter or use it as training material for new hires. They have hopefully become a HPWH champion and encourage their customers to install the technology because they feel confident in the performance of the technology, confident installing it, and confident in the satisfaction of their customers.

Heat Pump Water Heater Installation Tool

The Heat Pump Water Heater Installation Tool guides the user through the decision-making process for HPWH product selection and installation. While the process for a water heater design and installation is much simpler than that of an HVAC system, there are still factors for the contractor to consider and new concepts for an installer unfamiliar with the technology. The focus of the tool is on retrofit scenarios, as those are more complicated than new home construction installations. HPWHs are a very attractive option for new construction in certain areas of the country, and less work is needed in that sector of workforce development.

The differences posed by HPWH technology are explained through a scenario entered into the tool's form by the user. The required information is gathered relatively easily by someone on-site or with a few pictures of the existing equipment and its location. This means that the tool could be used by a homeowner, an installer, or an installer's call center staff. There is one page of required input information followed by one page of outputs that provides information on dealing with any potential challenges in the installation process and a suggested size for the HPWH to be installed.

Inputs page. The tool allows users to read background information about the tool, HPWHs, and their benefits for customers and installers before starting to input information. If the user is already familiar with the tool, the user can skip this section. They can then input basic home information such as zip code and number of bedrooms and bathrooms. Then information on the location of the water heater is collected, with special attention to the air volume in the space, likely temperatures (determined by the location in the home and climate zone), and the options for draining condensate from the water heater. These issues are not typically relevant for conventional storage water heaters but are important for the contractor to consider with HPWHs. Finally, users can enter information about the existing water heater and how well it serves the needs of the home.

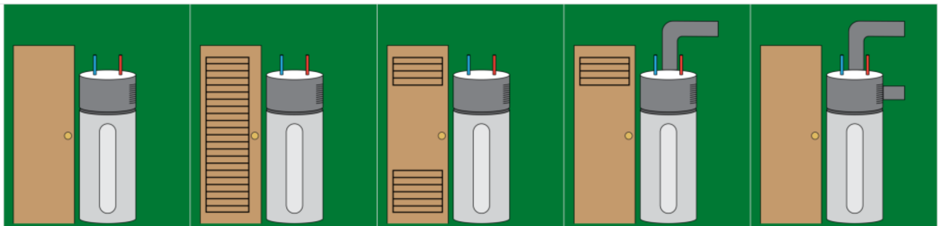
If a user plans to electrify in this retrofit (i.e., switching from a fossil fuel water heater to a HPWH), special attention must be paid to the electrical panel and wiring. Installers have multiple product options for different electrical scenarios, so the tool walks them through the decision-making process. If users are familiar with electrical panels and breakers, they can answer questions about the availability of circuits and receptacles. Users can also utilize the Electrical Panel Estimator to determine the ease of installing a HPWH without performing expensive panel upgrades. The estimator is nearly identical to the version found in the CCHP Decision Tool, with some minor changes for HPWHs. It is based on the NEC 220.83 calculation but does not replace a fully compliant calculation.

Outputs page. Based on the inputs, the tool produces a HPWH recommendation on this page, including the size in gallons and the voltage/amperage. Installation guidance is then given on up to five topics, if relevant:

- Air temperature: if the HPWH will be installed in a location that could see occasional temperatures outside of the compressor operating range, users are cautioned. If the HPWH will be installed in a location that will see frequent temperatures outside of the compressor operating range, users will be suggested to move the water heater location or not install a HPWH.
- Air volume: manufacturer requirements for air volume vary, so users are always reminded to check the exact values recommended for the specific product installed. However, based on the air volume available, users are given options to modify the space if necessary. These are presented in graphical form (shown in Figure 1) to give users more clarity on the available paths.
- Noise / Vibration: guidance is given on methods to reduce noise and vibration, and to consider changing the water heater location if the issue cannot be overcome.
- Condensate: instructions for draining condensate produced by the HPWH include multiple options for termination points, including an existing drain line, floor drain, sink, or outside. Guidance for gravity-fed lines or those using pumps are provided.

- Electrical: depending on the voltage/amperage of the recommended equipment, action items and guidance related to electrical work are given. These may range from modifications to the electrical panel, if necessary, to routing wiring or utilizing existing receptacles. Electrical work can add time and cost to a HPWH install, so helping contractors determine an effective strategy for avoiding unnecessary labor is important to customer satisfaction.

Air Volume Consider interventions to the space to accommodate air volume and airflow.



	Enclosed room	Fully louvered door	Upper and lower door grilles	Inlet or exhaust ducting and half-louvered door or single door grille	Inlet and outlet ducting
> 700 ft³	✓	✓	✓	✓	✓
84 - 700 ft³		✓	✓	✓	✓
< 84 ft³				✓	✓
Minimum Room Dimensions (ft)	8 x 8.75 x 10	3 x 3.5 x 8	3 x 3.5 x 8	None	None

Ducting should occur within the conditioned space to prevent positive or negative pressurization of the home. Use insulated flex duct (e.g., R-6) or insulate rigid duct to prevent condensation. Upper and lower door grilles should provide 250 square inches total Net Free Area (e.g., two 18 inch x 8 inch grilles), and have 5 feet of separation.

Figure 1. HPWH Installation Tool output regarding air volume and possible interventions.

Installation best practices are given in a list that does not change based on the user inputs. These include general installation tips that apply to most water heaters as well as HPWH-specific tips. For users interested in learning more, external informational resources are provided that explore the guidance given in the tool in more depth.

Methodology. The outputs of the HPWH tool can be broken into two groups: recommended HPWH type and size, and guidance to overcome potential installation barriers. The methodology for determining the latter output is simple and is mostly binary, since the questions are Yes/No. The methodology for determining HPWH type and size incorporates information about the available electrical equipment in the home, determined by the existing equipment or questions answered, the climate zone, water heater location, number of bedrooms and bathrooms, and the presence of one or more "upsizing" flags.

The core sizing methodology is based on the First Hour Rating (FHR) of HPWHs and code requirements for water heater sizing based on the number of bedrooms and bathrooms in a home. The International Plumbing Code (IPC), established by the International Code Council (ICC), and the Uniform Plumbing Code (UPC), developed by the International Association of Plumbing and Mechanical Officials (IAPMO), are the most commonly used plumbing codes in

U.S. states (ICC 2015; Green Drain 2024). See Table 1 for 2021 UPC requirements for residential water heaters.

Table 1. UPC requirements for First Hour Rating of residential water heaters

Number of Bathrooms	1 to 1.5			2 to 2.5				3 to 3.5			
Number of Bedrooms	1	2	3	2	3	4	5	3	4	5	6
First Hour Rating, Gallons	38	49	49	49	62	62	74	62	74	74	74

Source: 2021 Uniform Plumbing Code, Table 501.1(2). IAPMO 2021.

The methodology in the tool is based on the UPC table and variations of the table used by states. This table is then modified for each climate zone and location in the home to capture the differences in how HPWHs operate under different conditions. The FHR test conditions are set by DOE and include a standard flow rate, inlet and outlet water temperatures, and surrounding air temperature. The FHR seen on equipment reflects the performance under these conditions, but it may not reflect how the equipment performs under different conditions.

Consider two conventional water heaters, one with a warm inlet water temperature and one with a cold inlet water temperature. The former will produce hot water more quickly, since it needs to add less heat energy to the water. HPWHs are affected by this factor as well as the temperature of the surrounding air. Since HPWHs extract heat from the surrounding air to heat water inside the tank, a water heater in a warm room will be able to extract the heat more easily than one in a cold room. This means that the compressor can operate more efficiently, and the unit is less likely to enter electric resistance backup mode, which further decreases the efficiency (Shapiro and Puttagunta 2016).

To account for differences in inlet water temperature and surrounding air temperature, a mathematical model of a HPWH incorporates American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 99% Design Day data to determine air temperature and Typical Meteorological Year (TMY) data to estimate inlet water temperature. The first hour delivery of the HPWH is determined for the least optimal conditions that occur for peak water heating load, when the inlet water and air temperature are coldest. This is the difference between this calculated first hour delivery at winter design conditions and the FHR required by the code to size the HPWH.

As an example, consider a home in Climate Zone (CZ) 2 with a water heater installed in a conditioned space and a home in CZ 5 with a water heater installed in an unconditioned basement. The CZ 2 home may see similar conditions to the FHR test during the coldest month of the year, while the CZ 5 home will see much colder inlet water and surrounding air temperatures. If this HPWH in CZ 5 has, for example, 20% lower performance in these conditions, the FHR values in Table 1 will be adjusted up by 20%. So, a 2-bedroom, 2-bathroom house in CZ 2 may need a HPWH with an FHR of 49 gallons, while the same house in CZ 5 may need a HPWH with an FHR of 59 gallons to see similar performance.

After determining the FHR target for the scenario, this value is compared to FHR values of eligible HPWH types for that scenario. If the inputs have indicated that a 240-volt, 30-amp HPWH is the best option, the new FHR target is compared to FHR values for water heaters in that category to determine the most appropriate size. The final layer is an upsizing step if any answers indicate potentially high water usage in the home. The tank size from the previous step is then increased by one size.

Retrofit Decision Tool

The Retrofit Decision Tool ties the CCHP Decision Tool and HPWH Installation Tool together by considering the whole home and a variety of potential upgrades that could be performed in a retrofit focused on decarbonization. The tool uses basic information about the home including location, year of construction, size, existing mechanical systems and fuel types, and details about the building envelope. Using an energy modeling program based on U.S. building stock, a package of upgrades is recommended to make the home more likely to decarbonize. This tool specifically uses the phrase “zero carbon aligned” (ZCA) in its description and outputs. To be considered ZCA, buildings should have a low energy load that can reasonably be offset with on- and/or off-site renewable energy generation and - until the grid becomes decarbonized - can draw on grid energy at the times when it is cleanest. The structure of the tool is like the others in that it consists of one input page and one output page that contains guidance, action items, and further resources for exploring building science topics.

This tool is primarily aimed at homeowners and assumes that the user does not have deep technical knowledge of residential buildings. While users are linked to the HPWH Installation Tool and CCHP Decision Tool upon completion, if those upgrades are recommended, they may lack the prior knowledge required to complete those tools. The Retrofit Decision Tool can serve to educate homeowners and drive demand, such that they seek out contractors capable of installing HPs and HPWHs.

Retrofit decision analysis form. This form collects inputs required to compare the selected residence to the building stock used in the energy modeling program. Since homeowners may have less knowledge about the building than a contractor, it features helpful graphics and pictures to help users determine the information accurately. For information that may be more difficult to confirm, such as wall and ceiling insulation, users can answer “Not Sure.”

Retrofit decision report. Based on the analysis, a recommended package is given for the home. The following packages may be suggested:

- No Upgrade Recommended: These homes are already ZCA. This may be true for newer homes that are well insulated and already electrified.
- Equipment Electrification: These homes may already have enough insulation to be ZCA, however equipment may not currently be all-electric.
- Basic Envelope + Equipment Electrification: These homes may just need a small amount of added insulation and light window improvements along with the equipment electrification to become ZCA.
- Current Code Envelope + Equipment Electrification: These homes may need a relatively substantial envelope upgrade and equipment electrification to become ZCA.
- Beyond Code Envelope + Equipment Electrification: These homes are likely in a cold climate that requires even more substantial envelope upgrades and equipment electrification to become ZCA.

The recommended package is then broken down into the different components and described in more detail. Links are provided to other BASC guides and checklists relevant to each topic, along with links to the HPWH Installation Tool and CCHP Decision Tool. The recommended package and its components could then be used by the homeowner to perform some or all the recommended upgrades on their own, or as a list to work through with a contractor. Users will feel empowered with the knowledge of how to decarbonize their homes and can advocate for these upgrades throughout conversations with contractors.

Other PNNL Work Supporting Tools

In addition to the three tools described in this paper, PNNL has also developed many trusted resources on building science topics for contractors and homeowners. These resources are linked throughout the tools. Some examples of these resources include:

- BASC Guides: These guides cover a broad range of building science topics, from solar PV to attic insulation to wildfire protection. Guides can provide in-depth background information on a topic along with practical knowledge for the implementation of a measure.
- Building Science Education Solution Center (BSESC) Instructor Resources: Resources include lecture notes, problem sets, and presentations on topics ranging from HPWHs to indoor air quality. These are meant to bolster existing training programs or be used in the creation of new programs. The tools in this paper could be used to complement those resources.

Discussion and Next Steps

These three tools developed to aid in the decarbonization of residential buildings are neither perfect nor the whole picture when it comes to workforce development. The Cold Climate Heat Pump Decision Tool and Heat Pump Water Heater Installation tool mainly aim to address two pieces of the problem: contractor knowledge of new/emerging technologies and simplifying installations to make them more likely and more successful. The Retrofit Decision tool focuses on customer awareness and knowledge about how to consider the whole home on their decarbonization or efficiency journey.

The tools have been well-received by reviewers, collaborators, and SMEs. Reviewers thought they would be helpful for those who are seeking to gain knowledge on new technologies or improve their skills. However, the tools ultimately need to be adopted by contractors with their boots on the ground. These tools are not meant to be an academic or hypothetical exercise, but a practical aid for the workforce designing and installing equipment.

Effective marketing and partnerships with organizations that interface more directly with the workforce will be key components of adoption. An ongoing redesign of the BASC, one of DOE’s most visited websites, will provide visitors with easier access to the tools. Translation to other languages, such as Spanish, could also allow the tool to reach a wider and more diverse audience.

These tools benefitted from an Excel prototype to work out high level processes and methodology. However, they were able to be reviewed more effectively once they were sharable with reviewers as a webtool. The closer the tools came to their final structure, the more useful feedback became on technical matters. For others developing tools like these, it is important to balance the benefits of each stage of development with the overall timeline and project resources.

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