# Grid-connected heat pump water heater benefits for low-income households in the Southeastern United States

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## ABSTRACT

Energy efficient heat pump water heaters (HPWHs) reduce water heating energy consumption compared to dominant baseline technologies. However, a HPWH's first-cost premium can put it out of reach for low-income households. Grid-connected controls can further increase HPWH value to households by enabling dispatchable energy storage and shifting electricity use to cheaper, off-peak periods. This paper presents the results of a study that explored the benefits of load shifting HPWHs for 24 low-income households in the Southeast U.S., aiming to support increased product deployment in this demographic.

The study used EcoPort modules to shift HPWH load for a study sample consisting primarily of low-income adults and seniors in North Carolina. Building on prior studies, the study's HPWH operating schedules were designed to maximize shifted energy and minimize participant electricity costs based on local time-of-use rates. The study documented load profiles of grid-connected HPWHs in a less-studied demographic group and explored how certain groups may have particularly flexible loads due to their unique usage profiles.

The results are relevant for HPWH product performance in the Southeast. The study quantified HPWH load shifting performance during North Carolina's hot summer, temperate shoulder, and occasionally sub-freezing winter seasons, including installations in conditioned, semi-conditioned, and unconditioned spaces. Finally, study results also demonstrate how controlled HPWHs can provide value to the regional grid by reducing seasonal peaks via demand response. Other lessons learned include HPWH acceptance for low-income and senior users and best practices for maintaining HPWH connectivity and reliability among users without prior product experience.

## Project Background

In North Carolina, 73% of homes use electric resistance storage water heaters (ERWHs) making it the state with the third highest penetration of electric water heating and the state with the third largest fleet (3 million units) of these popular appliances (EIA 2020). Transitioning North Carolina's ERWHs to heat pump water heaters (HPWHs) could result in significant energy savings potential. North Carolina is also experiencing strong growth in annual peak electricity demand (Duke Energy 2024) and ranks fourth in the country in installed photovoltaic capacity. If North Carolina had 3 million HPWHs capable of load shifting, these appliances could flex to help reduce the system electric peak demand and to help accommodate the intermittent solar resource.

There has been little research targeting the potential to shift household water heating load in low-to-moderate-income (LMI) households. The relatively high upfront cost of HPWHs compared to ERWHs is a barrier for adoption in LMI households. To support increased product deployment in this demographic and within the Southeast U.S. where the potential for impact is high, this project investigates the benefits of load shifting HPWHs for 24 low-income households in North Carolina.

The project collected and analyzed short-interval electricity consumption data from 24 240-volt hybrid HPWHs equipped with EcoPort[1] universal communication modules (UCMs) from the summer of 2023 through the summer of 2024. These EcoPort-equipped HPWHs were installed by Rebuilding Together of the Triangle (RTT), the local affiliate of Rebuilding Together, a national nonprofit organization providing home repair and renovation services free of charge to those in need.

Study participants had received the HPWHs over the preceding two years as part of RTT-provided retrofits, and the EcoPort UCMs were installed in subsequent site visits in mid-2023. For approximately one week each month during the study year, the project team allowed the HPWHs to operate without intervention to establish baseline, non-load shifting daily patterns of water heater electricity consumption. The rest of the time, the team sent demand response messaging to the water heaters, shifting electricity consumption from peak periods to off-peak periods during the day.

The project received U.S. Department of Energy and charitable foundation funding and significant in-kind support from the North Carolina Justice Center (NCJC), RTT, Orange County, NC, and the Pacific Northwest National Laboratory (PNNL).

### Research Goals

The main goal of this research is to explore the energy saving and load shifting potential for HPWHs installed in LMI households in North Carolina. The study team also hopes to advance the body of knowledge about controlled HPWHs and their ability to generate benefits for the distribution grid. Specific topics addressed include:

- Quantification of the potential for peak demand reduction from HPWH in LMI households in the Southeast
- The impact of long load shifts on household hot water service
- Opportunities to make HPWH more available to LMI and senior households
- Analysis of HPWH load shifting electricity cost savings for North Carolina customers on time-of-use rates

### Advisory Group

To make the results of this research as relevant as possible to energy efficiency and low-income community advocates in North Carolina, the study team recruited local and industry experts to an Advisory Group (AG). The AG reviewed the study's experimental design and study results, and they provide ongoing input on the project. Study participants were not recruited to the AG. A list of AG members is available in Appendix A.

## Study Participants

To our knowledge, prior HPWH load shifting studies have not exclusively targeted LMI households. Low-income families often face a high energy cost burden. In North Carolina, households living at 50% of the Federal Poverty Level pay an average of 32.8% of their income for energy (Groundswell 2022). A primary motivation for the NCJC to partner with the study

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[1] EcoPort is the brand name for technology that has been certified compliant with the ANSI/CTA-2045 technical specification.

team was to demonstrate the potential economic benefits for LMI households in North Carolina of replacing less efficient water heaters with HPWHs.

## Recruitment

The original experiment design included a participant sample of sixty households. This number was ultimately not attainable. Program partner RTT installed the EcoPort-equipped HPWHs free-of-charge along with other home repair services and appliances – only 35 HPWHs were able to be installed before the study period began.

RTT maintains very good relationships with its clients and provided the study team with a warm introduction to each study candidate household. Using materials approved by the PNNL Institutional Review Board, the study team then reached out to explain the study, the participant requirements, and compensation (participants received $100 at the beginning and end of the study). If a candidate household responded positively, the study team either emailed or mailed an informed consent document and a copy of the first of two surveys they would be required to complete. This process was labor intensive, as many of the participants did not have or regularly use email and required phone calls - sometimes repeat calls as voicemail was often not an option. A study team member and a local technician then visited each home to retrieve the signed consent form, help the participant complete the initial survey, and install an EcoPort UCM. Although all the HPWHs had EcoPorts, not all HPWHs came from the factory with the EcoPorts enabled, requiring additional on-site work to connect the EcoPorts in some cases.

Leveraging the existing relationship with RTT, and a labor-intensive delivery model designed to remove any cost or installation responsibility from the participants, the study team was able to recruit 24 out of 35 potential participants. An evolution of the participant sample is shown in Figure 1. The candidate households were not "early adopters" as has often been the case in prior residential HPWH load shifting studies.

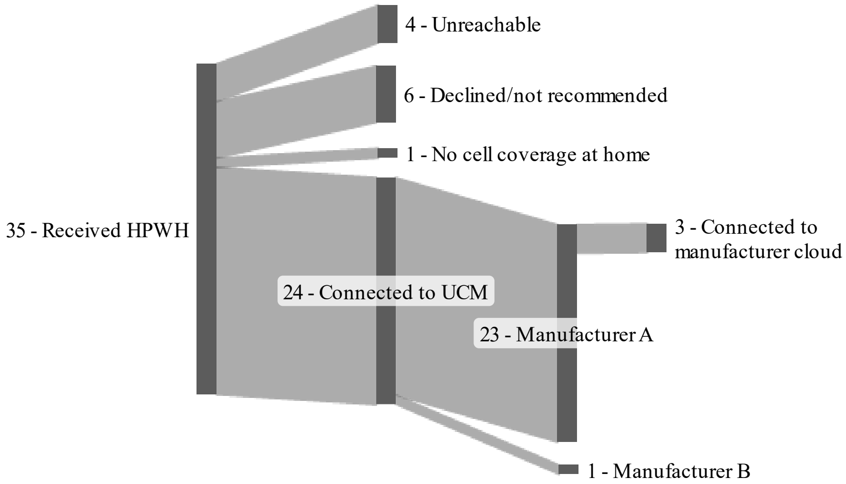

Figure 1. Evolution of the participant sample

The demographics of the study participants are shown in the following tables:

Table 1. Prior water heater fuel source

| Fuel source | Units |
|---|---|
| Electricity | 9 |
| Natural Gas | 12 |
| Not Reported | 3 |

Table 2. Customer electric utility

| Utility | Households |
|---|---|
| Duke Energy Carolinas | 7 |
| Duke Energy Progress | 8 |
| Piedmont | 1 |
| Town of Apex | 5 |
| Not Reported | 3 |

Table 3. Number of household occupants at the start of the study

| Occupants | Households |
|---|---|
| 1 person | 13 |
| 2 people | 7 |
| 3 people | 2 |
| 5 people | 1 |
| 6 people | 1 |

Table 4. Types of occupants

| Occupants include: | Households |
|---|---|
| Children (0-12 years old) | 4 |
| Teens (13-18 years old) | 3 |
| Adults (19-64 years old) | 11 |
| Seniors (65+ years old) | 13 |

The predominant participants in this study include seniors that live in a household with at most 2 people. All participants reside in Chatham, Durham, Orange, or Wake counties in North Carolina. Participants own their homes and land, have resided there for at least two years, and state their intention to stay there for three years after receiving RTT services. RTT limits gross annual income for participants to a maximum of $58,000 per year for a household of two in Wake County and to lesser amounts for single-person households and households in other counties. The U.S. Census Bureau reports the median household income for Wake County in 2022 as $96,806 (Census Bureau 2022). About eighty percent of RTT clients have incomes below fifty percent of the area median income.

Despite North Carolina's high penetration of ERWH, about half the study households had gas storage water heaters prior to receiving an EcoPort-equipped HPWH. The majority of participants are Duke Energy customers, with a near even split of customers between the Duke Energy Progress and Duke Energy Carolinas service territories. The study included one 80-gallon water heater and twenty-three 50-gallon water heaters.

## Energy Consumption Analysis

Pre-HPWH installation monitoring of participant water heating energy consumption was not within the scope of this project due to budget and logistical constraints. The study team was also not able to obtain historic electricity billing data from North Carolina utilities. Even if these data were available, RTT's home services are not limited to water heating; for example, they include home envelope improvements, HVAC, and other appliance retrofits. Due to the variety of retrofits participant households received and their broad impact on energy consumption, it is difficult to isolate the actual post-retrofit change in energy consumption solely due to the HPWH installation for participant households. Additionally, as mentioned above, participants had a mix of electric resistance and gas storage water heaters prior to receiving HPWHs, but for simplicity, this study did not assess the energy consumption or cost impact of switching from a gas storage water heater to a HPWH.

## Pre-Retrofit Estimated Electricity Consumption

To estimate the energy savings from adopting HPWHs, the study team developed estimates of pre-retrofit water heating electricity consumption based on the U.S. Energy Information Administration's (EIA) 2020 Residential Energy Consumption Survey (RECS) regional and state-level results and the number of members in the study participants' households. Table 5 shows the estimated annual pre-retrofit energy consumption for participants before the HPWH installation, by number of occupants.

Table 5. Annual water heating electricity consumption by number of occupants in the South census division, adjusted for owner-occupied single-family homes[2]

| Number of household members | Annual water heating energy consumption (kWh) |
|---|---|
| 1 | 1,525 |
| 2 | 2,490 |
| 3 | 3,582 |
| 4 | 4,586 |
| 5 | 4,657 |
| 6 or more | 5,945 |

*Source*: EIA 2020, Table CE4.9.

The study team also considered adjusting estimated water heating electricity consumption by income, but the RECS data indicated that annual average water heating electricity consumption did not vary significantly across the range of household incomes in the sample (EIA 2020, Table CE4.9).

Based on the RECS 2020 estimates and the actual occupancy of the study households, the estimated pre-retrofit total annual water heating electricity consumption for the 24 participant sample would have been approximately 46,460 kWh if all participants had previously had electric water heaters as represented in the RECS data. This estimate uses household occupancy as reported at the beginning of the study, but over the course of the study some participant households had new occupants move into the household, and these occupancy changes were not always reported to the study team. Therefore, this pre-retrofit energy use estimate may underrepresent the participant households' actual energy use based on occupancy.

## Post-Retrofit Estimated Electricity Consumption

All HPWHs in the study were equipped with e-Radio cellular UCMs provided as an in-kind contribution from PNNL. All but one HPWH in the study also came equipped with manufacturer proprietary, Wi-Fi-based connectivity. The study team encouraged participants to

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[2] EIA's South census division includes Alabama, Arkansas, Delaware, District of Columbia, Florida, Georgia, Kentucky, Louisiana, Maryland, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, Virginia, and West Virginia.

use this feature and provided technical support but were only successful in connecting three HPWHs to Wi-Fi. Participants were either not interested, had reservations about connecting an appliance to their home networks, or did not have home Wi-Fi.

The HPWHs transmitted electricity consumption data to the UCM cloud in sub-5-minute intervals. Electricity consumption data reporting varies based on the equipment manufacturer. One HPWH manufacturer in the study estimates unit power consumption via installed telemetry, and this measured data is reported by the UCM. The other manufacturer monitors when HPWH components are switched on and off and uses static estimates for power drawn by the compressor and by the heating element(s), which are reported by the UCM. The study team used UCM-reported electricity consumption data for analysis, but in the latter case where pre-determined, static power estimates were reported via the UCM, an adjustment factor was applied to power draw values based on prior PNNL field studies that verified the power draw of this manufacturer's product.

The team was able to collect continuous electricity consumption data from all 24 HPWHs with relatively few data collection interruptions over the course of the study. Reported data were averaged by season, and annual, non-load shifting electricity consumption was estimated based on average consumption by season and season length. Aggregated total annual non-load shifting energy consumption for the 24 units was estimated to be approximately 24,450 kWh for an estimated 47% reduction in water heating electricity from the pre-retrofit estimate. The estimated average annual energy savings per household was approximately 920 kWh. Given the lack of measured pre-retrofit water heating energy consumption data, the variability of water use by household (including changes in household occupancy over the course of the study), and the small sample size, this estimate may not reflect the true savings seen by participants, but it gives a sense of the scale of energy savings experienced by study participants.

### Other Factors Affecting Electricity Consumption

North Carolina is at the northern edge of the Southeast U.S., where water heaters are often installed in unconditioned spaces. Study participant HPWHs were installed in conditioned, semi-conditioned, and unconditioned spaces. HPWHs draw energy from the ambient air; therefore, their energy performance is more strongly affected by ambient air temperatures than ERWHs. HPWHs also require access to an adequate flow of ambient air as a heat source. If an HPWH is installed in a constrained space with inadequate airflow, normal operation will lower the temperature of the ambient air and decrease the HPWH's operating efficiency. Constrained spaces are commonly in conditioned spaces (like utility closets) but may be semi-conditioned or unconditioned. Due to the small size of the participant sample and lack of measured hot water consumption data we were not able to develop statistically significant estimates of the impacts of different ambient conditions on HPWH operation.

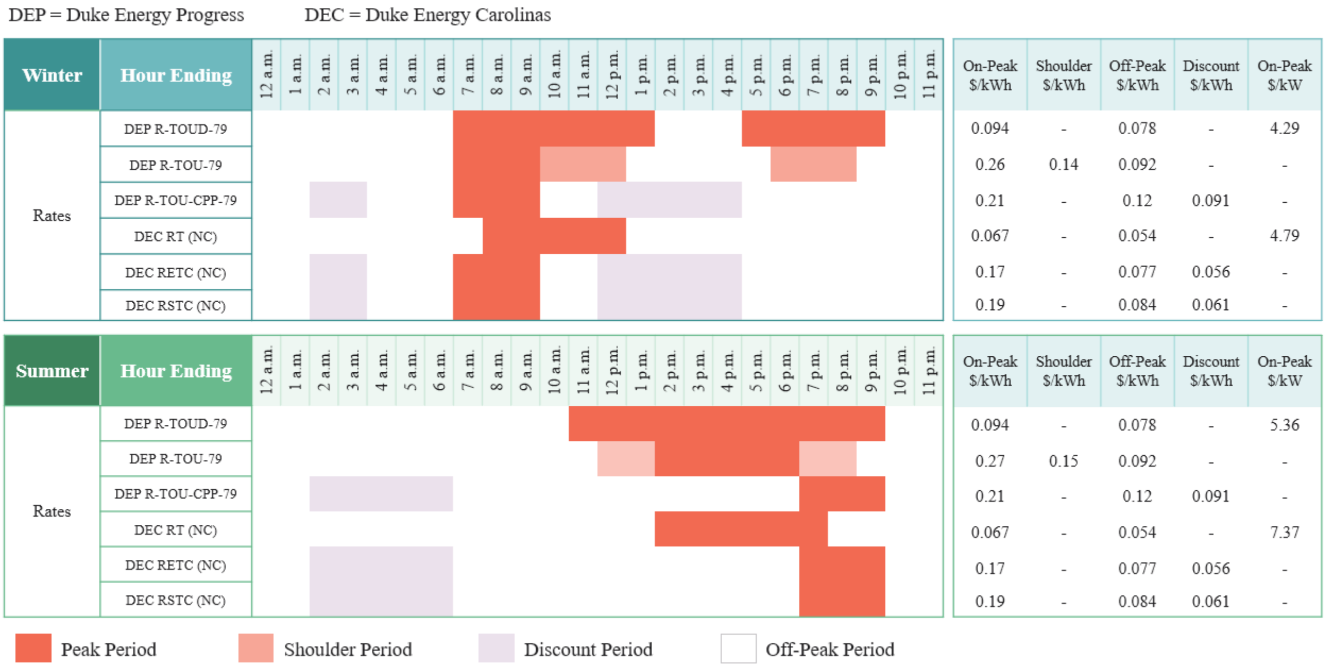
## Load Shifting Design

In addition to energy savings, demand response-enabled HPWHs may also be able to reduce water heating energy costs for households that have access to time varying electricity rates (e.g., time-of use, or TOU rates) by shifting electricity consumption for water heating to times when electricity is cheaper. The study implemented a load shifting schedule for participant water heaters designed to take advantage of Duke Energy residential TOU rates that were newly introduced at the time of study design. The study team did not ask participants to enroll in a TOU rate since other loads in the home would not be shifted. Instead, the study analyzed water heating electricity consumption patterns during baseline (non-load shifting) and load-shifting periods to estimate the impact on electricity costs as if the customers were on a TOU rate.

## Factors Considered in Experimental Design

### Utility Rates

Duke Energy Progress (DEP) and Duke Energy Carolinas (DEC) TOU rates were used as a starting point for the experimental design with the goal to shift water heating electricity consumption to off-peak periods with cheaper electricity prices. The rates used were those available at the time of the study design in early 2023 and are no longer offered. Both DEP and DEC tariffs defined distinct peak, shoulder and off-peak periods for summer and winter. Figure 2 shows peak, shoulder, off-peak, and discount periods for DEP and DEC TOU rates used in the study's design by season, along with energy rates by time of use and demand charges. Other details, such as critical peak rates for certain rate schedules, fixed fees and eligibility criteria are omitted from the figure for simplicity. Electricity prices ranged from $0.27 per kWh on peak to $0.05 per kWh in discount periods, depending on the rate.



DEP = Duke Energy Progress DEC = Duke Energy Carolinas

| Winter | Hour Ending | 12 a.m. | 1 a.m. | 2 a.m. | 3 a.m. | 4 a.m. | 5 a.m. | 6 a.m. | 7 a.m. | 8 a.m. | 9 a.m. | 10 a.m. | 11 a.m. | 12 p.m. | 1 p.m. | 2 p.m. | 3 p.m. | 4 p.m. | 5 p.m. | 6 p.m. | 7 p.m. | 8 p.m. | 9 p.m. | 10 p.m. | 11 p.m. | On-Peak $/kWh | Shoulder $/kWh | Off-Peak $/kWh | Discount $/kWh | On-Peak $/kW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rates | DEP R-TOUD-79 | | | | | | | | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | | | | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | | | 0.094 | - | 0.078 | - | 4.29 |
| | DEP R-TOU-79 | | | | | | | | 🟥 | 🟥 | 🟥 | 🟧 | 🟧 | 🟧 | | | | | | 🟧 | 🟧 | 🟧 | | | | 0.26 | 0.14 | 0.092 | - | - |
| | DEP R-TOU-CPP-79 | | | 🟪 | 🟪 | | | | 🟥 | 🟥 | 🟥 | | | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | | | | | | | | 0.21 | - | 0.12 | 0.091 | - |
| | DEC RT (NC) | | | | | | | | | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | | | | | | | | | | | | 0.067 | - | 0.054 | - | 4.79 |
| | DEC RETC (NC) | | | 🟪 | 🟪 | | | | 🟥 | 🟥 | 🟥 | | | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | | | | | | | | 0.17 | - | 0.077 | 0.056 | - |
| | DEC RSTC (NC) | | | 🟪 | 🟪 | | | | 🟥 | 🟥 | 🟥 | | | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | | | | | | | | 0.19 | - | 0.084 | 0.061 | - |

| Summer | Hour Ending | 12 a.m. | 1 a.m. | 2 a.m. | 3 a.m. | 4 a.m. | 5 a.m. | 6 a.m. | 7 a.m. | 8 a.m. | 9 a.m. | 10 a.m. | 11 a.m. | 12 p.m. | 1 p.m. | 2 p.m. | 3 p.m. | 4 p.m. | 5 p.m. | 6 p.m. | 7 p.m. | 8 p.m. | 9 p.m. | 10 p.m. | 11 p.m. | On-Peak $/kWh | Shoulder $/kWh | Off-Peak $/kWh | Discount $/kWh | On-Peak $/kW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rates | DEP R-TOUD-79 | | | | | | | | | | | | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | | | 0.094 | - | 0.078 | - | 5.36 |
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| | DEC RETC (NC) | | | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | | | | | | | | | | | | | 🟥 | 🟥 | 🟥 | | | 0.17 | - | 0.077 | 0.056 | - |
| | DEC RSTC (NC) | | | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | | | | | | | | | | | | | 🟥 | 🟥 | 🟥 | | | 0.19 | - | 0.084 | 0.061 | - |

🟥 Peak Period 🟧 Shoulder Period 🟪 Discount Period ⬜ Off-Peak Period

Figure 2. Duke Energy time-of-use rates (early 2023)

Although peak period timing differs across rates, at the time the study was designed the summer season peak period typically spanned 1 to 6 p.m. and/or 6 to 9 p.m. The winter season peak period included 6 to 9 a.m. for almost all rates examined, and one rate also included an evening peak period of 4 to 9 p.m. in the winter season. Based on the peak period schedule, the study scheduled daily load sheds for all participants between 1 and 9 p.m. in the summer season and between 6 a.m. and 12 p.m. and 4 p.m. and 9 p.m. in the winter season, which is a longer shifting time frame than most prior studies.

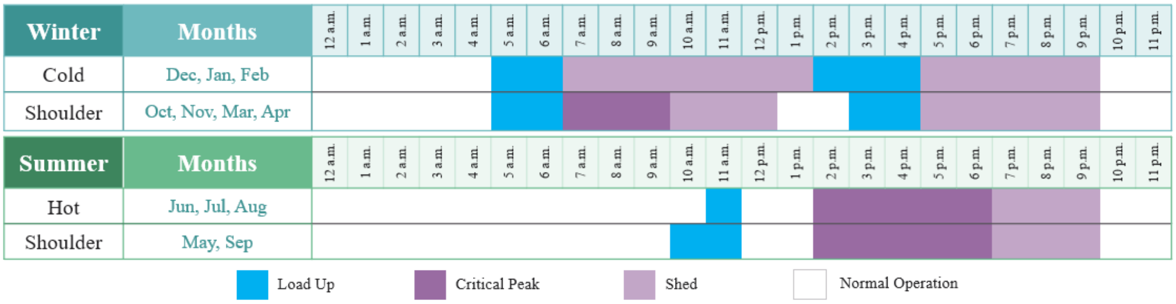
## Weather and Seasons

In addition to the different on-peak, off-peak, and shoulder periods shown in Figure 2, DEP's former TOU rates defined a longer summer season (April to September) than did DEC's former TOU rates (May/June to September). To maximize the significance of the study results, the study team put all participants on a common load shifting schedule with a summer season of May to September and a winter season of October to April. This schedule captures much of the overlap between the DEC and DEP rate summer seasons and keeps April as a winter load shifting month because historic April temperatures in the region are more typical of cool season water heating operational patterns. Each month is assigned a season based on the utility TOU rates noted above – the summer load shifting schedule aims to shift load out of afternoon and evening peak windows, while the winter schedule shifts load out of the morning and evening peak windows. Additionally, summer and winter shifting were further segmented into hot and shoulder months (for summer) and cold and shoulder months (for winter). The load shifting plan draws on findings from prior PNNL HPWH load shifting studies that informed water heating pre-heating and load reduction period lengths, strategies for different weather conditions, and water heater demand management commands to optimize load shifting (Butzbaugh et al. 2022).

## Experimental Design

The above factors were synthesized to create the load shifting schedules used for this study. To establish a baseline (non-load shifting) load profile, the participants' HPWHs were allowed to run independently without demand management requests for approximately one week each month. Outside of these baseline data collection periods, the HPWHs were controlled to shape the participant's water heating load profile using the following requests: "Load Up" - increase energy use by heating water up to the user setpoint; "Shed" - avoid heating water unless there is a risk that the user will receive cold water, e.g., by reducing the water heater setpoint temperature; and "Critical Peak" - reduce demand more aggressively than shed, e.g., by reducing the water heater setpoint to a lower temperature than the Shed command. The CTA-2045 protocol describes how complying devices exchange information, but it does not specify what those devices do in response to demand management requests; exact response algorithms are proprietary and vary by HPWH brand. Other CTA-2045 requests were deemed unsuitable for the study and not used; for example, the "Advanced Load Up" command, which can result in water heating above the user setpoint for additional energy storage was not used because the participant households did not have water heater mixing valves to prevent scalding from over-heated water.

The study team compared HPWH electricity use during load shifting periods to usage during non-load shifting periods to document the energy shifted and potential cost savings to participants. Figure 3 summarizes the study's load shifting schedules, designed to minimize participant water heating costs based on Duke Energy TOU rates.



| Winter | Months | 12 a.m. | 1 a.m. | 2 a.m. | 3 a.m. | 4 a.m. | 5 a.m. | 6 a.m. | 7 a.m. | 8 a.m. | 9 a.m. | 10 a.m. | 11 a.m. | 12 p.m. | 1 p.m. | 2 p.m. | 3 p.m. | 4 p.m. | 5 p.m. | 6 p.m. | 7 p.m. | 8 p.m. | 9 p.m. | 10 p.m. | 11 p.m. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cold | Dec, Jan, Feb | ☐ | ☐ | ☐ | ☐ | ☐ | 🟦 | 🟦 | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | 🟦 | 🟦 | 🟦 | ▨ | ▨ | ▨ | ▨ | ▨ | ☐ | ☐ |
| Shoulder | Oct, Nov, Mar, Apr | ☐ | ☐ | ☐ | ☐ | ☐ | 🟦 | 🟦 | 🟪 | 🟪 | 🟪 | ▨ | ▨ | ▨ | ☐ | ☐ | 🟦 | 🟦 | ▨ | ▨ | ▨ | ▨ | ▨ | ☐ | ☐ |

| Summer | Months | 12 a.m. | 1 a.m. | 2 a.m. | 3 a.m. | 4 a.m. | 5 a.m. | 6 a.m. | 7 a.m. | 8 a.m. | 9 a.m. | 10 a.m. | 11 a.m. | 12 p.m. | 1 p.m. | 2 p.m. | 3 p.m. | 4 p.m. | 5 p.m. | 6 p.m. | 7 p.m. | 8 p.m. | 9 p.m. | 10 p.m. | 11 p.m. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hot | Jun, Jul, Aug | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | 🟦 | ☐ | ☐ | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | ▨ | ▨ | ▨ | ☐ | ☐ |
| Shoulder | May, Sep | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | 🟦 | 🟦 | ☐ | ☐ | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | ▨ | ▨ | ▨ | ☐ | ☐ |

🟦 Load Up　🟪 Critical Peak　▨ Shed　☐ Normal Operation

Figure 3. Study load shifting schedule

Due to the small participant sample size, to collect the greatest amount of comparable data all participants were kept on the same load shifting schedule regardless of household occupancy or water heater installation location.

The coldest months of the year in the study region are during the Winter-Cold load shifting schedule when the daily average temperature is in the mid-40's °F. Compared to the Winter-Shoulder schedule, Winter-Cold has a longer afternoon load up period to provide adequate time for the HPWH to recover and heat water given the low ambient temperatures. This schedule also employs "Shed" commands for load reduction, which do not allow tank temperatures to drift as low as "Critical Peak" commands do, to account for longer recovery times due to the low ambient temperatures.

The Winter-Shoulder schedule includes utility TOU winter months with warmer ambient temperatures compared to the Winter-Cold months. This allows the use of the more aggressive "Critical Peak" command in the morning shed to further decrease energy use, with a slightly shorter afternoon load up period than for the Winter-Cold schedule.

The Summer-Shoulder schedule includes utility TOU summer months with milder temperatures. This schedule features a longer load up period in the morning to account for milder temperatures than are expected during the Summer-Hot period. There is a long load shed window in the afternoon to minimize energy consumption – the "Critical Peak" command is employed for the first five hours, followed by a "Shed" command in the evening. Some evening recovery may occur during the later Shed window if needed, but full recovery should not occur until the conclusion of the TOU peak window.

Finally, the Summer-Hot schedule includes utility TOU summer months with the hottest temperatures. This schedule matches the Summer-Shoulder schedule with the exception of a shorter morning load up period due to hot ambient temperatures.

## Load Shifting Results

Study data collection will continue through late summer 2024, but results through June 2024 are described below. Figure 4 shows load shifting time windows as well as baseline (non-load shifting) and load shifting average daily demand profiles for all study schedules.

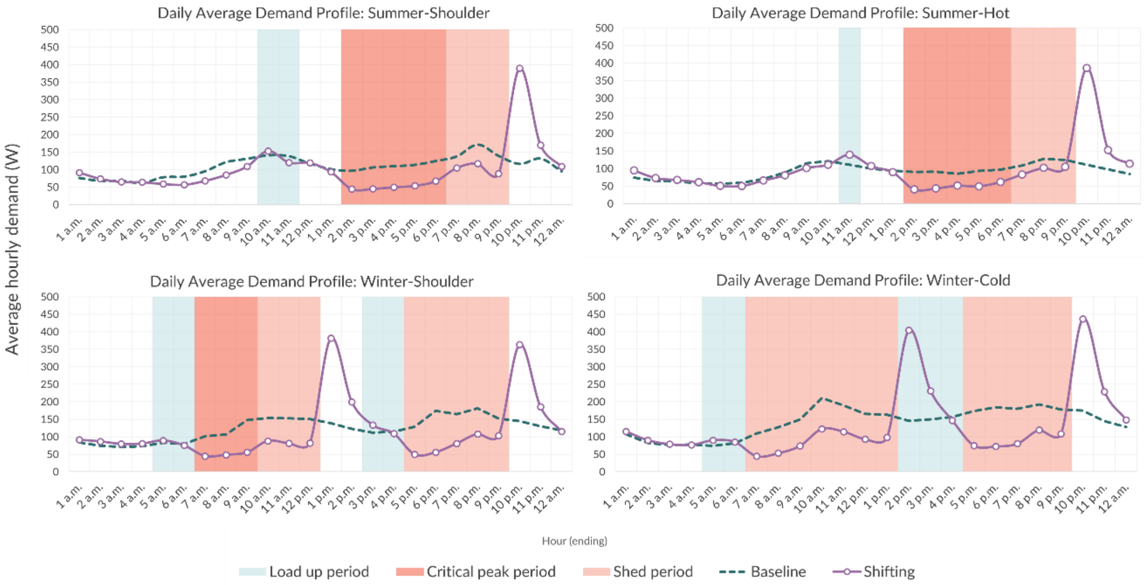


Figure 4. Baseline and load shifting average daily demand profiles for all study schedules

The demand profiles show that the participant water heaters responded to water heating demand management signals as expected, with minor load increases compared to the baseline, non-load shifting periods for load up periods, and load reductions compared to the baseline for critical peak and shed periods. Water heater load tended to recover at the end of the shed period, but average recovery load was in the range of the heat pump compressor power, rather than being dominated by electric resistance element operation. Due to the prevalence of low-occupancy households in the study, water heater energy usage for this population is generally low. Participant water heaters reliably shifted load out of peak periods while still providing participants with sufficient hot water to meet their daily needs.

## Winter Morning Peak

In addition to daily load shifting, the study conducted a test peak demand response event, scheduled to coincide with North Carolina's annual winter morning electricity demand peak. The purpose of this event was to demonstrate how HPWH demand response can provide utility and regional grid benefits in addition to customer cost savings. Historical data show that peak demand in the region has typically occurred around 7:00 a.m. on a very cold winter weekday (Duke Energy 2020). Therefore, the test demand response event was conducted from 6:00 to 9:00 a.m. on January 17, 2024, a cold day with an event period temperature of approximately 20 °F. Figure 5 shows the results of this event.

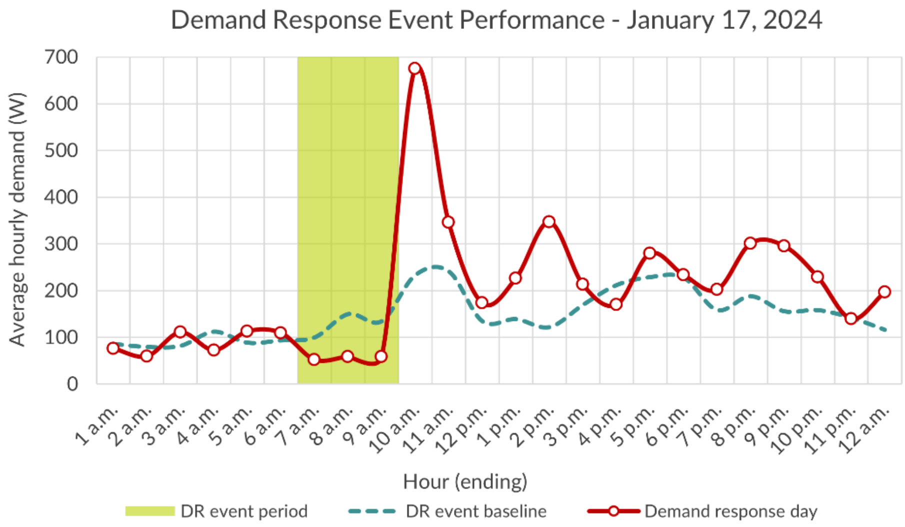


Figure 5. Results of peak day demand response event

The demand response event used a two-hour load up period followed by a three-hour critical peak period to demonstrate the ability of the HPWH to aggressively reduce load during the coldest conditions that often drive regional peak demand. This differs from the less aggressive "Shed" request used during daily load shifting in the Winter-Cold period. The HPWHs successfully minimized operation during this period, largely avoiding the use of heat pump compressors or electric resistance elements for the duration of the event. Compared to a DR event baseline of four similarly cold, non-load shifting days the same week, the participant HPWHs reduced demand by an average of 72 W per participant for the duration of the event. This suggests both that in the mornings during the DR event baseline period many HPWHs in the participant sample did not need to operate much to maintain setpoint temperature and that HPWH controls can be leveraged to effectively minimize electricity demand on command. The result of the annual peak test also suggests that, at least for residential customers like the study participants, implementing the Critical Peak load reduction request during the Winter-Cold period may not cause hot water run outs.

## Energy and Customer Cost Impacts

The Duke Energy TOU rates described above include peak period windows of at least five hours. The experiment design therefore included load shifting windows of six to eight hours, which is longer than the load shifting windows used in prior studies. In October 2023, Duke Energy issued new TOU rates that differ from the rates used in this study. The new rates include different winter and summer season months, peak periods limited to 3 hours (6 to 9 a.m. in winter and 6 to 9 p.m. in summer), and new discount periods that offer lower rates overnight and on winter afternoons.[3] Therefore, under the new rates, controlled HPWHs should be able to more easily avoid peak periods and shift electricity consumption to discount periods to reduce household water heating costs.

Table 10 shows load shifting results in terms of energy saved and shifted.

Table 10. Load shifting results by schedule

| Shifting schedule | Shed periods | Average daily energy savings (kWh, % of non-shifting baseline) | | Average morning load shifted (kWh, % of non-shifting baseline) | | Average evening load shifted (kWh, % of non-shifting baseline) | |
|---|---|---|---|---|---|---|---|
| Summer – Hot | Evening: 1-9 p.m. | 0.10 | 4% | | | 0.12 | 30% |
| Winter – Shoulder | Morning: 6 a.m.-12 p.m.<br>Evening: 4-9 p.m. | 0.11 | 4% | 0.19 | 43% | 0.35 | 50% |
| Winter – Cold | Morning: 6 a.m.-1 p.m.<br>Evening: 4-9 p.m. | 0.20 | 6% | 0.38 | 35% | 0.28 | 33% |
| Summer – Shoulder | Evening: 1-9 p.m. | 0.34 | 12% | | | 0.11 | 25% |

Participants in the study were able to shift 35-43% of their baseline water heater electricity use in the morning period and 25-50% of water heating electricity use in the evening period. The effect of load shifting on overall electricity consumption was minor; daily electricity savings averaged 4-12% depending on season.

Household occupancy affected load shifting results. High occupancy households were able to shift more energy compared to lower occupancy households since they had higher baseline energy usage from which to shift load. Both low and high occupancy households were able to shift a similar percentage of their baseline, non-load shifting energy use. Table 11 shows results by occupancy.

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[3] See Duke Energy Progress Time-of-Use webpage for more details: https://www.duke-energy.com/home/billing/time-of-use.

Table 11. Load shifting results by schedule and occupancy

| Shifting schedule | Occupants | Count in sample | Average daily energy savings (kWh, % of non-shifting baseline) | | Average morning load shifted (kWh, % of non-shifting baseline) | | Average evening load shifted (kWh, % of non-shifting baseline) | |
|---|---|---|---|---|---|---|---|---|
| Summer – Hot | 1 | 14 | 0.09 | 3.8% | | | 0.14 | 35% |
| Winter – Shoulder | | | 0.02 | 0.8% | 0.19 | 47% | 0.25 | 47% |
| Winter – Cold | | | 0.03 | 1.1% | 0.38 | 41% | 0.32 | 48% |
| Summer – Shoulder | | | 0.24 | 9.2% | | | 0.07 | 18% |
| Summer – Hot | 2 | 6 | 0.03 | 1.5% | | | 0.11 | 38% |
| Winter – Shoulder | | | -0.16 | -6.5% | 0.09 | 20% | 0.20 | 41% |
| Winter – Cold | | | 0.09 | 2.7% | 0.53 | 43% | 0.30 | 45% |
| Summer – Shoulder | | | 0.19 | 7.7% | | | 0.10 | 34% |
| Summer – Hot | >= 3 | 4 | 0.26 | 9.7% | | | 0.06 | 11% |
| Winter – Shoulder | | | 0.86 | 19.7% | 0.35 | 62% | 0.92 | 57% |
| Winter – Cold | | | 0.98 | 18.6% | 0.90 | 59% | 0.95 | 51% |
| Summer – Shoulder | | | 0.93 | 23.6% | | | 0.28 | 30% |

Based on energy consumption during non-load shifting days when the water heaters did not receive demand management signals, participant average annual non-load shifting HPWH energy consumption was estimated to be around 1,020 kWh. Participant water heating cost was estimated for both the non-load shifting case and the load shifting case, assuming that load shifting periods align with peak periods and using average costs of $0.26 per kWh on peak and $0.09 per kWh off peak (based on the former DEP R-TOU-79 rate, the simplest TOU rate reviewed). Using these on-peak and off-peak rates and extrapolating study results over the course of a year, the annual per participant water heating electricity cost would have been approximately $180 on the TOU rate without load shifting and $136 with load shifting, therefore, a participant on a TOU rate could save about $44 per year on water heating electricity costs by load shifting.

As noted, study participants were not actually moved to Duke Energy’s former TOU rates and remained on the electricity tariffs they had selected before the study began. In terms of actual study participant impact, load shifting resulted in a minor overall reduction in electricity usage that would translate to an average cost decrease of about $7.50 annually per participant using Duke’s non-TOU residential average rate of $0.12 per kWh.

Although load shifting while on TOU rates may reduce water heating electricity costs for controlled HPWHs, because TOU rates apply to all electricity usage on a meter they may increase the electricity costs of other home electric appliances like space heating and air conditioning if those loads cannot also be shifted off peak. Unlike HPWH, although electric space heating and cooling may be equipped with demand response technology, they do not usually have thermal storage. If the amount of electricity consumption that cannot be shifted is significant, moving to a TOU rate could increase customer bills overall.

## Effect on Water Heater Operation

Because this study did not install participant water heaters, the study team did not control participants’ water heating operation mode (e.g., heat pump, hybrid, or electric resistance mode) at the time of installation, nor did we ask participants to change the operation mode except in instances of troubleshooting. All participants generally operated their water heaters in a hybrid mode that prioritized the use of the heat pump compressor but allowed electric resistance elements to operate when needed to meet hot water demand. We reviewed the effect of the load shifting schedule on water heater component operation both during and immediately after load shifting windows, where electric resistance element operation is assumed at times when water heater power draw exceeds 500 W. Table 12 shows the average percentage of shift window hours with electric resistance element (ER) usage with and without load shifting, as well as the average shift window demand with and without load shifting. Although the incidence of on-peak ER element usage was low before load shifting, load shifting reduced the incidence of on-peak ER usage by 30-60% depending on the season, and it also reduced peak demand.

Table 12. Percentage of shift window hours with ER usage, for baseline (non-load shifting) and load-shifting cases, by season

| Season | Daily shift hours | % of shift window hours with ER use, non-load shifting | % of shift window hours with ER use, load shifting | Avg. shift window (on-peak) demand (W), non-load shifting | Avg. shift window (on-peak) demand (W), load shifting | Avg. shift window (on-peak) demand *reduction* from shifting (W) |
|---|---|---|---|---|---|---|
| Summer - Hot | 8 | 2.4% | 1.7% | 102.3 | 66.8 | 35.5 |
| Summer - Shoulder | 8 | 4.3% | 1.7% | 124.8 | 77.4 | 53.4 |
| Winter - Cold | 12 | 5.3% | 2.1% | 168.7 | 88.1 | 80.5 |
| Winter - Shoulder | 11 | 4.0% | 1.6% | 146.9 | 72.6 | 74.2 |

The water heater demand tended to recover in the one hour after the end of the shift window, as seen in Figure 4. This effect is quantified in Table 13, which shows an average demand increase of about 230-280 W in the hour immediately after load shifting, as well as a 2-3x increase in the incidence of ER element usage in that hour, compared to non-load shifting days. Even so, on average the post-shift demand is within the range of the heat pump compressor power.

Table 13. Percentage of 1-hour post-shift window hours with ER usage, for baseline (non-load shifting) and load-shifting cases, by season

| Season | % of post-shift window hours with ER use, non-load shifting | % of post-shift window hours with ER use, load shifting | Avg. post-shift window demand (W), non-load shifting | Avg. post-shift window demand (W), load shifting | Avg. post-shift window demand *increase* from shifting (W) |
|---|---|---|---|---|---|
| Summer - Hot | 3.4% | 11.1% | 110.5 | 385.8 | 275.3 |
| Summer - Shoulder | 4.1% | 14.0% | 116.1 | 389.9 | 273.8 |
| Winter - Cold | 4.3% | 11.7% | 160.2 | 420.7 | 260.4 |
| Winter - Shoulder | 4.3% | 11.7% | 142.0 | 372.8 | 230.9 |

Finally, we reviewed the per household effect of load shifting on water heater component usage, demonstrated in Table 14. As expected, before load shifting larger occupancy households (e.g., #13 and #31) relied on ER usage more frequently than smaller households due to higher hot water usage. For these households, load shifting reduced but did not eliminate on-peak usage of ER elements. Another household that experienced this effect was #29. This participant had a

50-gallon water heater sized for one occupant and reported one occupant at the beginning of the study, but at least 5 additional guests and occupants moved into the home over the course of the study, stretching the water heater to its capacity limits.

Table 14. Percentage of shift window hours with ER usage, for baseline (non-load shifting) and load-shifting cases, by season and participant

| | | Summer - Hot | | Summer - Shoulder | | Winter - Cold | | Winter - Shoulder | |
|---|---|---|---|---|---|---|---|---|---|
| Alias # | No. occupants at start of study | % of shift window hours with ER use, non-load shifting | % of shift window hours with ER use, load shifting | % of shift window hours with ER use, non-load shifting | % of shift window hours with ER use, load shifting | % of shift window hours with ER use, non-load shifting | % of shift window hours with ER use, load shifting | % of shift window hours with ER use, non-load shifting | % of shift window hours with ER use, load shifting |
| 10 | 2 | 0.2% | | 0.5% | 0.3% | 3.2% | 4.9% | 1.7% | 5.4% |
| 11 | 1 | | | | | | | | |
| 12 | 1 | | | | | | | | |
| 13 | 6 | 31.3% | 25.4% | 45.0% | 24.7% | 31.3% | 12.0% | 31.5% | 14.0% |
| 14 | 2 | | | | | | | | 0.1% |
| 15 | 1 | | | | | 18.7% | 11.9% | 1.0% | 3.0% |
| 16 | 1 | 2.5% | | 1.0% | | 0.4% | 0.2% | 0.7% | |
| 17 | 1 | 0.9% | | 1.6% | 0.6% | 4.4% | 0.3% | | |
| 18 | 1 | 0.6% | | | | | 0.6% | | 0.1% |
| 19 | 2 | 0.7% | 0.4% | | 0.6% | 2.4% | 3.2% | 3.1% | 2.9% |
| 20 | 2 | 1.6% | | | 0.3% | 4.0% | 0.8% | 2.1% | 0.2% |
| 21 | 2 | | | | 0.3% | 0.4% | 0.2% | | 0.2% |
| 22 | 1 | | | | | | | | |
| 23 | 1 | | | | | 0.4% | 1.1% | | 0.2% |
| 24 | 3 | 2.0% | | | | | | 1.0% | |
| 25 | 2 | | | | | 4.4% | 1.5% | | |
| 26 | 1 | 0.2% | | | | 0.4% | | | |
| 27 | 1 | | | | | | | | |
| 28 | 1 | | | | 0.6% | 0.4% | 0.6% | 0.3% | 0.3% |
| 29 | 1 | 21.9% | 10.6% | | 13.8% | 7.9% | 0.4% | 12.0% | 5.1% |
| 30 | 3 | | | | | 0.8% | 0.6% | | |
| 31 | 5 | 7.8% | 4.9% | 29.5% | 5.5% | 38.5% | 12.5% | 29.4% | 6.0% |
| 32 | 1 | | 0.9% | 9.8% | 2.7% | | | 2.4% | 2.1% |
| 34 | 1 | | 0.4% | 10.7% | | 10.3% | 0.3% | 12.9% | 0.1% |

## Other Participant Observations

As noted above, this study was unusual in that participants were all eligible to receive services for LMI households delivered by RTT. In addition to modest incomes most participant households consisted of one or two senior adults only. Participants were not “early adopters” and came to the study looking for affordable and dependable water heating, rather than the latest in energy efficient water heating technology. The study team received a few instances of negative participant feedback, including occasional comments about cold air, noise, and long water heating recovery times as participants became used to their new HPWH. However, the only enduring complaints were related to HPWH that malfunctioned in some way requiring replacement, unrelated to the study, or that were likely undersized due to changes in occupancy. There were no reports of lack of hot water due to load shifting. The participant surveys indicated that almost all participant households never or rarely ran out of hot water, ran out of hot water less frequently than with their prior non-HPWH water heater, that their water temperature was "just right" and that they would recommend a HPWH to family and friends.

For households that experienced issues, HPWH user experience may have been improved by increasing the size of the HPWH to better match household hot water consumption. Installers should also be aware that not every location in a home that can accommodate an electric resistance water heater is also appropriate for a HPWH, especially in tight homes or small spaces. Household occupancy fluctuated somewhat over the course of the study due to participant health challenges and new occupants moving in. In some cases, water heaters were undersized for this additional load, so we recommend upsizing units where feasible to ensure hot water availability for homes where occupancy fluctuates or for multi-generational homes with many occupants. We further recommend better educating customers to set expectations about both the energy saving benefits and limitations of HPWH technology (like slower recovery times).

We found that many of the participants in the study either did not have access to the internet or were not comfortable using the internet as a means of communication with the project. We recommend that all water heating demand response programs include non-internet-based enrollment and support options to make them more inclusive and accessible to more households. Furthermore, programs should not require home Wi-Fi or participant app connections, although these can be leveraged for households that have access to these features. Our experience was that demand response via cellular EcoPort modules was a reliable way to connect to HPWHs.

Finally, over the course of the study a couple HPWHs had issues that required troubleshooting, repair, or replacement. While HPWH warranties typically cover parts for ten years, we found that they cover labor costs for much shorter periods, typically one year if at all. Even if the manufacturer agrees to replace a HPWH unit, customers may find themselves responsible for unaffordable labor costs. Support for both equipment *and* labor costs for warranty claims and re-installations is especially important for low-income households. We recommend that programs work with HPWH manufacturers and installers to provide additional support for labor costs in HPWH warranty claims for the first several years of product life.

## Conclusions and Recommendations

This study demonstrated that EcoPort-equipped controlled HPWHs can reduce water heating electricity costs for low-income households in the Southeast. Under TOU rates available when the study was designed, most of the utility customer savings come from reduced energy consumption thanks to the efficient HPWH technology, rather than from leveraging water heater controls to be able to take advantage of less expensive electricity.

This study also demonstrated that demand responsive HPWH can reduce load during grid peak periods without customer intervention and without causing cold water incidents. Seniors in low occupancy homes with low hot water usage may have greater flexibility to shift water heating times compared to other users. So, even though they offer a smaller magnitude of load reduction, they may offer greater reliability of load shed, making them a good target for inclusion in demand response programs.

The TOU rates considered in this study were difficult to take advantage of due to their long peak periods. TOU rates that are favorable to load shifting, with targeted peak periods and low off-peak costs, would incentivize better load shifting performance.

Finally, including LMI and hard-to-reach households, like the senior participants in this study, in HPWH load shifting programs is possible and can be successful when the programs are designed to respond to their needs and interests.

## Appendix A. Advisory Group Membership

The Advisory Group includes the following individuals: SEEA - Maggie Kelley Riggins, Ashley McBride, Sydney Roberts; Rebuilding Together for the Triangle - Dan Sargent; NEEA - Geoff Wickes; NCJC - Claire Williamson; Advanced Energy - Jonathon Coulter; Clean Energy Fund - Jen Weiss, Michelle Myers; New Buildings Institute - Joe Wachunas; PNNL - Josh Butzbaugh, Sam Rosenberg, Fatih Evren; IBACOS - Ari Rapport; NORESCO - Ben Edwards; Sally Robertson (Freelance); and Energy Solutions - Chris Granda, Daniela Urigwe, Helen Davis, George Chapman.

## References

Butzbaugh J.B., E.T. Mayhorn, T.D. Ashley, C.E. Metzger, K.E. Fenaughty, and D. Parker. 2022. *Field Study of Grid-connected Heat Pump Water Heaters in the Southeast US: The Next Right Thing*. Washington, DC: ACEEE. https://www.pnnl.gov/publications/field-study-grid-connected-heat-pump-water-heaters-southeast-us-next-right-thing

Census Bureau. 2022. “QuickFacts: Wake County, North Carolina.” https://www.census.gov/quickfacts/fact/table/wakecountynorthcarolina/PST045223.

Duke Energy. 2020. *Duke Energy Winter Peak Demand Reduction Potential Assessment.* Charlotte, NC: Duke Energy. https://cleanenergy.org/wp-content/uploads/Duke-Winter-Peak-Demand-Reduction-Potential-Assessment-Final-Report.pdf.

Duke Energy. 2024. “Carolinas Resource Plan.” https://www.duke-energy.com/-/media/pdfs/our-company/carolinas-resource-plan/january-24-fact-sheet.pdf?rev=8e61a3e3e8c844daaf4f2d5b6635c687

EIA (Energy Information Administration). 2020. *Residential Energy Consumption Survey*. Washington, DC: EIA. https://www.eia.gov/consumption/residential/.

Groundswell. 2022. *Big Data Reveals the Inconvenient Truth About the Uncool Energy Burdens of Rural North Carolina*. https://groundswell.org/news/big-data-reveals-the-inconvenient-truth-about-the-uncool-energy-burdens-of-rural-north-carolina/