Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Project 72577 – Technology Integration

Task 3: Establish Hot Water Draw Profiles, Develop Lab Homes Protocols, and HPWH Baseline Characterization

PNNL Contacts:
Walt Hunt walter.hunt@pnnl.gov
Cheryn Metzger cheryn.metzger@pnnl.gov

U.S. DEPARTMENT OF ENERGY

Background and Related Projects

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- **Pacific Northwest HPWH Field Study**
  - PNNL Led Project through BTO
  - Project produced a robust Water Heating Dataset
  - Original Project Focus on Characterizing Load Shifting Potential of HPWHs
  - ~150 Heat Pump Water Heater Field Sites
  - ~100 Electric Resistance Water Heater Field Sites
  - 1+ Year of Field Data Collection
  - Customer Survey Data for HPWH Field Sites

- **Max Tech Electric HPWH with Low-GWP Halogenated Refrigerant**
  - ORNL Led Project through BTO
  - Project Scope to Develop Max Tech HPWH for Specific Design Parameters
  - Project Scope includes Laboratory Testing for Standard Conditions
  - ORNL Project to Hand-Off Max Tech HPWH Proto-types to ORNL and PNNL Teams for Field Assessment in Lab Homes and Occupied Homes

FY19 PNNL Project Scope

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- **Part A:** Using the Pacific Northwest Water Heating Dataset, Establish Representative Hot Water Draw Profiles for examining the Field Performance of the Max Tech HPWH at Lab Homes.

- **Part B:** Develop Test Protocols for Max Tech HPWH Evaluation at PNNL Lab Homes. Testing planned for FY 20.

- **Part C:** Using the Pacific Northwest Water Heating Dataset, Characterize Baseline Power Profiles for HPWHs with Survey Data

Establish Representative Hot Water Draw Profiles

Hot Water Draw Profiles – Dataset

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- 98 Field Sites with Electric Resistance Water Heater
- Timeframe: 2017 – 2018; Weekdays (Mon – Fri) Only Considered
- Corrected CTA 2045 Power and Present Energy Data
- Filtered Out Days with Total Hot Water Consumption below 5 Gallons
- Starting Point: 4,925 Total Days of Field Data Collection
- Unknown Occupancy at Electric Resistance Field Sites
- Assumptions for Groundwater Temperature and Water Heater Efficiency used to Determine Hot Water Usage from Power Data
- Daily Median Hot Water Usage Across Field Data was 46 Gallons

Hot Water Draw Profiles – Strategy

Key Characteristics for Hot Water Usage Profile:

- Total Consumption
- Event Distribution
- Profile Shape (Peaks)

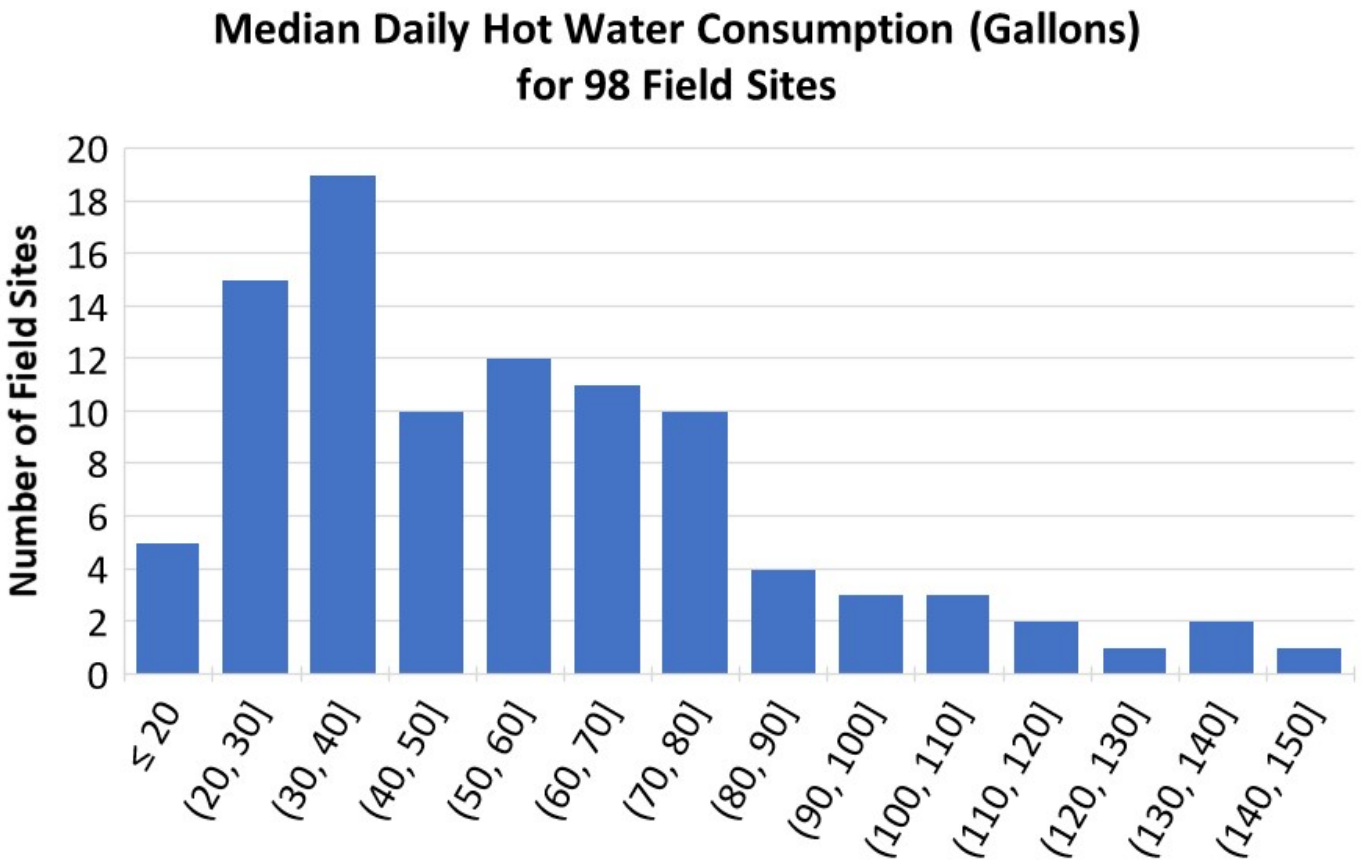
Analytical Measures to Identify Representative Day from Field Data:

- Total Daily Consumption
- Hours with Significant Draw (i.e. 5+ Gallons)
- Time (Hours) between AM and PM Peaks
- Ratio of 3-Hour AM and PM Peaks
- Ratio of Daily 3-Hour Peak to Daily Total Consumption

AM and PM Peaks were considered in consecutive 3-hour windows. For example, PM Peak would be largest cumulative hot water usage in 3-hour window from 12PM – 11PM.

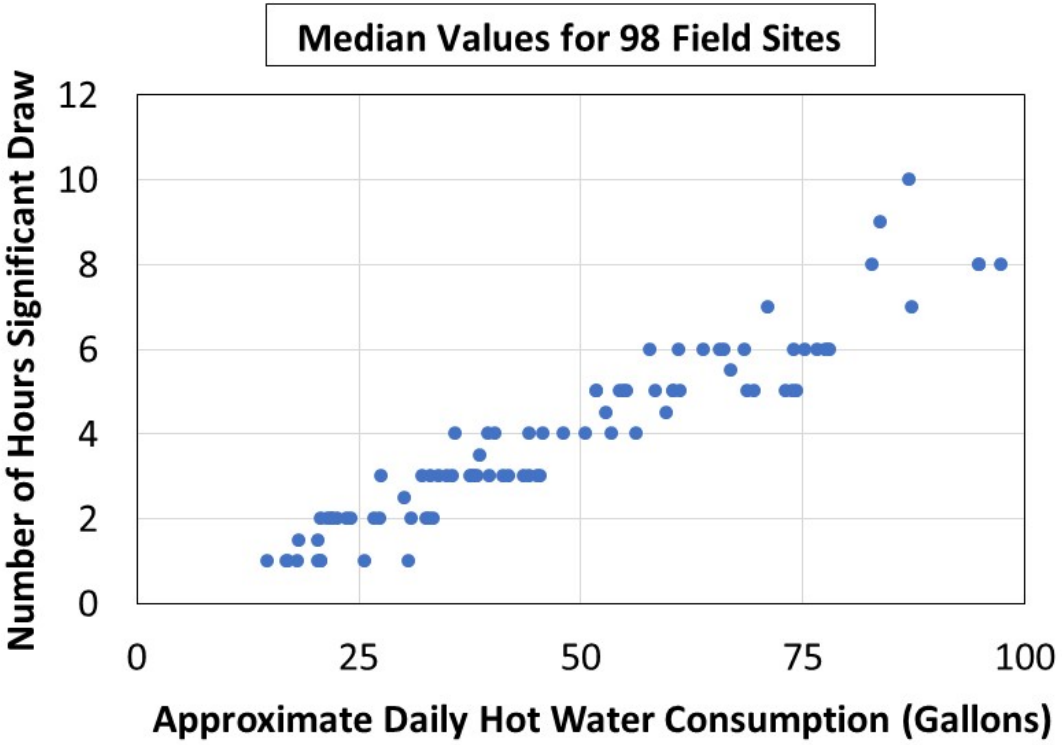
Hot Water Draw Profiles – Key Takeaways

- Median Daily Hot Water Usage of 98 Field Sites: ~49 gallons
- 25th Percentile: ~33 gallons; 75th Percentile: ~70 gallons



Hot Water Draw Profiles – Key Takeaways

- Daily 3-Hour Peak in PM with Comparable 3-Hour Peak in AM
- Total Consumption is Proportional to Hours with Draw over 5 Gallons



As shown in figure, lower total daily consumption corresponds with fewer hours with a significant hot water draw (i.e. 5+ gallons), and higher total daily consumption corresponds with more significant draw hours.

Hot Water Draw Profiles – Analysis Sequence

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- **Step 1:** Determine Median Daily Hot Water Consumption for Each Site
  - 98 Field Sites: 98 Median Values
  - Provides equal weight for each field site

- **Step 2:** Determine 25th, 50th, and 75th Percentile from Dataset of Step 1
  - Percentiles provide Small, Medium, and Large Hot Water Draw Targets

- **Step 3:** Using the Small, Medium, and Large Hot Water Draw Targets ±5 gallons, develop Small, Medium, and Large Data Subset from the 4,925 Days of Field Data
  - Data Subsets: Small = 747 Days; Medium = 621 Days; Large = 439 Days

- **Step 4:** Determine Median Values for Four Remaining Analytical Measure (e.g. Hours with a Significant Draw) for Each Data Subset (Small, Medium, Large)
  - Results shown in Tables on Slide 6 for “Median of Subset”

Hot Water Draw Profiles – Analysis Sequence

- **Step 5:** For Each Small, Medium, and Large Data Subset, Filter Data to Contain:
  - Hours with Significant Draw (±1 hour)
  - Time between AM and PM Peak (exact interval)
  - Days Remaining in Subset: Small = 59 Days; Medium = 59 Days; Large = 37 Days

- **Step 6:** For Remaining Daily Profiles in Each Subset, Conduct Similarity Analysis using the Median Ratio of AM and PM 3-Hour Peaks and Ratio of Daily 3-Hour Peak to Daily Total
  - Individual Day closest to Median Values is selected as Representative Day for Dataset
  - Results shown in Tables on Slide 6 for “Selected Day”

Hot Water Draw Profiles – Identification

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Small Draw Profile

	Total Daily Consumption	Significant Draw	Time Difference AM and PM Peak	Ratio of AM and PM Peaks	Ratio of Daily Peak and Total
Median of Subset	6,018 Wh	3 Hours	10 Hours	0.84	0.41
Selected Day	5,775 Wh	3 Hours	10 Hours	0.85	0.35

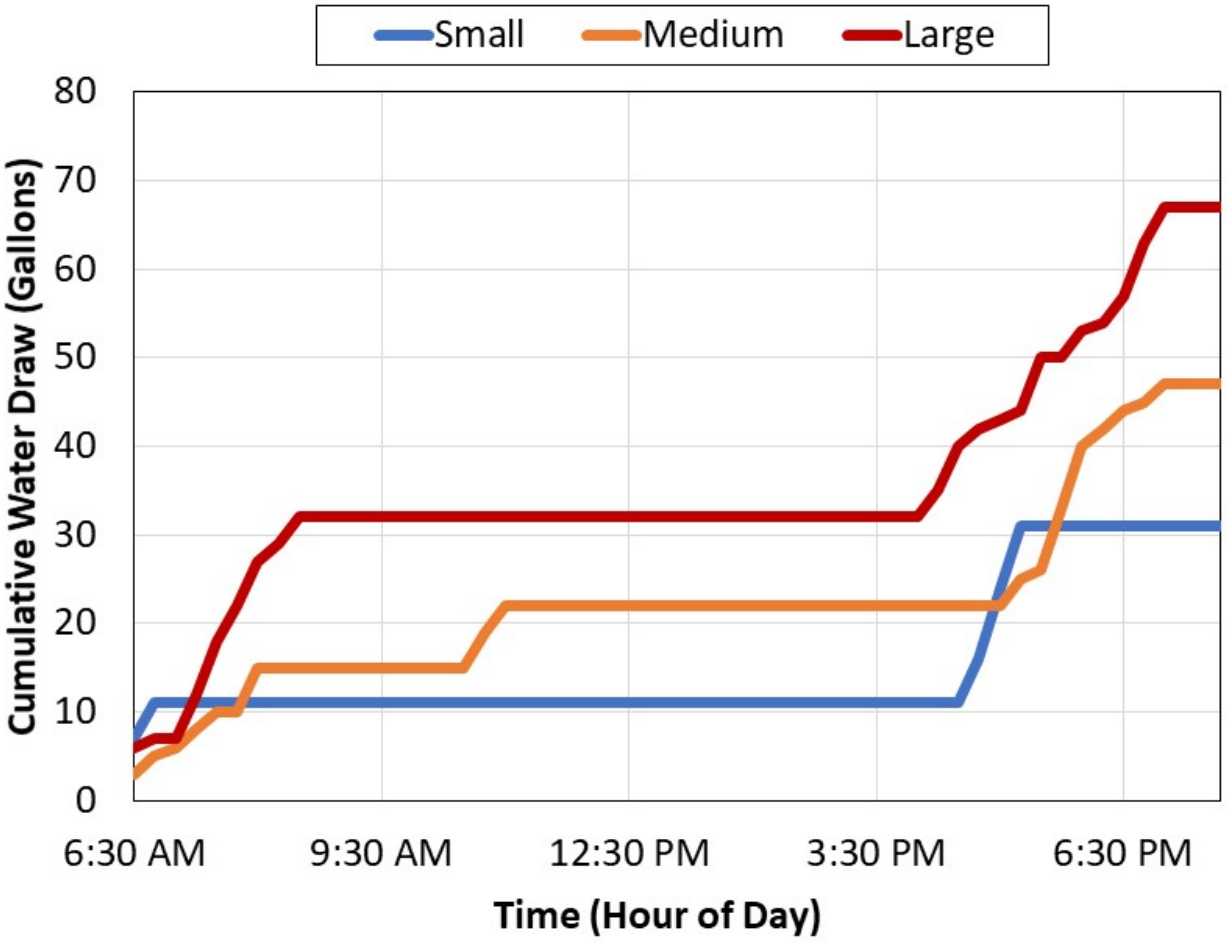
Medium Draw Profile

	Total Daily Consumption	Significant Draw	Time Difference AM and PM Peak	Ratio of AM and PM Peaks	Ratio of Daily Peak and Total
Median of Subset	8,925 Wh	4 Hours	11 Hours	0.77	0.38
Selected Day	8,706 Wh	5 Hours	11 Hours	0.73	0.39

Large Draw Profile

	Total Daily Consumption	Significant Draw	Time Difference AM and PM Peak	Ratio of AM and PM Peaks	Ratio of Daily Peak and Total
Median of Subset	13,500 Wh	6 Hours	11 Hours	0.91	0.35
Selected Day	12,750 Wh	7 Hours	11 Hours	0.96	0.36

Hot Water Draw Profiles – Results



	Total Daily Gallons
Large	67
Medium	47
Small	31

Time difference between AM and PM Peak was used as an analytical measure for identifying a representative profile. Separately in analysis, 6:30 AM was determined to be the most common start for hot water draw profile.

Hot Water Draw Profiles – Results

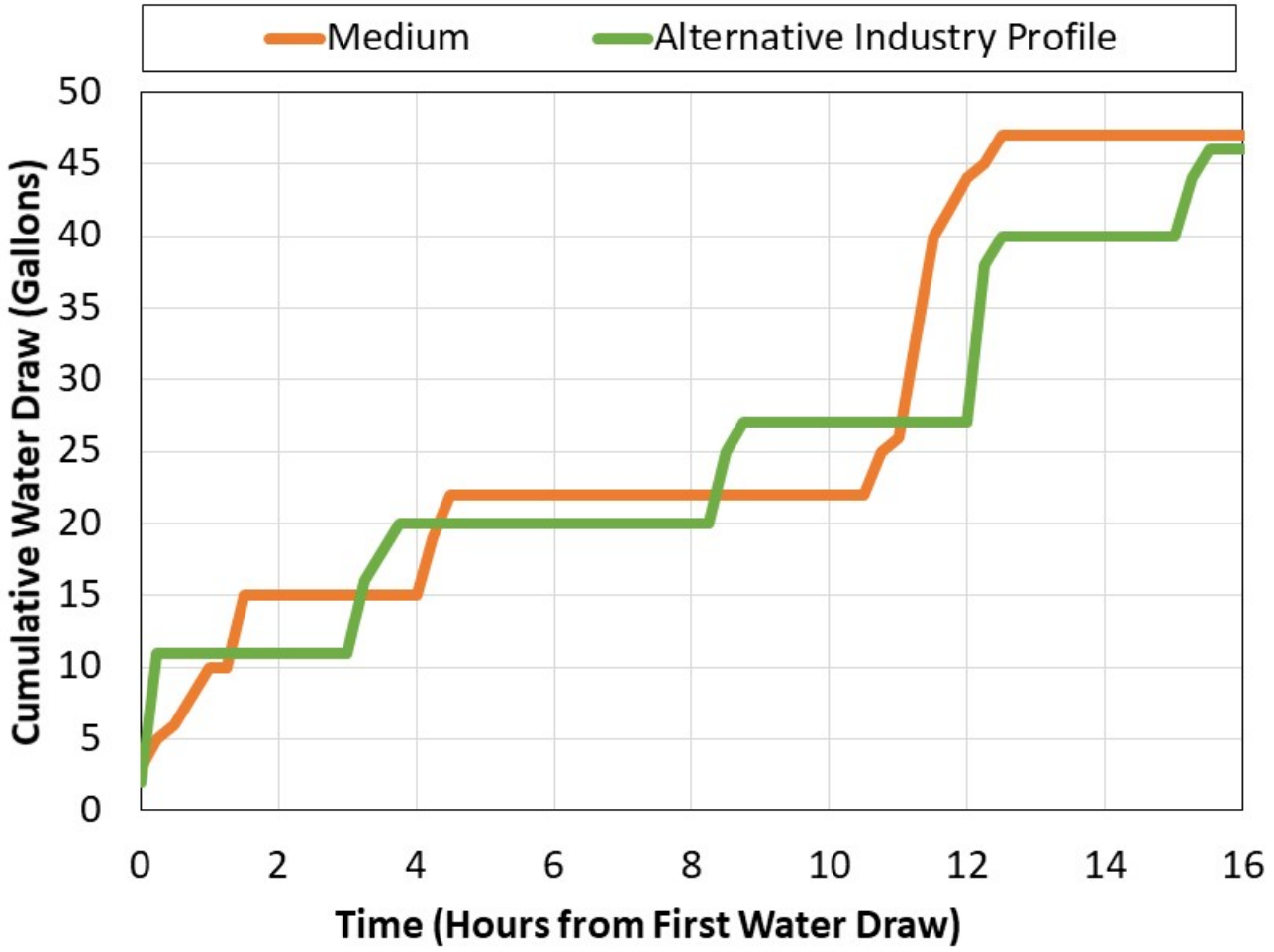
- Small, Medium, and Large Draw Profiles were Identified
- Hot Water Consumption (Gallons) Profiles shown for 15-minute Time Increments

Time	Gallons of Hot Water
6:30 AM	7
6:45 AM	4
4:45 PM	5
5:00 PM	8
5:15 PM	7

Time	Gallons of Hot Water
6:30 AM	3
6:45 AM	2
7:00 AM	1
7:15 AM	2
7:30 AM	2
8:00 AM	5
10:45 AM	4
11:00 AM	3
5:15 PM	3
5:30 PM	1
5:45 PM	7
6:00 PM	7
6:15 PM	2
6:30 PM	2
6:45 PM	1
7:00 PM	2

Time	Gallons of Hot Water
6:30 AM	6
6:45 AM	1
7:15 AM	5
7:30 AM	6
7:45 AM	4
8:00 AM	5
8:15 AM	2
8:30 AM	3
4:15 PM	3
4:30 PM	5
4:45 PM	2
5:00 PM	1
5:15 PM	1
5:30 PM	6
6:00 PM	3
6:15 PM	1
6:30 PM	3
6:45 PM	6
7:00 PM	4

Hot Water Draw Profiles – Comparison



Alternative Profile shown is 3-Occupant Profile from Appendix E of Heat Pump Water Heater Model Validation Study. The two field-based profiles have comparable total daily hot water consumption. The alternative profile consists of 5 time intervals with hot water draws more evenly distributed throughout the day.

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Protocol Development for Lab Home Evaluation of Max Tech HPWH

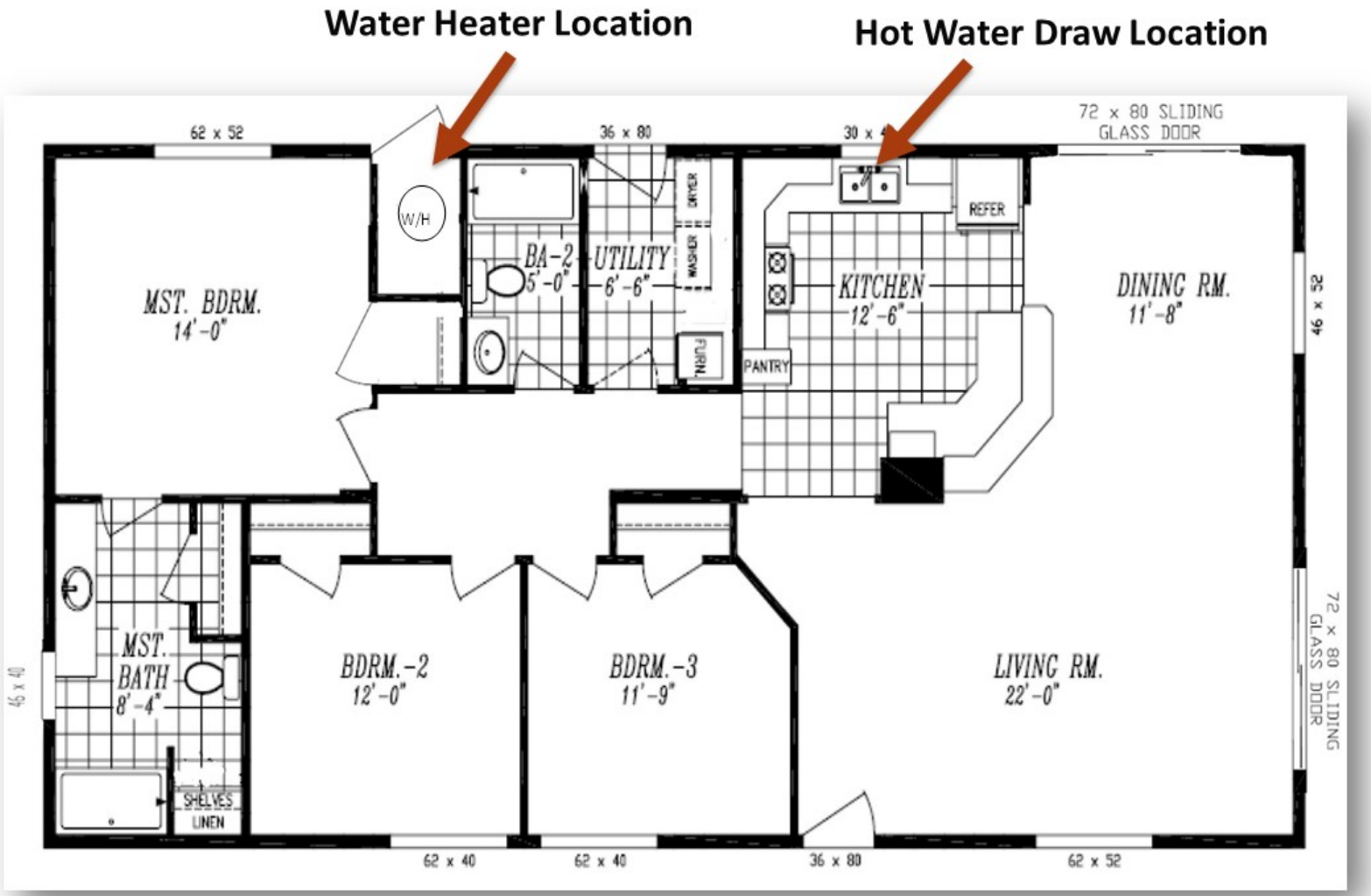
Lab Home Testing: Home Characteristics

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- **Represents Existing Homes**
  - 3 BR/2BA 1493-ft^2 double-wide, factory-built to HUD code
  - 13 SEER/7.7 HSPF heat pump central HVAC
  - R-22 floors, R-11 walls & R-22 ceiling
  - 195.7-ft^2 (13% of floor) window area
  - Incandescent lighting
- **Cold Climate (Winter)**
- **Hot-Dry Climate (Summer)**
- **Low-risk Data Collection**
  - Equipment Flexibility
  - Controlled Hot Water Draws
- During testing, homes will be identical, except for windows

Lab Home Testing: Home Layout

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965



Lab Home Testing: Protocol

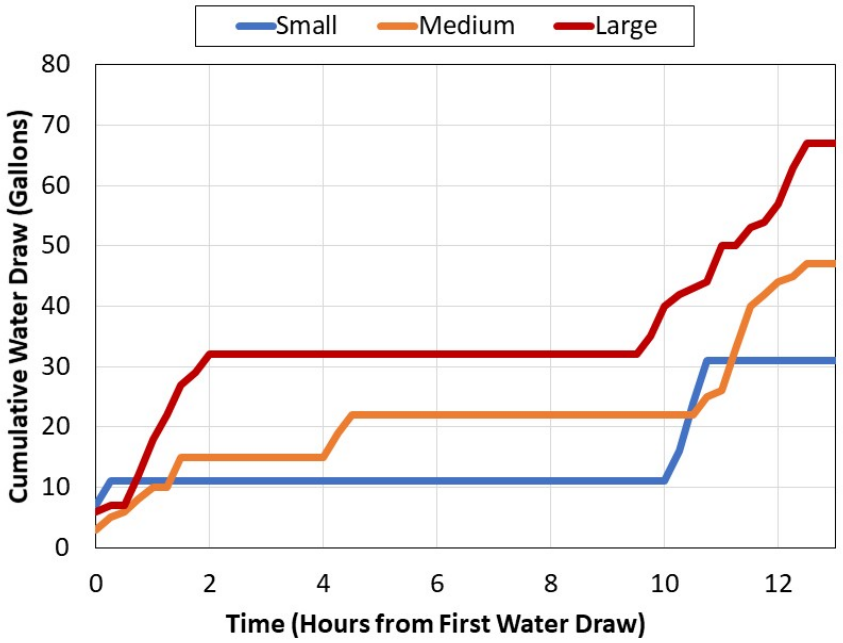
Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Water Heating Equipment

- Standard R-134a HPWH
- Low GWP Max Tech HPWH

Imposed Hot Water Draw Profiles

- PNNL Established Profiles in FY19
  - Small (31 daily gallons)
  - Medium (47 daily gallons)
  - Large (67 daily gallons)



Data Analysis

- Performance under Field-Based Draw Profiles
- Performance for Cold and Hot-Dry Climate

Lab Home Testing: Data Acquisition

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Planned HWPH Measurements at PNNL Lab Homes

- Hot Water Flow Rate
- Outlet (Hot) Water Temperature
- Inlet (Cold) Water Temperature
- Surrounding Air Temperature and Humidity
  - Semi-Conditioned Closet Space
  - Conditioned Indoor Space adjacent to Closet
- HPWH Power Consumption
  - Backup Electric Heat Usage
  - Operating Performance

Field Testing: FY19 Progress

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- Tentative Selection of 2 Field Sites in Portland, OR area
- Field Sites were participates in NW HPWH CTA2045 Study (FY19)
- Over 1 Year of Baseline HPWH Performance Data
  - HPWH Power Consumption
  - Hot Water Delivery Temperature (Pipe Temperature)
  - Air Temperature Surrounding HPWH (Inlet Air)
- Existing HPWH at Selected Field Sites
  - R-134a Refrigerant
  - Standard Industry Efficiency

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

HPWH Baseline Power Profile Characterization

HPWH Power Profile Characterization

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Overall Dataset

- 147 HPWH Sites included in Field Data Monitoring and Survey
- Timeframe: 2017 – 2018; Weekdays (Mon – Fri) Only Considered
- Corrected CTA 2045 Power Consumption Data
- Normal HPWH Operation (No DR Events Included)

Homeowner Survey

- Does at least 1 Adult not work outside of Home for 4+ days of week?
- Number of Occupants in Household
- Manufacturer of HPWH
- Location / Climate

Data Analysis

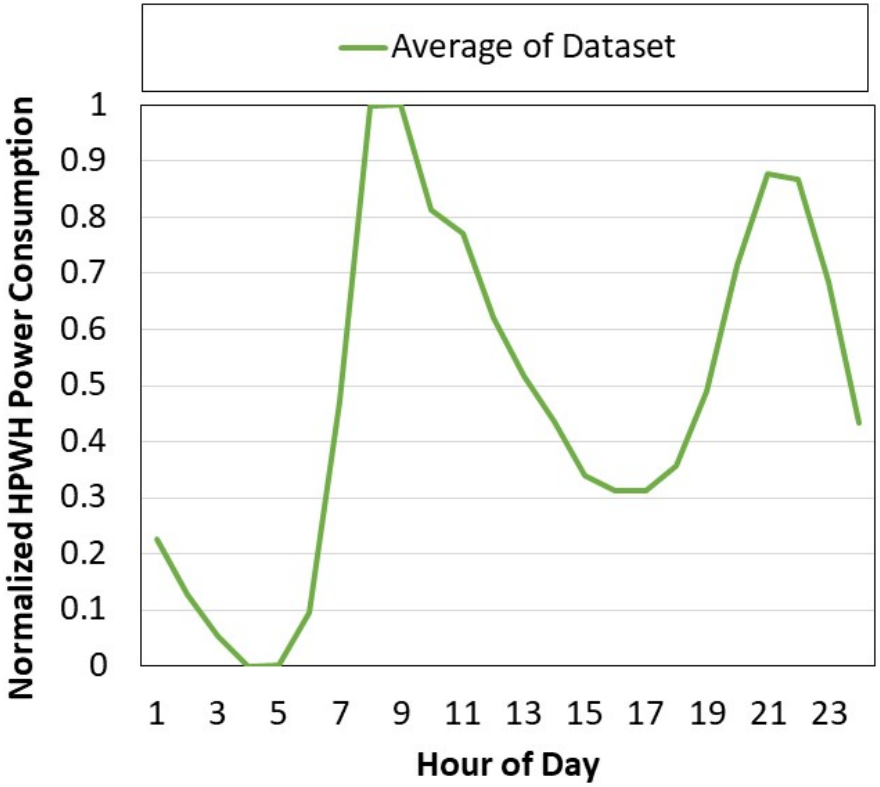
- 24 Hour Averaged HPWH Power Profile
- Summary Characteristics for Data View: Sample Count, Energy Use, Peak Hour
- Normalized for Each Dataset for Comparison of Profile Shape

HPWH Power Profile Characterization

Does at least 1 Adult not work outside of Home?

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Normalized Profile Comparison



Summary of Averaged Profile

	Overall Dataset
Sample Home Count	147
Average Home Occupancy	2.9
Daily Energy Usage (Wh)	3,869
Hourly Peak Power (W)	263

Profile Description:

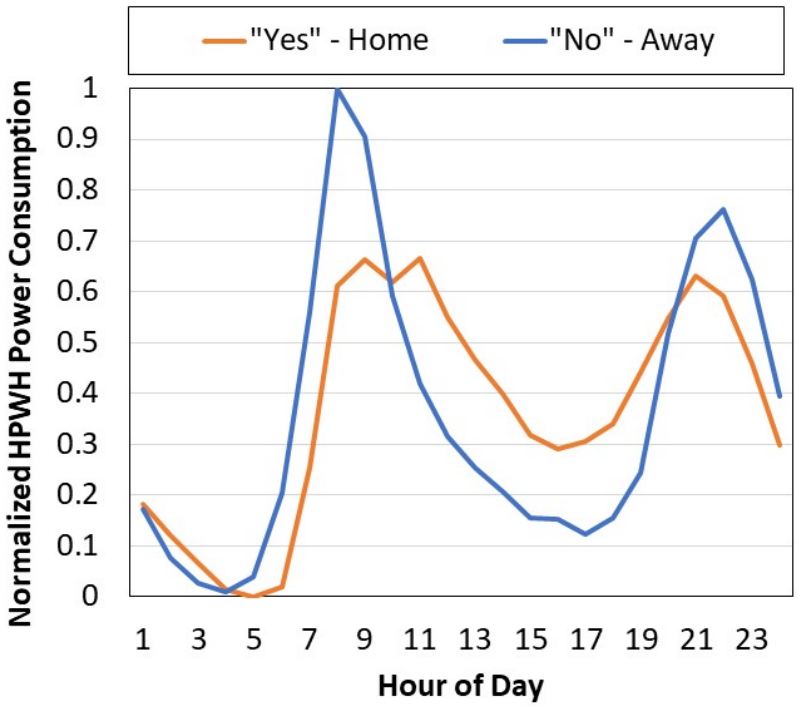
- Graph is an average of Overall Dataset throughout ~1 Year Data Collection
- Comparable AM and PM Peak in both Magnitude and Time Duration

HPWH Power Profile Characterization

Does at least 1 Adult not work outside of Home?

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Normalized Profile Comparison



Summary of Profiles

	"Yes" - Home	"No" - Away
Sample Home Count	96	51
Average Home Occupancy	2.9	3.1
Daily Energy Usage (Wh)	3,893	3,827
Hourly Peak Power (W)	242	331

Profile Impact Observation:

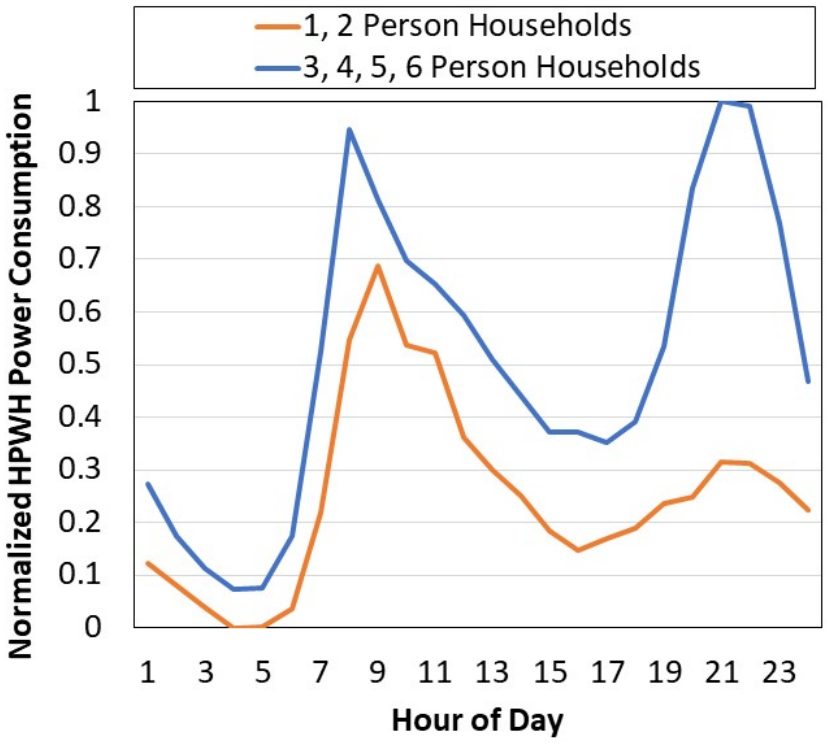
- "Yes" or "Home" profile shows broad AM Peak and comparable PM Peak
- "No" or "Away" profile shows narrow and more dominant AM Peak
- Comparable Energy Usage yet Significant Difference in Peak Demands

HPWH Power Profile Characterization

Number of Occupants in Household

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Normalized Profile Comparison



Summary of Profiles

	1, 2 Person Household	3, 4, 5, 6 Person Household
Sample Home Count	72	75
Average Home Occupancy	1.9	3.9
Daily Energy Usage (Wh)	3,005	4,700
Hourly Peak Power (W)	246	332

Profile Impact Observation:

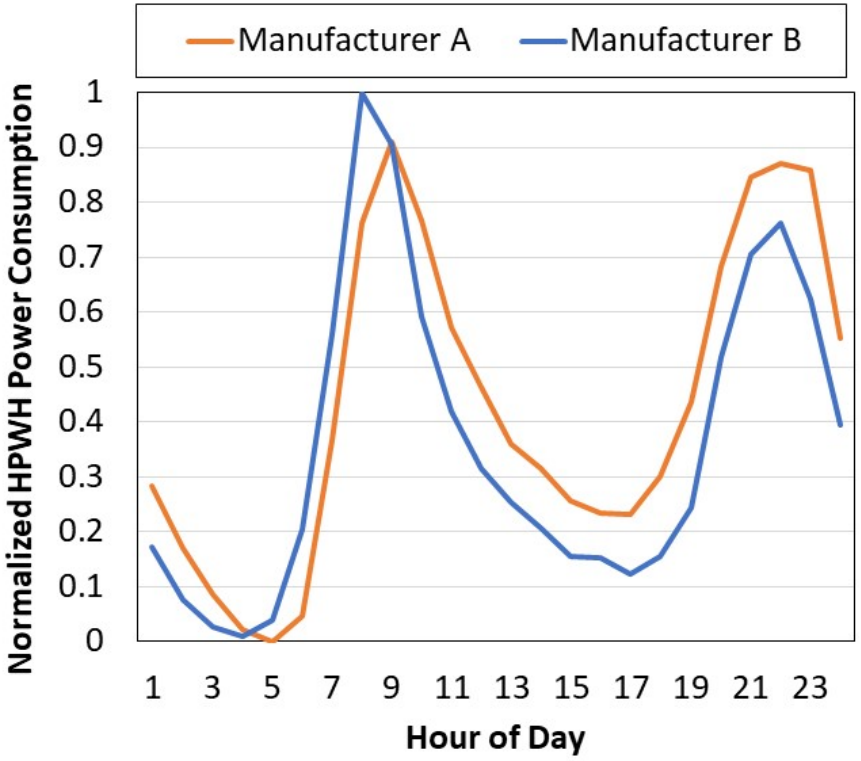
- Both smaller (1, 2) and larger (3, 4, 5, 6) household counts show significant AM Peak
- Larger (3, 4, 5, 6) households show more comparable AM and PM Peak (Dual Peak)
- Smaller (1, 2) households show more dominant AM Peak compared to PM Peak

HPWH Power Profile Characterization

HPWH Manufacturer

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Normalized Profile Comparison



Summary of Profiles

	Manufacturer A	Manufacturer B
Sample Home Count*	29	102
Average Home Occupancy	3.0	2.8
Daily Energy Usage (Wh)	242	261
Hourly Peak Power (W)	3,192	3,532

*All 16 sites removed from coldest territory due to disproportionate manufacturer ratio.

Profile Impact Observation:

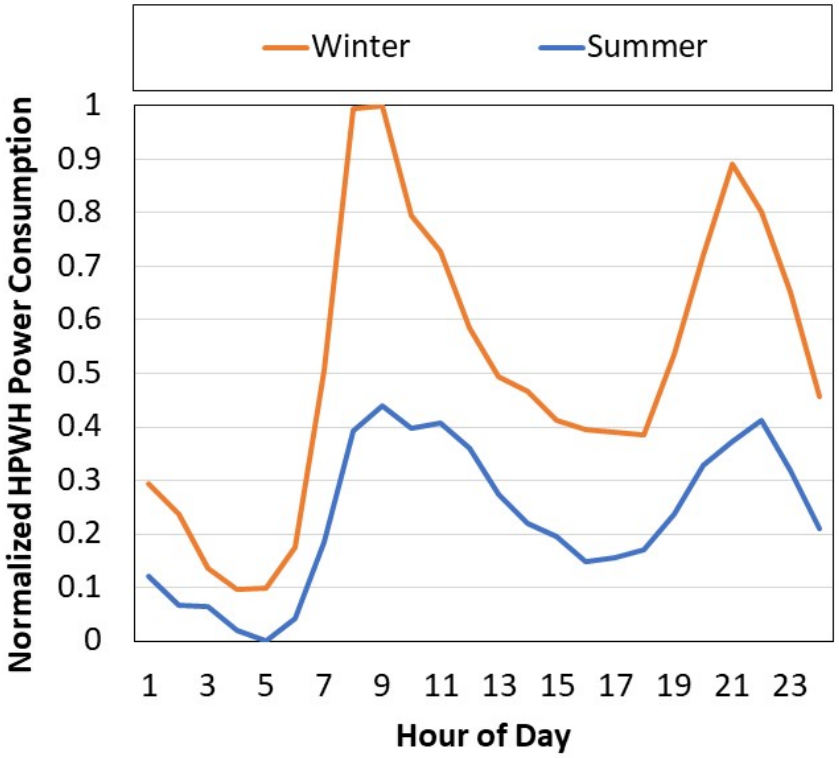
- Comparable profile magnitude and profile shape between two represented HPWH manufacturers in field survey.

HPWH Power Profile Characterization

Seasonal – Climate

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Normalized Profile Comparison



Summary of Profiles

	Winter	Summer
Sample Home Count	147	147
Average Outdoor Temperature	~45°F	~70°F
Daily Energy Usage (Wh)	4,971	2,917
Hourly Peak Power (W)	357	185

Profile Impact Observation:

- Comparable Winter and Summer Profile Shape
- Expected Increase in Energy Use in Winter due to Decreased Efficiency of HPWH in Colder Ambient Air

Questions or Comments

PNNL Contacts:
Walt Hunt walter.hunt@pnnl.gov
Cheryn Metzger cheryn.metzger@pnnl.gov