Hot Water Distribution System Losses in a Net-Zero Home

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ACEEE Hot Water Forum

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Overview of Presentation

Purpose: To share results on time delays and water waste in delivering hot water from a distribution system in a single family test house and the accompanying energy losses in that system

- Description of the experiment
- Results
  - Wait Time
  - Water Waste, by fixture and total
  - Energy Waste, by fixture and total

Net-Zero Energy Residential Test Facility

- Type: Single-Family
- Stories: 2
- Bedrooms: 4
- Baths: 3
- Floor Area: 2,709 sq. ft.
- Basement Area: 1,518 sq. ft.
- Smart Grid Ready
- A virtual family of four occupies the house replicating the actual
  - Water Usage
  - Appliances
  - Heat Load Associated with People (Sensible and Latent)
- Information: *https://www.nist.gov/el/net-zero-energy-residential-test-facility*
- Data: *https://pages.nist.gov/netzero/*

Hot Water System

Two-tank system:

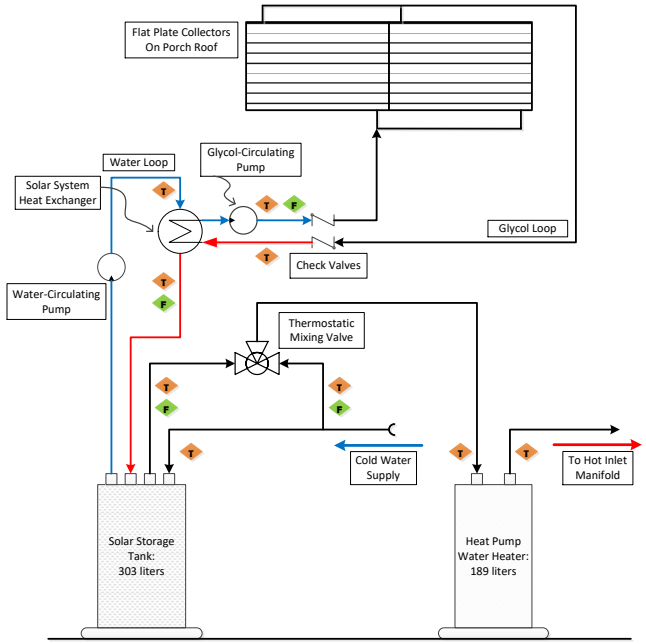
- 50 gallon solar preheat tank
- 50 gallon Heat Pump Water Heater downstream

Distribution System:

"Home-run" PEX manifold system

Fixtures:

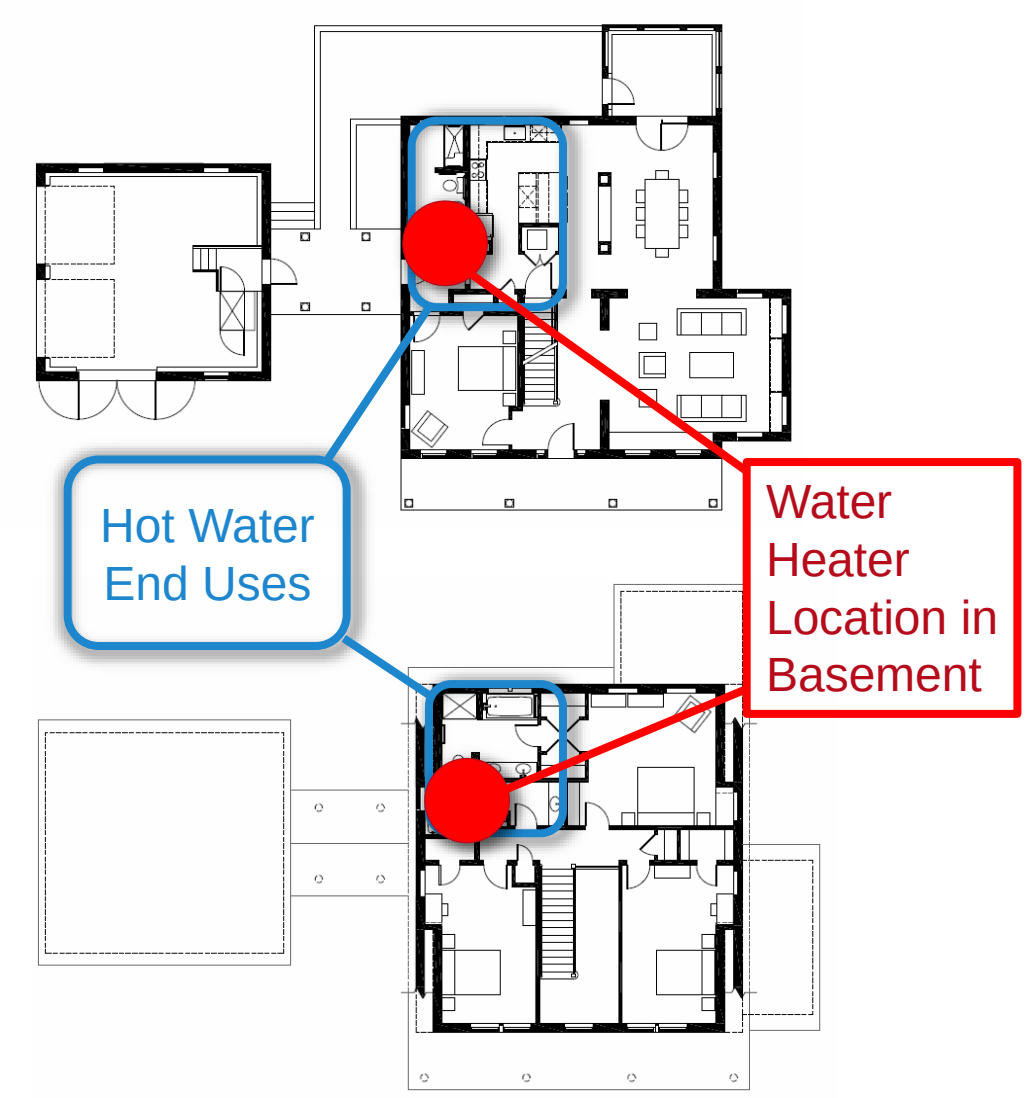
- Showerheads: 3 (2 in use)
- Sinks: 4 (3 in use)
- Tub: 1
- Dishwasher: 1
- Clothes Washer: 1



Hot Water Fixture Layout

First Floor

Second Floor



Hot Water Distribution System

- Home-run, manifold system with 3/8” PEX tubing to each fixture
- Copper pipe between water heater and manifold: 1 inch diameter, 3 m (9.8 ft)
- R-3 ($h \cdot ft^2 \cdot °F/Btu$) insulation on hot water lines
- Solenoid valves trigger water draws

PEX lengths from manifold to fixture

End Use	Length [m (ft)]	Volume [L (gal)]
First Floor		
Kitchen Sink	8.3 (27.3)	0.55 (0.14)
Clothes Washer	7.0 (23.0)	0.46 (0.12)
Dishwasher	8.8 (29.0)	0.58 (0.15)
Second Floor		
Master Bath Sink	10.2 (33.4)	0.67 (0.18)
Bath 2 Sink	11.2 (36.7)	0.73 (0.19)
Master Bath Shower	12.8 (41.9)	0.84 (0.22)
Bath 2 Shower	9.3 (30.6)	0.61 (0.16)
Master Bath Tub	11.2 (36.9)	0.74 (0.20)

Operation

Test Period: February 2015 through January 2016

Fixtures Used:

2nd Floor: Master Bath sink, shower, & tub;
Hall Bath sink & shower

1st Floor: Kitchen sink + dishwasher, clothes washer

Emulated draws of a 4-person family based on DOE's Building America Benchmark.

Average Water Usage at Fixtures (not including clothes washer and dishwasher)	70 gal/day
Water Heater Setpoint Temperature	120 °F
Sink target temperature	105 °F ± 5 °F
Shower and tub target temperature	110 °F ± 5 °F
Heating/Cooling Set Points	70 °F/ 75 °F

No toilet usage
Fixture draw volumes determined from start of draw, not based on achieving a "usable" temperature.

Key Fixture Information

FIXTURE	Events Per Week	Average Draw Volume [L (gal)]	Average Hot Water Flow Rate [lpm (gpm)]
Kitchen Sink	199	2.4 (0.63)	4.5 (1.2)
Master Bath Sink	43	2.4 (0.63)	5.3 (1.4)
Hall Bath Sink	38	2.4 (0.63)	5.0 (1.3)
Master Bath Shower	14	33.1 (8.75)	6.3 (1.7)
Hall Bath Shower	5 7	33.1 (8.75) 53.0 (14.0)	7.2 (1.9)
Master Bath Tub	2	113.6 (30.0)	9.9 (2.6)
Clothes Washer	6	53.0 (14.0)	3.8 (1.0)
Dishwasher	5	7.2 (1.9)	2.3 (0.6)

Experimental Measures

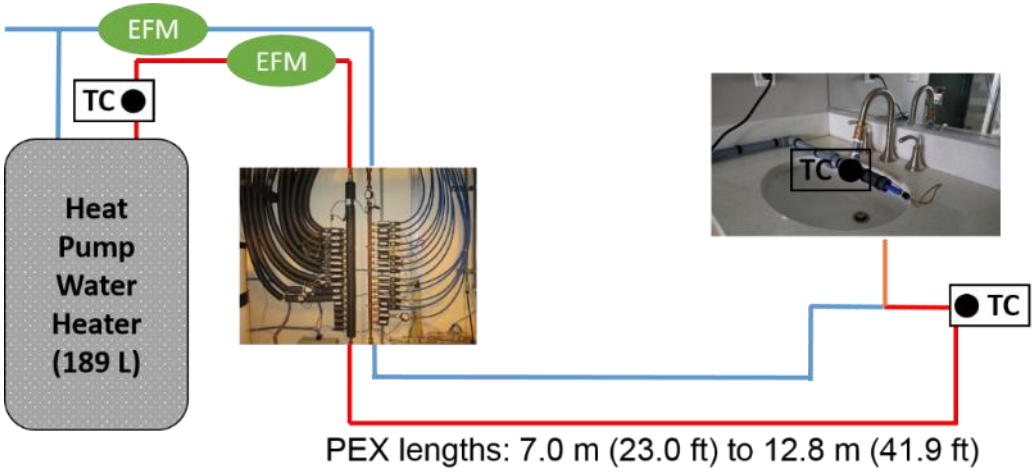
Electrical energy consumption

Electromagnetic flowmeters on hot and cold lines

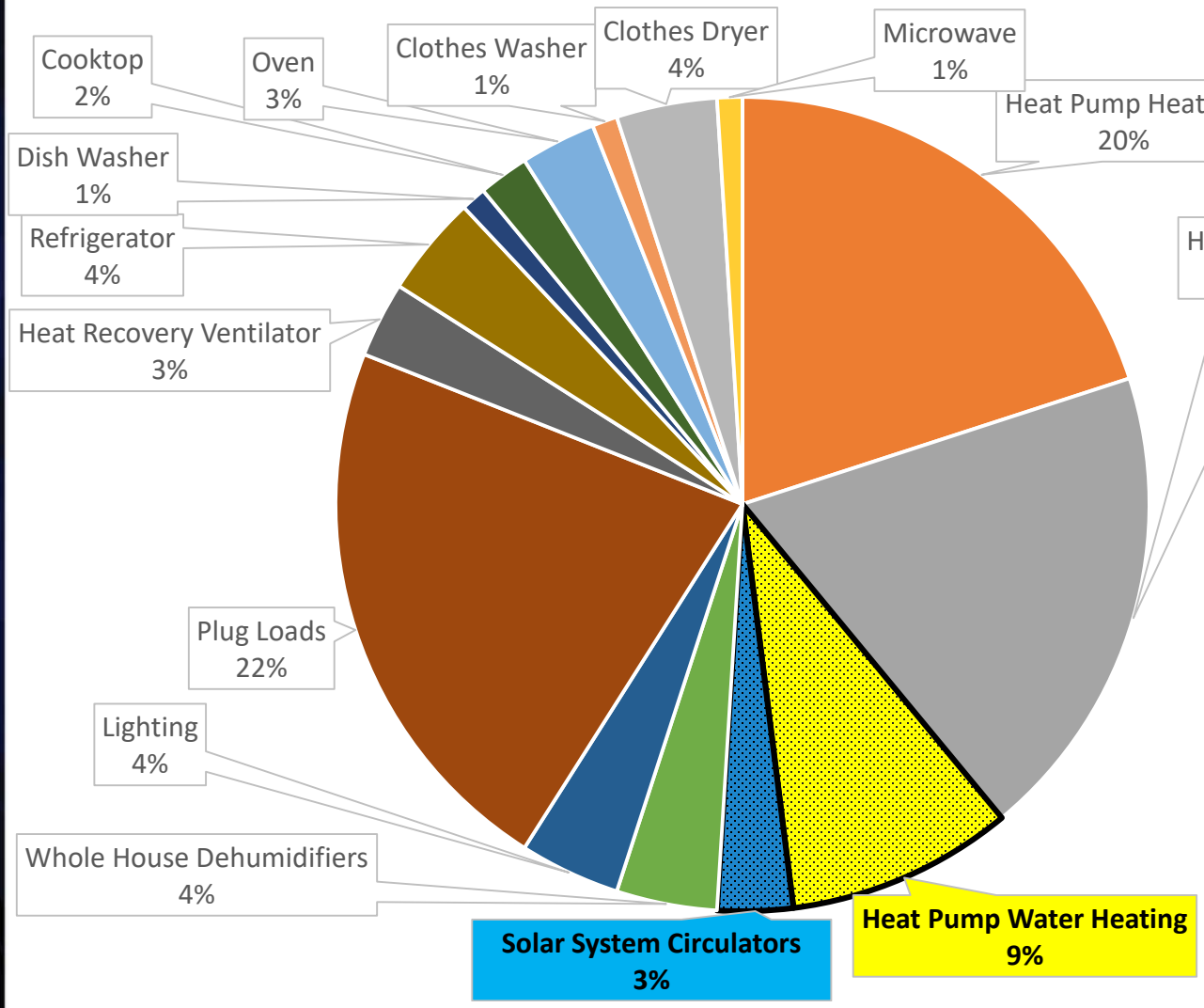
Embedded thermocouples measure water temperatures out of water heater and at end fixtures, both the mixed temperature and the hot temperature at the fixture.

Temperature and flow data collected at 3 s intervals during draws.

Mass of water measured for each draw.



Overall Annual Energy Consumption



Water Heating

Annual Energy Use

HPWH: 1118 kWh

Solar: 333 kWh

Total: 1451 kWh

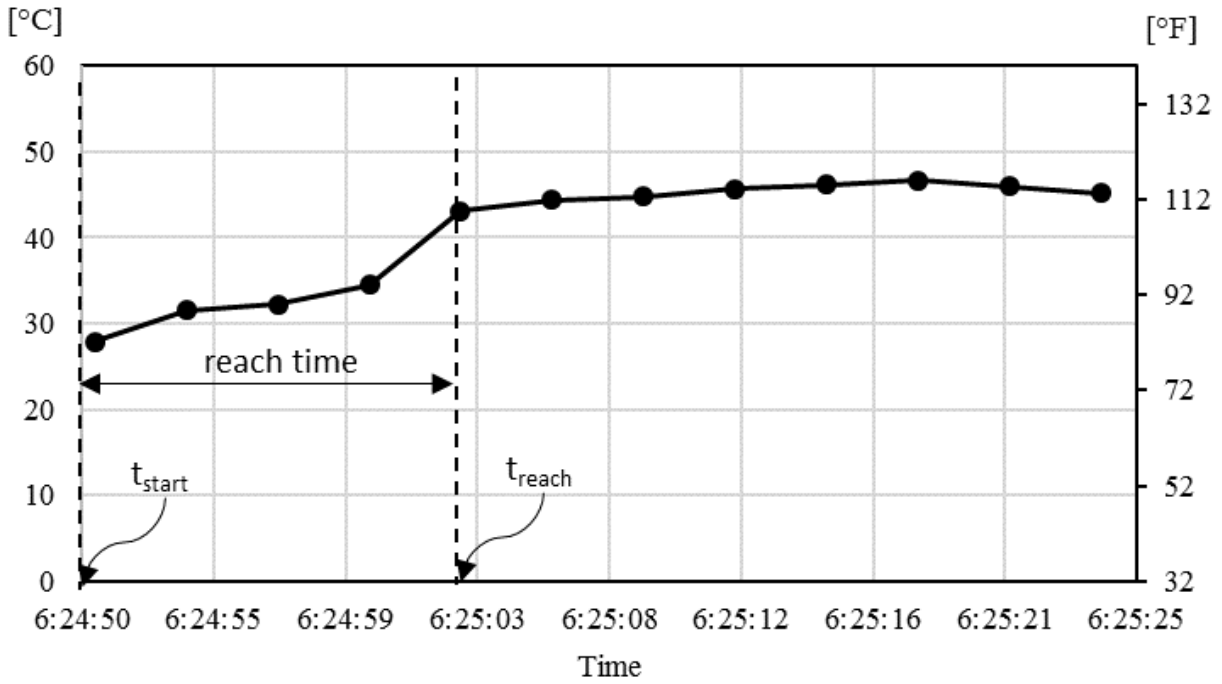
Thermal Energy Delivered: 3280 kWh

System COP: 2.26

Time To Achieve Temperature

“Reach Time”: Time from when draw is initiated until it achieves a minimum threshold temperature at fixture of 100 °F (38 °C) for sinks and 105 °F (41 °C) for showers and baths

Water Waste: amount of water delivered below usable temperature

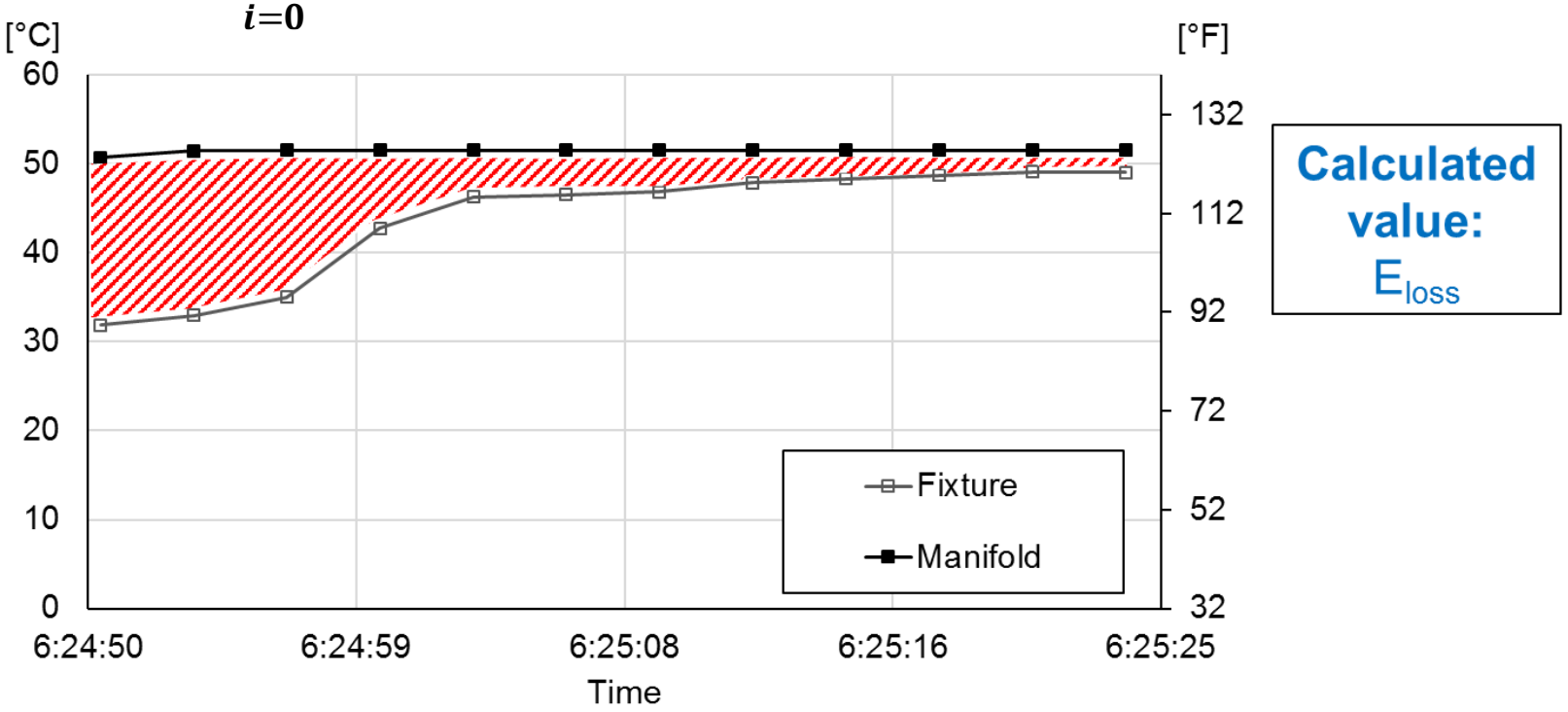


Example of mixed water temperature during a draw at the kitchen sink

Determination of Energy Loss

Control Volume: From exit of water heater to end of hot water tubing at fixture

$$E = \sum_{i=0} \rho_i V_i c_{p,i} \left(T_{manifold,i} - T_{fixture,hot,i} \right)$$

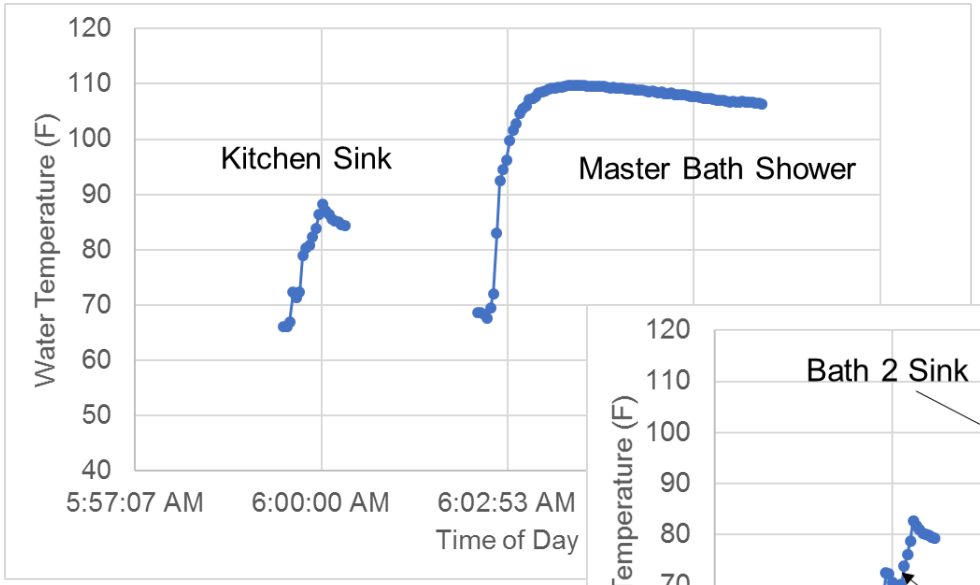


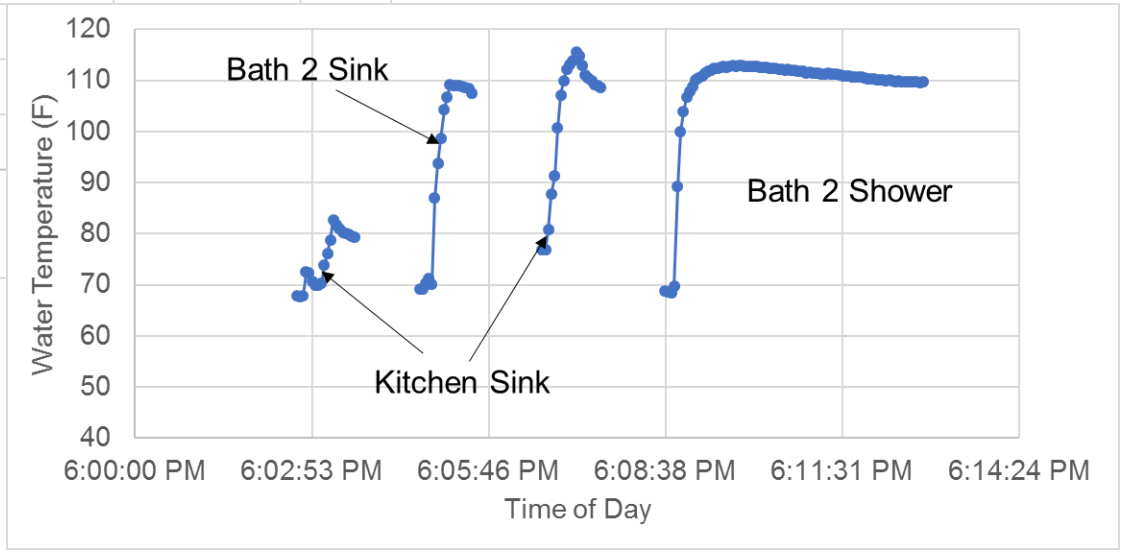
Example of energy imbalance during a draw at the kitchen sink

Results – Wait Times

Average Wait Time for Hot Water and Duration of Draws			
Fixture	**Avg Reach Time [min:sec]**	**Avg Duration [min:sec]**	**% wait**
Kitchen Sink	0:08	0:32	25 %
Master Bath Sink	0:12	0:25	49 %
Bath 2 Sink	0:14	0:24	57 %
Master Bath Shower	0:34	3:58	14 %
Bath 2 Shower	0:15	4:36	5 %
Master Bath Tub	0:16	8:37	3 %
Clothes Washer	0:53	1:38	44 %
Dishwasher	2:06	2:58	71 %

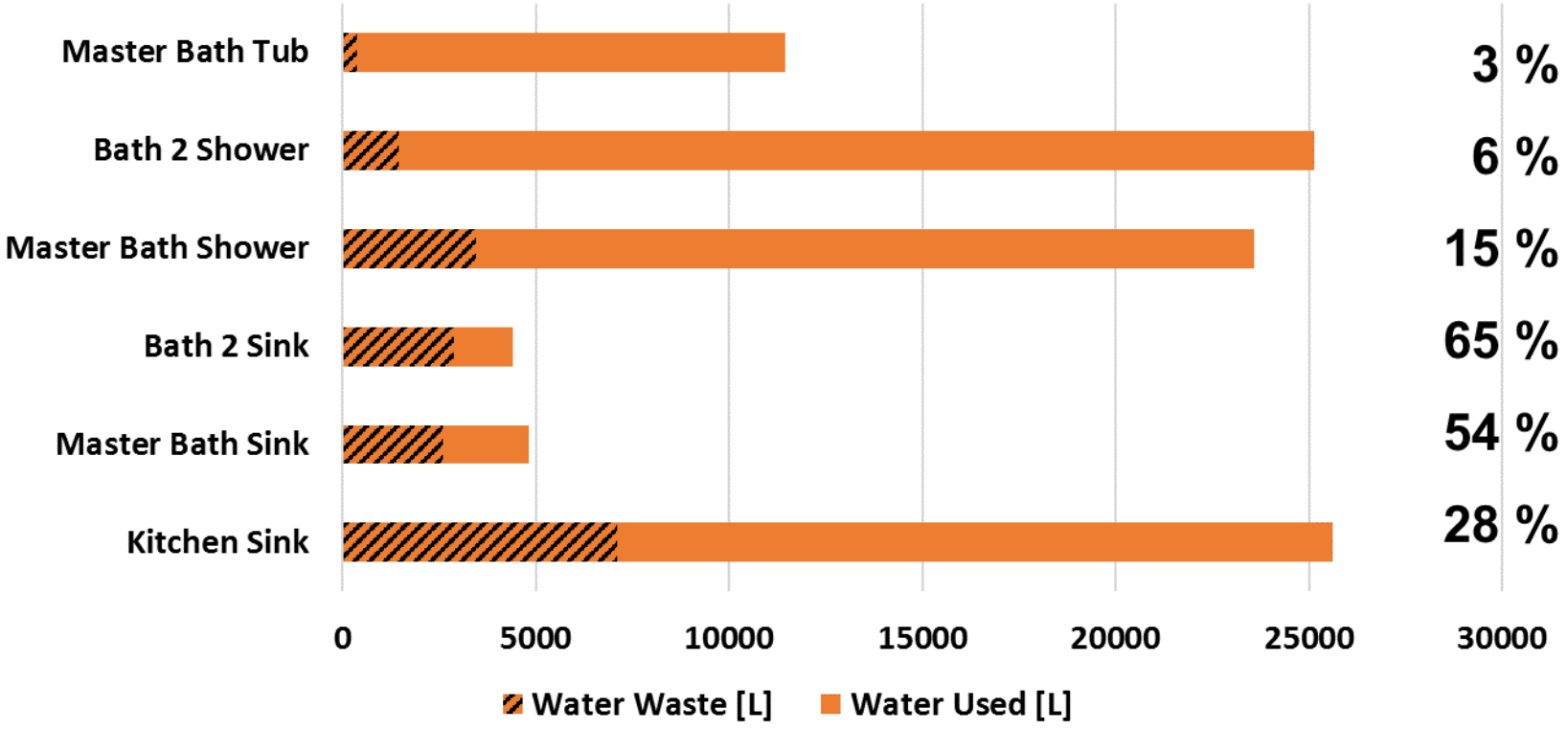
Impact of Clustering





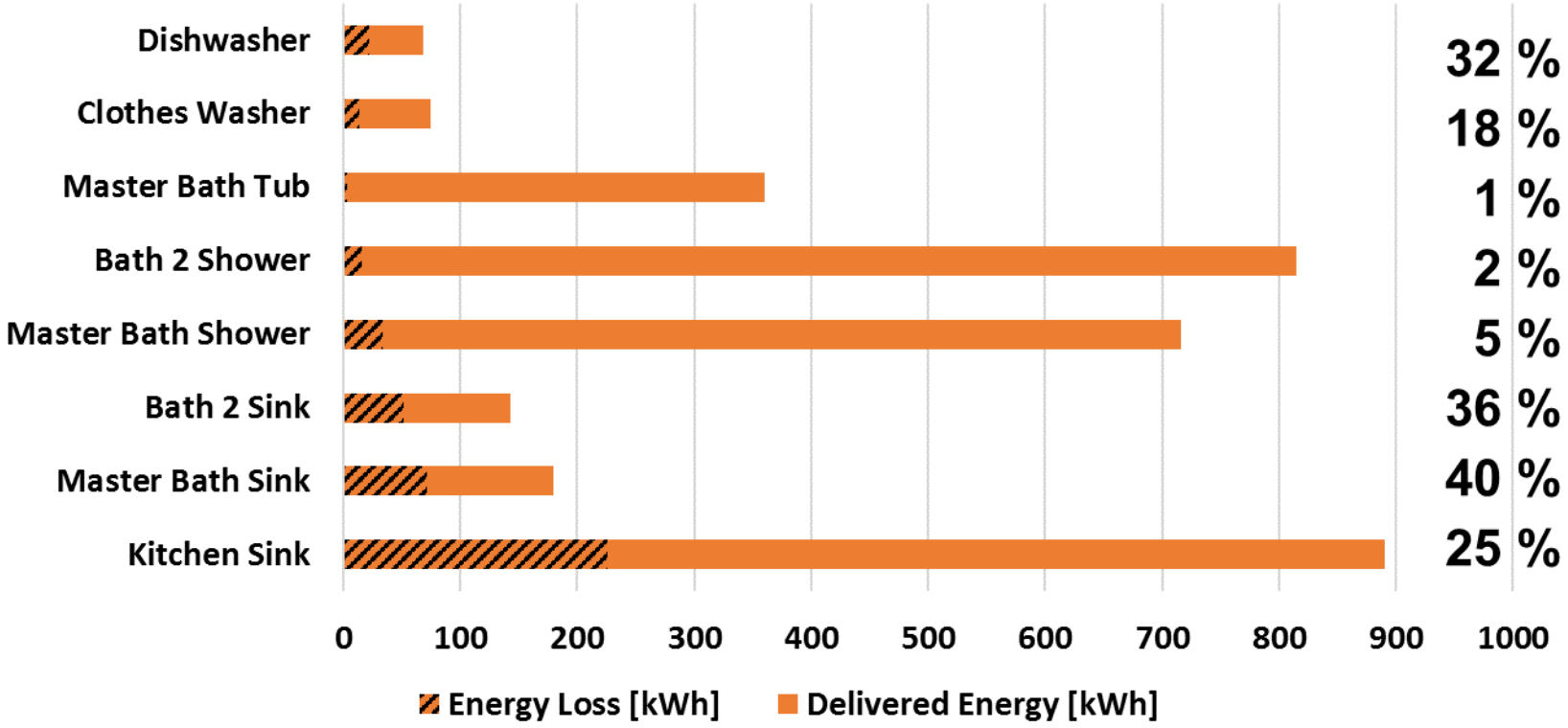
- Despite the “home-run” system isolating pipes to fixtures, all fixtures still share about 0.4 gallons in the piping between water heater and manifold
- This volume is twice as great as the volume in the PEX tubes
- Even in home-run systems, wait times depend upon events at other fixtures

Water Waste



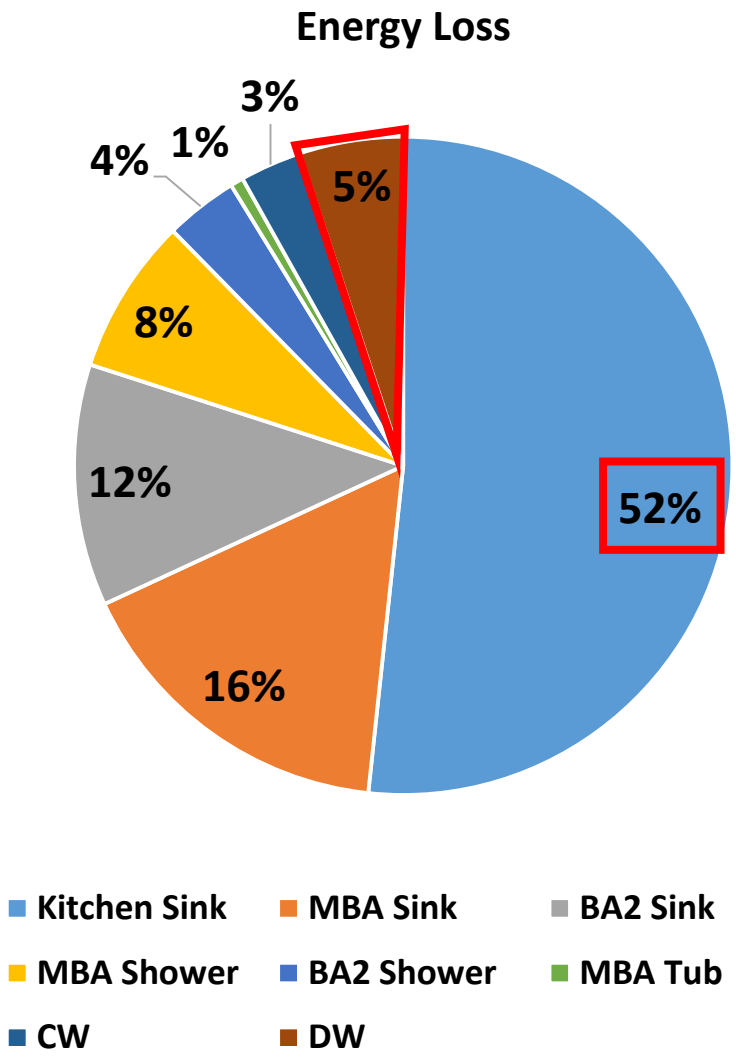
Overall, 19 % of water throughout the year was delivered at a temperature below the usable temperature [17 941 L (4740 gal)]

Energy Loss



Overall, 13 % of energy delivered by water heater into pipes is lost in the distribution system (436 kWh)

Where is the energy waste?



- **52 %** energy losses from **Kitchen Sink** despite being 29 % of use
- All sink energy losses are **80 %** of total v. 40 % of drawn volume
- **5 %** energy losses from **Dishwasher** v. 2 % of use
- Baths contribute to least energy waste

Annual Energy Loss

Energy loss through distribution, Q_{loss} [kWh]	437
Thermal energy to heat water, Q_{load} [kWh]	3246
$\eta_{dist} = \frac{Q_{load} - Q_{loss}}{Q_{load}}$	0.87
Total electrical energy to heat water [kWh]	1451
Electrical energy wasted [kWh] $\{\eta_r = 2.26\}$	193
$ wasted (@ $0.14 per kWh)	$27
$ wasted if electric resistance were used	$61

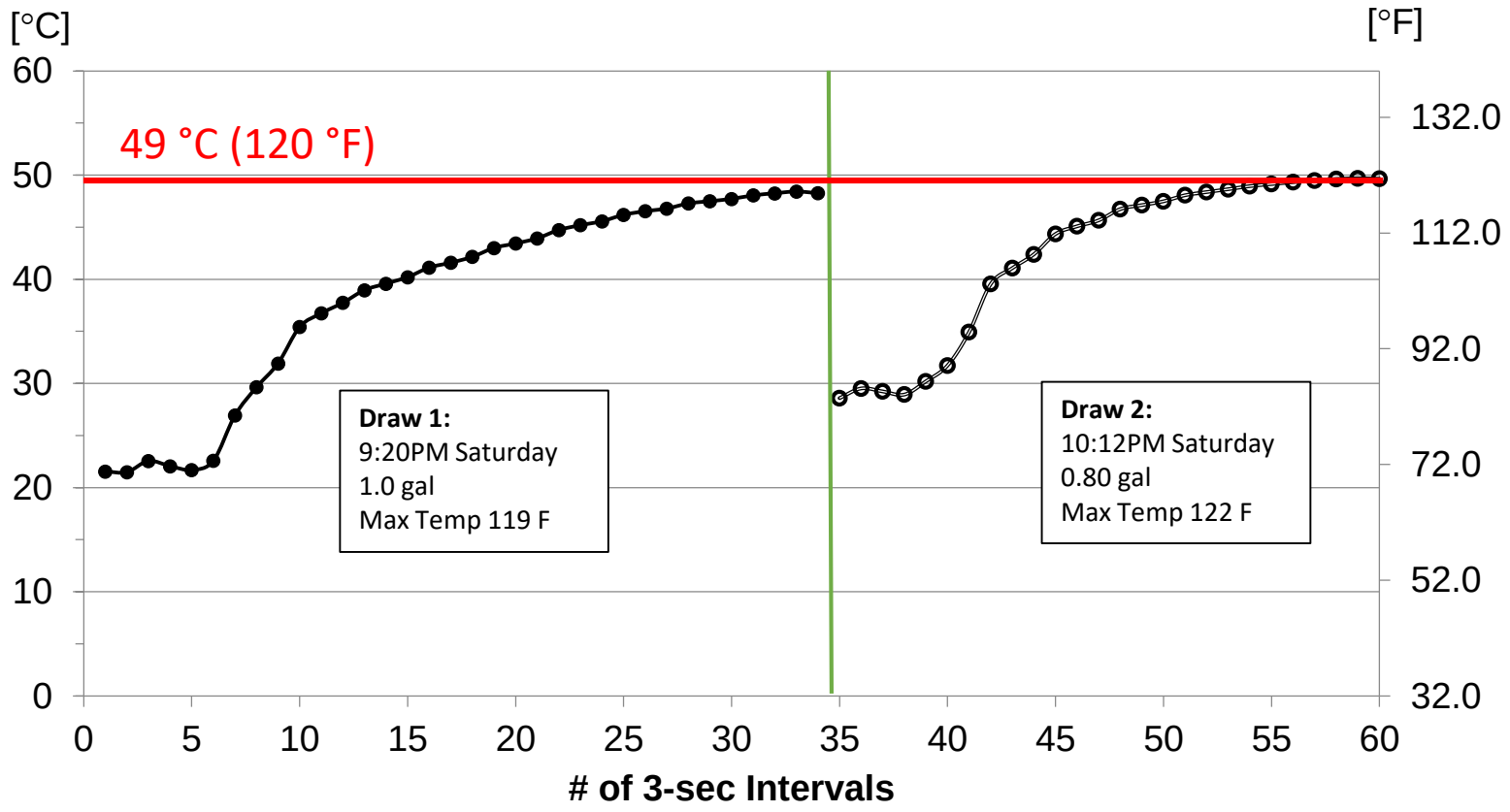
Rough estimate of impact on space conditioning:

Heating (COP = 2.3, 166 days): saves $13

Cooling (COP = 4.3, 140 days): costs $6

Net impact on space conditioning costs: -$7

Dishwasher



- Two short draws, nearly an hour apart
- Only reaches max WH outlet temperature at the very end

Dishwasher Cold vs. Hot Water Delivery: Simple Analysis

Parameter	Value
Volume Per Cycle	1.8 gallons
Mains Inlet T	70 F
Hot Water Delivery T	122 F
Thermal Energy from cold to hot	0.23 kWh/cycle
Electricity Requirement: Cold Water Delivery Resistance Heating by DW (COP = 1). Cost at $0.14 per kWh	0.23 kWh/cycle $0.032 per cycle
Electricity Requirement: Hot Water Delivery (COP = 2.26), Resistance Heating by DW to get up to Delivery T (COP = 1) Cost at $0.14 per kWh	0.18 kWh/cycle $0.025 per cycle
Yearly dishwasher cycles	160
Annual energy difference	9.0 kWh
Annual energy cost difference	$1.26

Conclusions

In a fairly compact home-run distribution system for an average sized single family home

- Wait times for hot water ranged from about 8 s to 14 s on average at sinks
- Wait times at showers were approximately 15 s to 35 s
- Manifold system still shows some traits of a trunk & branch system on account of large volume of water between water heater and manifold inlet.
- 13 % of energy lost in distribution system
- Electric energy waste in this house: $20 per year (when accounting for impact on space conditioning and water heating system with COP = 2.26)
- Dishwasher: gets relatively cool water, but still appears to be cost-effective to pipe hot water to unit. Results could be different, though, if less efficient water heating options were used (e.g., resistance)