BUILDINGENERGY BOSTON

Hot Water Electrification: Methods to Reduce First Costs, Embodied Carbon, and Operating Costs

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Learning Objectives

1. Identify the difference between central systems and individual heaters.

2. Evaluate the physics behind domestic hot water.

3. Analyze the effect of heat pumps in series on system COP.

4. Understand opportunities for improving hot water systems in our buildings.

5. Advocate for implementation of new code that now allows for engineered downsizing of potable water piping.

Electrification of DHW is a tough nut to crack

Cost of Energy

Electricity:

- Total cost in January: $5,060.29
- Total kWh use: 22200 kWh

→ **$0.28/kWh**

Gas:

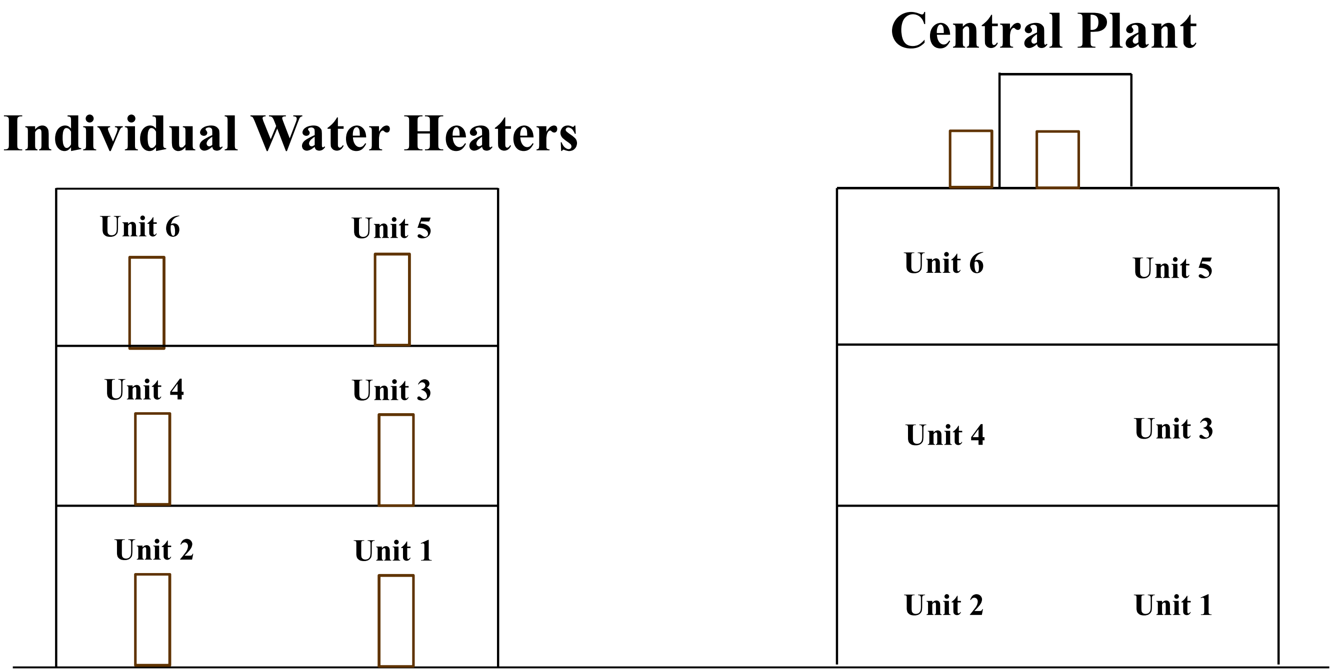
- Total cost in January: $5,542.46
- Total therm use: 3996 therms
  - $1.39/therm

→ **$0.05/kWh**

Electricity is 5.6 x more expensive than gas

Electric and Gas Cost for the Month of January 2024, Multi Family Building, New Bedford, MA

Individual Heaters vs Central Water Plant



Individual Heaters

Issues with local water heaters

- Take up space

Hybrid heat pump issues

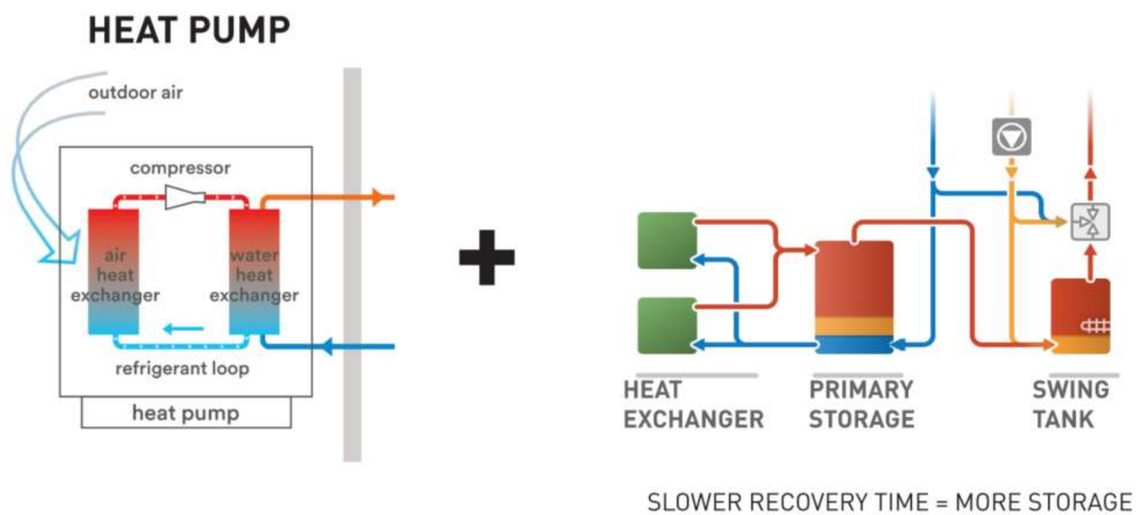
- Heat pumps in series
- Cold draft
- Better suited for commercial kitchens

There is no individual DHW solution that has a low operating cost.

Central Plant

- CO_2 based
- High upfront and operating cost compared to central gas plant
- Chance for COP 2-3
- High temperature
- Low recovery/high storage
- New to market

Electric ASHP Domestic Hot Water Central System



Heat Capacity Water vs Air

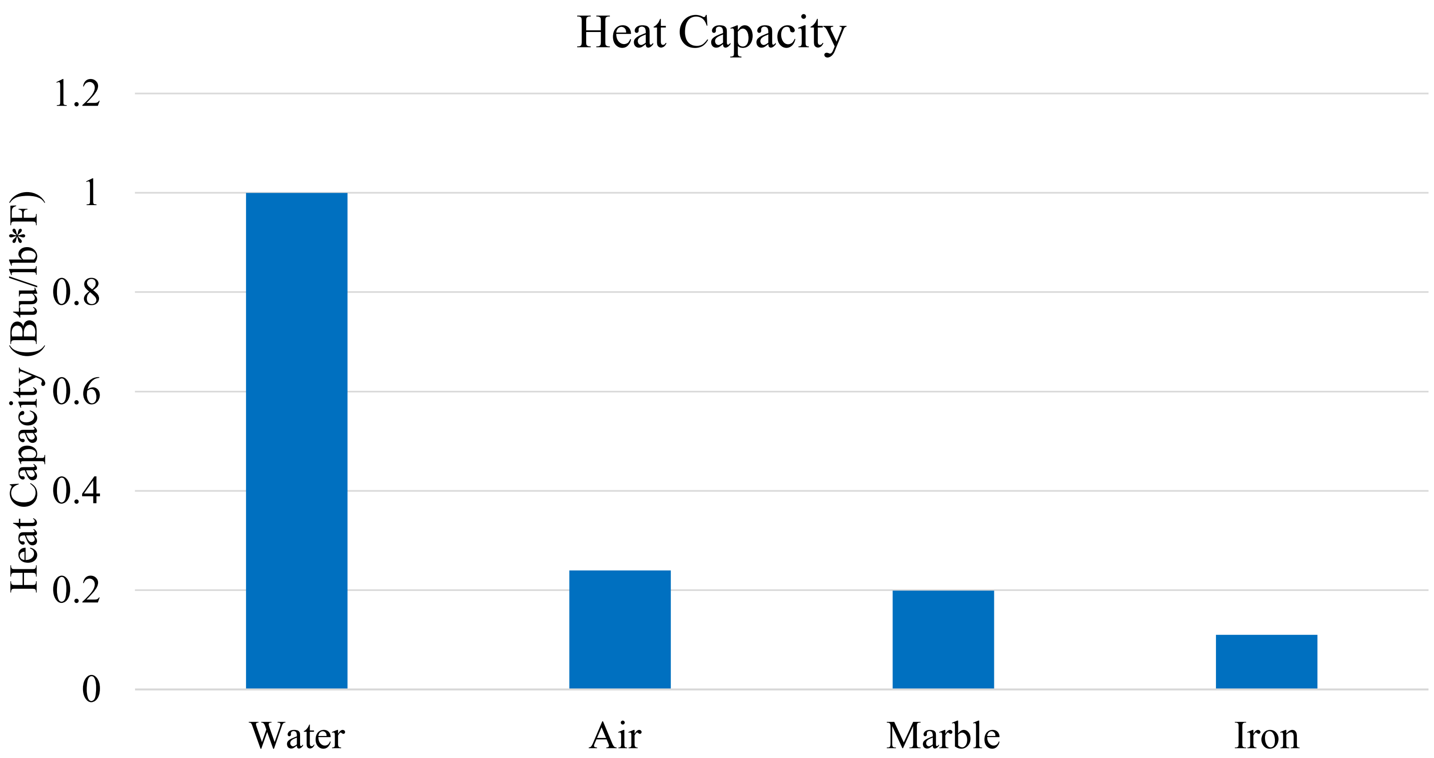
Heat capacity is the measure of energy required to raise a quantity of a substance by one temperature degree. Heat capacities for water and air:

Water: $\boldsymbol{1\ \frac{BTU}{lb \bullet F}}$

Air: $\boldsymbol{0.24\ \frac{BTU}{lb \bullet F}}$

The energy required to heat water is 4 x that of air! Therfore with a hybrid heat pump we need to move a lot of air.

Heat Capacity Comparison



Water has the highest heat capacity of any common substance!

Winter Condition - Temperature Difference Water vs Air

The temperature difference for water is significantly greater than air

Water: 45°F → 125°F

Air: 70°F → 55°F

We are increasing water tempertures more than 5x more than air.
5-1/3 in this case.

Winter Condition - Quantity of Water vs Air

$$\left(200\ \frac{ft^3}{min}\right) \times (170\ mins^{1}) \times \left(0.075\ \frac{lb}{ft^3}\right) = 2550 \text{ lbs of air} \longrightarrow 2.1 \text{ air changes/hr}$$

$$(20\ gals^{2}) \times \left(8.33\ \frac{lb}{gal}\right) = 167 \text{ lbs of water}$$

We need to move much more air to extract the heat needed for hot water production.

1: In the winter condition the temperature rise is from 45°F to 125 °F
2: 20 gallons of 125 °F water equates to approximately 30 gallons of hot water out of the faucet

Summer Condition - What amount of energy is required to heat 20 gallons from 70°F to 125°F?

(Gallons) x (Temperature Difference) x (Specific Heat) x (Pounds/Gallon) = Energy

$$\boldsymbol{(20\ gals)\ x\ (125°F - 70\ °F\ \Delta T)\ x\ (1\ \frac{BTU}{lb \bullet F})\ x\ (8.33\ \frac{lb}{gal}) = 9,163\ BTUs}$$

Summer Condition - What amount of energy is extracted from the apartment.

Total energy to heat the water: ***9,163 BTUs***

Portion of energy from electricity = ***(1/3) x 9,163 = 3,054 BTUs***

Portion of energy from apartment = ***(2/3) x 9,163 = 6,109 BTUs***

Assumes a COP 5 water heater efficiency

Summer Condition - What is the HPWH run time when we heat 20 gallons from 70°F to 125 °F?

Assumptions:

1. 70 degrees F entering air temperature (EAT)
2. 55 degrees F leaving air temperature (LAT)
3. 9,163 BTUs moved from air to water
4. 200 CFM water heater fan volume

$$\frac{\text{Energy}}{[(\text{Volume/Time}) \times (\text{Temperature Difference}) \times (\text{Specific Heat}) \times (\text{Density})]} = \text{Time}$$

$$\frac{\textbf{9,163 BTUs}}{(200 \ \frac{ft^3}{min}) \times (70\ °F - 55\ °F) \times (0.24 \ \frac{BTU}{lb \bullet F}) \times (0.075 \ \frac{lb}{ft^3})} = \textbf{170 minutes}$$

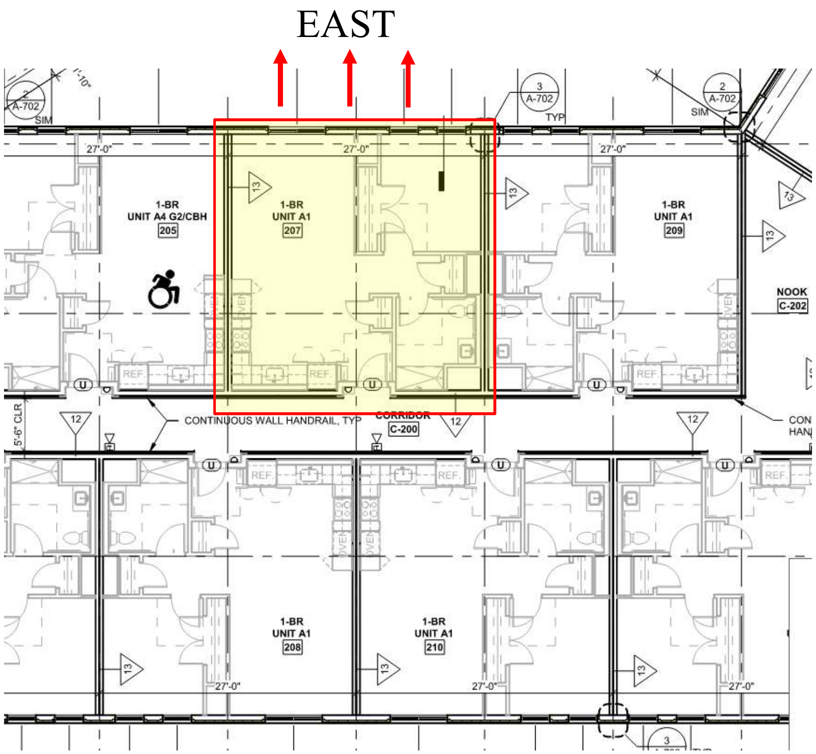
Conclusion: A significant cold draft of 200 CFM and 55 degrees F is discharged into the apartment for over 170 minutes. An uncontrolled source of cold air is likely to cause occupant comfort issues.

Cooling Load Study

- One bedroom, 700 SF, apartment with an Eastern exposure
- Peak cooling load with Boston design conditions: 7,000 Btu/hr
- Amount of cooling contributed by the water heater: 6,100 Btu/hr

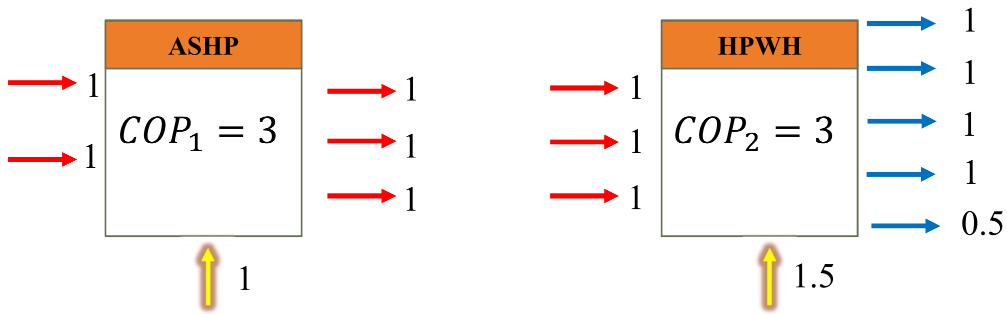
$$\frac{6{,}100\ Btu/hr}{7{,}000\ Btu/hr} = 87\%$$

Heat pump water heater will overcool even in the summer.



Heat Pumps in Series

Two Heat Pumps in Series



COP is the ratio of useful heating provided to the energy required.

For a COP_1 of 3, the ASHP uses 1 unit of energy that is electricity powering the compressor to move 2 units of heat from the outdoors. This results in 3 units of heat delivered to the corridor.

For a HPWH with a COP_2 of 3, all 3 units of the heat moved by the ASHP are utilized by the HPWH.

The HPWH uses 1.5 units of energy that is electricity powering the compressor to move the 3 units of heat from the corridor. This results in 4.5 units of heat delivered to hot water.

The total COP for this system would be the heat output 4.5 divided by the energy input, 2.5, which equals 1.8.

Heat Pumps in Series Math Steps

$$O_x = E_x + I_x \quad (1)$$

Where, O = heat output of system, E = electricity used in the process, I = energy extracted from an outside medium.

$$COP_x = \frac{O_x}{E_x} \quad (2)$$

The entire output by heat pump 1 is used as input by heat pump 2, therefore:

$$O_1 = I_2 \quad (3)$$

The total COP of the system is defined as the heat output of the last heat pump in the series divided by the total electricity used by the system to achieve that output.

$$COP_{total} = \frac{O_3}{E_1 + E_2} \quad (4)$$

Replace the numerator of Equation 4 by rearranging Equation 2.

$$COP_{total} = \frac{COP_2 E_2}{E_1 + E_2} \quad (5)$$

Replace the first term in the denominator by rearranging Equation 2.

$$COP_{total} = \frac{COP_2 E_2}{\frac{O_1}{COP_1} + E_2} \quad (6)$$

Replace O_1 with Equation 3.

$$COP_{total} = \frac{COP_2 E_2}{\frac{I_2}{COP_1} + E_2} \quad (7)$$

Mathematical Derivation Courtesy of Hans Moritz Gunther and Lauren Gunther

Math Steps Continued

In order to put the I term in terms of COP and E, insert Equation 1 into Equation 2 and rearrange to solve for I:

$$COP_x = \frac{E_x + I_x}{E_x} = 1 + \frac{I_x}{E_x} \tag{8}$$

$$I_x = E_x(COP_x - 1) \tag{9}$$

Now, insert Equation 8 in for the I terms in Equation 6.

$$COP_{total} = \frac{COP_2 E_2}{\frac{E_2(COP_2 - 1)}{COP_1} + E_2} \tag{10}$$

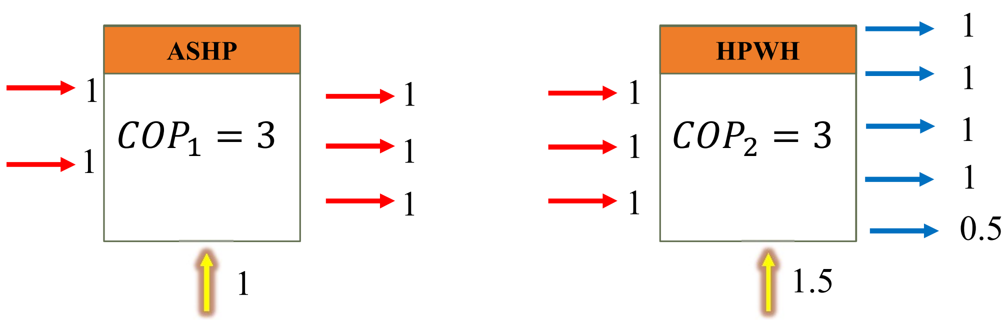
Cancel out E_2 from the equation

$$\boxed{COP_{total} = \frac{COP_2}{\frac{(COP_2 - 1)}{COP_1} + 1}} \tag{11}$$

Mathematical Derivation Courtesy of Hans Moritz Gunther and Lauren Gunther

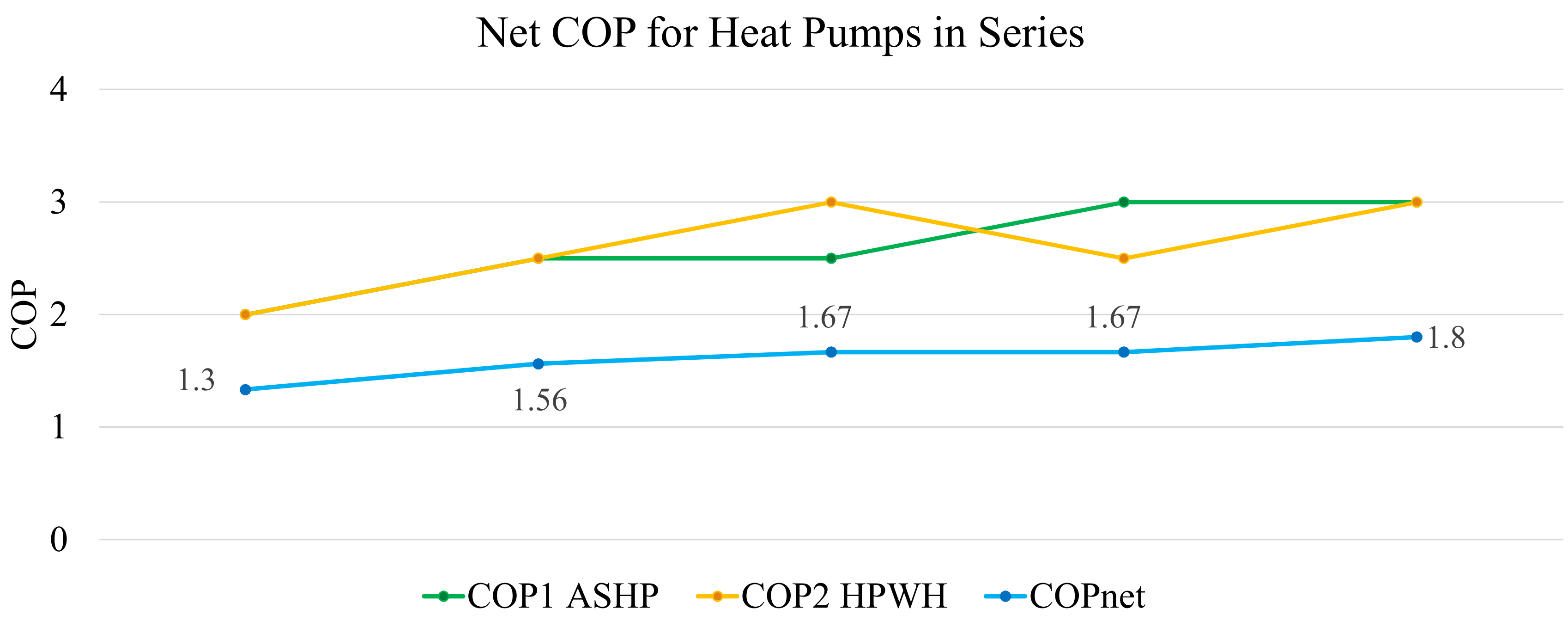
Plug and Chug

Looking at the original example, with a total COP of 1.8, we see the same output with this equation.

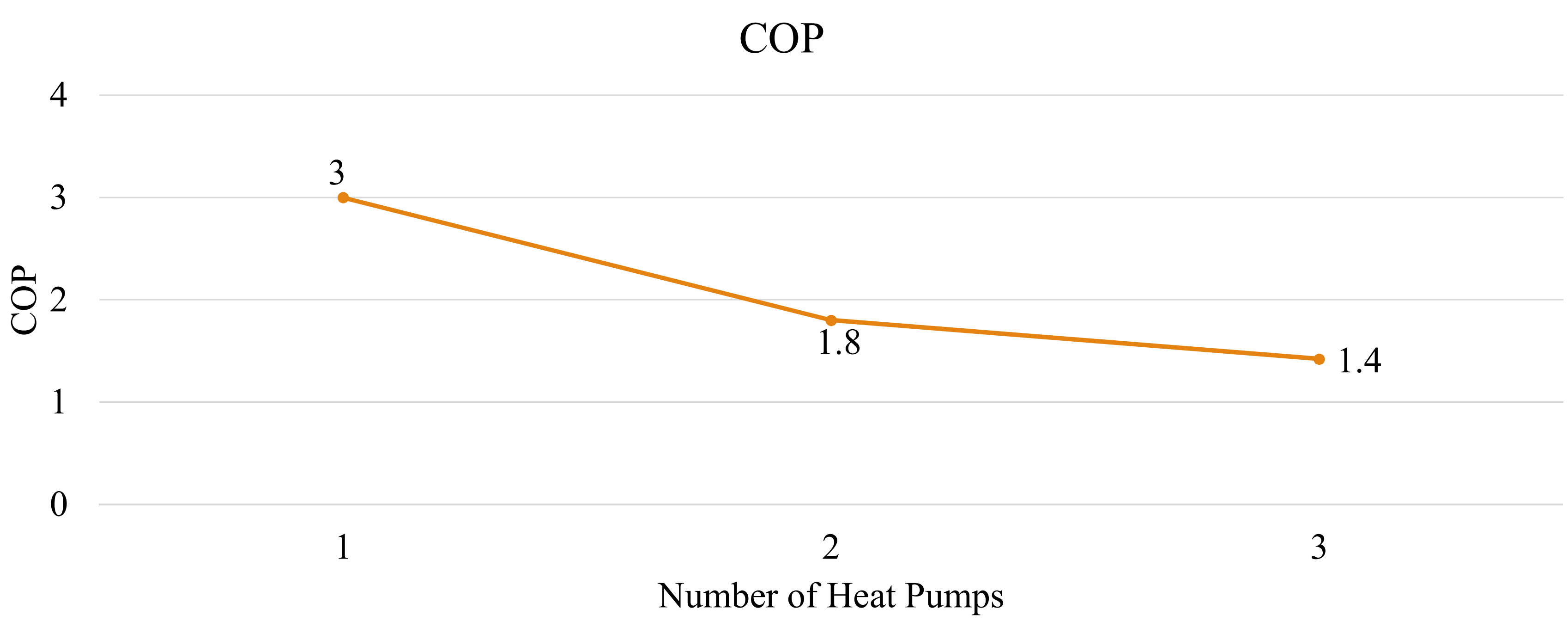


$$\frac{COP_2}{\left(\frac{COP_2 - 1}{COP_1}\right) + 1} = \frac{3}{\left(\frac{3-1}{3}\right) + 1} = 1.8$$

Graphical Representation



Number of Heat Pumps vs COP



How can we reduce electricity use in hot water heating?

Seasonal Water Temperature – MWRA

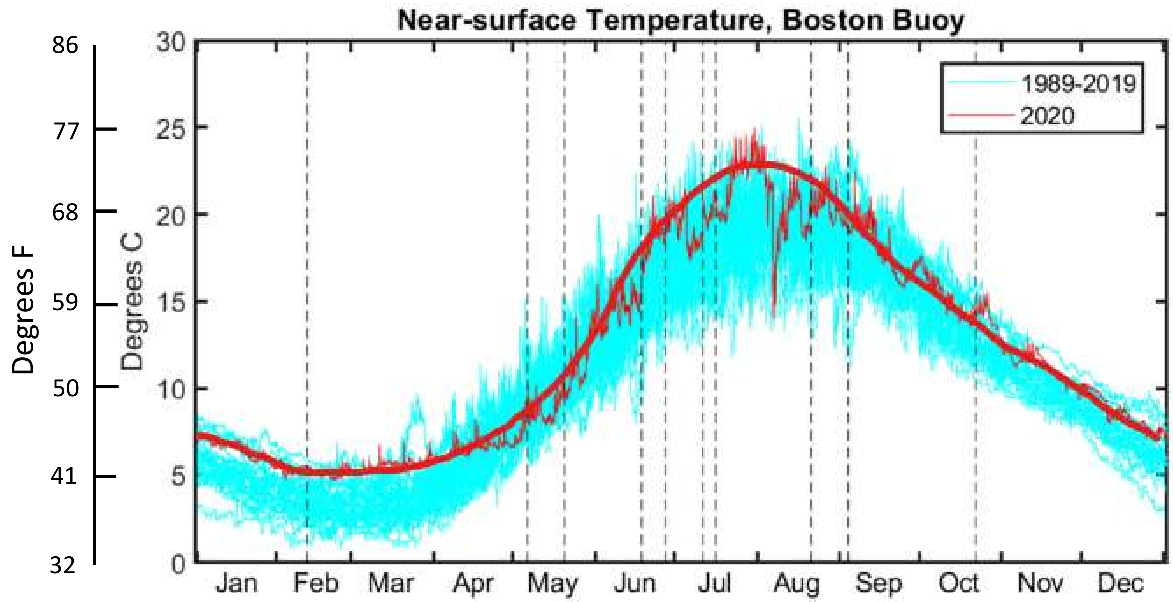
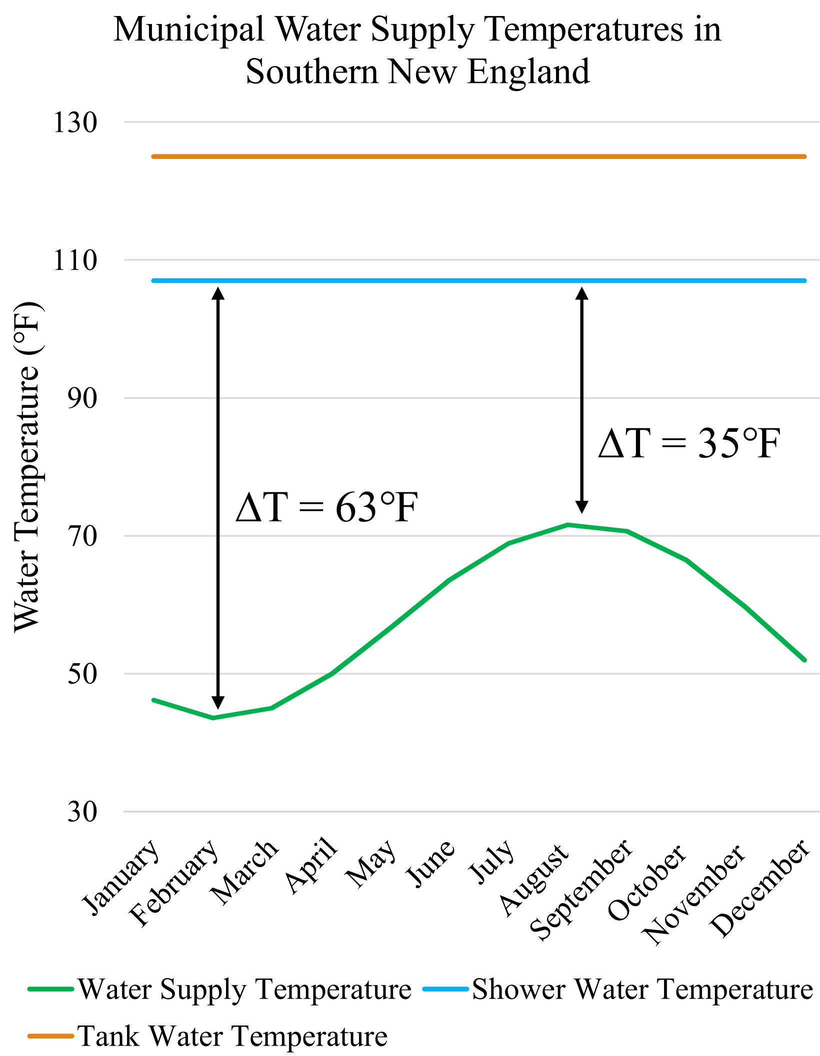


Figure 2-1. **Comparison of 2020 (solid red line) surface water temperature (°C) at Buoy 44013 ("Boston Buoy") in the vicinity of the nearfield with 1989-2019 (cyan lines).** The vertical dashed lines are when the 10 surveys were conducted in 2020.

Massachusetts Water Resources Authority Environmental Quality Department Report, October 2021

Seasonal Water Temperature – Mass Save Guidelines



Mass Save Hourly Simulation Guidelines: Version 2.4, January 2022

Drain Water Heat Recovery

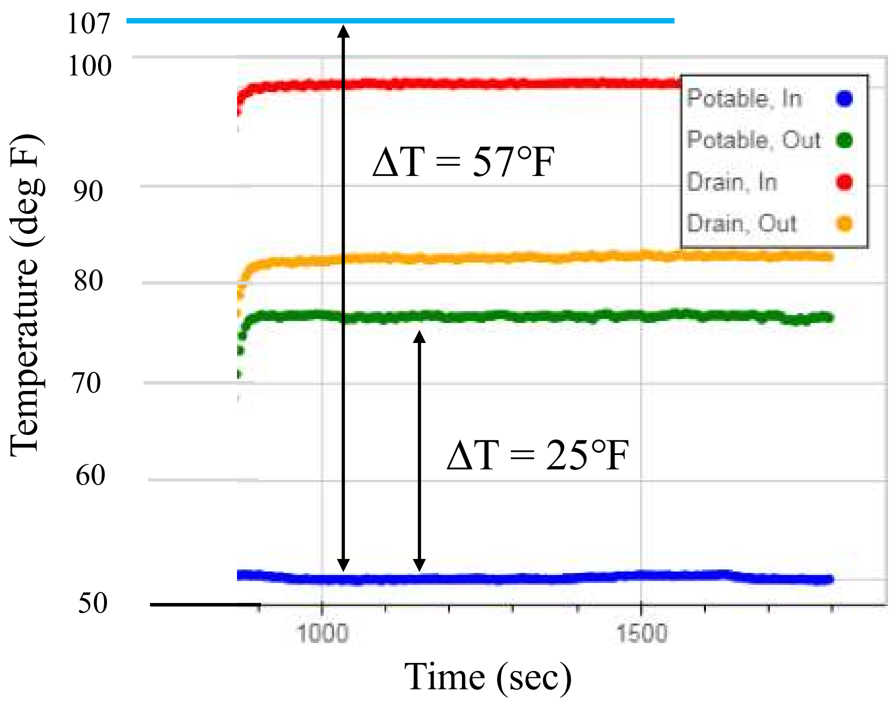
Drain Water Heat Recovery (DWHR) Definition

DWHR works by
using the outgoing
<u>warm drain water</u>
to pre-heat the incoming
<u>cold fresh water</u>

Fresh Inlet ~ 46°F Drain Inlet ~ 101°F Fresh Outlet ~ 75°F

Drain Water Heat Recovery Technologies Research Slides, Gerald Van Decker, Renewability Energy Inc.

Potable vs Drain Temperatures



$$\frac{\Delta T\ 25°F}{\Delta\ T\ 57°F} = 44\%\ \text{Reduction}$$

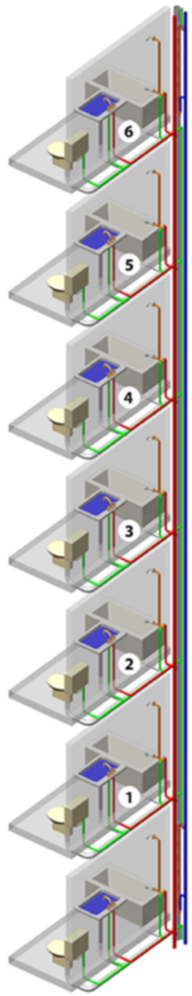
Drain water recovery reduces the temperature we need to raise the water by 44%!

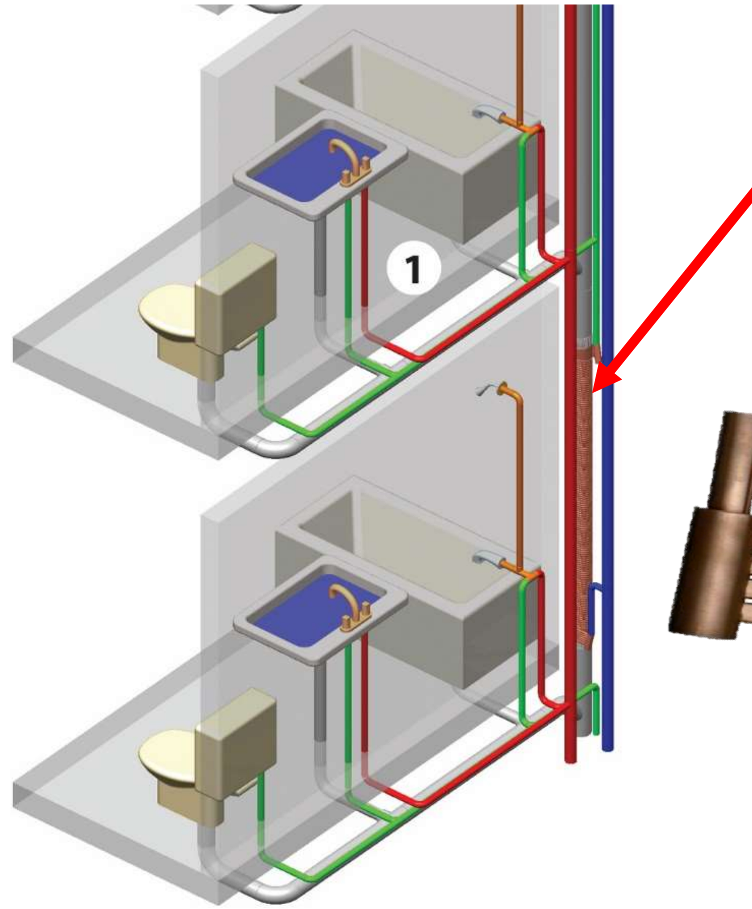
Drain water heat recovery: Why you should care, and how much energy it can save, Peter Grant, Berkeley Lab, 2017

6 Story Midrise Stacked Bathrooms

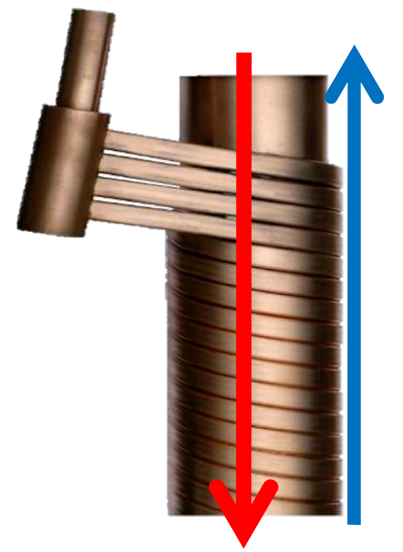
Fresh water from DWHR to cold water supply at fixtures.

- Shower water is approximately 60% of water use in an apartment
- Heat requirement for 60% of use is reduce in round numbers by 50%
- Assuming no recovery for sinks then overall heat requirement is reduced





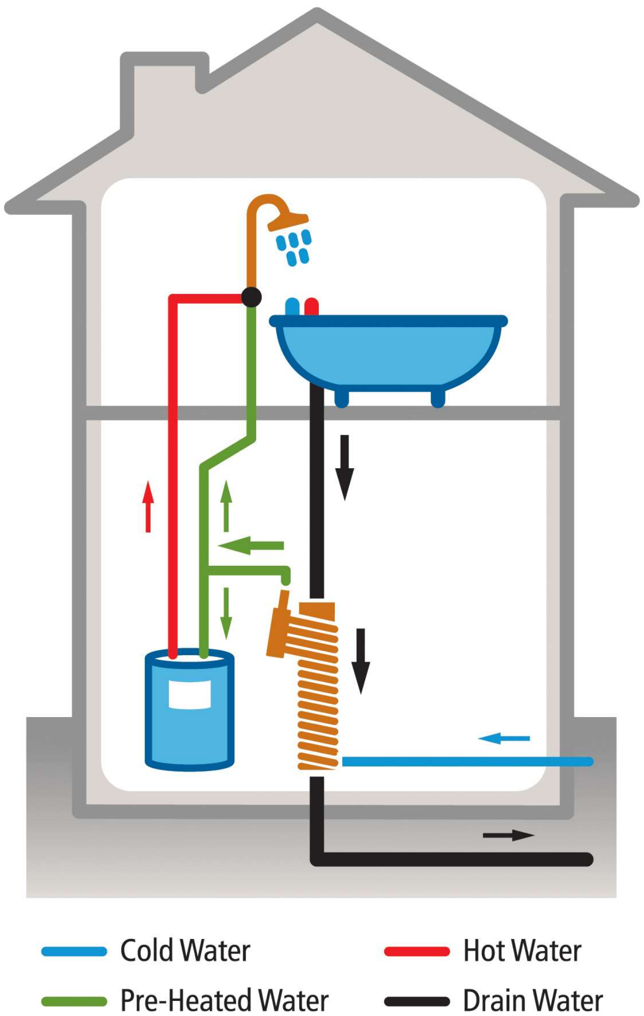
DWHR located at bottom of 6 story stack



4 in. diameter, 72 in. long, 1 in. water piping
Cost to contractor: $819

Drain Water Heat Recovery Technologies Research Slides, Gerald Van Decker, Renewability Energy Inc.

DWHR configuration when water heater is in apartment

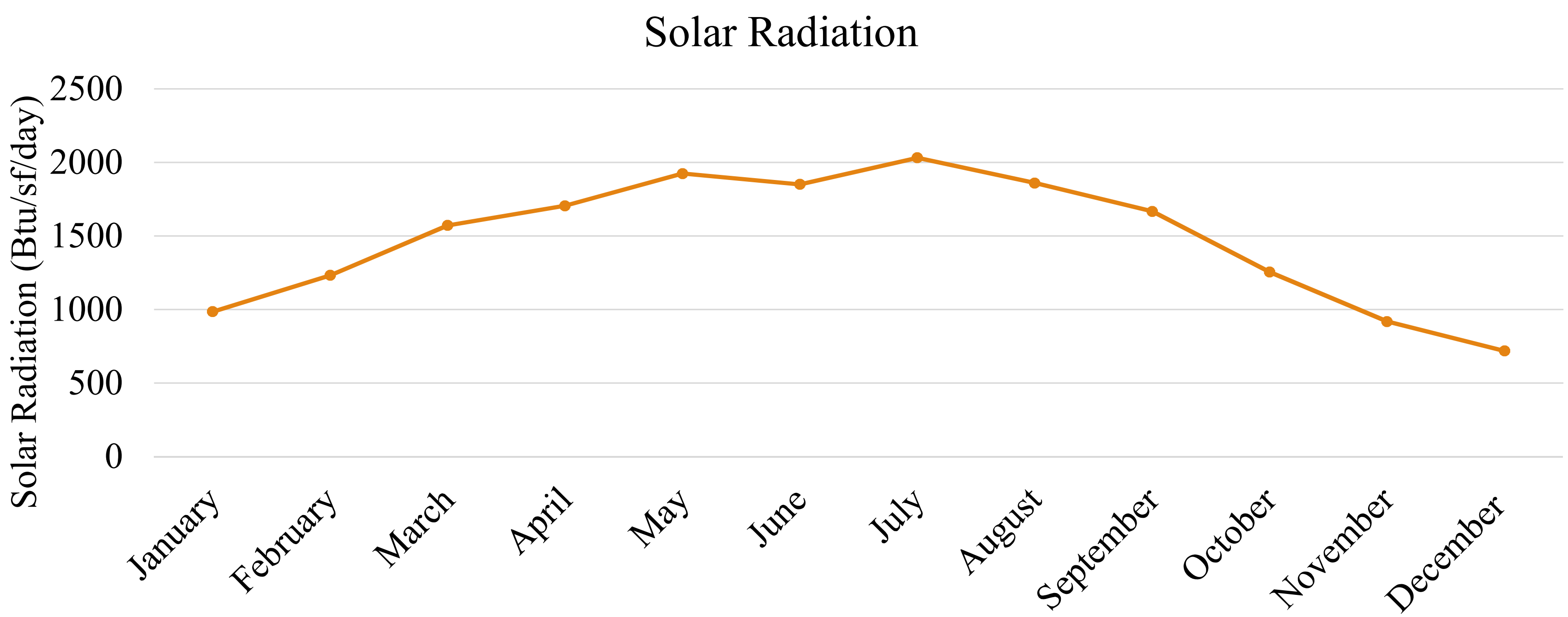


Power Pipe Flow Diagram

Drain Water Heat Recovery Technologies Research Slides, Gerald Van Decker, Renewability Energy Inc.

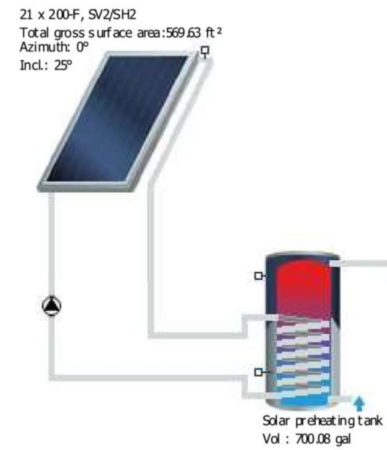
Solar Thermal

Solar Radiation in Boston

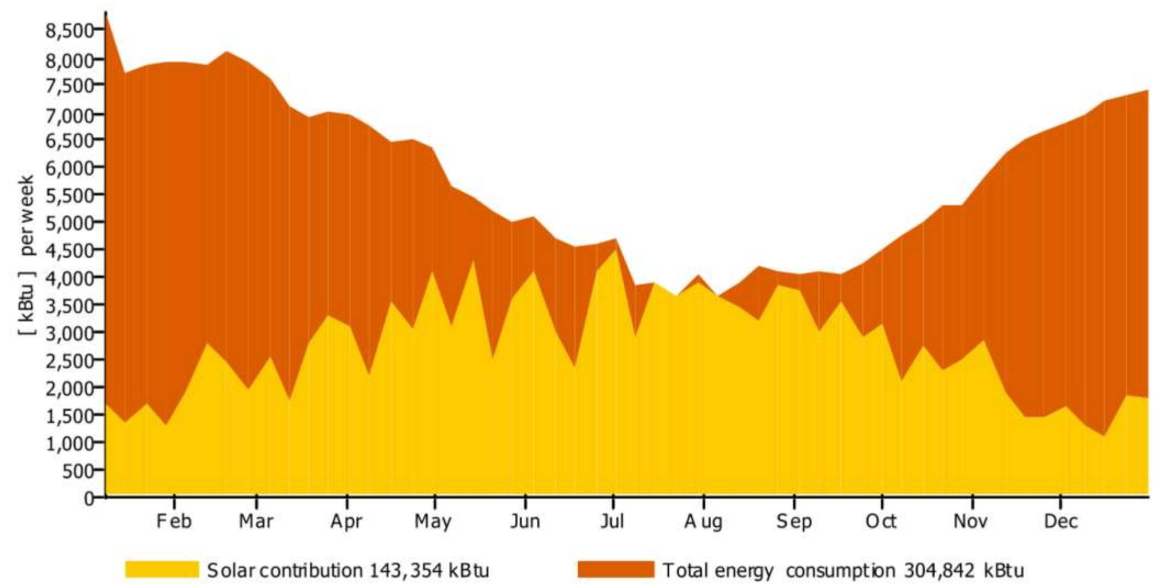


PVWatts Calculator – National Renewable Energy Laboratory

Solar Thermal Preheating



Solar energy consumption as percentage of total consumption



Daniel Khait, Jody Samuell, Kevin Flynn- Viessmann, T*SOL Software

Assumptions:

- 100 unit building
- 1.5 people per unit
- 13 gallons/day/person

Outputs:

- 21 panels
- Solar panel area: 570 SF
- DHW solar fraction: 47%

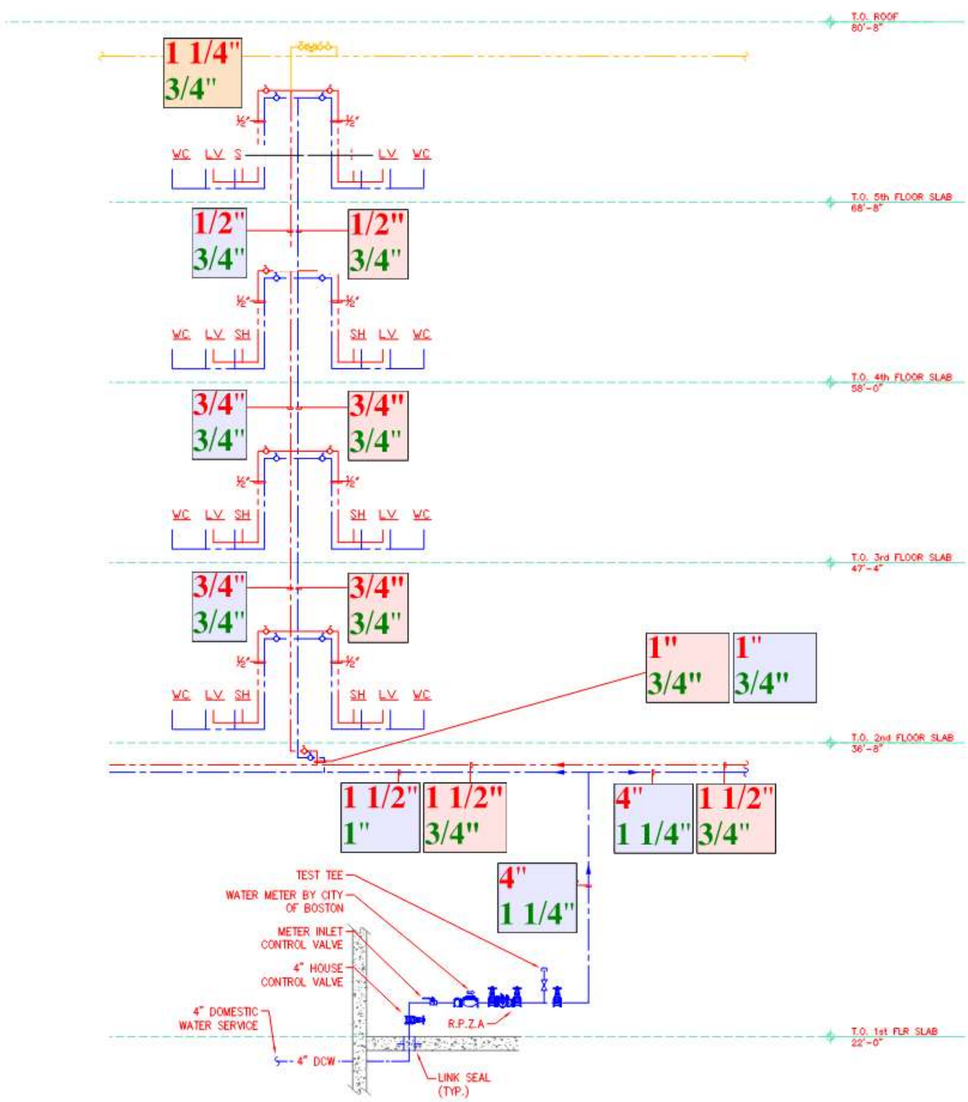
Cost: $140,000

Downsizing Potable Water Piping

Case Study | Old Colony Phase 6 South Boston, MA

- 5 story multi family building
- 116,000 GSF
- 94 dwelling units

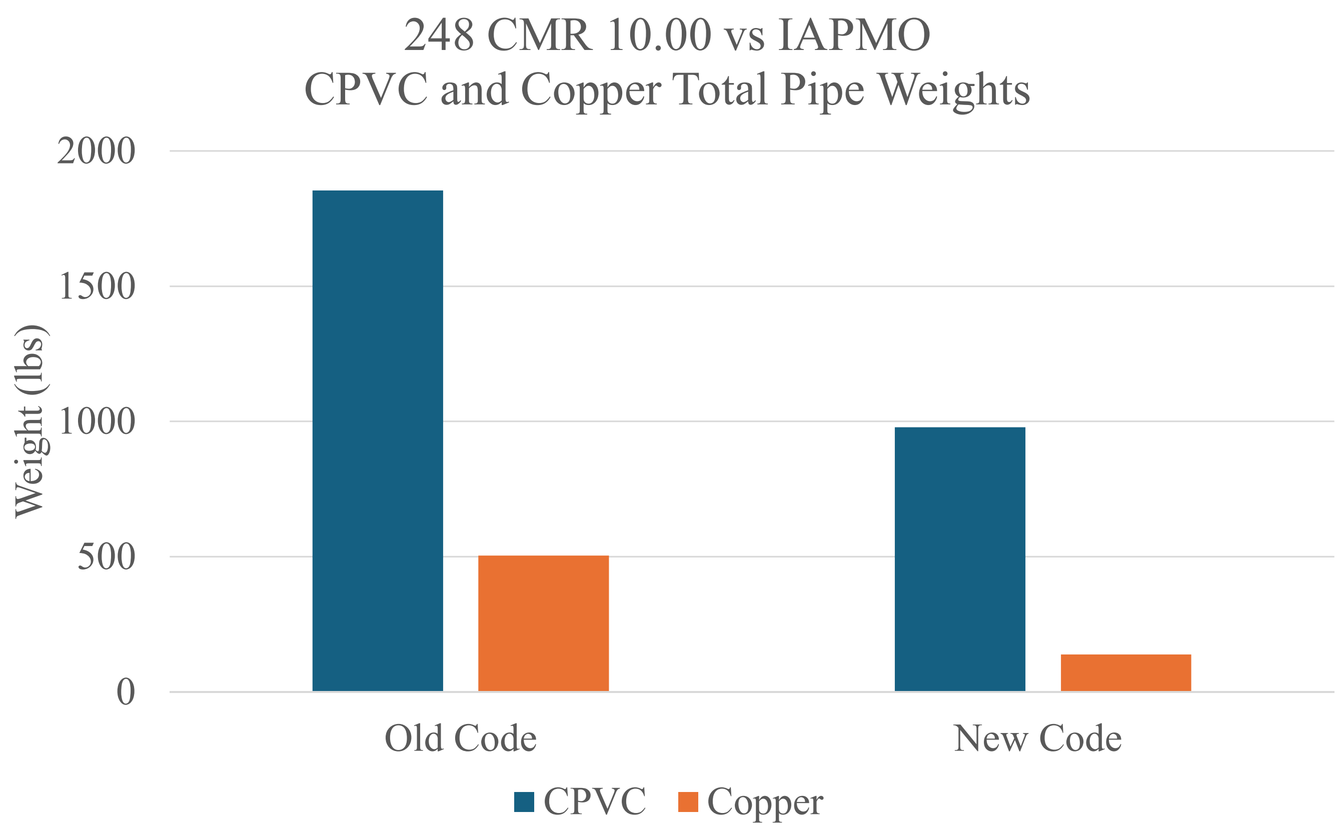
Boston Planning & Development Agency



248 CMR 10.00 (12/23 edition) Sizing vs IAPMO Water Demand Calculator Sizing

Pipe Size Distribution – 248 CMR 10.00 vs IAPMO Water Demand Calculator

Potable Water Distribution Downsizing



47% weight reduction in CPVC piping – pounds saved: 876 lbs

72% weight reduction in Copper piping – pounds saved: 366 lbs

Pipe densities from: Charlotte Pipe and Foundry Company

Potable Water Distribution Downsizing

GWP[1] Reduction Using IAPMO

Reduction	Copper	CPVC	**Total**
$kgCO_2e$	809	2,052	**2,861**
%	72%	44%	**50%**

[1]GWP (A1-A3) Data Sources: One Click LCA (Copper) & Manufacturer EPRs (CPVC)

Thank You!

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