Electric Water Heater Modeling and Adding Mixing Valve

- A comprehensive model for the heat transfer process in an EWH, which switches between a one-node model and a two-node model
  - One-node model

$$Q_{elec} - \dot{m}C_p(T_w - T_{inlet}) + UA_{wh}(T_{amb} - T_w) = C_w\,\frac{dT_w}{dt}$$

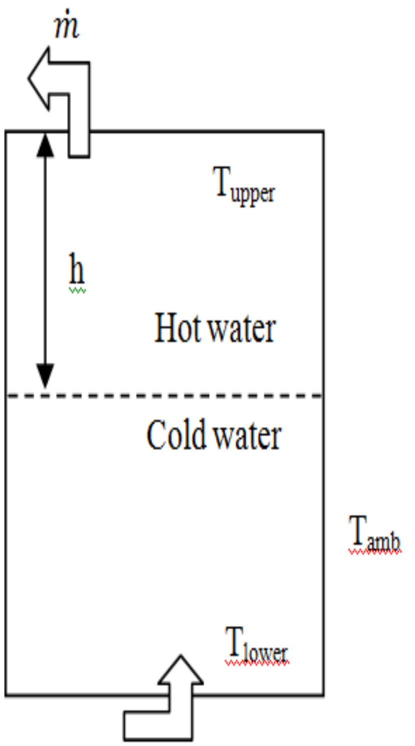
  - Two-node model

$$dh/dt = a - b * h$$

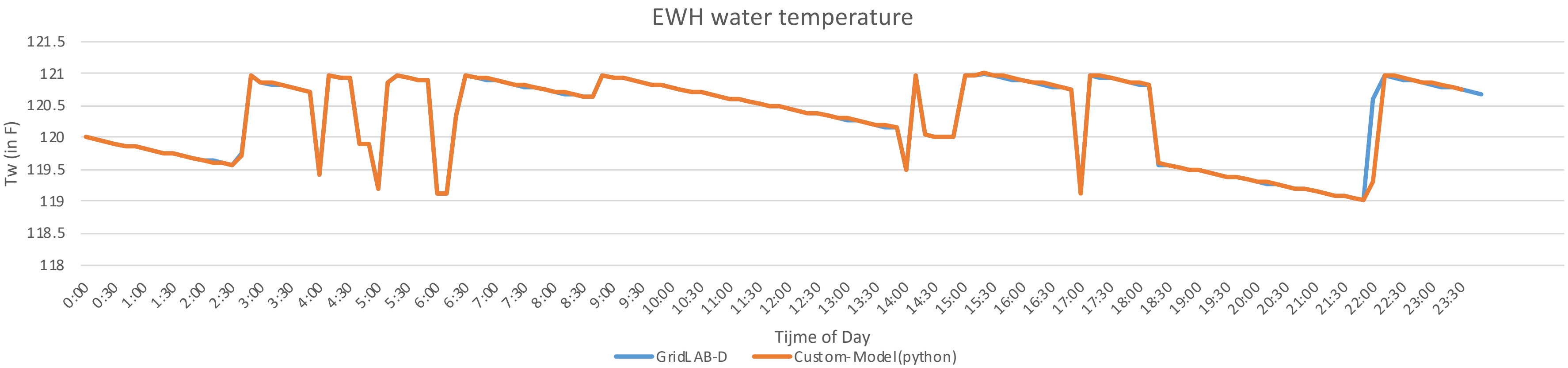
$$a = \frac{Q_{elec} + UA_{WH} * (T_{amb} - T_{lower})}{C_W * (T_{upper} - T_{lower})} * H - \frac{\dot{m} * C_p}{C_W} * H$$

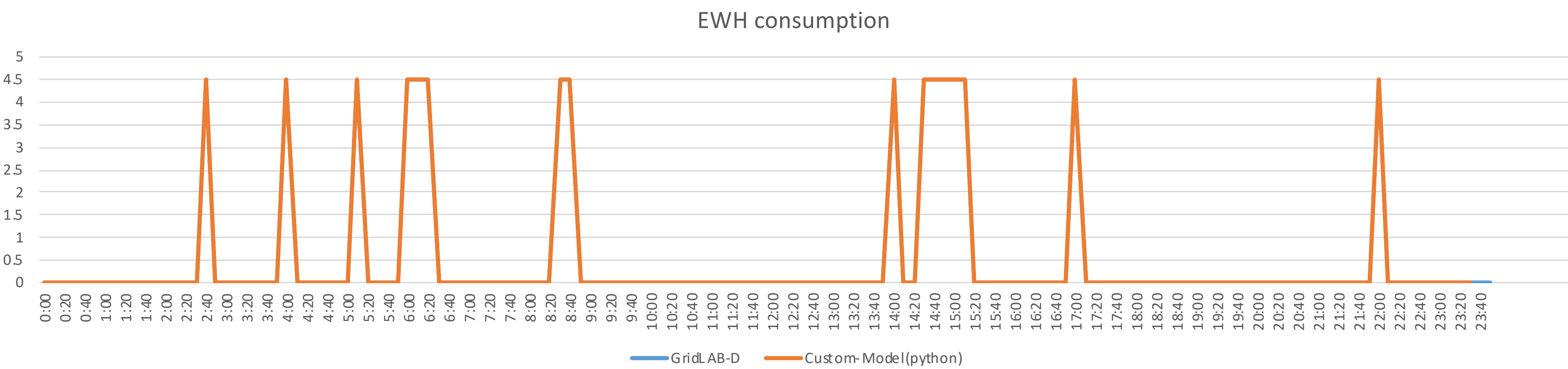
$$b = UA_{WH}/C_W$$

Q_{elec} : heating capacity of the resistor; C_p : thermal capacitance
T_w : water temperature; T_{inlet} : temperature of inlet water;
UA_{wh} : thermal conductance of the tank shell; T_{amb} : room temperature;
C_w : thermal capacitance; H : maximum height of the water tank; T_{lower} : set to inlet water temperature

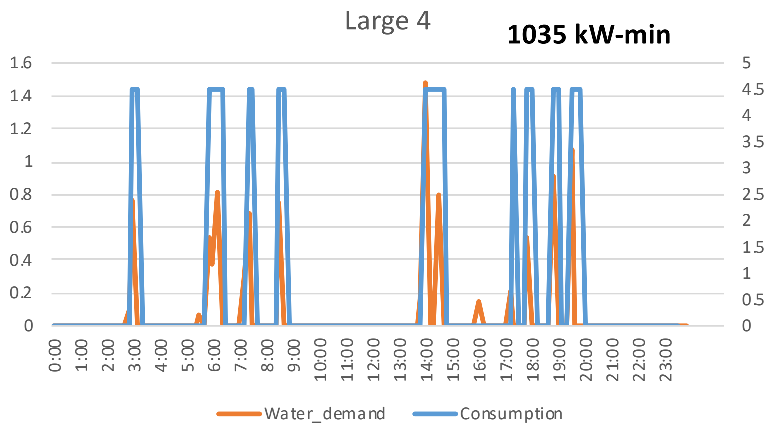


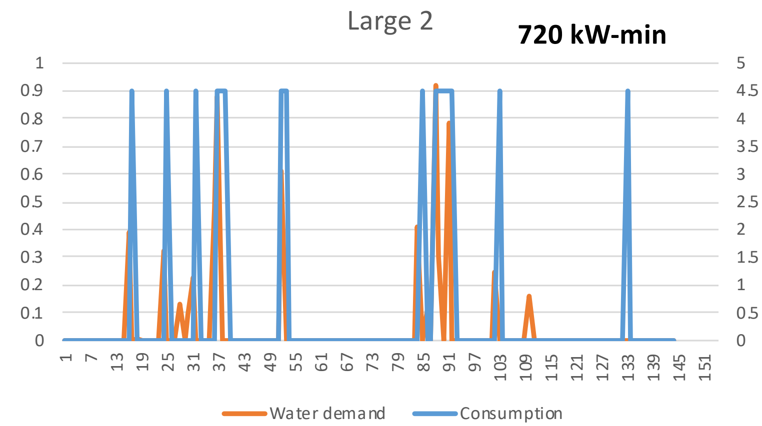
Modelling Approach (GridLAB-D Model)

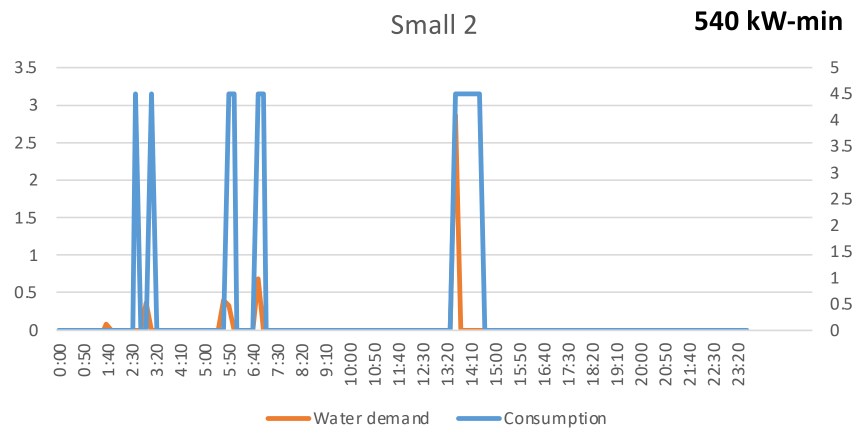




Demand vs Consumption

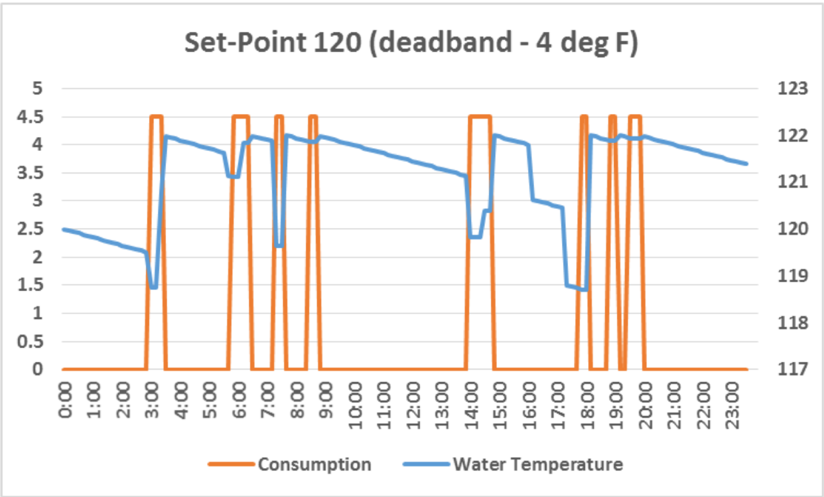




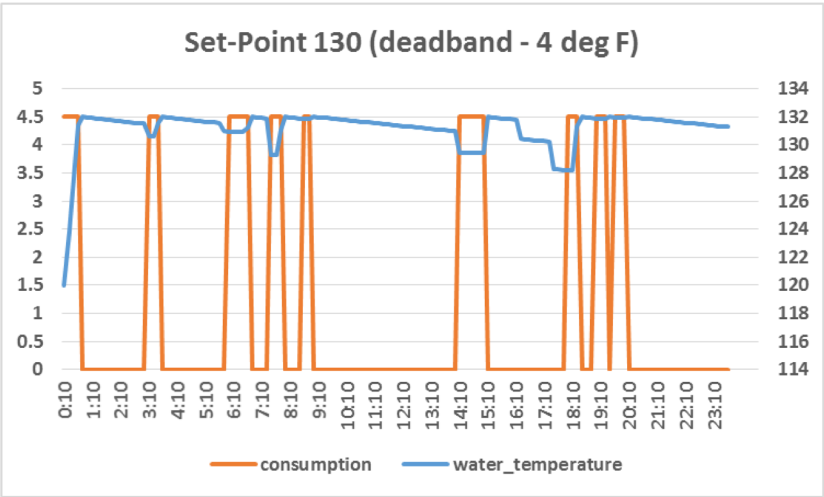


Set-point on Consumption [Large 4]

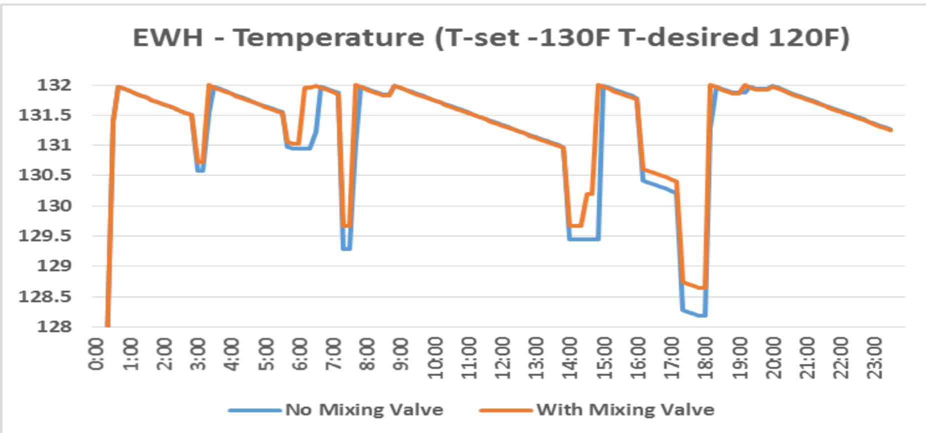
1035 kW-min

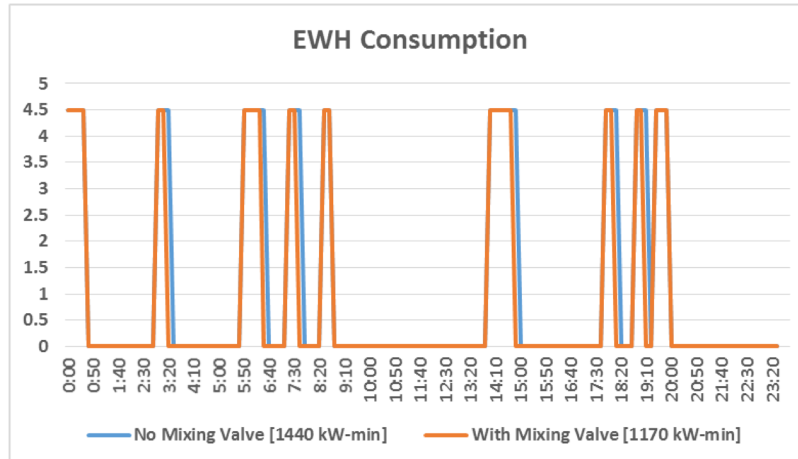


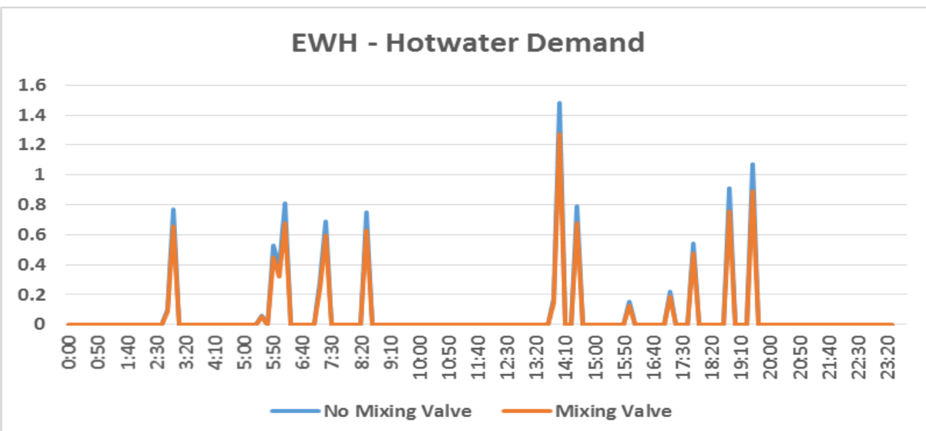
1440 kW-min



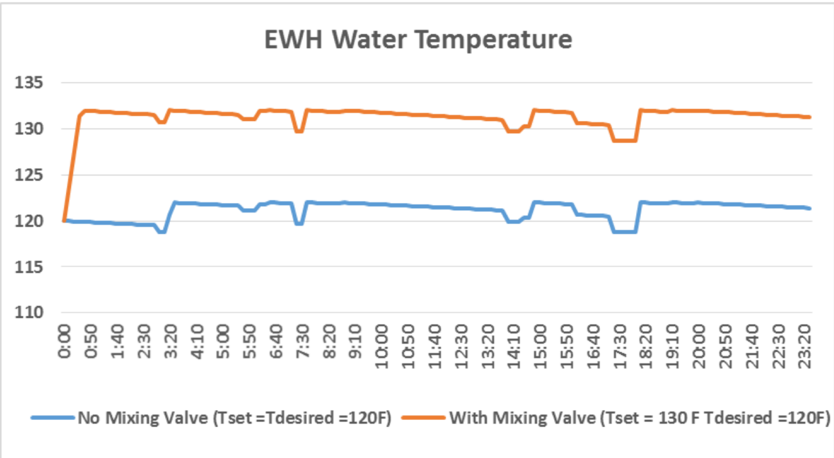
Adding Mixing Valve

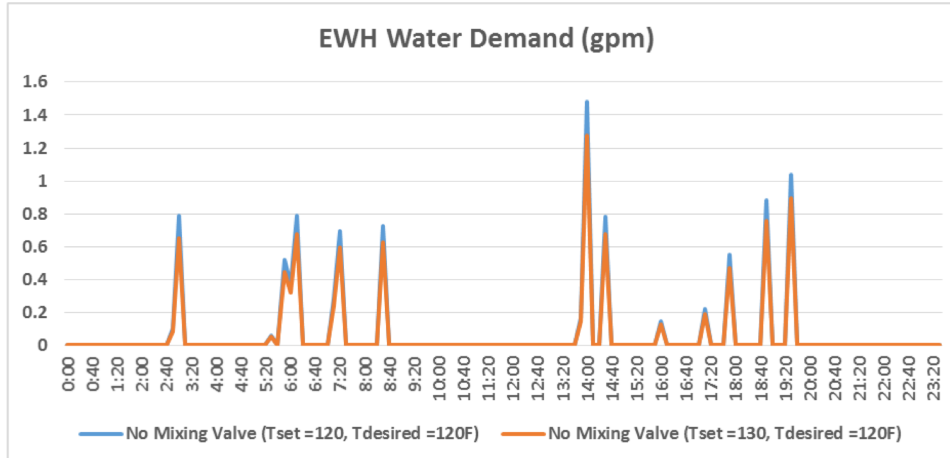




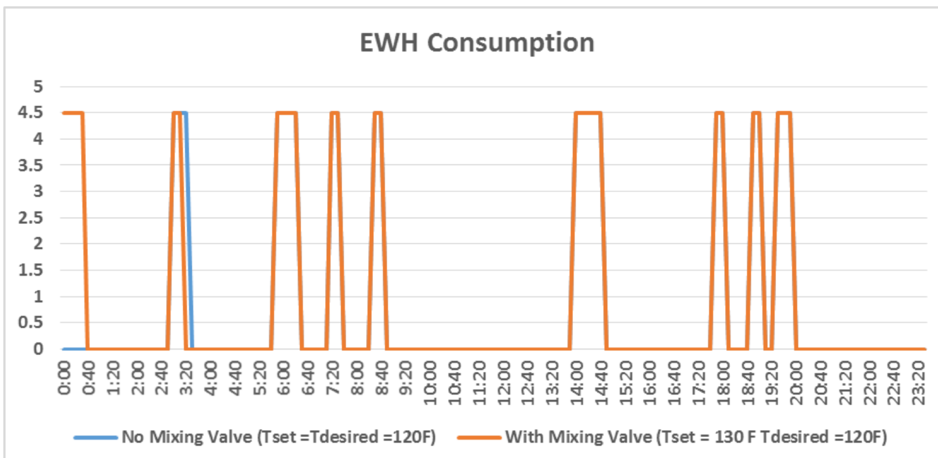


Comparing With and Without Mixing Valve





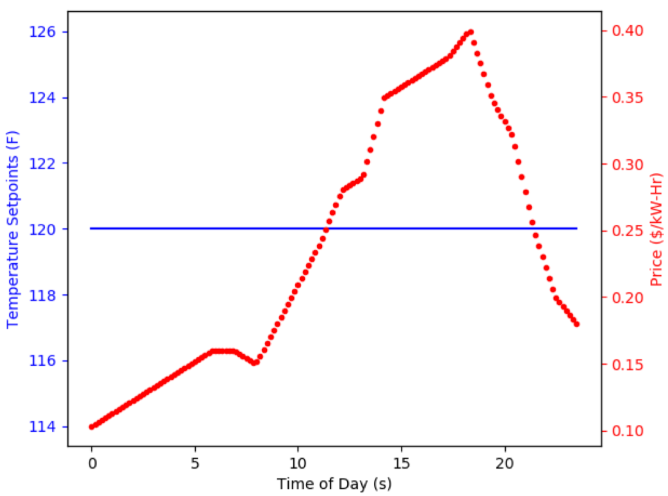
No Mixing Valve 1035 kW-min
With Mixing Valve 1170 kW-min



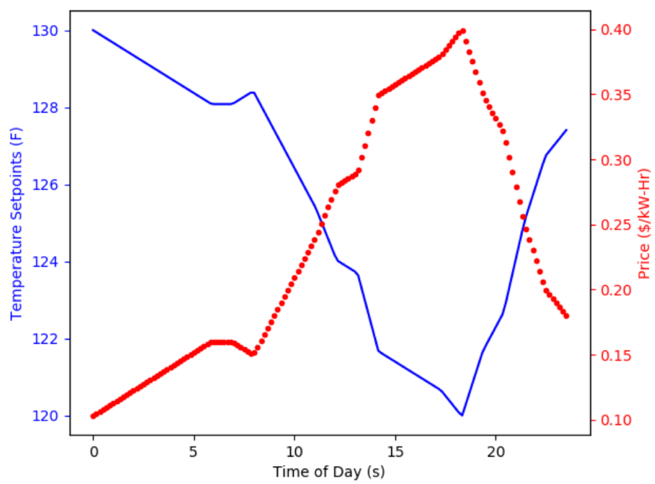
Price – Variation of Set-Points (Real Time)

$$T_{setpoint} = T_{desired} + \left(Range * \frac{P_{max} - P(t)}{P_{max} - P_{min}}\right)$$

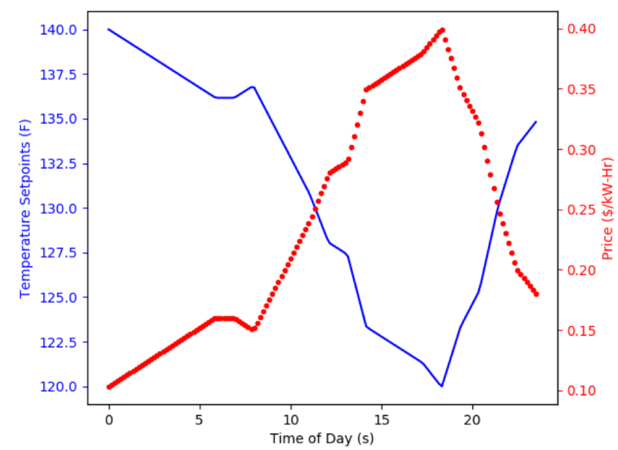
0°F



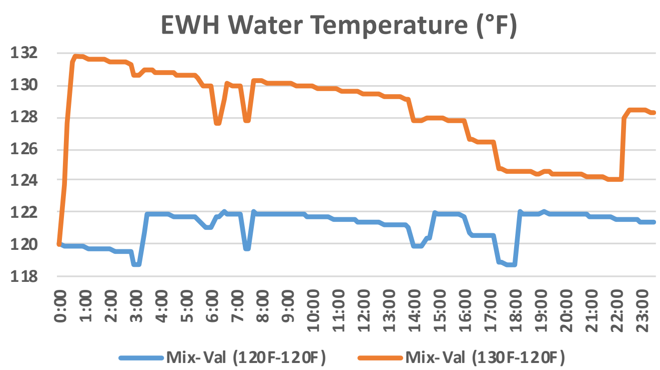
10°F

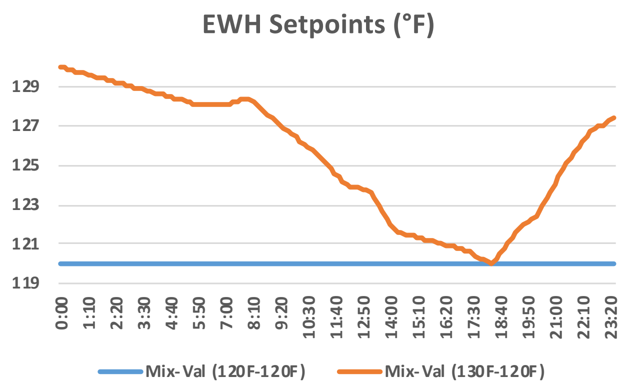


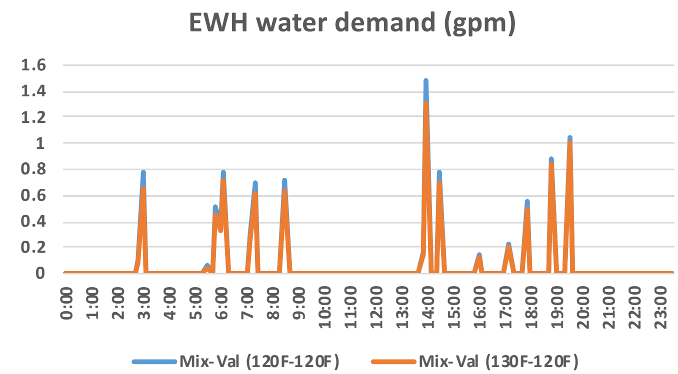
20°F



Mixing Valve (Cost Reduction – Pre heating)

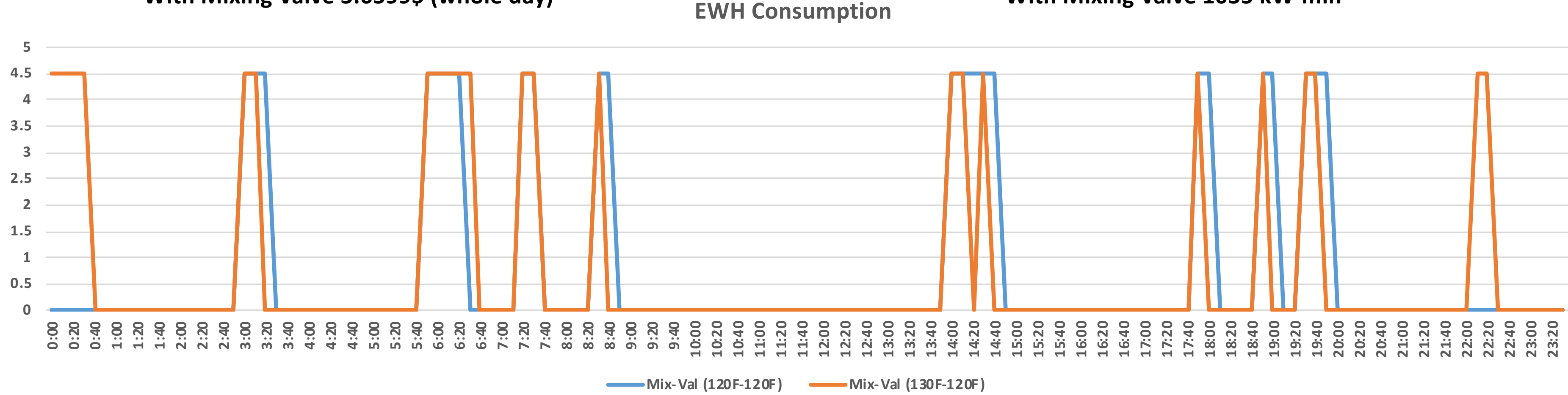




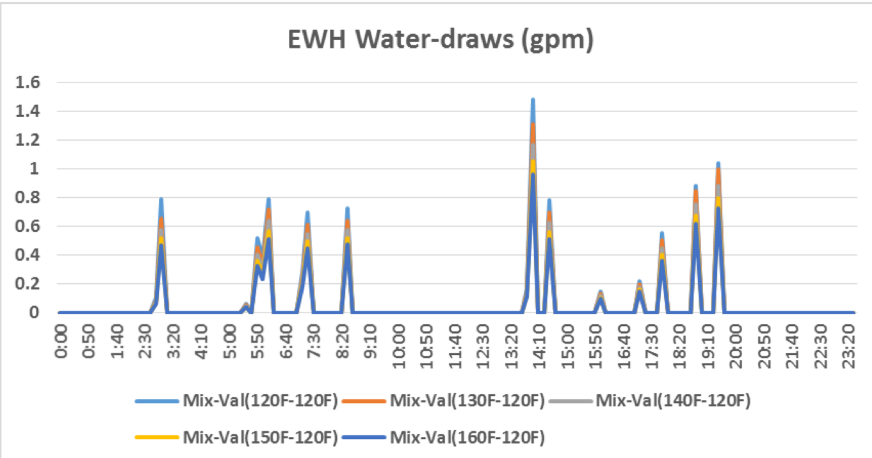


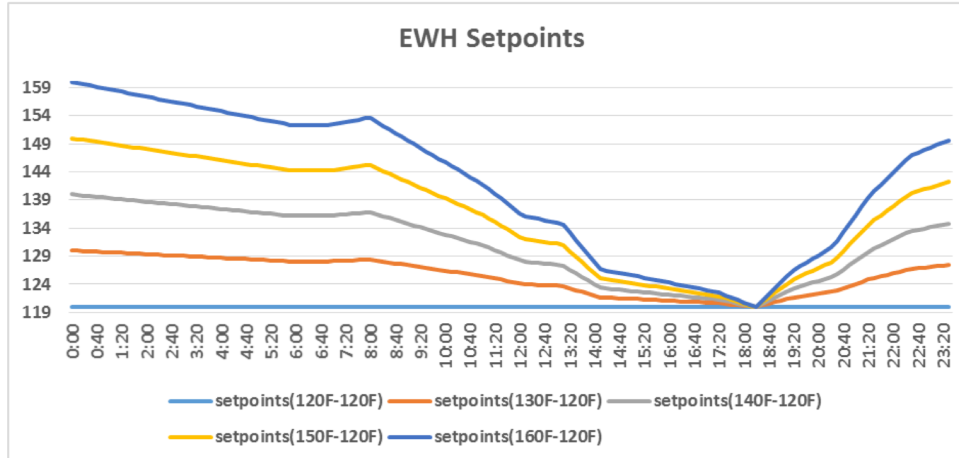
No Mixing Valve 4.48 $ (whole day)
With Mixing Valve 3.6599$ (whole day)

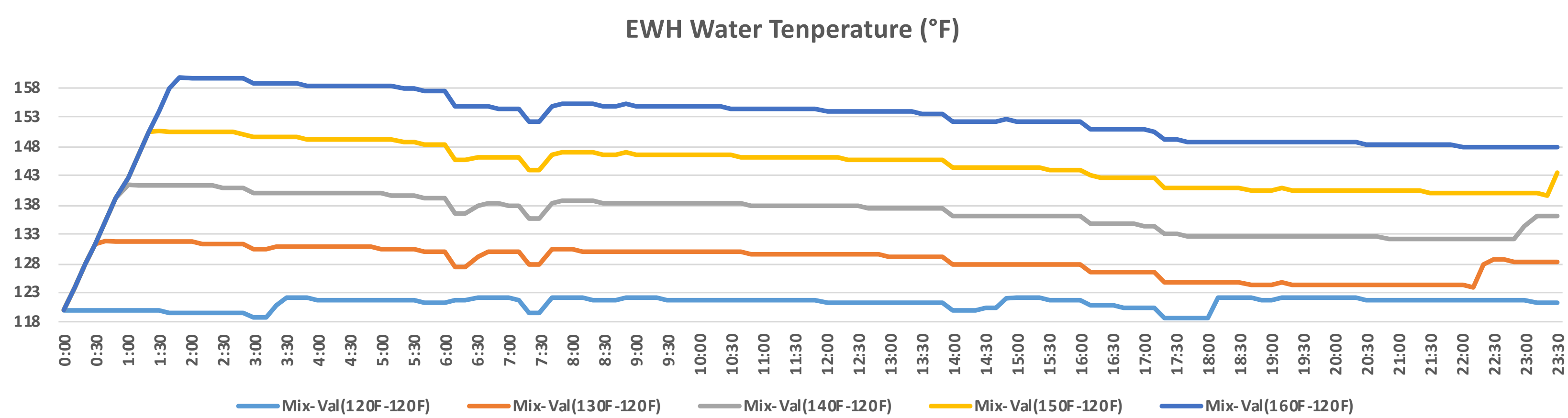
No Mixing Valve 1035 kW-min
With Mixing Valve 1035 kW-min



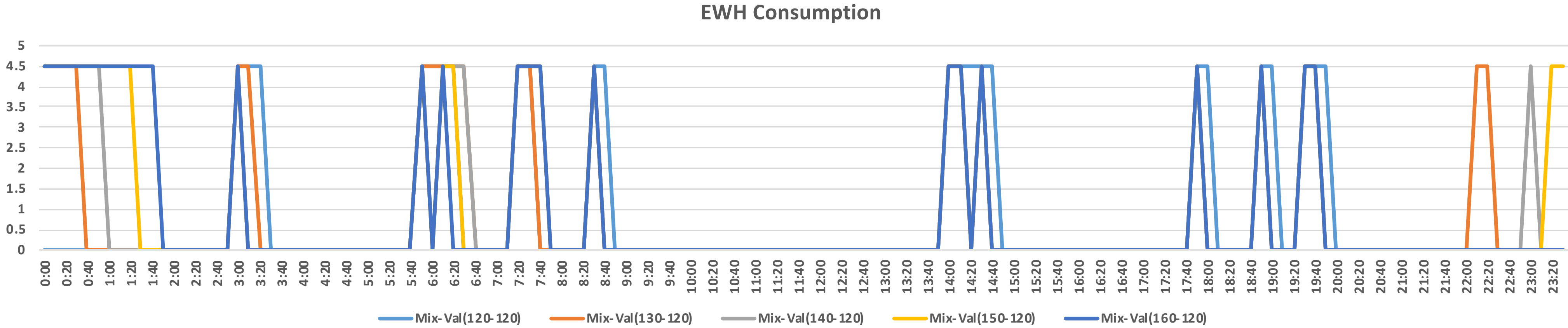
Mixing Valve (Real Time – Pre heating)







Mixing Valve (Cost Reduction – Pre heating)



No Mixing Valve - 1035 kW-min
Mixing Valve (130 -120) - 1035 kW-min
Mixing Valve (140 -120) - 1035 kW-min
Mixing Valve (150 -120) – 1170 kW-min
Mixing Valve (160 -120) – 1125 kW-min
Mixing Valve (170 -120) – 1170 kW-min
Mixing Valve (180 -120) – 1305 kW-min

No Mixing Valve - 4.489 $ (whole day)
Mixing Valve (130 -120) – 3.659 $
Mixing Valve (140 -120) – 3.5467 $
Mixing Valve (150 -120) – 3.8144 $
Mixing Valve (160 -120) – 3.5997 $
Mixing Valve (170 -120) – 3.6677 $
Mixing Valve (180 -120) – 3.9506 $

Formulating DA Optimization Problem

DA Optimization using one node

$$\textbf{MINIMIZE :} = \sum_{\boldsymbol{T}=\mathbf{1}}^{\mathbf{24}} \boldsymbol{P_{DA}}(\boldsymbol{T}) * \boldsymbol{Q_{elec}}(\boldsymbol{T})$$

$$Q_{elec} - \dot{m}C_p(T_w - T_{inlet}) + UA_{wh}(T_{amb} - T_w) = C_w \frac{dT_w}{dt}$$

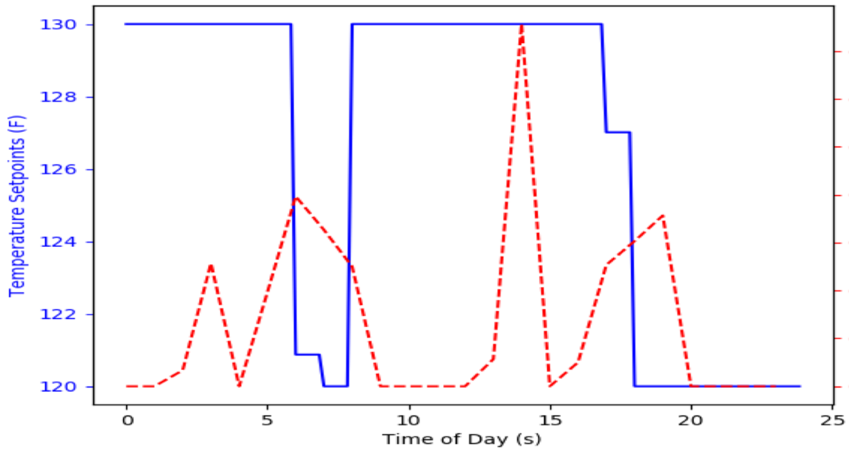
$$T_{tank(T+1)} - T_{tank(T)} = (1/C_w) * [Q_{elec} - \dot{m}C_p\left(T_{tank(T)} - T_{inlet}\right) + UA_{wh}\left(T_{amb} - T_{tank(T)}\right)]$$

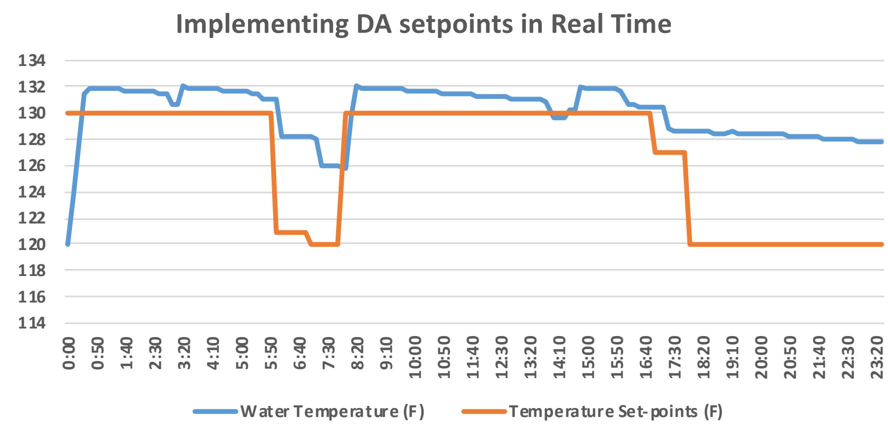
Incorporating Mixing Valve (Approximation):

$$\dot{m} = W_{draw\_tank} = W_{draw\_actual} * (\frac{T_{desired} - T_{inlet}}{T_{tank} - T_{inlet}})$$

$$\dot{m}_{DA}C_p(\dot{T_w} - T_{inlet}) = W_{draw\_actual} * \left(\frac{T_{desired} - T_{inlet}}{T_{tank} - T_{inlet}}\right) * C_p * (T_{tank} - T_{inlet})$$

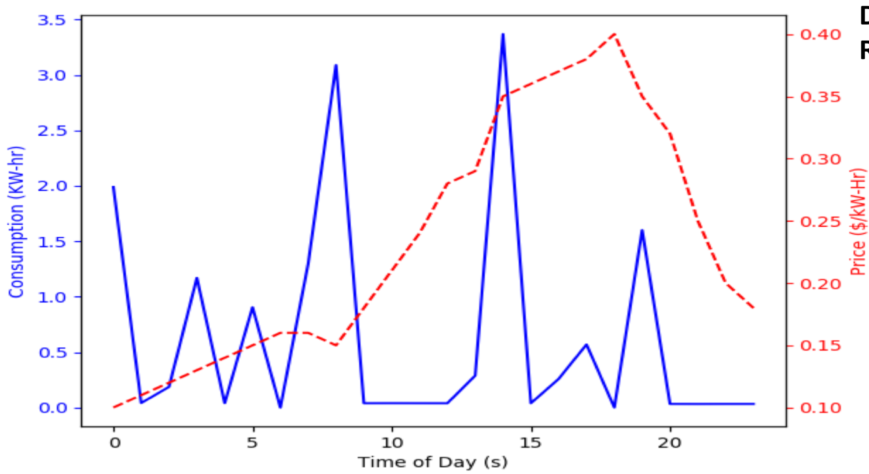
DA Optimization

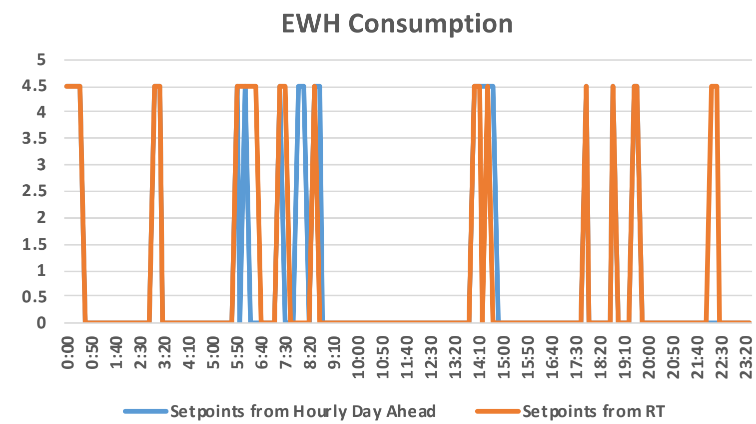




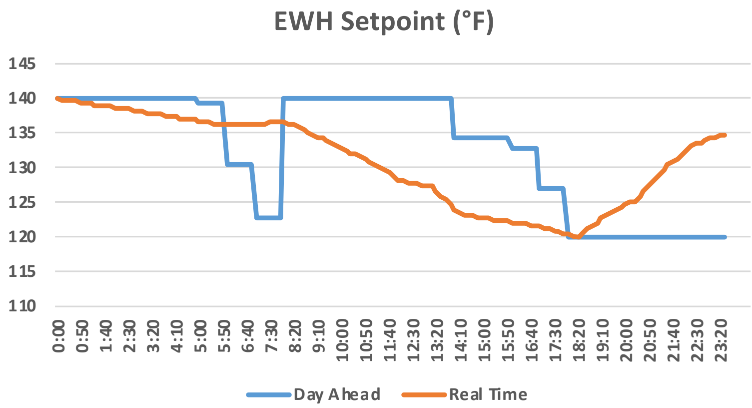
DA (hourly setpoints) 3.7199 \$ (whole day)
RT (price linear setpoints) 3.6599\$ (whole day)

DA (hourly setpoints) 990 kW-min
RT (price linear setpoints) 1035 kW-min

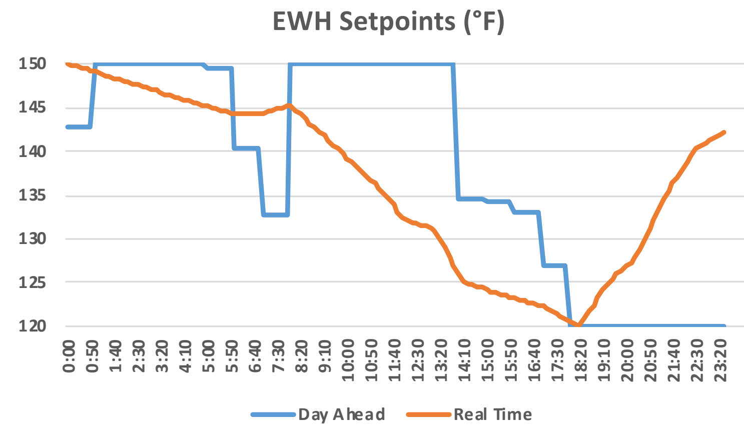




DA Optimization

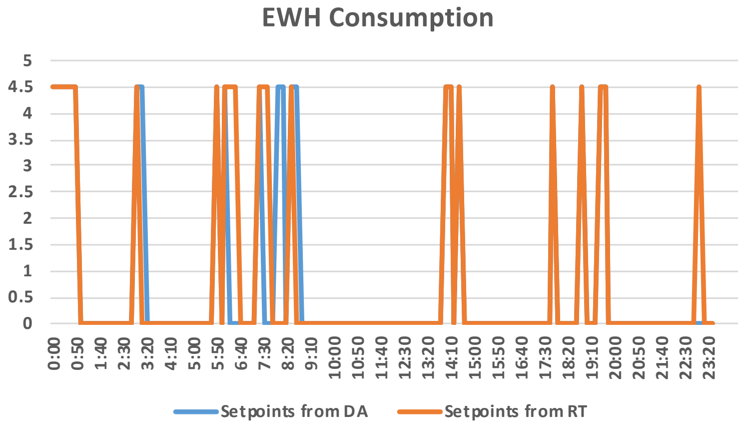


DA (hourly setpoints) 3.3449 $ (whole day)
RT (price linear setpoints) 3.5467 $ (whole day)

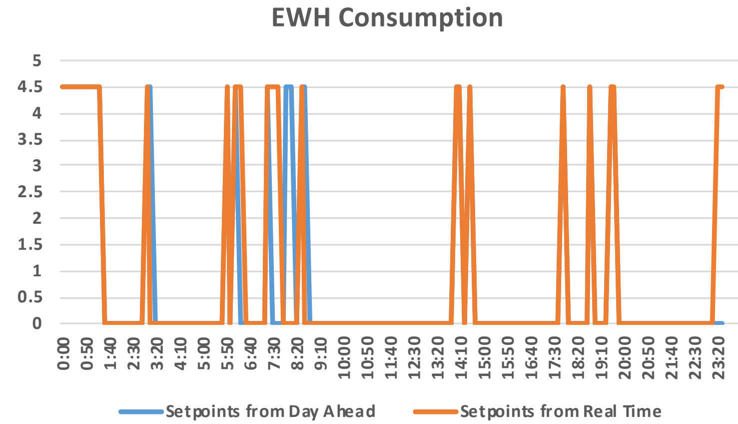


DA (hourly setpoints) 3.5925 $ (whole day)
RT (price linear setpoints) 3.8144 $ (whole day)

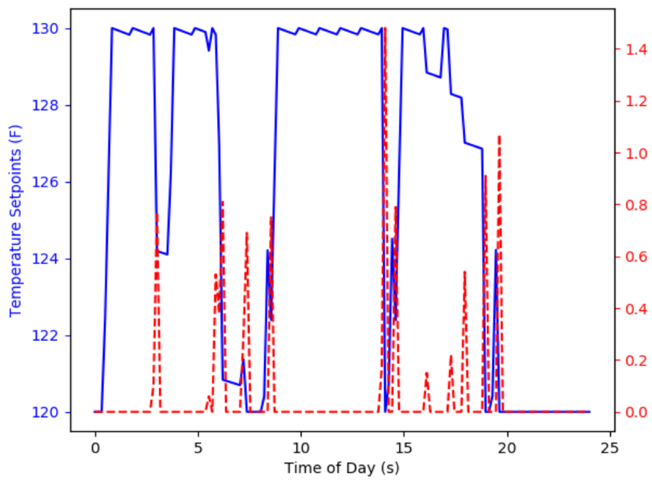
DA (hourly setpoints) 990 kW-min
RT (price linear setpoints) 1035 kW-min

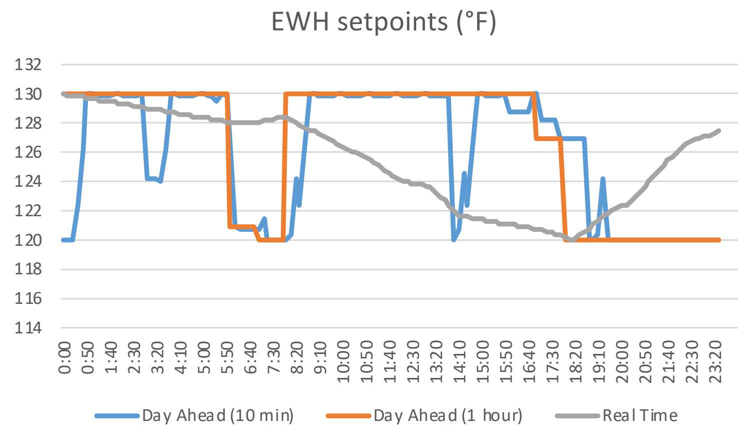


DA (hourly setpoints) 1125 kW-min
RT (price linear setpoints) 1170 kW-min



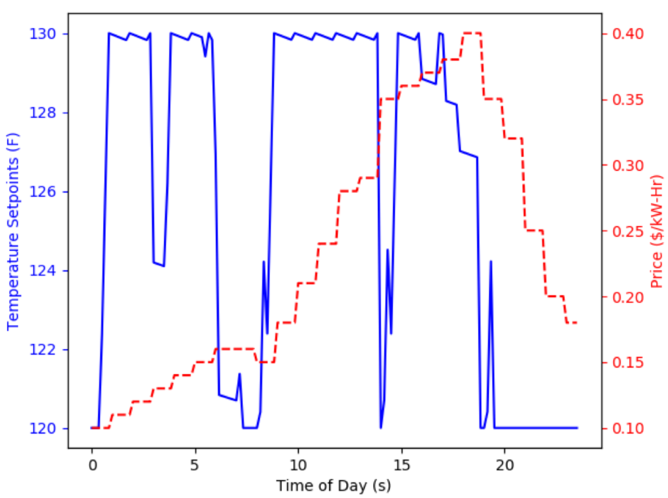
Case -130°F: DA Optimization (10 min ~ 1 hour)

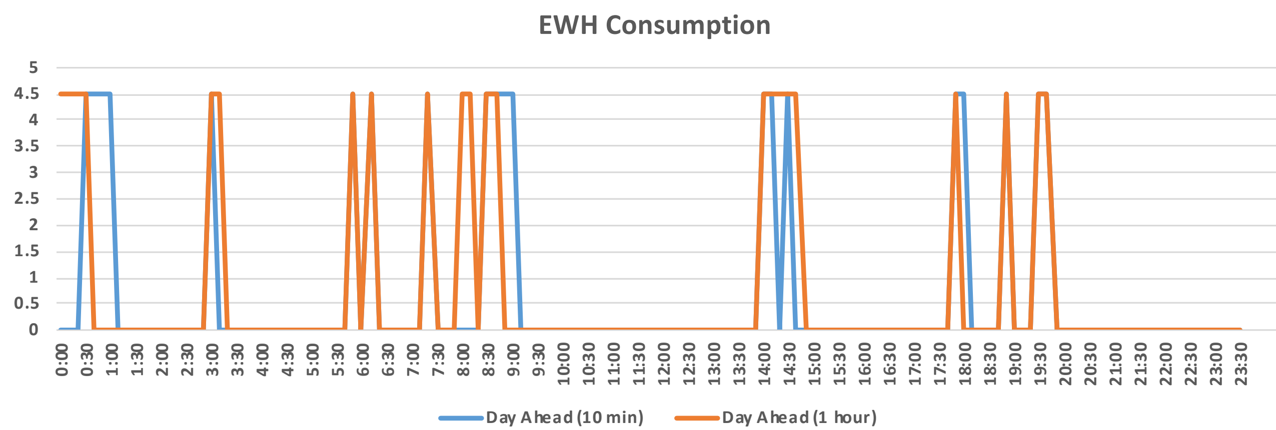




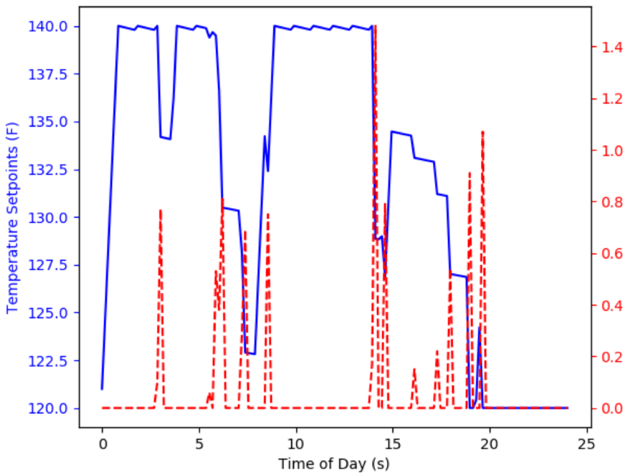
Daily Energy Cost:
DA (10 min setpoints) 3.427 $
DA (hourly setpoints) 3.7199 $
RT (price linear setpoints) 3.6599 $

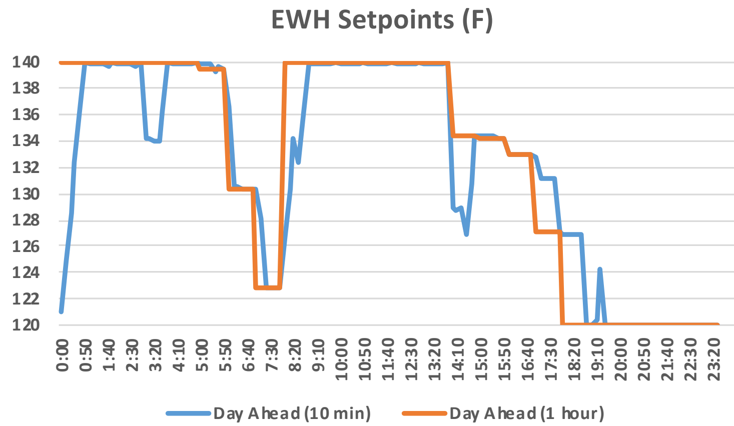
Daily Energy Consumption:
DA (10 min setpoints) 900 kW-min
DA (hourly setpoints) 990 kW-min
RT (price linear setpoints) 1035 kW-min





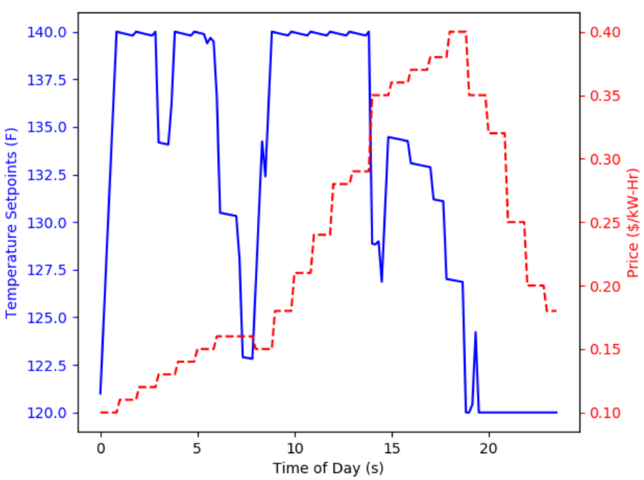
Case -140°F: DA Optimization (10 min ~ 1 hour)

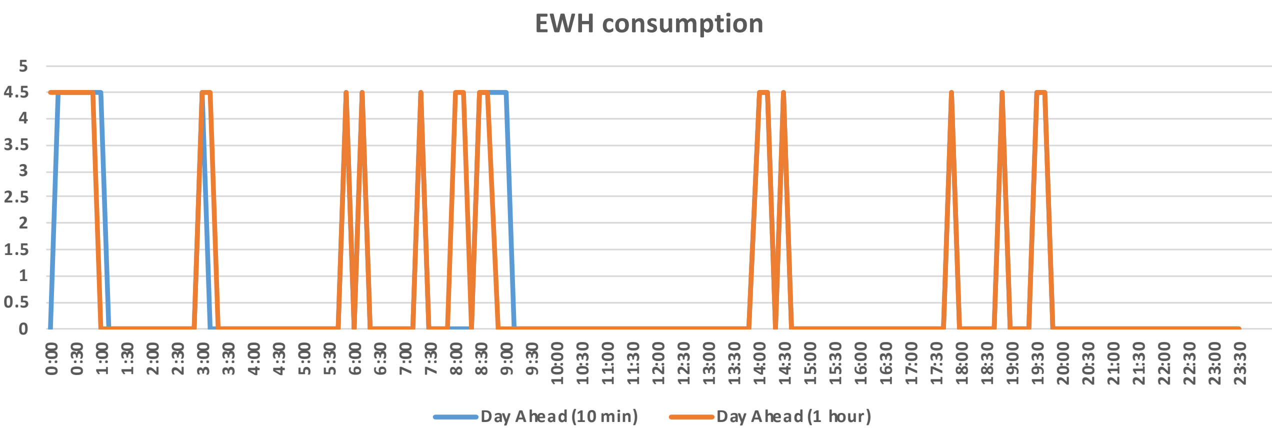




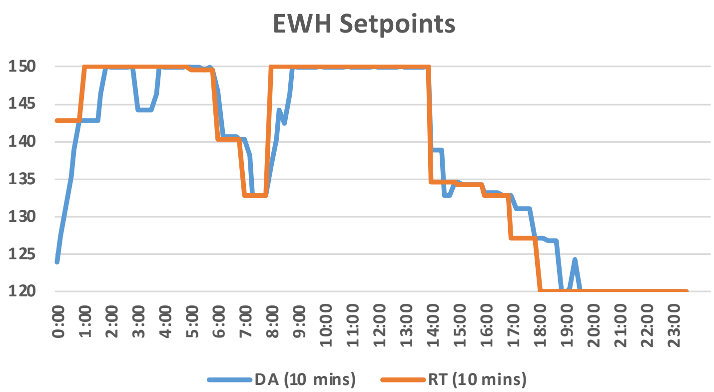
Daily Energy Cost:
DA (10 min setpoints) 3.2774 $
DA (hourly setpoints) 3.3449 $
RT (price linear setpoints) 3.5467 $

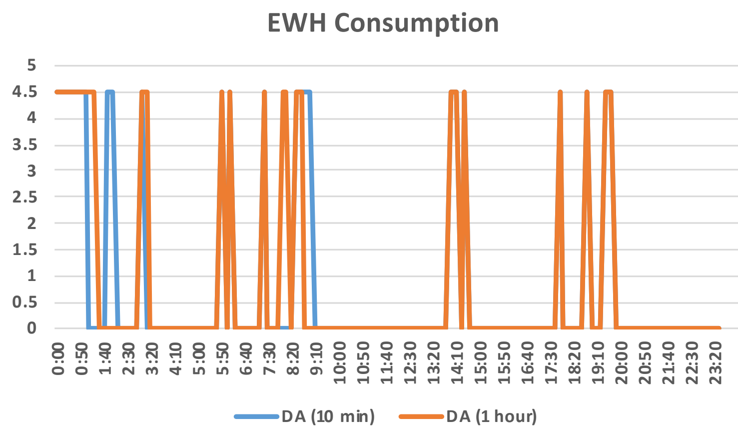
Daily Energy Consumption:
DA (10 min setpoints) 945 kW-min
DA (hourly setpoints) 990 kW-min
RT (price linear setpoints) 1035 kW-min





Case -150°F: DA Optimization (10 min ~ 1 hour)





Daily Energy Cost:

DA (10 min setpoints) 3.525 $

DA (hourly setpoints) 3.5925 $

RT (price linear setpoints) 3.8114 $

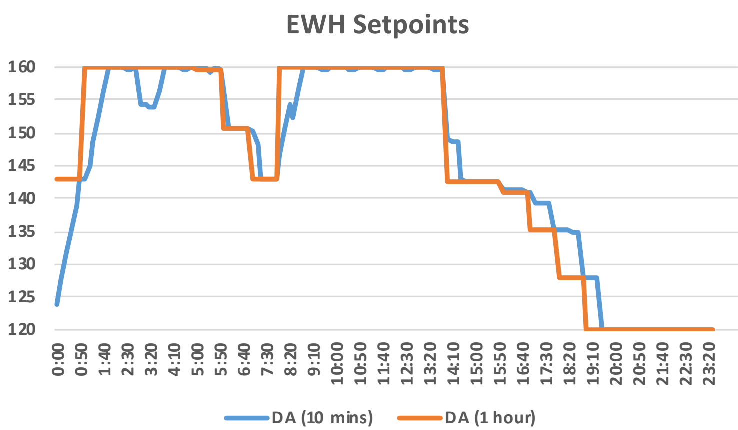
Daily Energy Consumption:

DA (10 min setpoints) 1080 kW-min

DA (hourly setpoints) 1125 kW-min

RT (price linear setpoints) 1170 kW-min

Case -160°F:



Daily Energy Cost:

DA (10 min setpoints) 3.7725 $

DA (hourly setpoints) 3.840 $

RT (price linear setpoints) 3.5997 $

Daily Energy Consumption:

DA (10 min setpoints) 1215 kW-min

DA (hourly setpoints) 1260 kW-min

RT (price linear setpoints) 1125 kW-min

Incorporating Mixing Valve in GLD-EWH

```
double tank_volume[gal]; // the volume of water in the tank when it is full
double tank_UA[Btu]; // the UA of the tank (surface area divided by R-value)
double tank_diameter[ft]; // the diameter of the water heater tank
double water_demand[gpm]; // the hot water draw from the water heater
double heating_element_capacity[kW]; // the power of the heating element
double inlet_water_temperature[degF]; // the inlet temperature of the water tank
enumeration {GASHEAT=1, ELECTRIC=0} heat_mode; // the energy source for heating the water heater
enumeration {GARAGE=1, INSIDE=0} location; // whether the water heater is inside or outside
double tank_setpoint[degF]; // the temperature around which the water heater will heat its contents
double thermostat_deadband[degF]; // the degree to heat the water tank, when needed
double temperature[degF]; // the outlet temperature of the water tank
double height[ft]; // the height of the hot water column within the water tank
double demand[gpm]; // the water consumption
double actual_load[kW]; // the actual load based on the current voltage across the coils
double previous_load[kW]; // the actual load based on current voltage stored for use in controlle s
complex actual_power[kVA]; // the actual power based on the current voltage across the coils
double is_waterheater_on; // simple logic output to determine state of waterheater (1-on, 0-off)
double gas_fan_power[kW]; // load of a running gas waterheater
double gas_standby_power[kW]; // load of a gas waterheater in standby
```

http://gridlab-d.shoutwiki.com/wiki/Tech:Residential

Figure 2 shows a schematic representation of the water heater model in which Tavg is the average water temperature throughout the tank and Tamb is the ambient temperature. The thermal capacitance of the water Cw is a function of the tank volume:

$$C_w = V(gal)\frac{1(ft^3)}{7.48(gal)}\frac{62.4(lb_m)}{1(ft^3)}\frac{1(Btu)}{1(lb_m\dot{F}}$$

The thermal conductance of the tank shell (or "jacket") UA is calculated from the known R-values of the sides and top of the tank divided into their corresponding areas.

One-Node Model

Considering Figure 2 and treating the water heater as a single node with thermal capacitance C_w, a conductance UA to ambient conditions, with mass flow rate and heat input rate of Q_{elec}, a heat balance on the water node is as follows:

$$Q_{elec} - \dot{m}C_p\left(T_w - T_{inlet}\right) + UA\left(T_{amb} - T_w\right) = C_w\frac{dT_w}{dt}$$

or,

$$dt = \frac{C_w}{\dot{m}C_pT_{inlet} + UAT_{amb} - \left(UA + \dot{m}C_p\right)T_w + Q_{elec}}dT_w$$

The time required to change the tank's temperature from an initial temperature T_0 to a new temperature T_1 is given by integrating that equation.

$$t_1 - t_0 = \int_{T_0}^{T_1}\frac{1}{\frac{\dot{m}C_pT_{inlet}+UAT_{amb}+Q_{elec}}{C_w} - \frac{UA+\dot{m}C_p}{C_w}T_w}dT_w$$

That is an integral of the form $dx/(a+bx)$, which has solution $\log(a+bx)/b$. Therefore, the final model of the time required to raise (or lower) the tank's temperature is

$$t_1 - t_0 = \frac{1}{b}\log(a + bT_w)\Big|_{T_0}^{T_1}$$

tank_water_demand = water_demand[i]*(T_mixed - Tlower)/(Tw - Tlower)

Deration due to Mixing Valve
Electric Water Heater

Understanding EWH physics

One node Model

$$Q_{elec} - \dot{m}C_p(T_w - T_{inlet}) - UA_{wh}(T_w - T_{amb}) = C_w \frac{dT_w}{dt}$$

Two node Model

$$dh/dt = a - b * h$$

$$a = \frac{Q_{elec} + UA_{WH} * (T_{amb} - T_{lower})}{C_W * (T_{upper} - T_{lower})} * H - \frac{\dot{m} * C_p}{C_W} * H$$

$$b = UA_{WH}/C_W$$

Q_{elec} : heating capacity of the resistor; C_p : thermal capacitance
T_w : water temperature; T_{inlet} : temperature of inlet water;
UA_{wh} : thermal conductance of the tank shell; T_{amb} : room temperature;
C_w : thermal capacitance; H : maximum height of the water tank; T_{lower} : set to inlet water temperature

Switching from two-node to one-node:

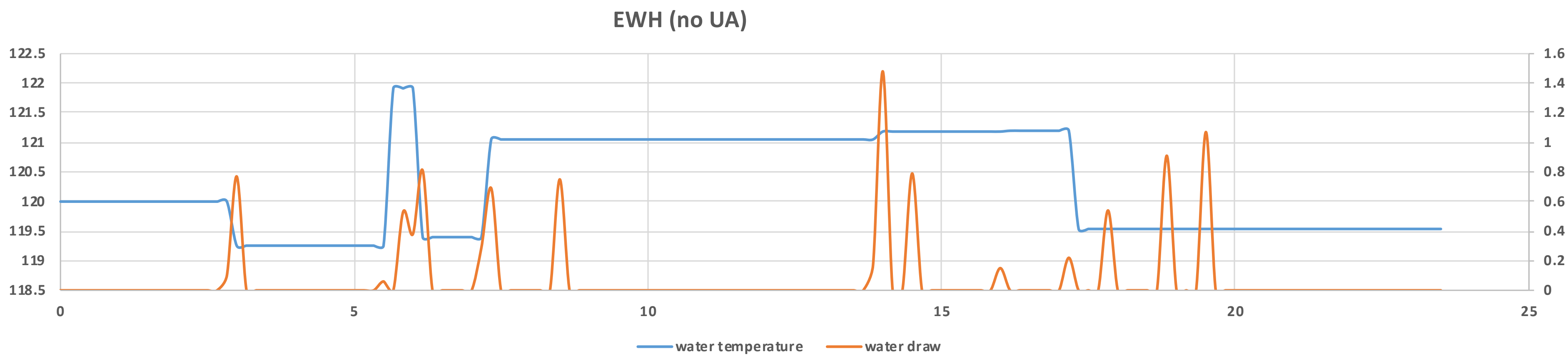
If flag=2
    if $h=H$ and dh/dt >= 0
        flag is set to 1 and h is set to H
    end

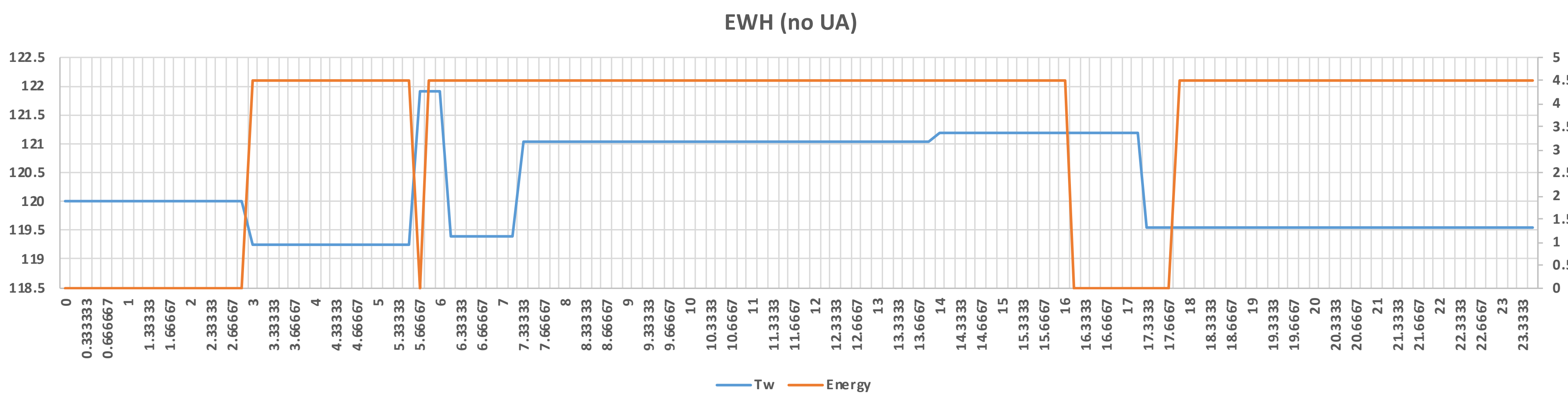
Switching from one-node to two-node:

If flag=1
    if $\dot{m} > \dot{m}_{min}$
        flag=2 and Tw is held constant with the current value
    end

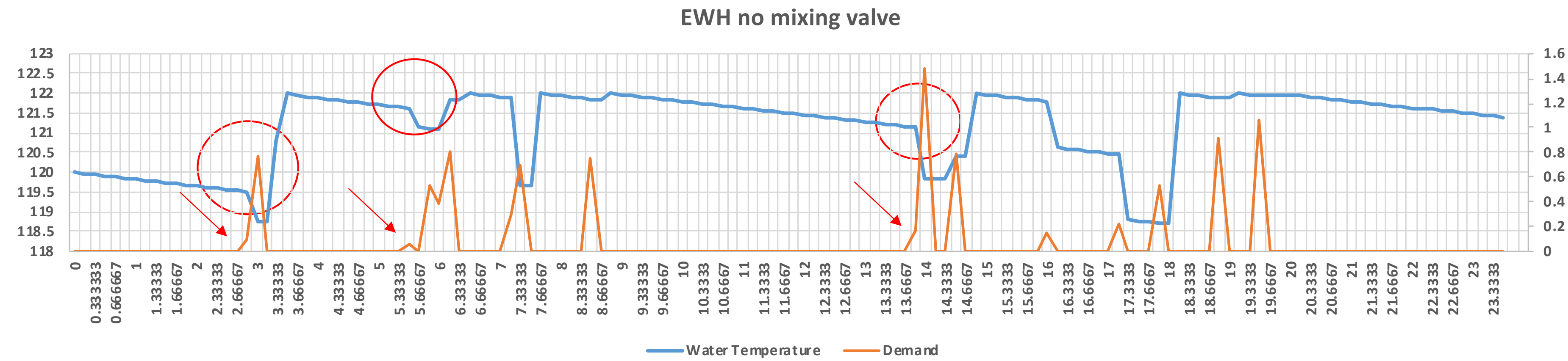
where $\dot{m}_{min}$ is a tolerance value that can trigger a change in h so that dh/dt<0. This switching action means that whenever there is a sufficiently large hot water consumption, EWH is at a depletion stage and the two-node model is applied.

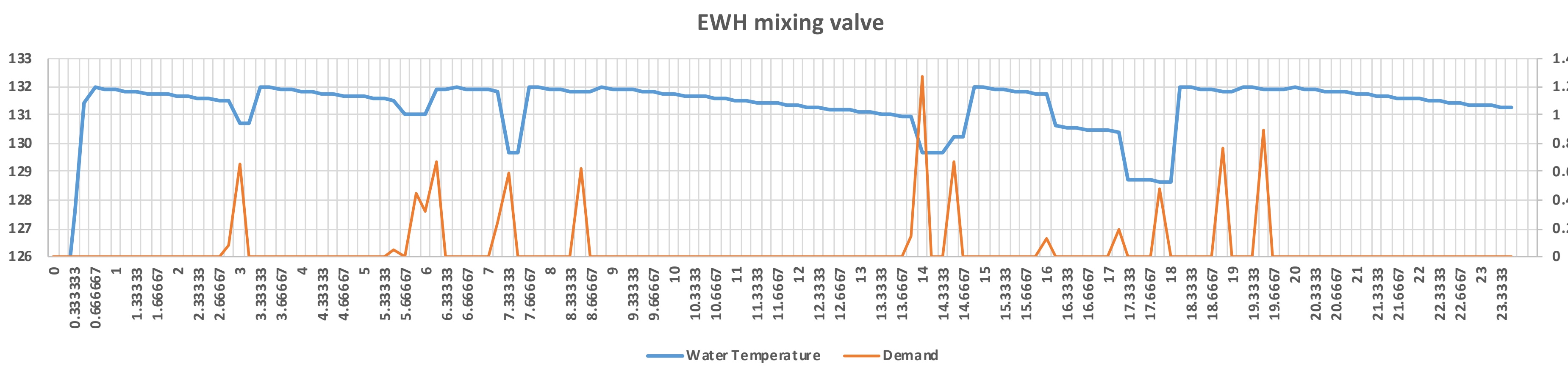
Non Lossy EWH



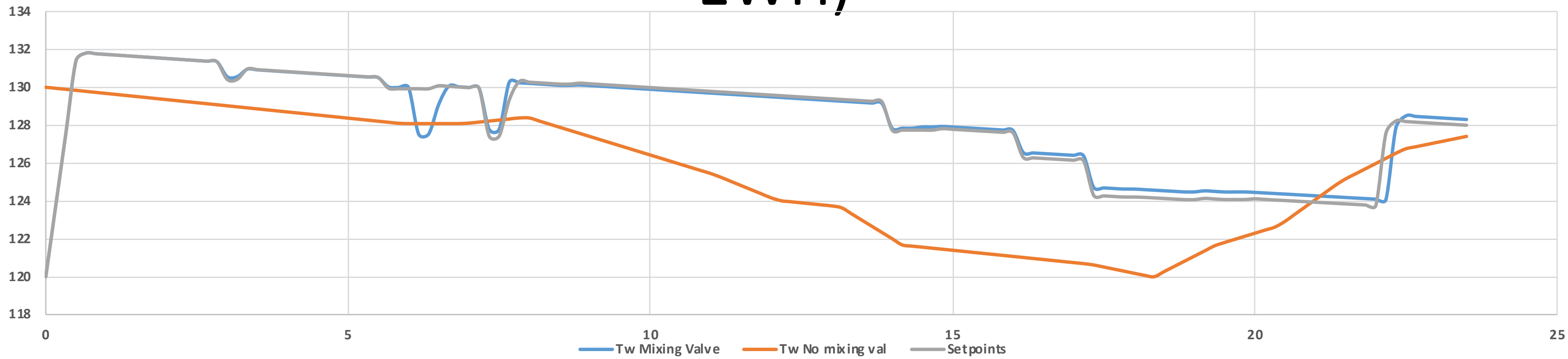


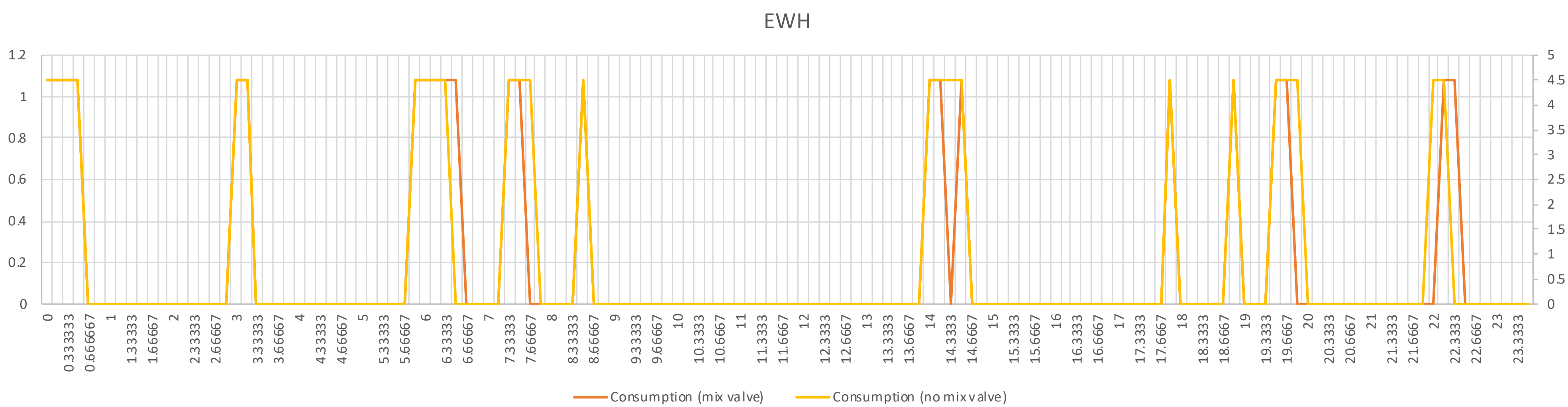
Operation of EWH (2 node model for vertical EWH)

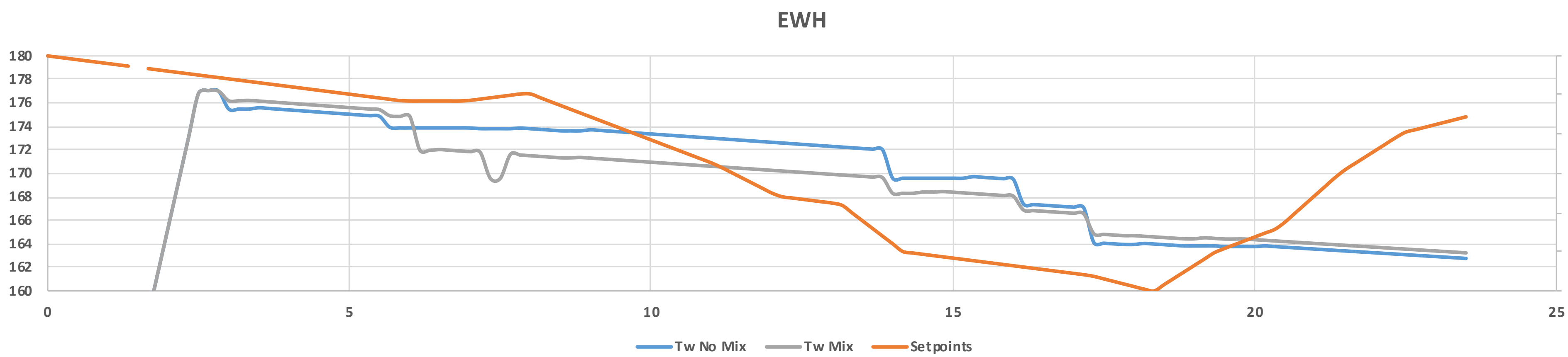




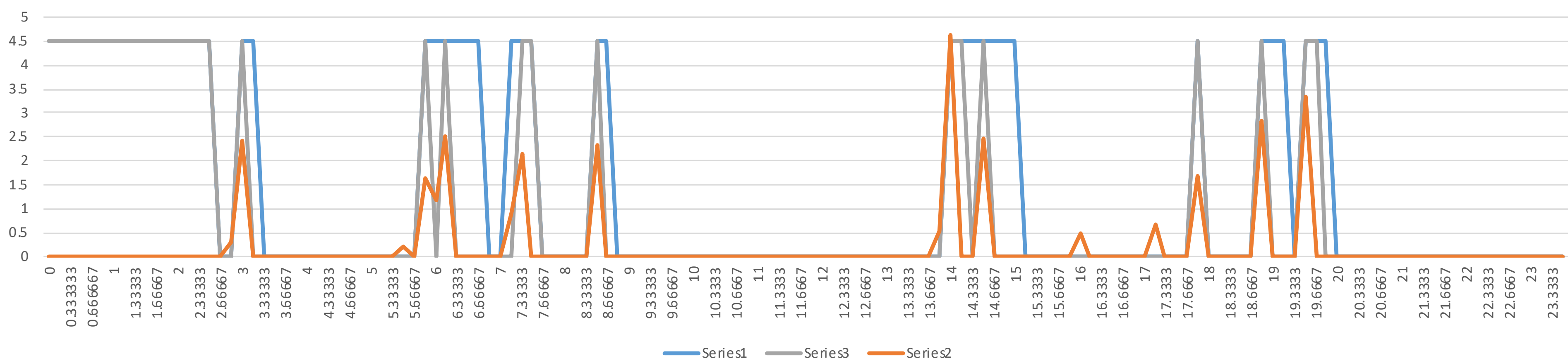
Operation of EWH (2 node model for vertical EWH)





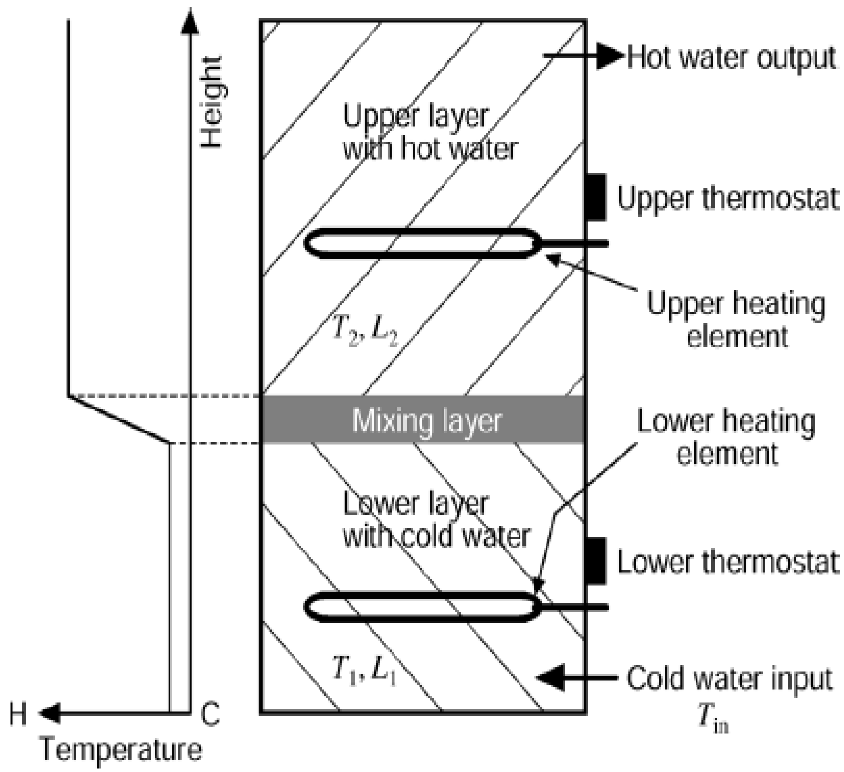


EWH
Tw No Mix
Tw Mix
Setpoints



Series1
Series3
Series2

Two Zone model for EWH



$$c\rho V_1 \frac{dT_1}{dt} = p_{1e} - p_{a1} - p_{21}$$

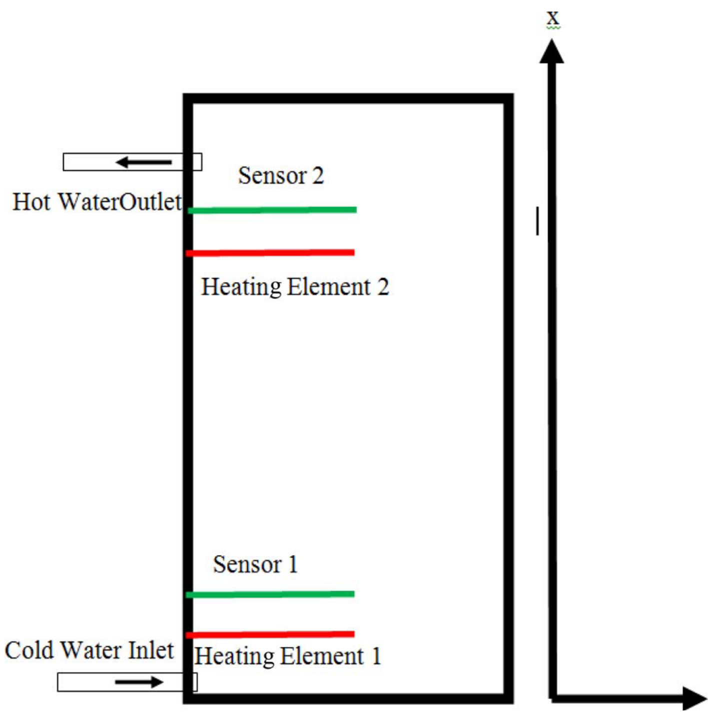
$$c\rho V_2 \frac{dT_2}{dt} = p_{2e} - p_{a2} + p_{21} - p_{hw}$$

The cumulative amount of water Vacc, which is used after T1 reaches T2 once, is considered. The temperature of water moving from the lower volume to the upper volume is T1 when Vacc > V1, and it is T2 when Vacc ≤ V1.

When T1 reaches T2 by heating the lower layer, Vacc is reset to zero. The two cases and its corresponding heat fluxes can be presented as follows

$$p_{21} = \left\{ \begin{array}{ll} c\rho \frac{dV}{dt}(T_2 - T_{inlet}), & V_{acc} \leq V_1 \\ c\rho \frac{dV}{dt}(T_1 - T_{inlet}), & V_{acc} > V_1 \end{array} \right\}$$

Baseline PDE model for EWH



$$\frac{\partial T}{\partial t} + V\frac{\partial T}{\partial x} = (D_c + D_a)\frac{\partial^2 T}{\partial x^2} + \frac{Q_{\text{ele}}}{\rho c_v} + \frac{U \cdot A_s}{AH\rho c_v}(T_{\text{amb}} - T)$$

water_diff = water_k0/water_rho/water_cv

dt = dx*dx/2.0/water_diff/20000.0

Overview of future Plans for EWH

- Model a Thermally Stratified model (for example 10 layer with 10s as time steps)
- Calibrate the model with the PDE model
- Compare Consumption and water temperature results with the PDE model:
  - One node (done)
  - One node/Two node -> GridLAB-D model
  - Two zone model (if required)
  - Stratified model PDE model
- Adding Mixing valve
- Comparing peak demand deferral due to preheating for:
  - One node
  - One node/Two node -> Gridlabd model
  - Two zone model ->
  - Stratified model PDE mode

Overview of future Plans for EWH

- Completed:
  - Modelling one node model
  - Modelling one node/two node model (GridLAB-D)
  - Comparing deferral due to preheating for them
  - Formulating the DA objective function (with Mixing Valve for one node)
  - Formulating the PDE Model (but not fully tested)
- Pending:
  - Testing the PDE model
  - Modelling and Calibration of the stratified model for PDE
  - Comparing performance for each model
  - Comparing energy deferral ability of each mode

Overview of future Plans for EWH

- To Do List:
  - Document the bidding strategy for EWH agent (discussed in Last meeting)
  - Deliver materials regarding the models
  - If permissible how to communicate offline