Model-Based Optimization for a Campus District Cooling System

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Overview

- Background and motivation
- Models for district cooling systems
- Case study
- Conclusion

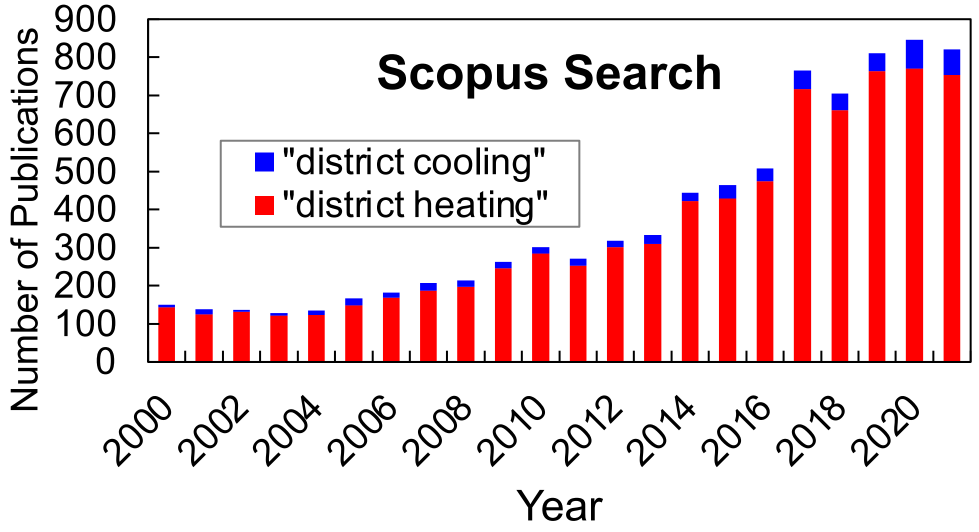
Background and Motivation

Why District Cooling?

- Space cooling is growing faster than any other building end use [1]
- None had modeled complete district cooling systems (plant + distribution) featuring hydraulics nor waterside economizers

Gaps in Scientific Literature

- District cooling studies are generally limited



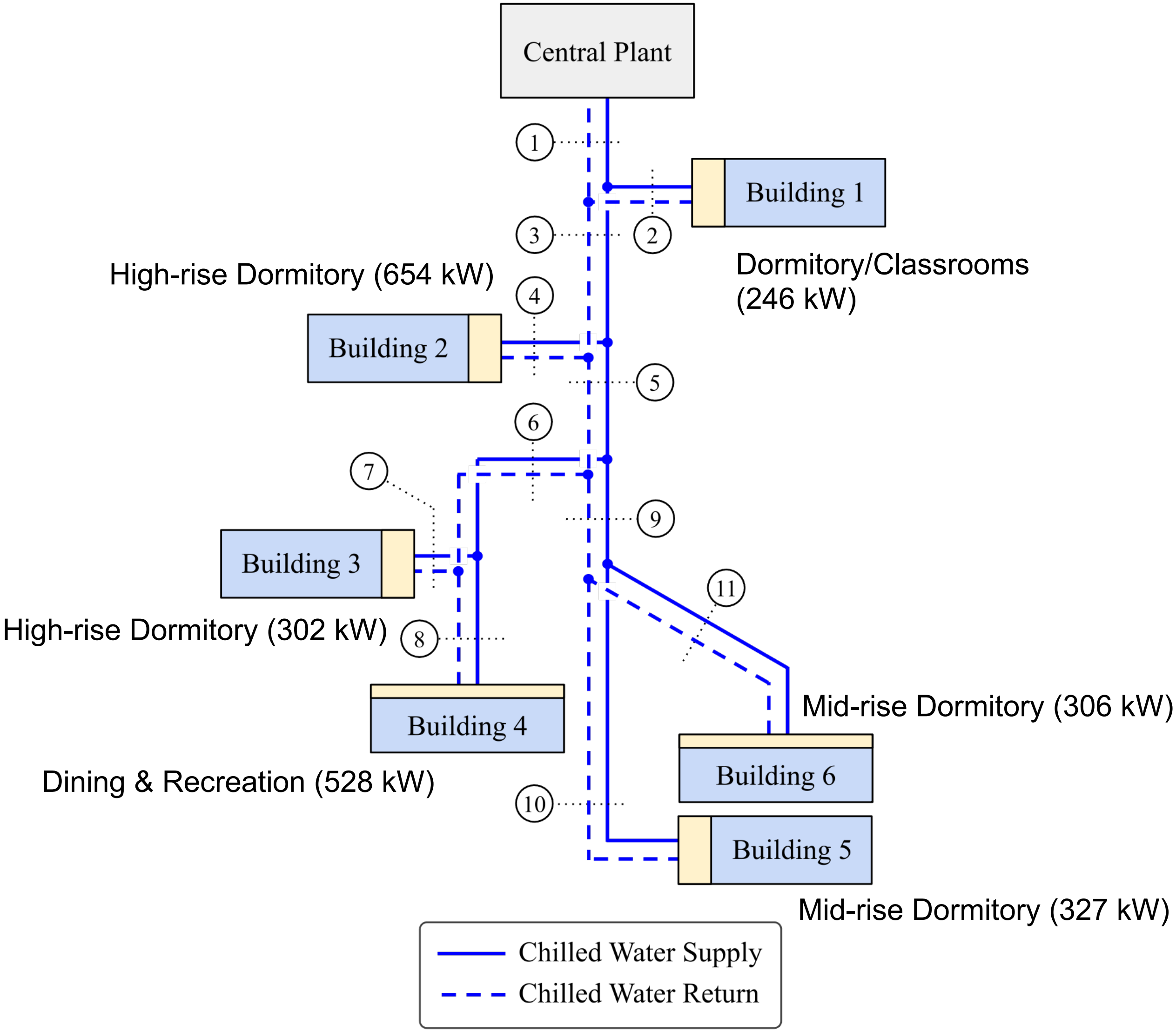
Objectives

- Demonstrate how Modelica can enable complete district cooling energy analysis
- Identify investment-free energy efficiency strategies for a real-world case study
- Evaluate carbon and operational cost savings due to energy retrofits

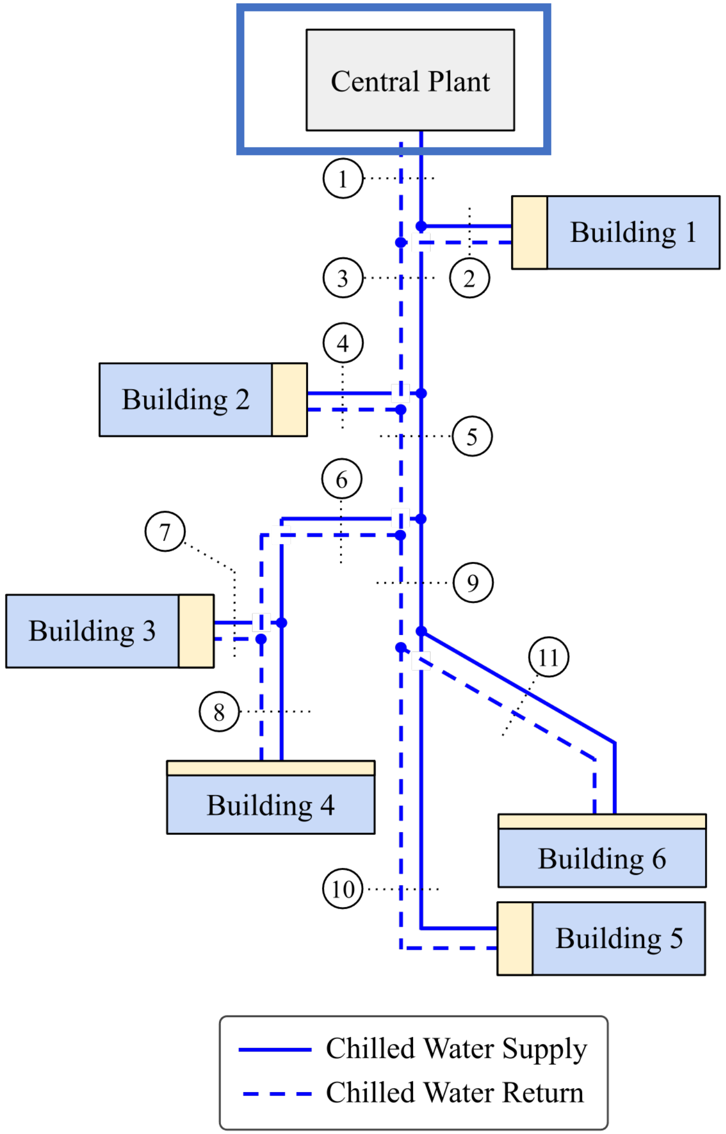
[1] International Energy Agency. 2018. The future of cooling.

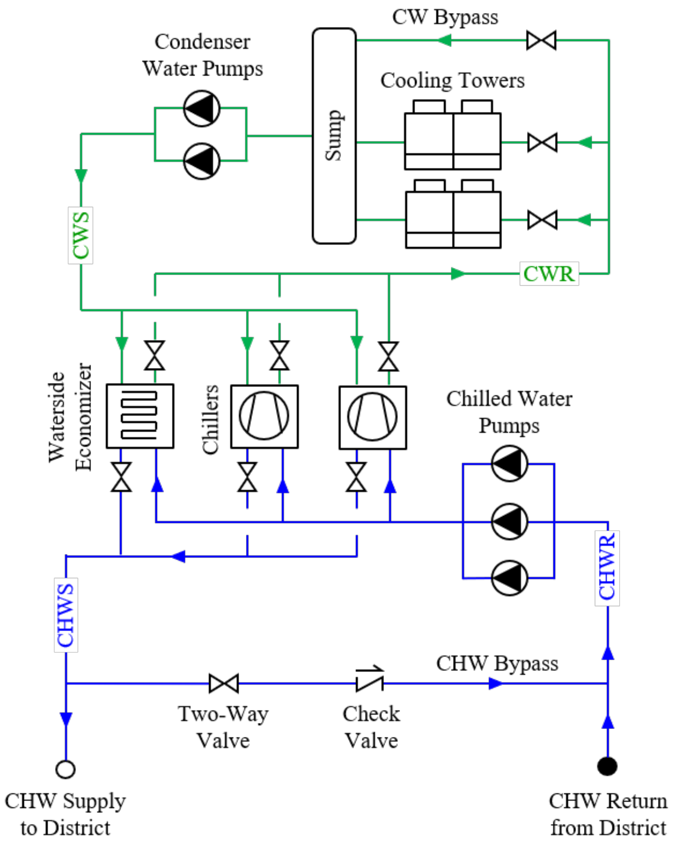
Case Study

- A satellite campus of University of Colorado in Boulder, CO
- Six Buildings:
    - Floor area: 93,990 m^2 (1,011,699 ft^2)
    - Peak load: 2.4 MW
- Radial network with 1.5 km pipes



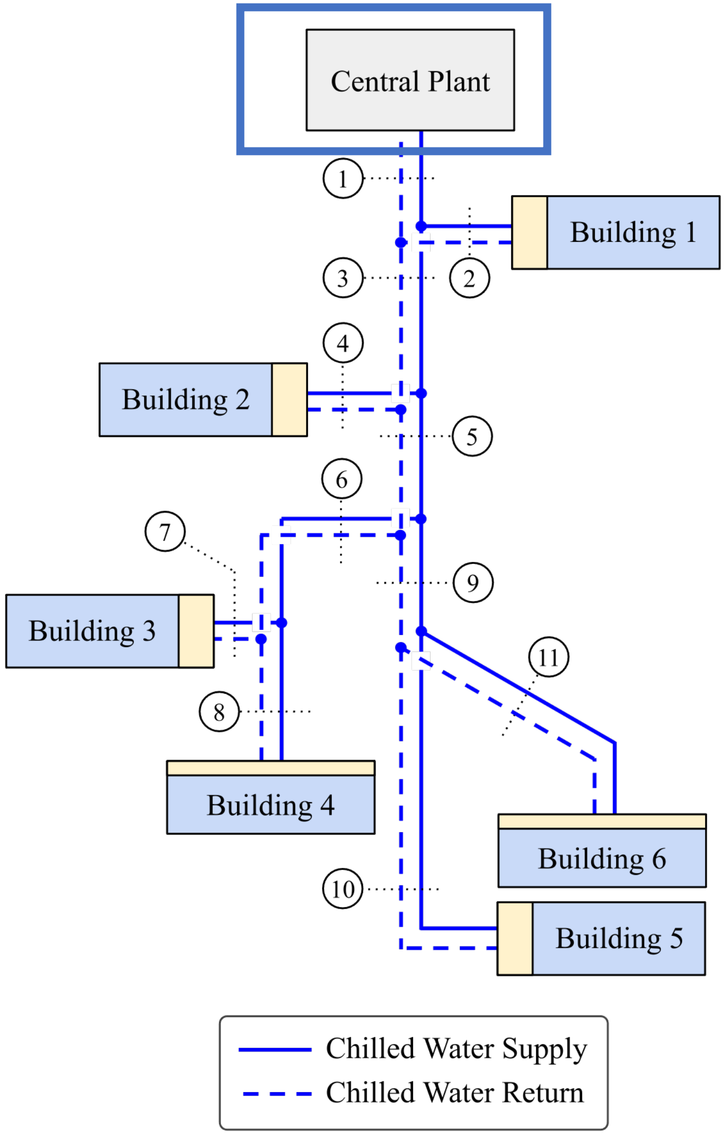
Central Plant

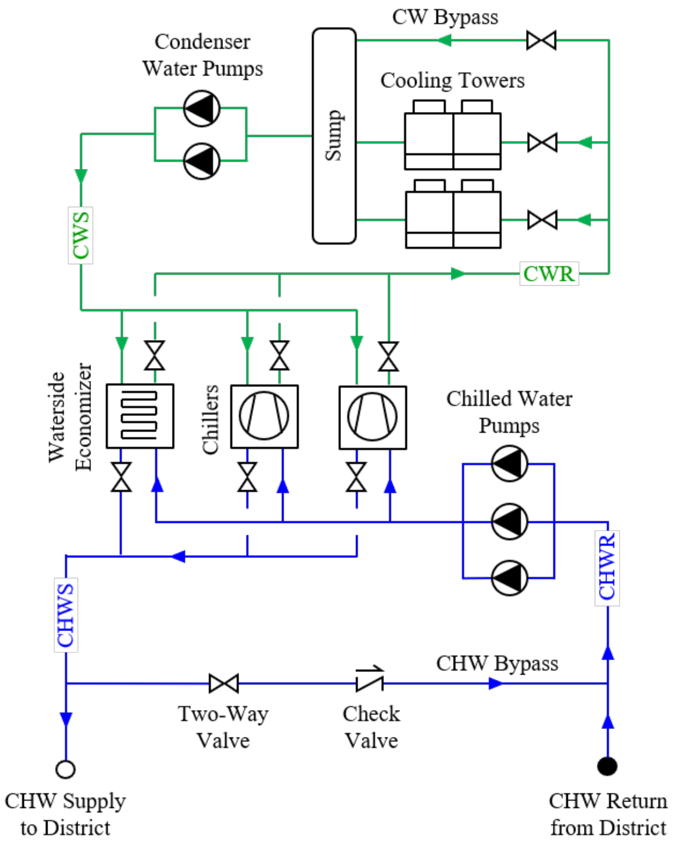




- Two single compressor chillers (2455 kW each)
- Three chilled water pump (30 kW each)
- Two condenser water pump (56 kW each)
- Non-integrated water side economizer
- Four cooling tower units (22 kW each)

Central Plant





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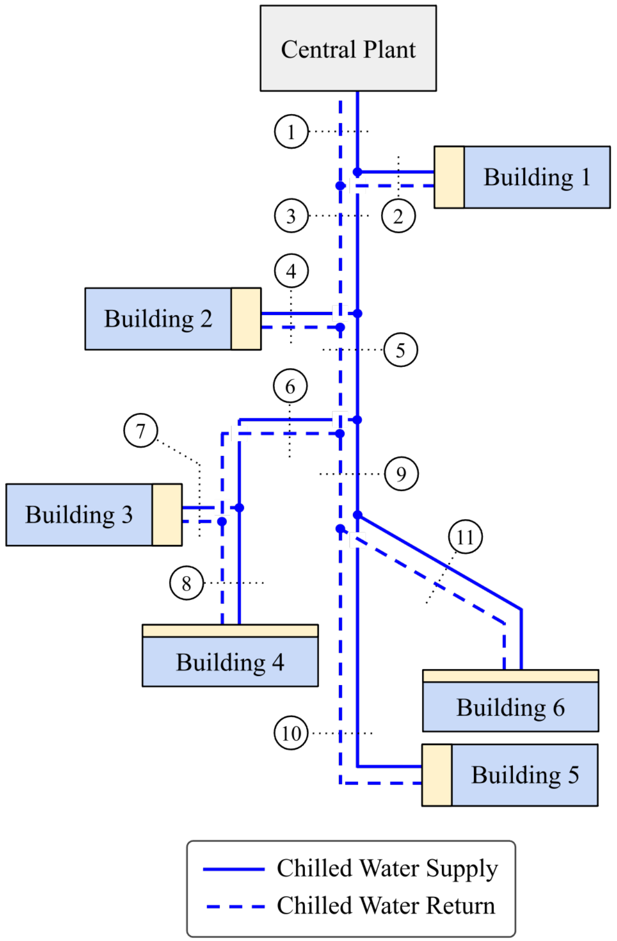
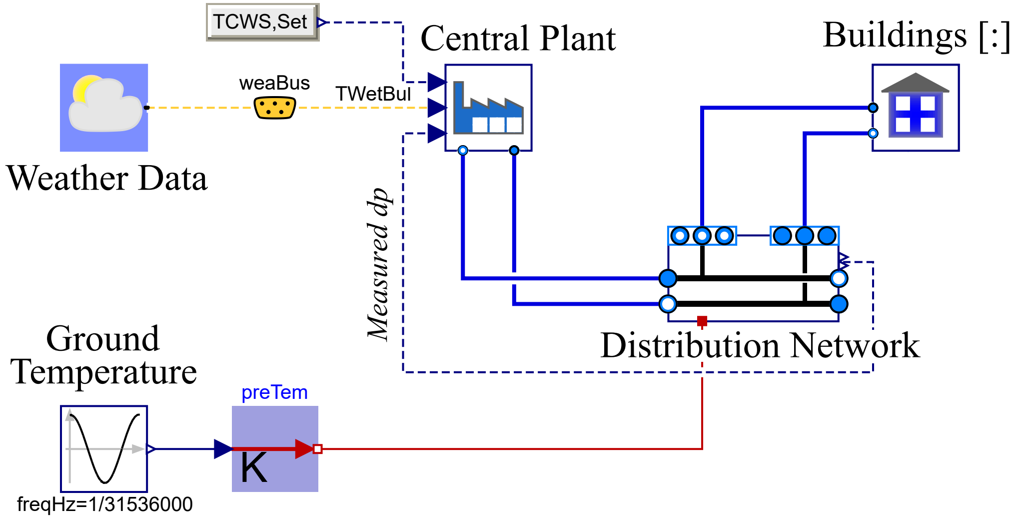
Modeling: District Cooling Systems

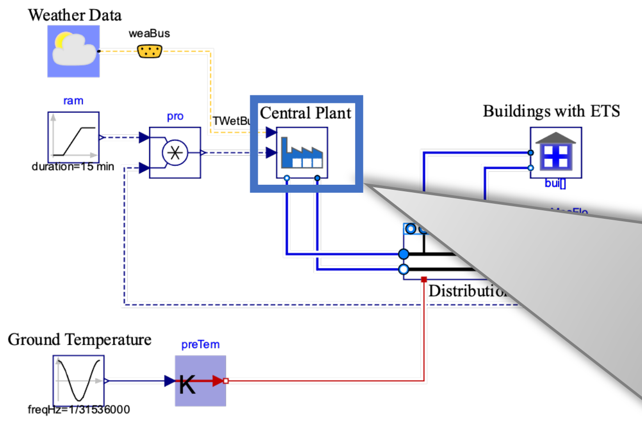


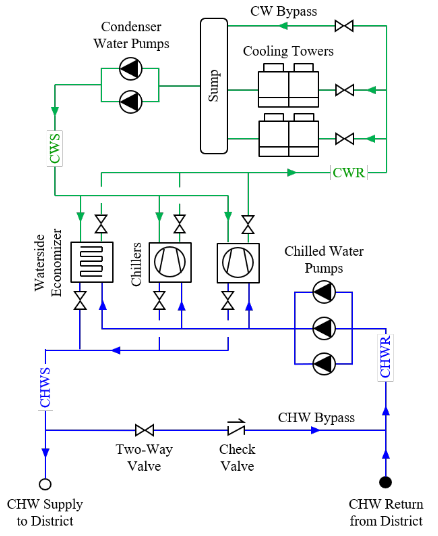
System Schematics



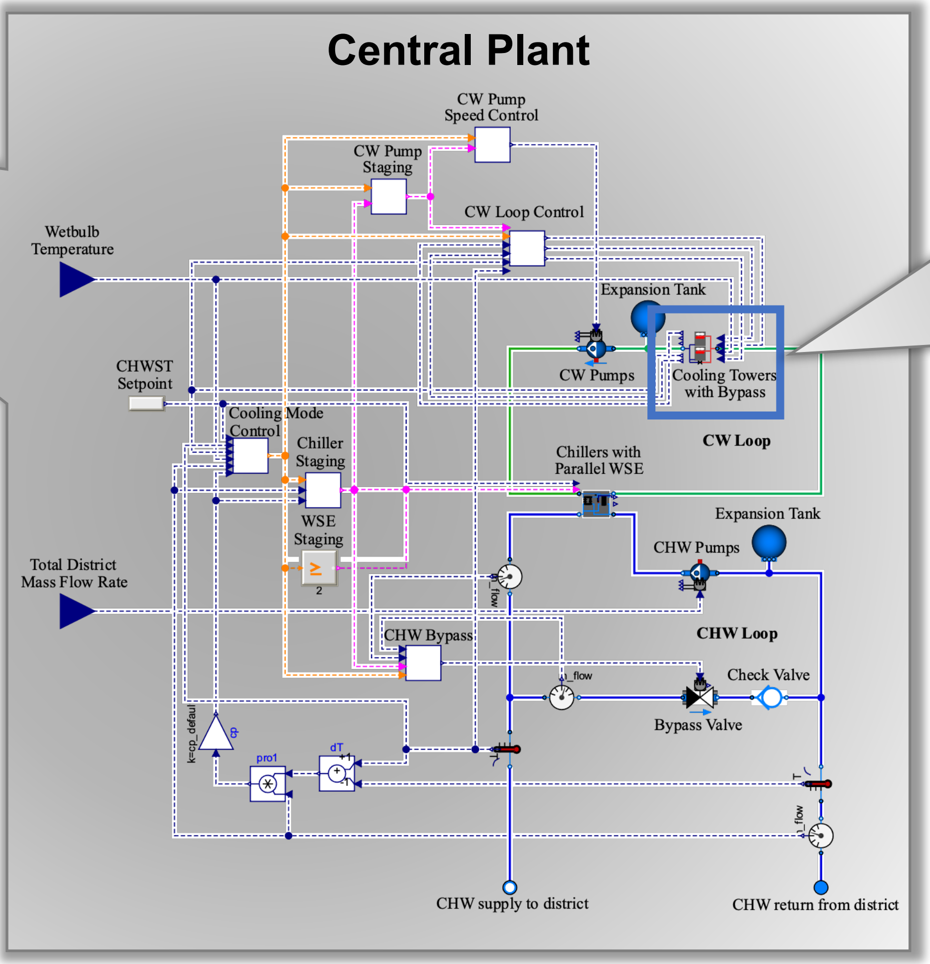
Top-Level Model

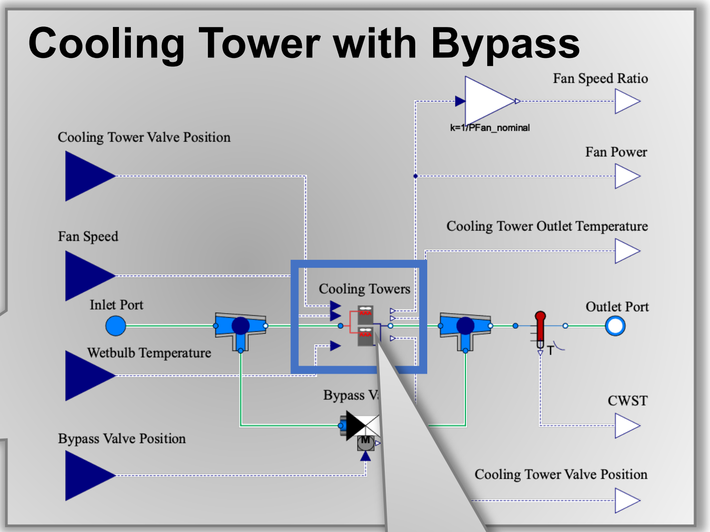
Central Plant

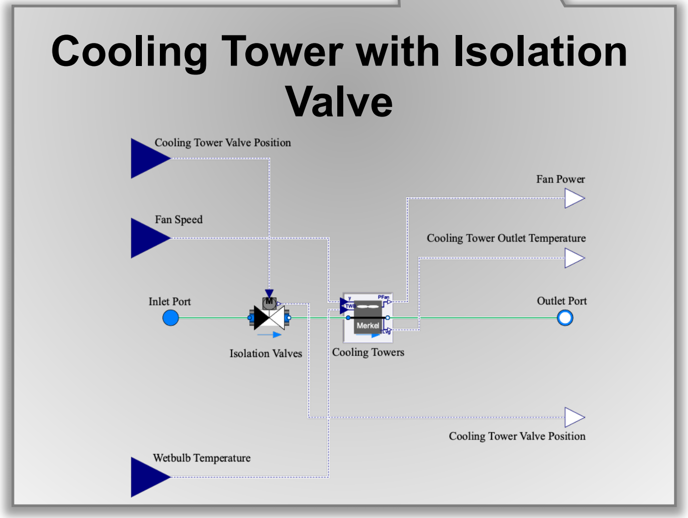




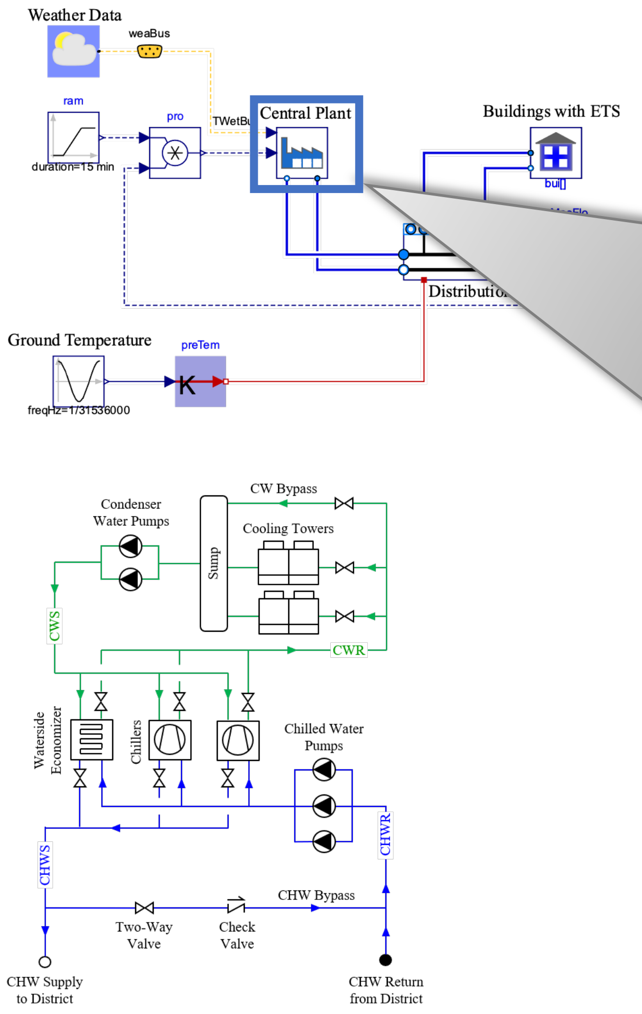
System Schematic



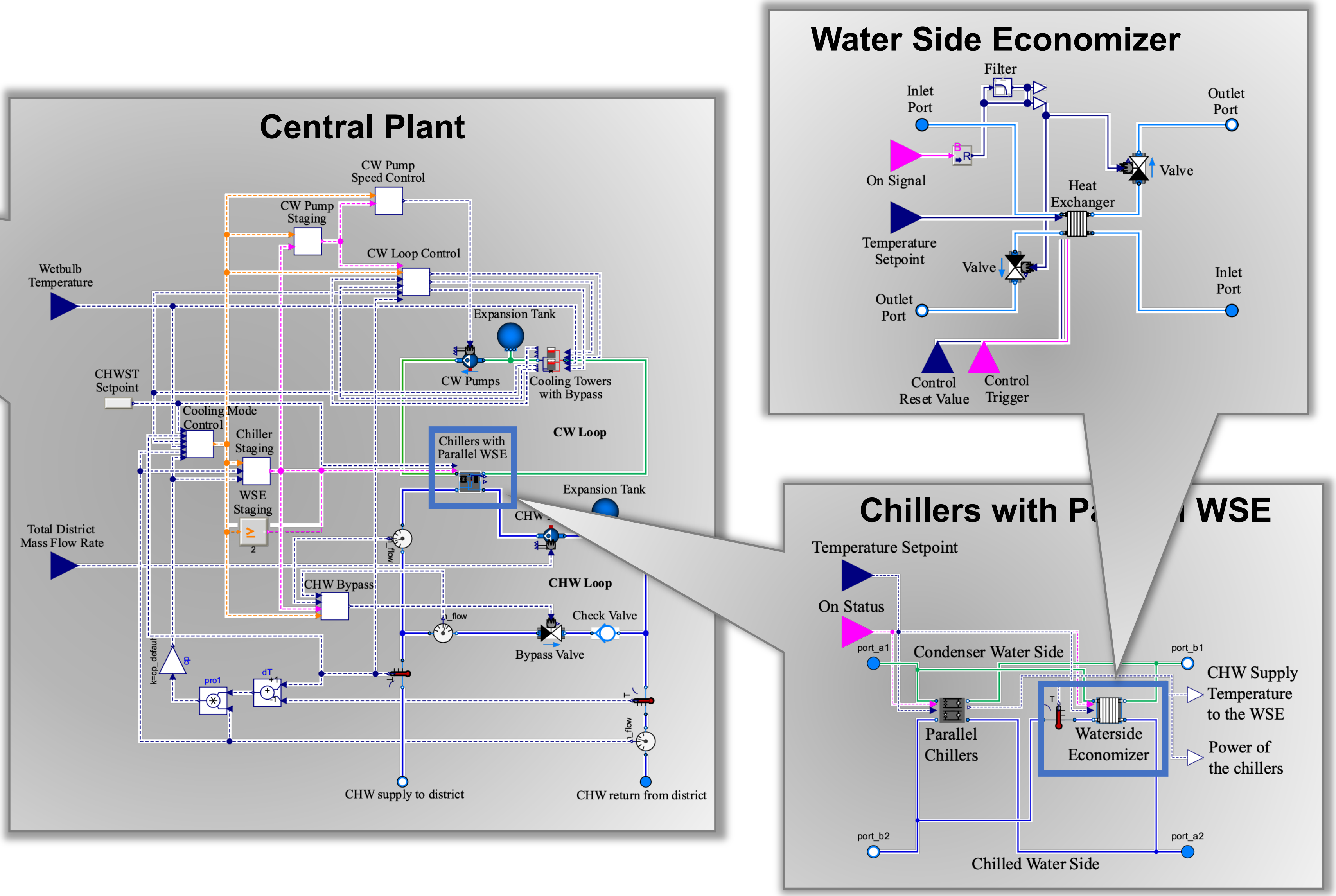




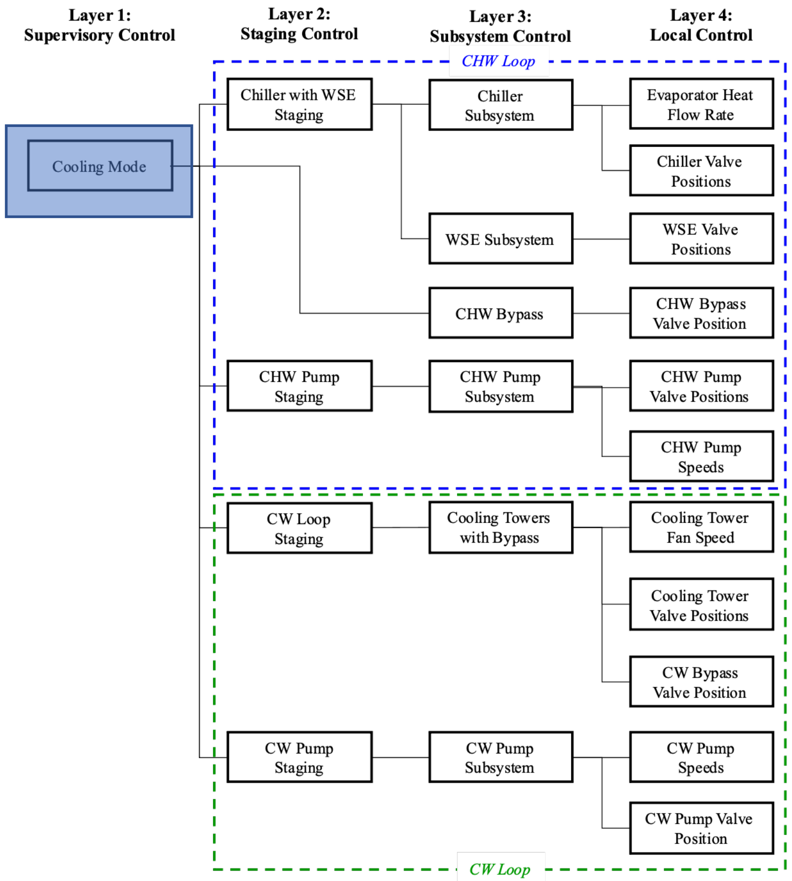
Central Plant



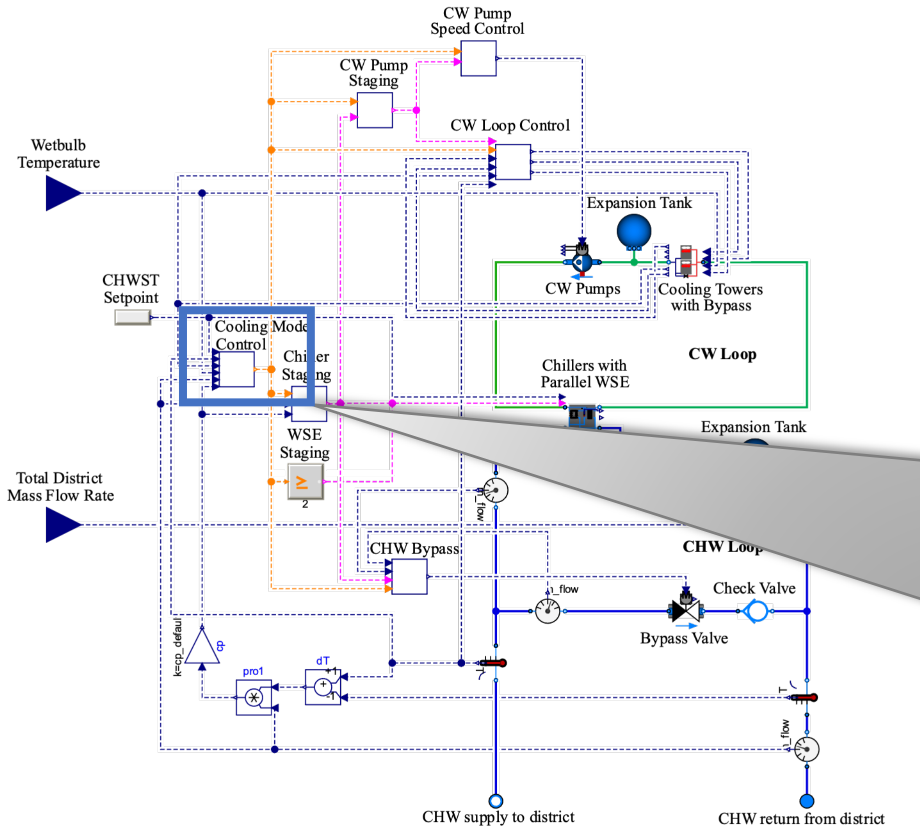
System Schematic

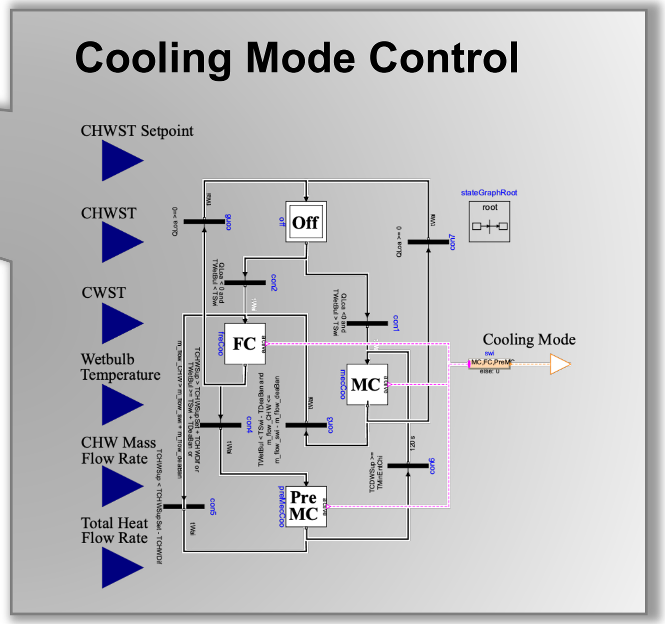


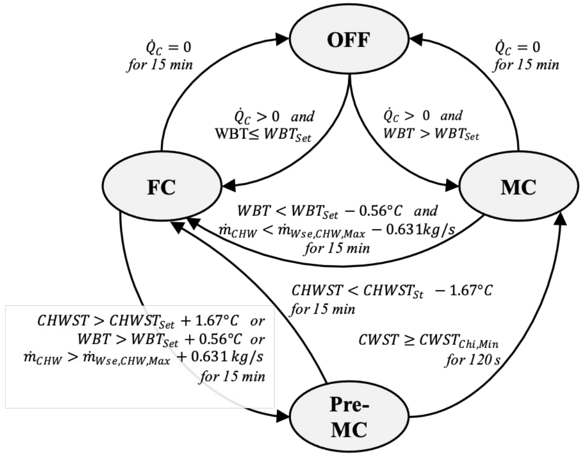
Control Layer 1: Cooling Mode Control



Central Plant

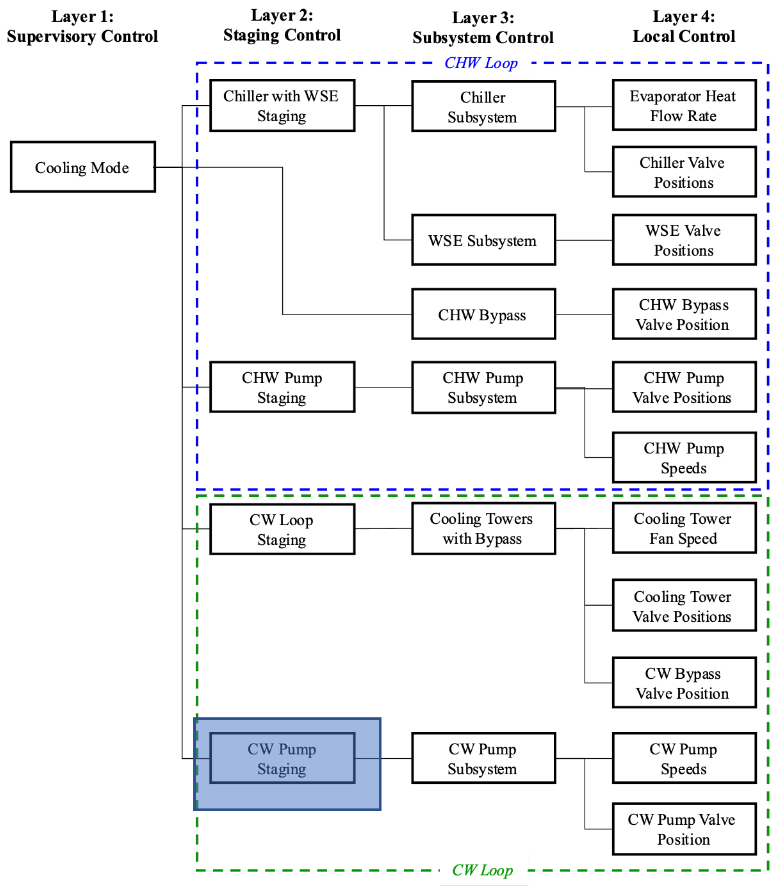


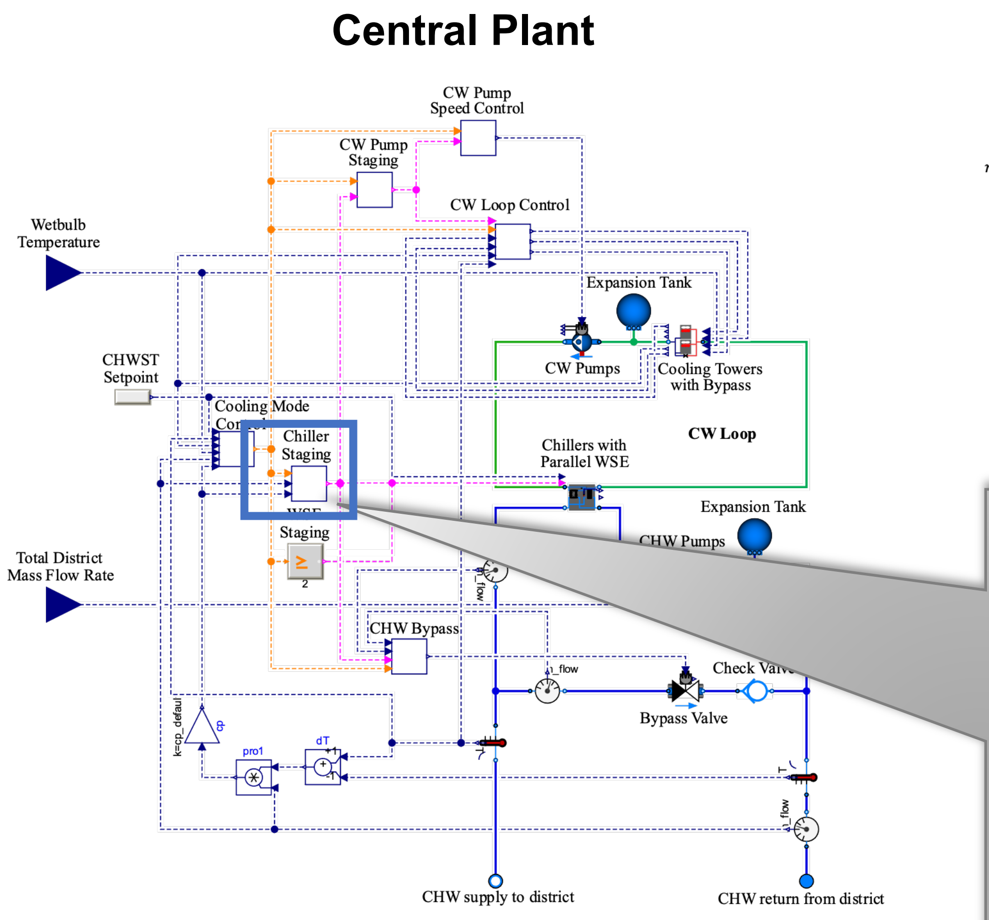


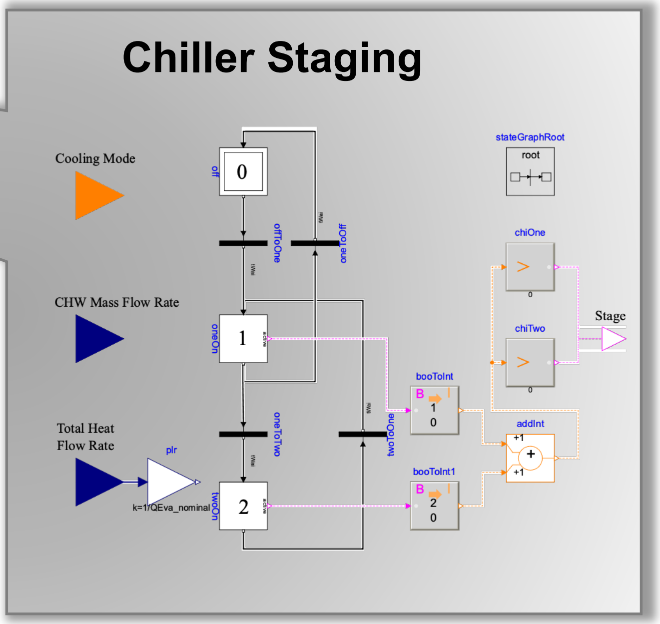


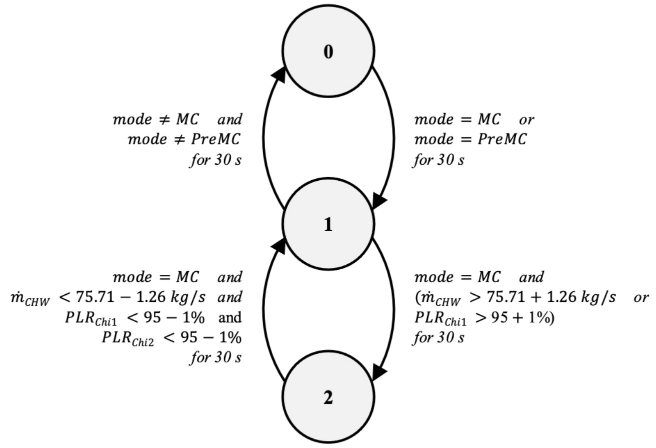
State Graph

Control Layer 2: Chiller Staging Control



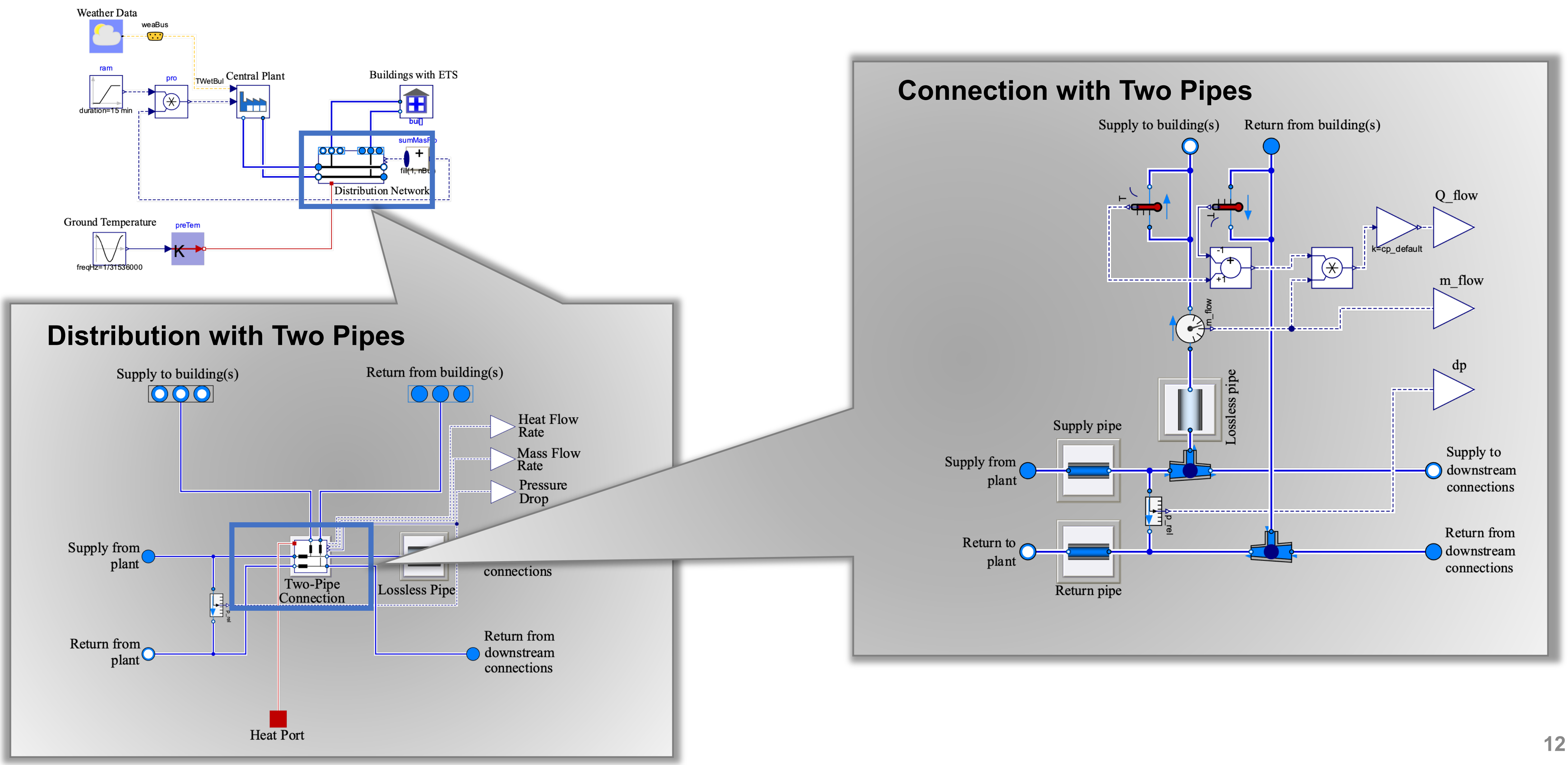




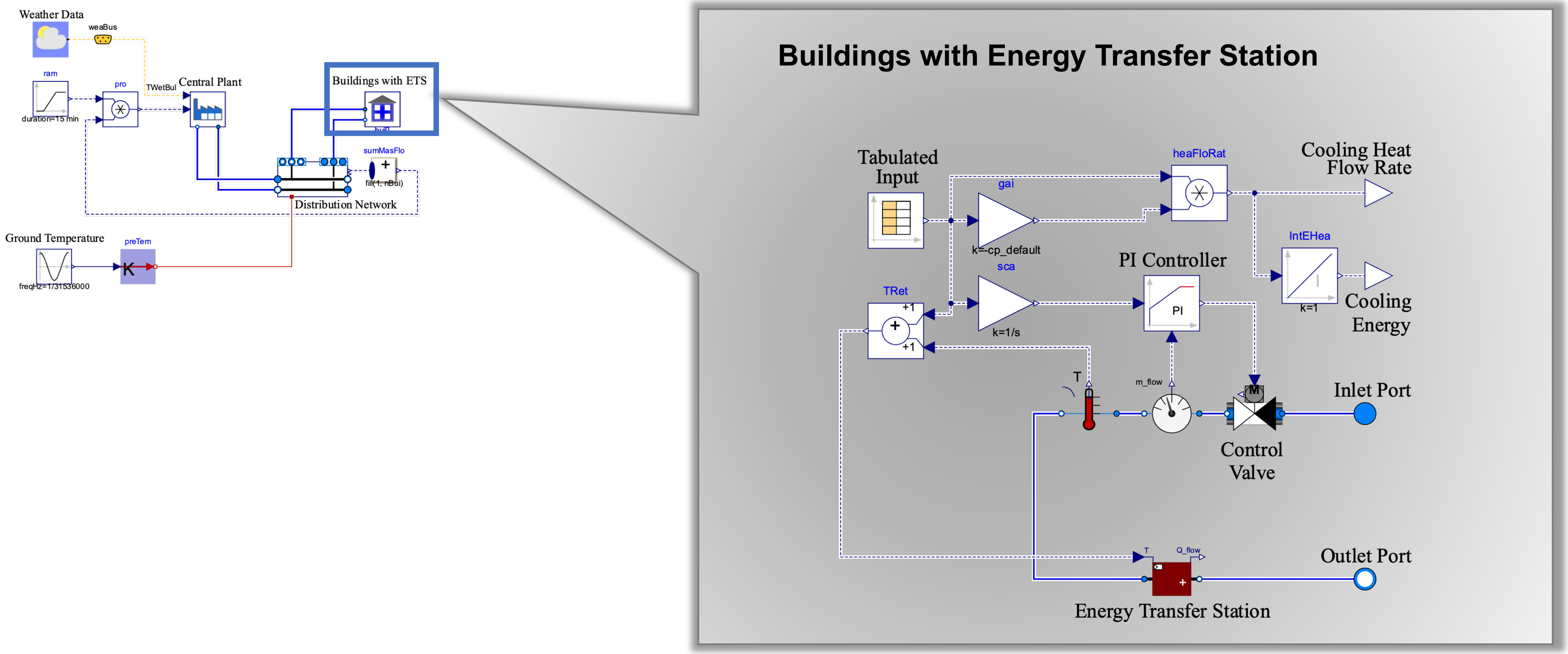


State Graph

Distribution Network



Buildings with Energy Transfer Station



Validation of Models

Location	CVRMSE (%) Acceptable range: [0,30%]				NMBE (%) Acceptable range: [–10,10%]			
	$\dot{Q}_{CHW}$	$\dot{m}_{CHW}$	T_{CHWS}	T_{CHWR}	$\dot{Q}_{CHW}$	$\dot{m}_{CHW}$	T_{CHWS}	T_{CHWR}
Plant	18.8	12.9	0.3	0.2	9.7	7.4	–0.1	–0.1
Chiller	22.2	15.5	0.2	0.3	8.7	7.4	–0.1	–0.1
Building 1	2.2	0.7	0.2	0.2	0.04	1.1	0.1	0.2
Building 2	2.4	0.1	0.2	0.2	0.02	0.6	–0.01	–0.02
Building 3	3.6	0.4	0.3	0.3	0.02	0.8	0.2	0.2
Building 4	1.3	0.7	0.2	0.2	–0.02	–0.1	0.04	0.04
Building 5	1.6	0.4	0.2	0.2	0.04	0.4	0.08	0.07
Building 6	2.2	0.5	0.2	0.2	–0.05	0.5	0.01	0.01

CVRMSE (Coefficient of Variation of the Root Mean Square Error)

$$\text{CVRMSE} = \frac{\sqrt{\frac{\sum (y_i - \hat{y}_i)^2}{N-1}}}{\bar{y}}$$

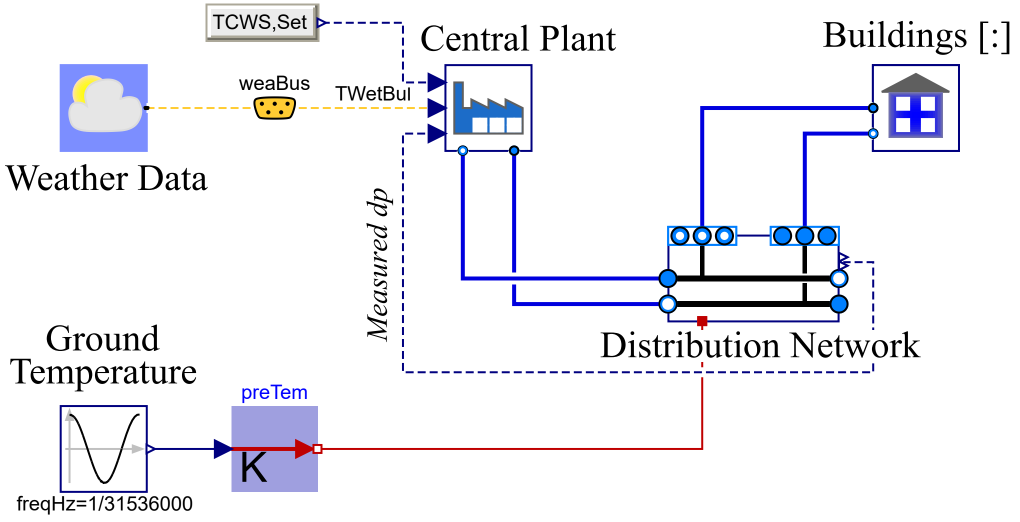
Normalized Mean Bias Error

$$\text{NMBE} = \frac{\sum (y_i - \hat{y}_i)}{(N-1)\bar{y}}$$

Acceptable range is based on ASHRAE Guideline 14

Model-Based System Optimization

- Condenser Water Supply Temperature
- Condenser Water Flow Rate
- Waterside Economizer



CW Supply Temperature Setpoint Optimization

Optimization Problem

Total plant energy

$$\min_{x \in [\underline{x}, \overline{x}]} E_{Pla,i}\left(T_{CW,set}(x)\right)$$

Condenser water supply temperature setpoint

$$E_{Pla,i} = \int \Big(P_{CH}\big(T_{CW,set}(x), s\big) + P_{CWP}\big(T_{CW,set}(x), s\big) + P_{CHWP}\big(T_{CW,set}(x), s\big) + P_{CT}\big(T_{CW,set}(x), s\big)\Big)\, ds$$

Power of the:

(chillers)

(CW pumps)

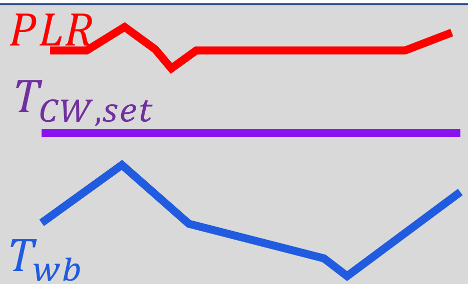
(CHW pumps)

(cooling towers)

Setpoint Methods

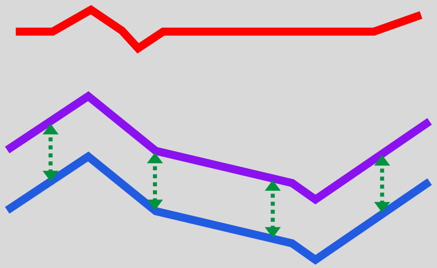
Constant Setpoint

$T_{CW,set} = constant$



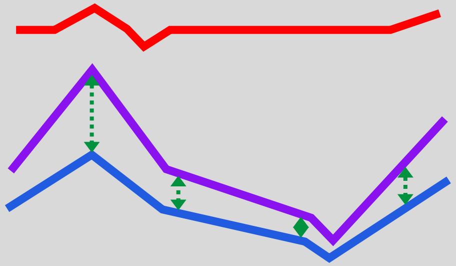
Fixed Approach

$T_{CW,set} = T_{wb} + T_{app}$



Adjusted Approach

$T_{CW,set} = T_{wb} + \left(T_{app} + r_{PLR} PLR\right)$



Results of Optimizing Condenser Water Supply Temperature

$$T_{CW,set}(x_1) = x_1,$$

$$T_{CW,set}(x_1) = T_{wb} + x_1,$$

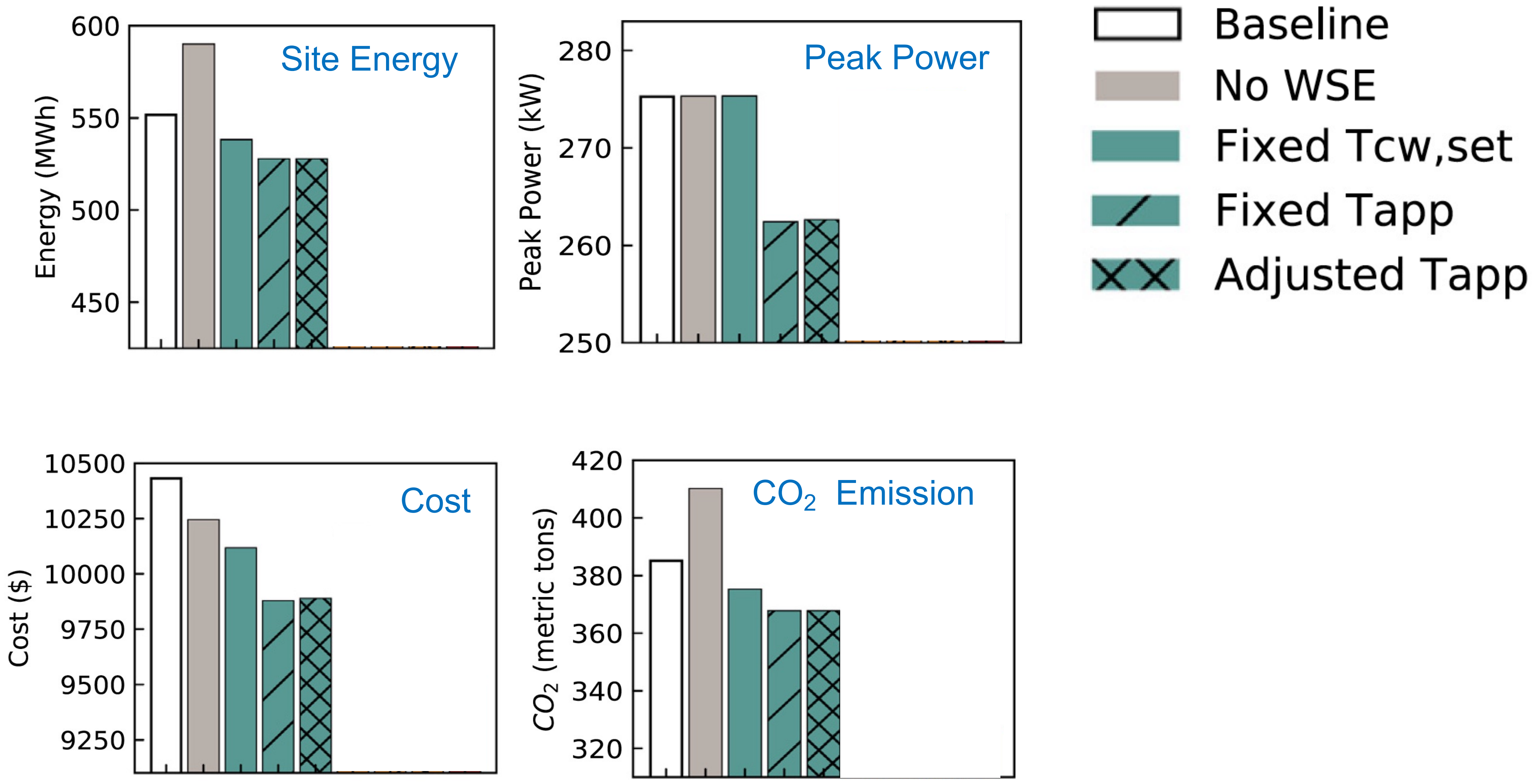
$$T_{CW,set}(x_1, x_2) = T_{wb} + x_1 + x_2\,\mathrm{PLR}$$

Table 4

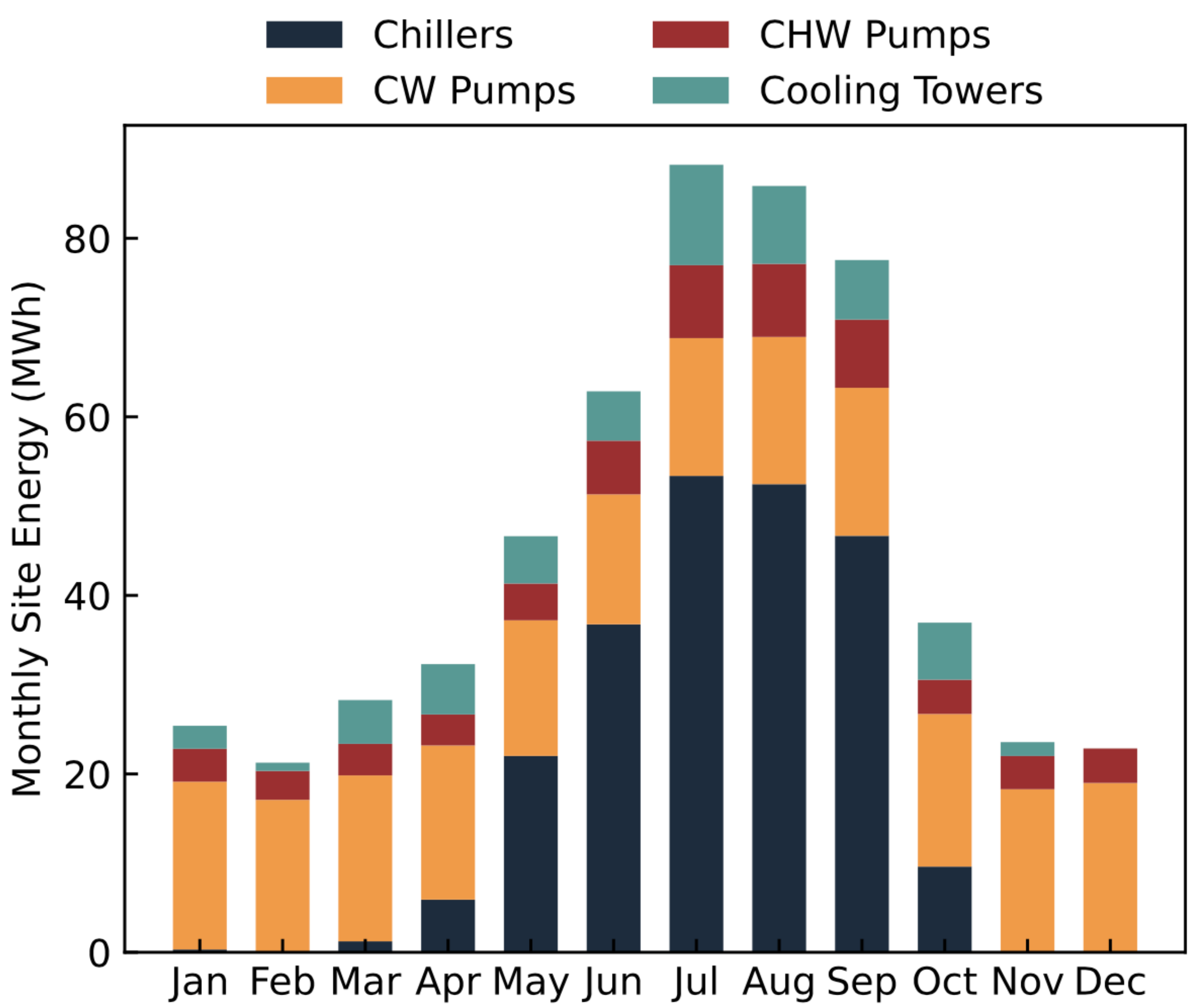
Condenser water supply temperature optimization results.

Case	Optimized x		Energy	Savings
	Variable	Value	(MWh)	(%)
Baseline (no optimization)	x_1	15.6 °C	551.8	–
Fixed $T_{CW,set}$	x_1	18.7 °C	537.9	2.5
Fixed T_{app}	x_1	1.9 °C	527.5	4.4
Adjusted T_{app}	x_1	2.1 °C	527.5	4.4
	x_2	−0.44		

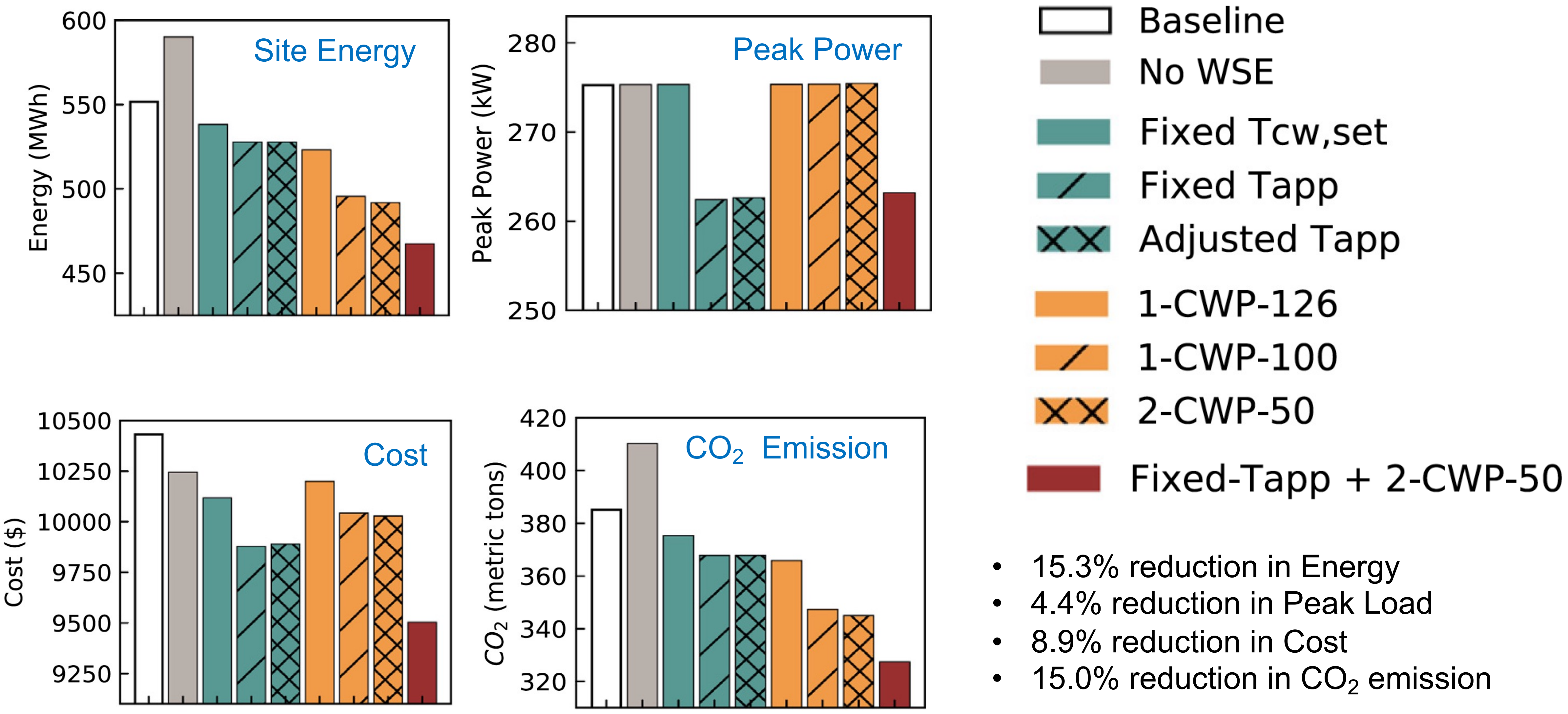
Summary of Results



In baseline, pumps contribute significantly to site energy use



Summary of Results: Condenser water pump flow reduction



- 15.3% reduction in Energy
- 4.4% reduction in Peak Load
- 8.9% reduction in Cost
- 15.0% reduction in CO_2 emission

Conclusion

- Developed open source models for the Modelica Buildings for the design and operation of district cooling systems

- Case study shows significant reductions in terms of energy (15.3%), cost (8.9%) and CO_2 emission (15%).

Reference

K. Hinkelman, J. Wang, W. Zuo, A. Gautier, M. Wetter, C. Fan, N. Long. 2022. “Modelica-Based Modeling and Simulation of District Cooling Systems: A Case Study.” Applied Energy, 311, pp.118654.

Questions?

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