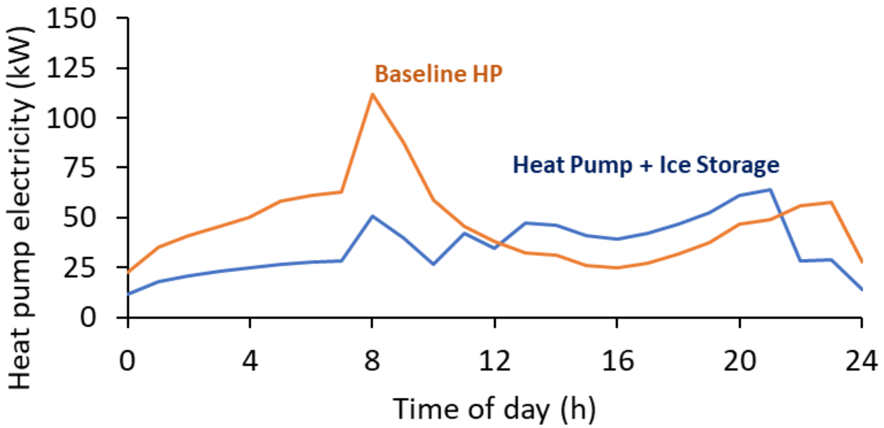
Ice storage for efficient and flexible decarbonization of hydronic space heating



National Renewable Energy Laboratory
Jason Woods, Senior Research Engineer
303.441.9727; jason.woods@nrel.gov
WBS 3.2.2.56

Project Summary

Objective and outcome

This project will develop optimal sizing and control for ice storage for both heating and cooling, and it will demonstrate the efficiency and load shifting potential with modeling and hardware-in-the-loop experiments.

The outcome will be a clear path for deploying these systems in buildings, providing low-carbon heating and cooling.

Team and Partners

Trane Technologies

Stats

Performance Period: 01/01/2023-12/31/2025

DOE budget: $1,400k, Cost Share: $150k

Milestone 1: Model complete and initial scenario (prior to optimization) showing at least 10% energy savings and 25% load reduction

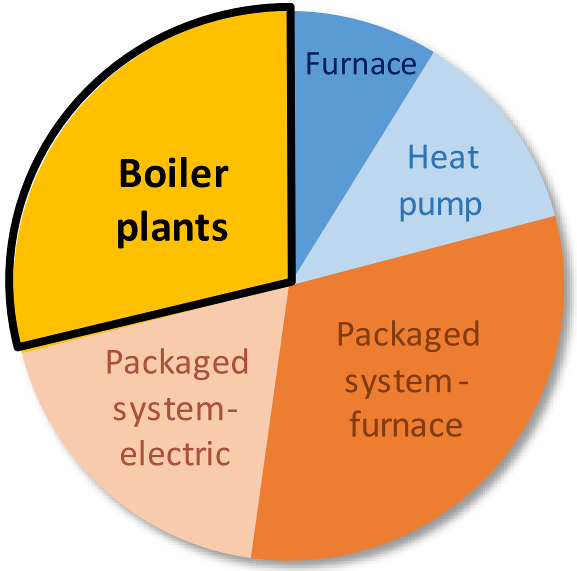
Milestone 2: Optimal system size and controller operation determined for chosen use case. Compare modeled performance to target of >20% energy savings and >50% peak demand reduction

Milestone 3: Hardware-in-the-Loop experiment results showing system operation and integrated supervisory control achieves 20% energy savings and 50% peak demand reduction

Problem

- Decarbonization requires a shift away from fuel-fired equipment.
- **30% of commercial-building floorspace** is heated by a boiler, most often with natural gas.

- Switching to heat pumps means these hydronic systems can be powered by clean electricity (from renewables onsite or the electric grid), but the following barriers are preventing their use:
  1. Heat pumps have significantly **lower efficiency and lower heating capacity at cold temperatures**, with back-up electric heating elements lowering efficiency further.
  2. Peak heating demand is in the early morning hours, **when efficiency is lowest, the grid is most strained in the winter, and wind or solar generation is the lowest**.

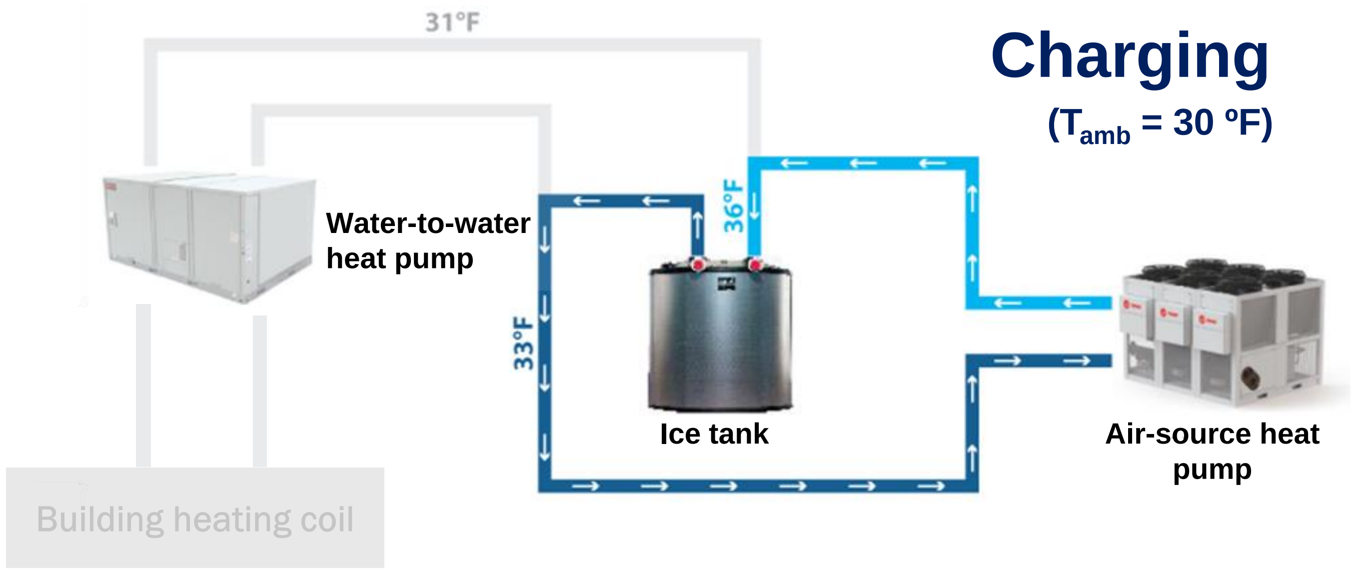


U.S. commercial building heating system by floor area

Alignment and impact

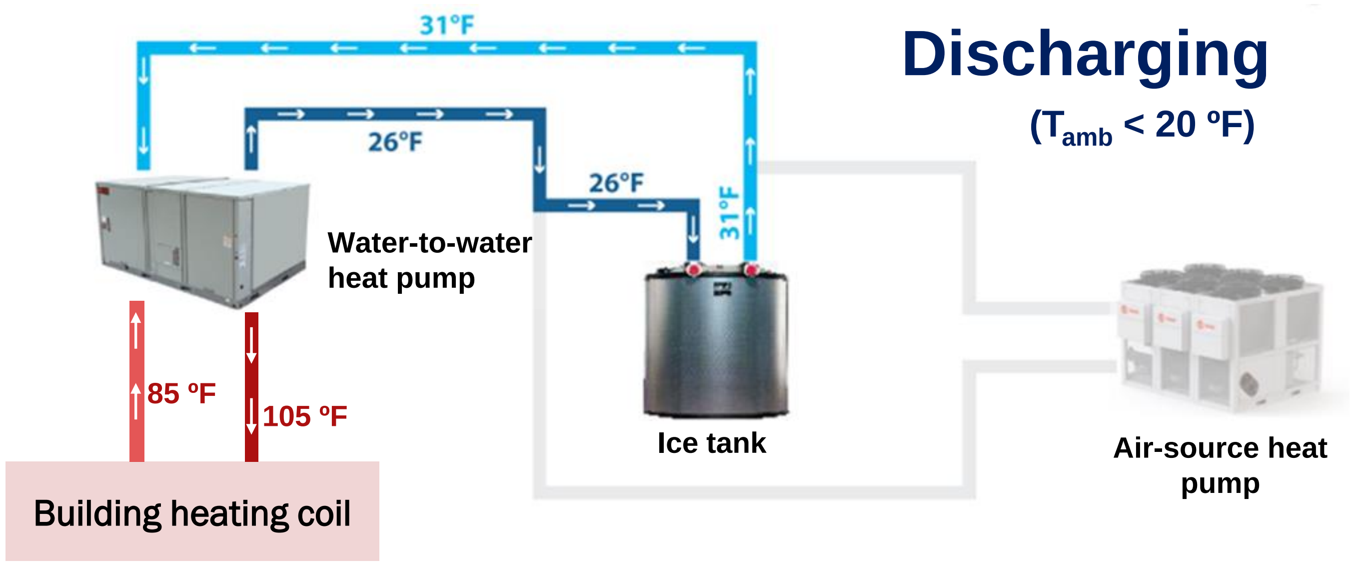
Proposed technology: Couple ice storage with heat pumps in hydronic systems to:

- **Reduce peak demand**
- **Reduce energy use**



Charging

(T_{amb} = 30 ºF)



Discharging

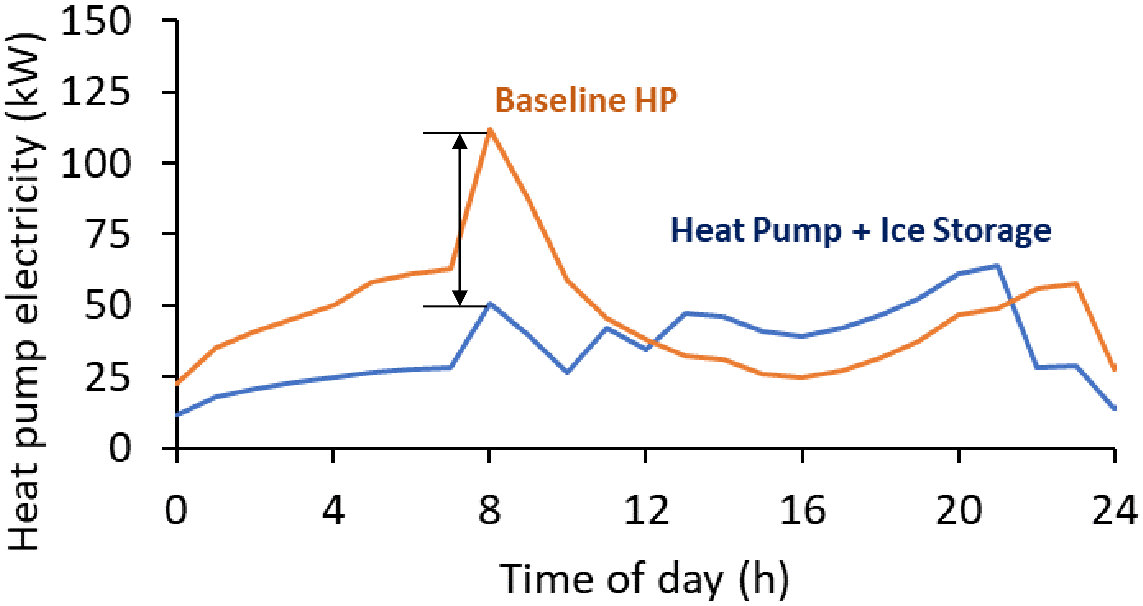
(T_{amb} < 20 ºF)

Alignment and impact

Proposed technology: Couple ice storage with heat pumps in hydronic systems to:

- **Reduce peak demand** by operating the air-source heat pump during off-peak periods

- **Reduce energy use** by
    1. Shifting air-source heat pump operation to warmer ambient conditions and minimizing the use of electric-resistance backup



Preliminary analysis using load profile from EnergyPlus **large office** reference building.

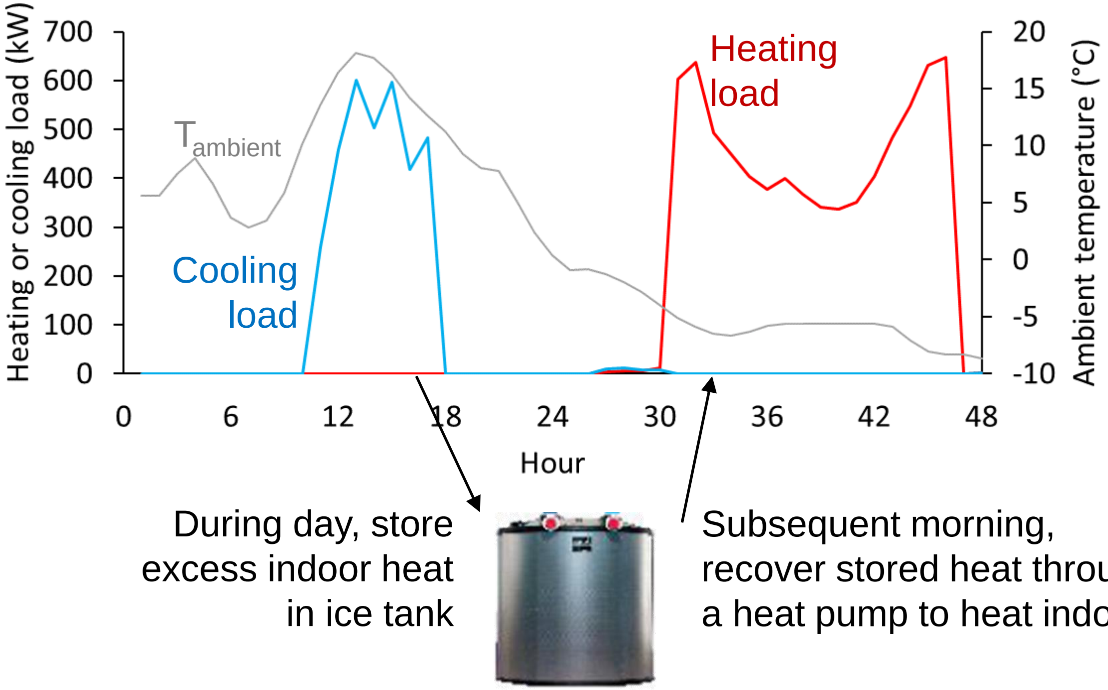
Alignment and impact

Proposed technology: Couple ice storage with heat pumps in hydronic systems to:

- **Reduce peak demand** by operating the air-source heat pump during off-peak periods
- **Reduce energy use** by
  1. Shifting air-source heat pump operation to warmer ambient conditions and minimizing the use of electric-resistance backup
  2. Recovering waste heat in the winter, which is normally exhausted outside through economizing

Preliminary analysis using load profile from EnergyPlus **large office** reference building.

	Heating demand (kW), % reduction	Heating energy (kWh_e), % reduction
3A	27%	4%
4A	41%	4%
5B	48%	12%
6A	58%	13%



During day, store excess indoor heat in ice tank

Subsequent morning, recover stored heat through a heat pump to heat indoors

Alignment and Impact

Connection to priorities towards DOE BTO 2050 vision

Accelerate building electrification

Enable cost-effective electrification without electric resistance backup by using ice thermal storage.

Transform the grid edge at buildings

Expand the use of flexible ice storage technology from summer-only use to both summer and winter

Prioritize equity, affordability, and resilience

Prioritize the deployment of this electrification technology in low-to-moderate income schools by working with school districts, electric utilities, and community-based organizations

Long-term Impact:

- Grid-connected heat pump with ice storage system providing year-round flexibility, resilience, improved heating efficiency, and lower CO_2 emissions.

Approach

Outcome 1: A design and optimal control strategy for this heating and cooling plant with ice storage

Develop modeling platform for ice storage for heating and cooling

- Create new model in EnergyPlus for a heating and cooling plant with ice storage
- Leverage Python user-defined components

Develop optimal control

- Develop a model-predictive control (MPC) algorithm to find the optimal dispatch for ice-storage heating and cooling central plant

Evaluate sizing and control method through modeling

- Determine optimal equipment sizes and calculate annual energy and operating cost in multiple climates:
  - Baseline scenario (no storage)
  - Ice storage heating and cooling with typical controls
  - Ice storage heating and cooling with MPC

Approach

Outcome 2: Demonstrated efficiency, load shifting potential, and optimal controls with real equipment and supervisory controller

Setup heat pump + ice storage system at NREL

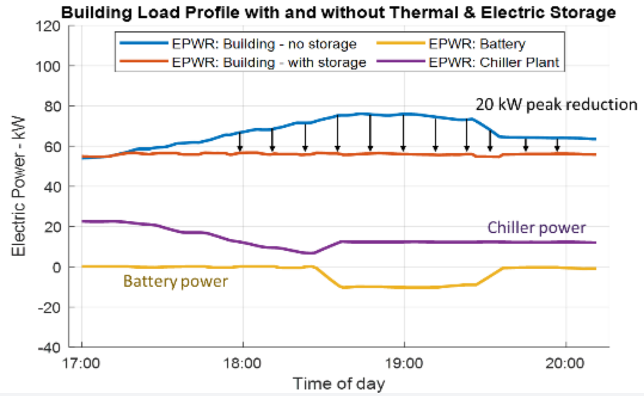
- Modify existing cooling-only system to a heating and cooling plant

Implement supervisory controller in the lab

- Create supervisory controller using MPC to determine optimal equipment operation in real time in the laboratory

Perform hardware-in-the-loop experiment

- Demonstrate load flexibility and efficiency in both heating and cooling operation, and validate modeling



Approach - Advisory Group

- Engage diverse HVAC and energy efficiency perspectives to:
  - **Contextualize** barriers faced by commercial and community-serving, low-to-moderate income organizations (such as schools)
  - **Advise** on technology and system functionality
  - **Provide** ongoing input as the project evolves

Research questions that will be supported by the advisory group:

1. What are the barriers to implementing central heat pumps in low to moderate-income schools, and how could this technology address these barriers?
2. Can the operational demand reduction, energy savings, and load shifting capabilities of the technology be leveraged to address first cost barriers to low- to moderate-income school districts through the electric utility?

Photo from NREL

Progress – Advisory Group

- **Advisors engaged** to date include:
  - **School districts** serving disadvantaged students
  - **NGOs** providing need-based energy efficiency assistance
  - **HVAC design engineers**
  - **Large utility** professionals
  - **Electric co-op** professionals
  - **Equipment manufacturer** engineers and sales team

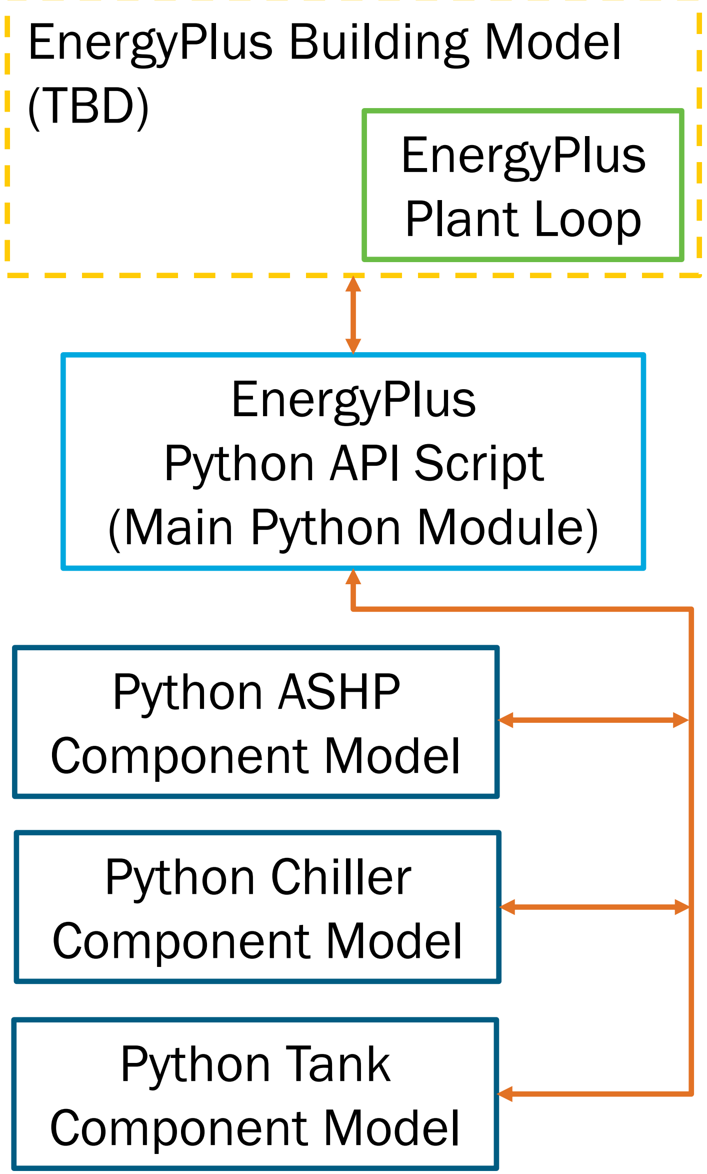
Dennis Schroeder, NREL

Outcome 1: Flexible Python-based simulation engine forms the foundation for optimal design and controls

Building simulation environment:
- Leverage EnergyPlus as the simulation engine
- Use EnergyPlus' built-in plant loop and its components, where possible (pumps, heat exchangers, cooling/heating coils, etc.)
- Employ user-defined (Python) components for custom/novel equipment and controls
- Plant loop + Python model can be connected to any building model with hydronic systems

EnergyPlus and Python (dynamic system integration)

Simulation Environment



EnergyPlus Building Model (TBD)

EnergyPlus Plant Loop

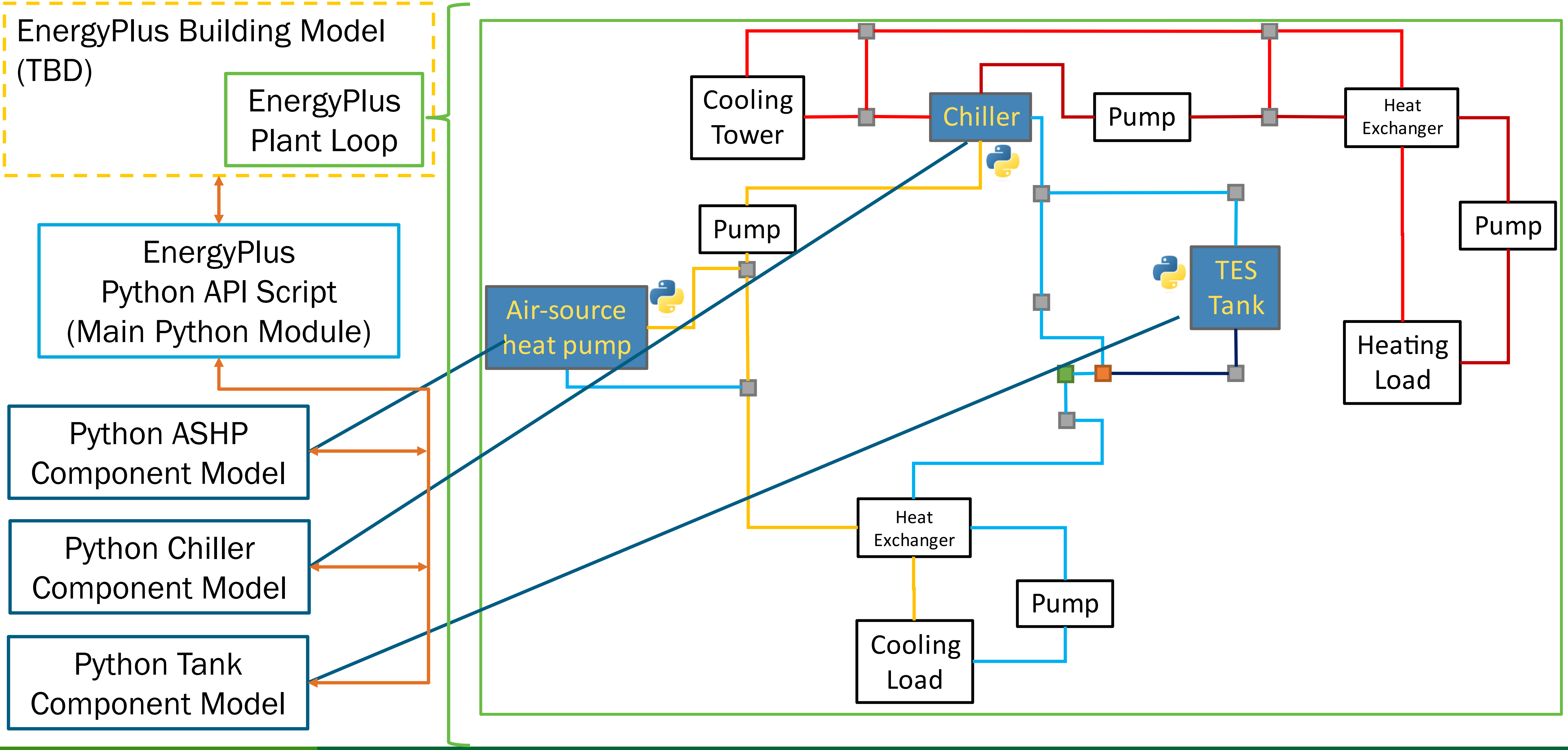
EnergyPlus Python API Script (Main Python Module)

Python ASHP Component Model

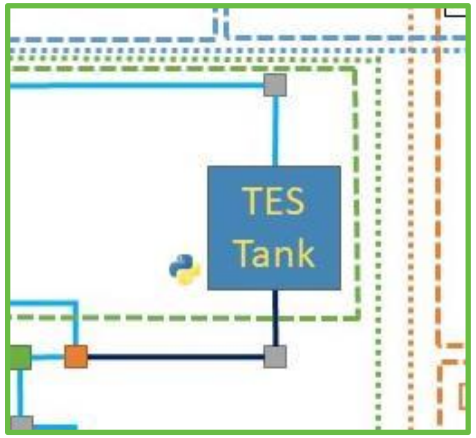
Python Chiller Component Model

Python Tank Component Model

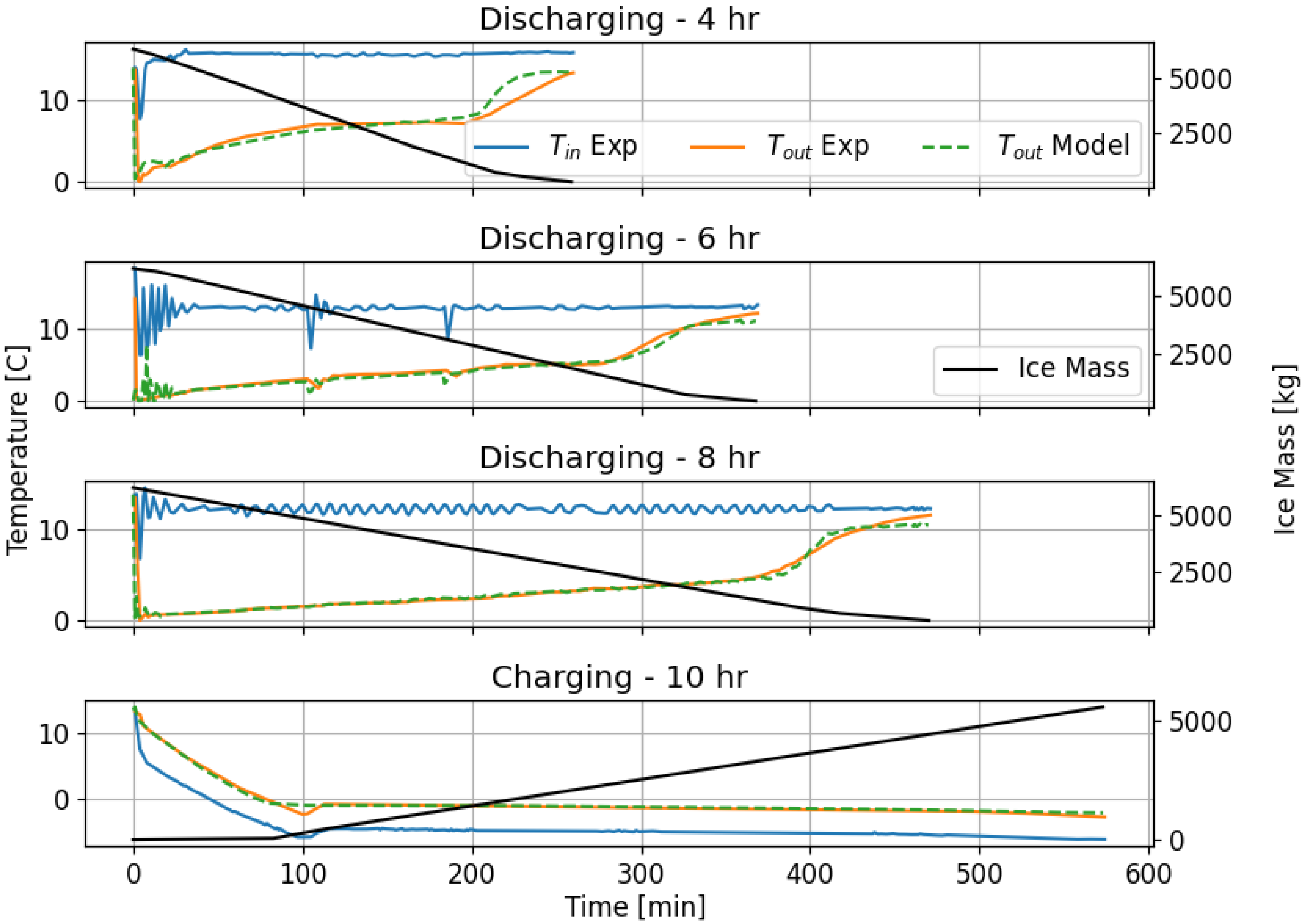
User-defined python components allow for unique plant-loop integration in EnergyPlus



Example: Custom Python model for ice tank



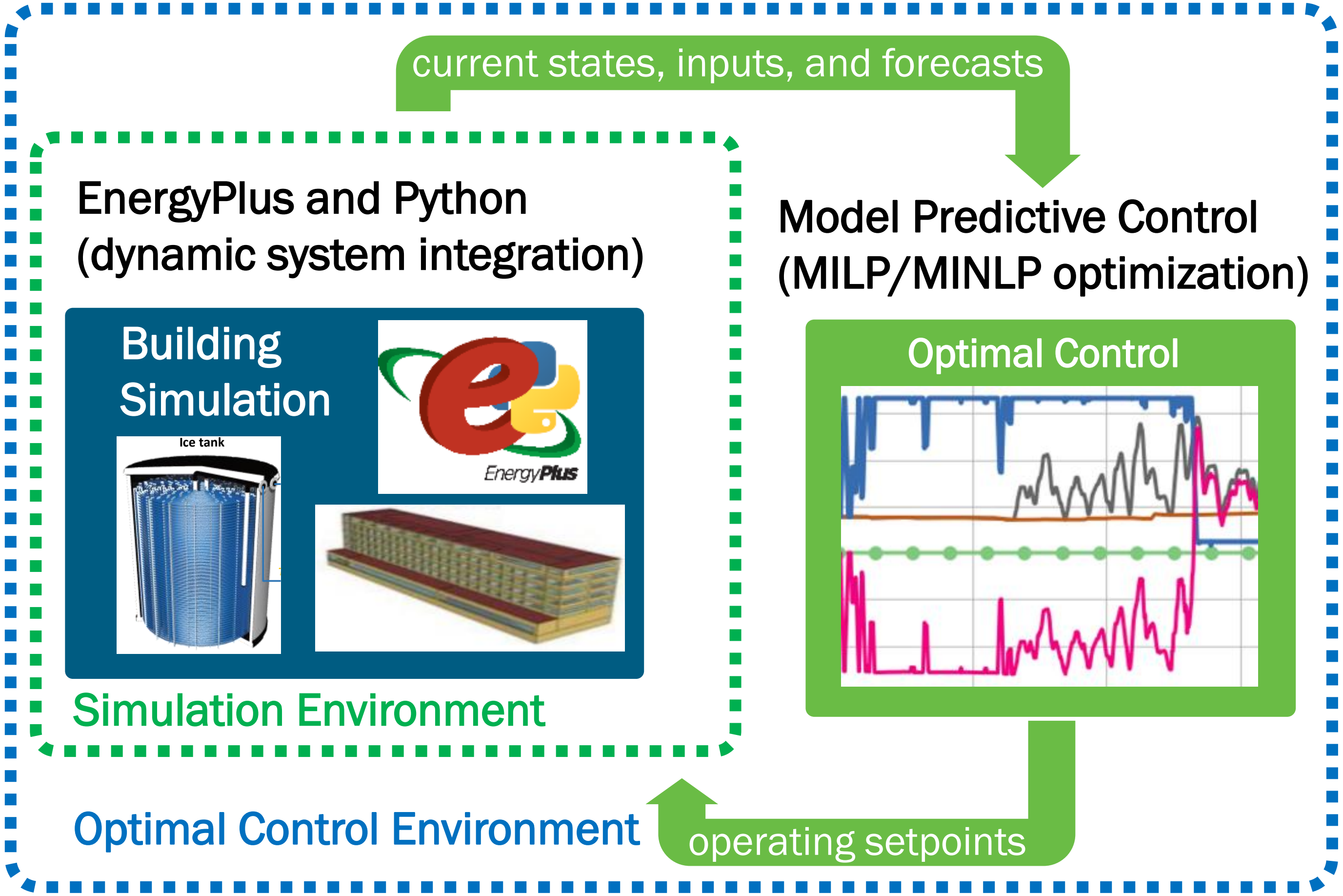
Model Validation



Custom Python Ice Tank Model

- Developed standalone Python-based model of ice-on-coil tank modeling bulk physics:
  - Lumped capacitance of PCM
  - Effectiveness-NTU heat exchange model
- Validate/calibrate data with experimental data sets. In this case, 3 discharging experiments and 1 charging experiment

The next layer integrates model predictive control for optimal dispatch



current states, inputs, and forecasts

EnergyPlus and Python (dynamic system integration)

Building Simulation

Simulation Environment

Model Predictive Control (MILP/MINLP optimization)

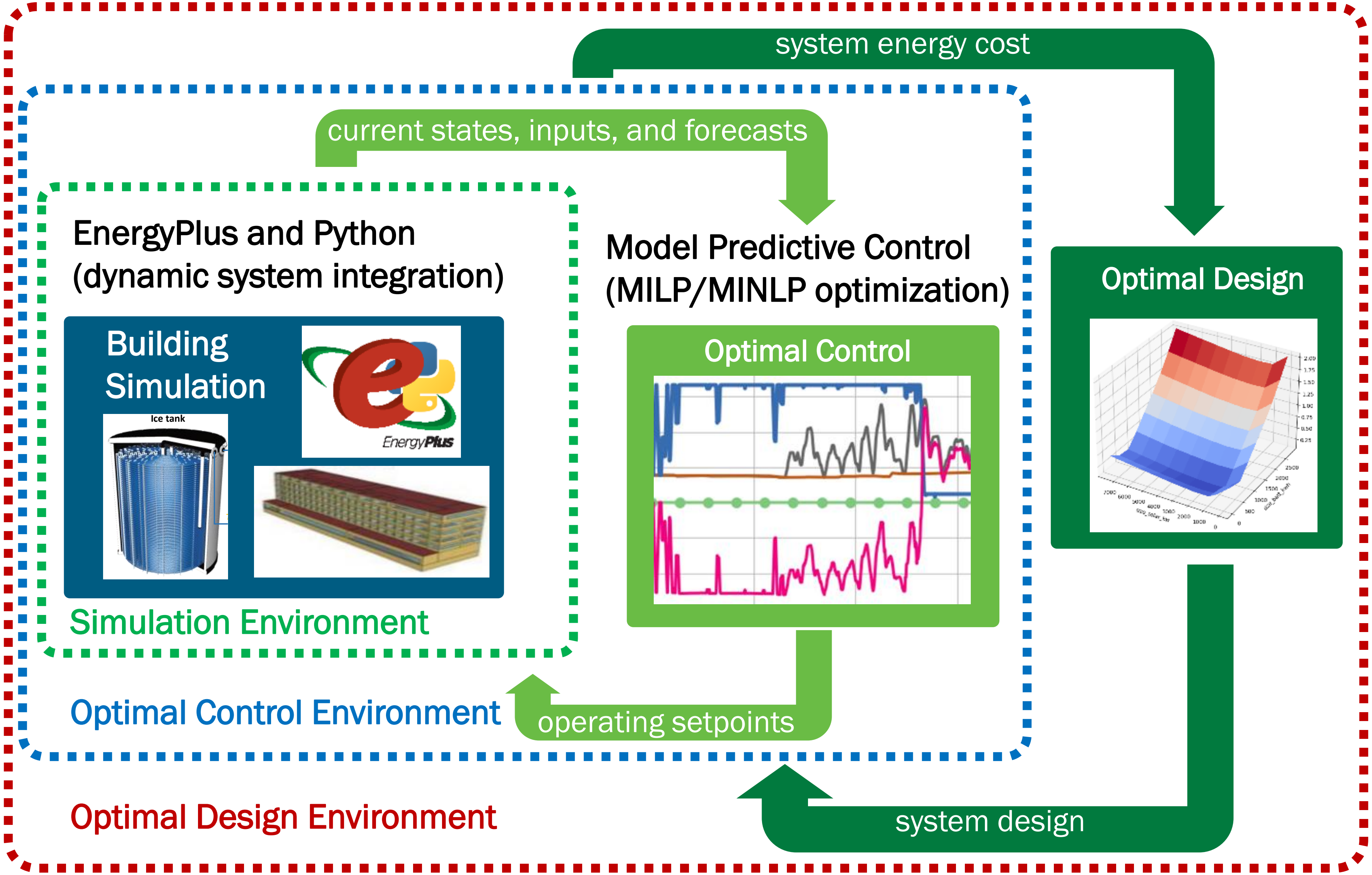
Optimal Control

Optimal Control Environment

operating setpoints

- For a given size and configuration, a model predictive control (MPC) algorithm will **minimize:**
  - **Total energy use**
  - **Electric utility costs**
  - **Greenhouse gas emissions**
- We will leverage prior work done by NREL on MPC for ice storage for cooling applications

The final layer optimizes the system design and sizing

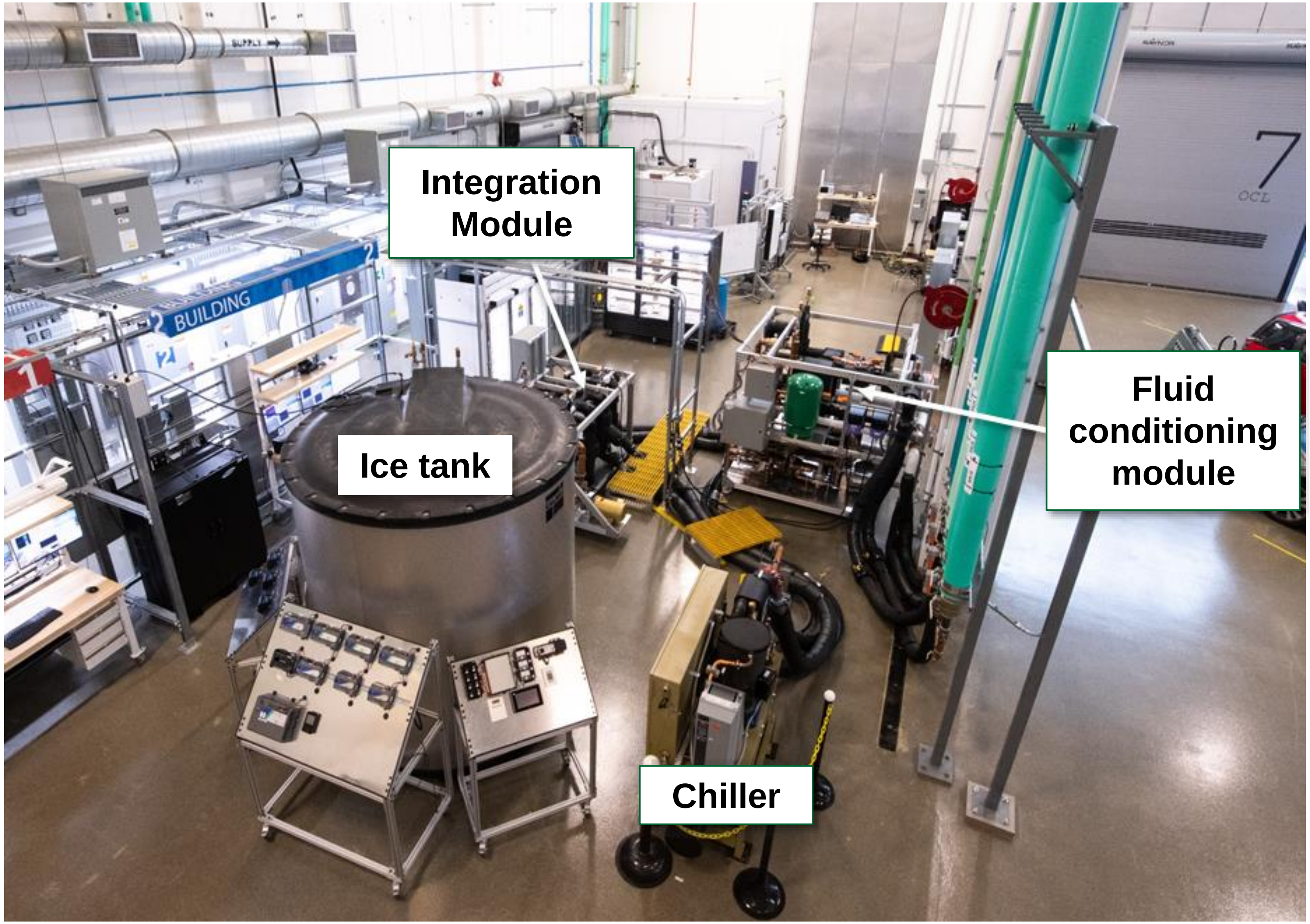


- Based on the optimal control for each size, a parameter sweep of system sizes will determine the **optimal tank and equipment sizing** that minimizes life-cycle costs

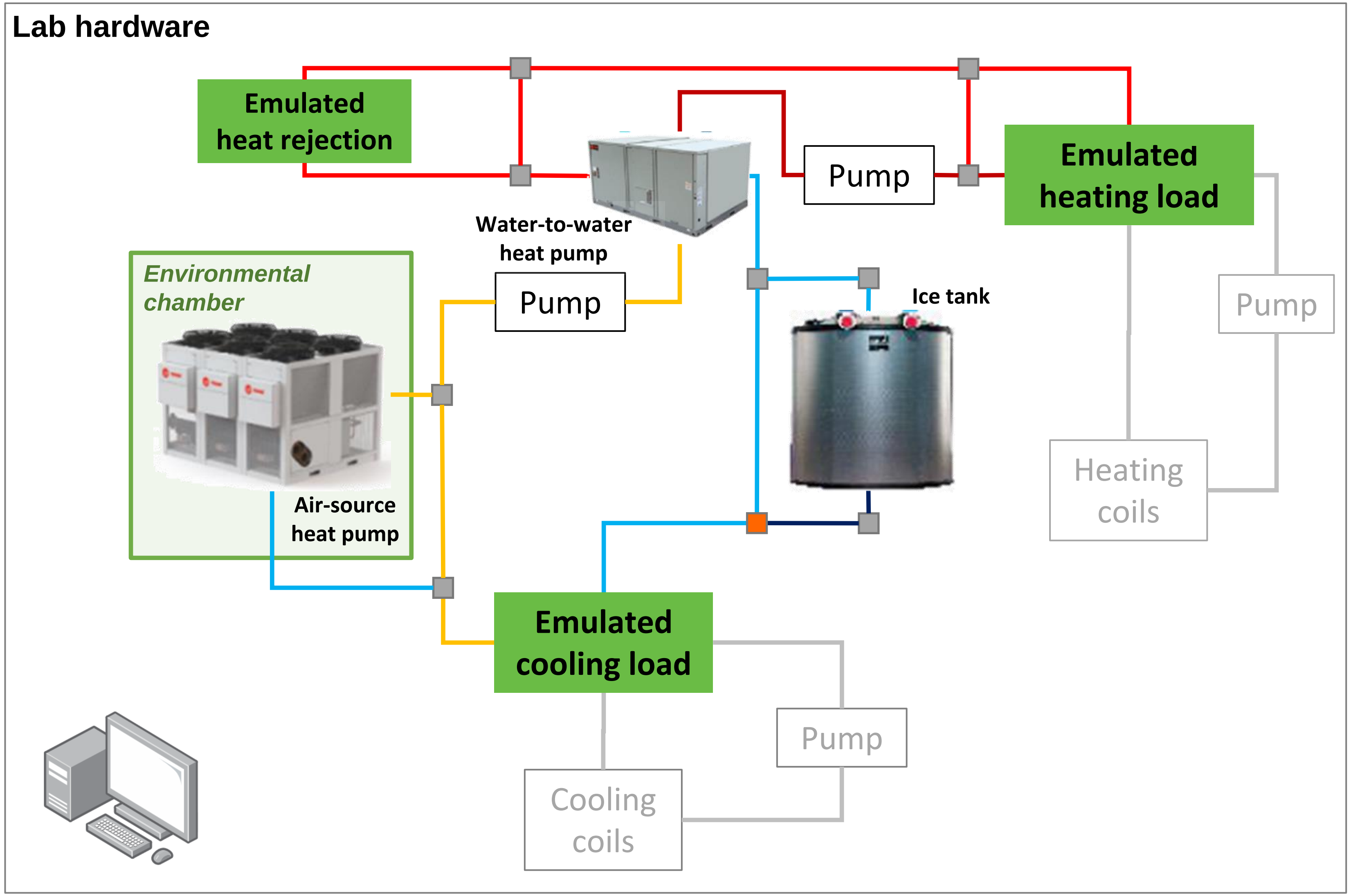
Outcome 2: Measure system performance in the lab, and validate modeled results

- **Existing equipment at NREL laboratory is designed for cooling operation**

- **We will update this to enable heating operation**
  - This also provides insight on the steps required for converting a central chiller plant to a central heating + cooling plant

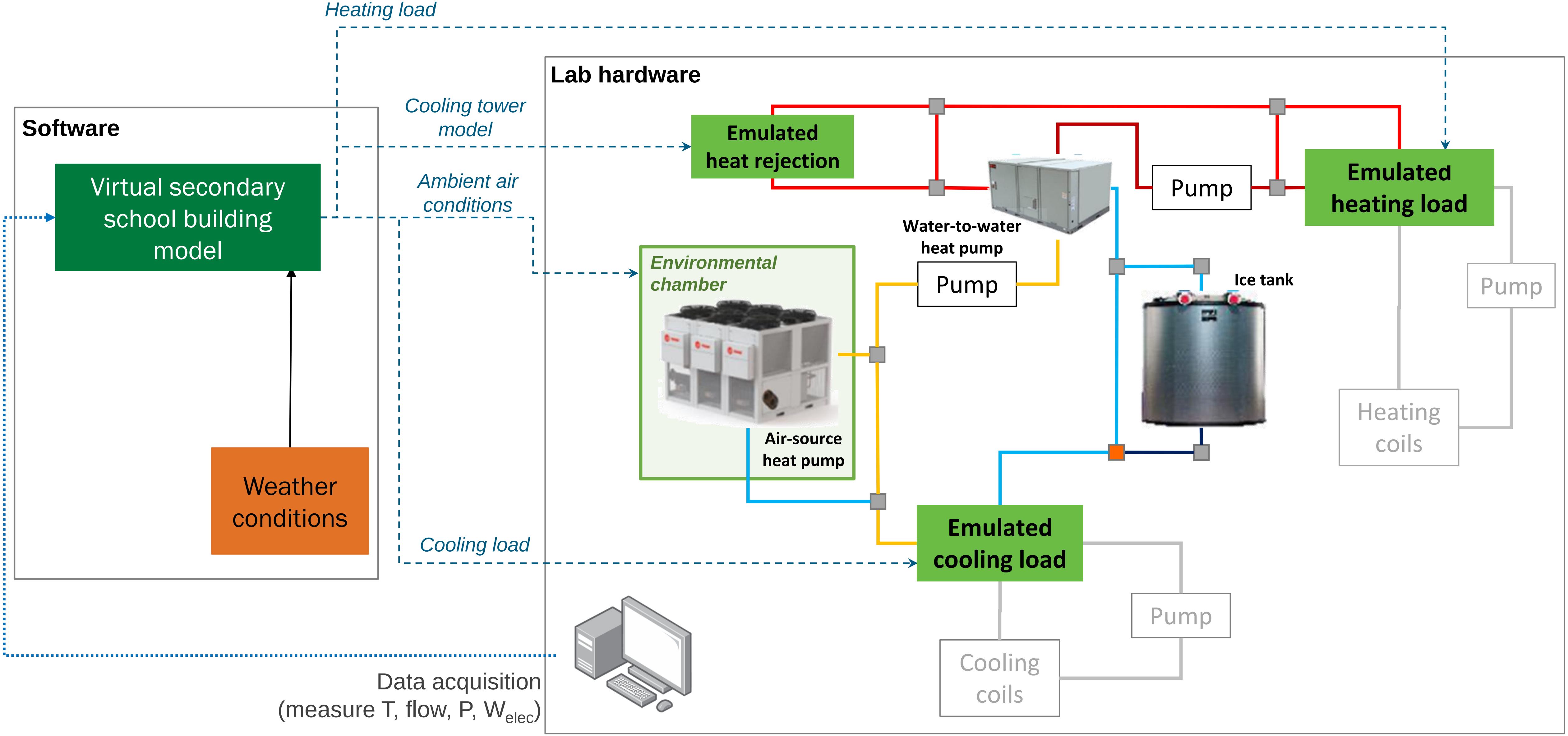


Experiments will include heat pump equipment and ice thermal storage tank

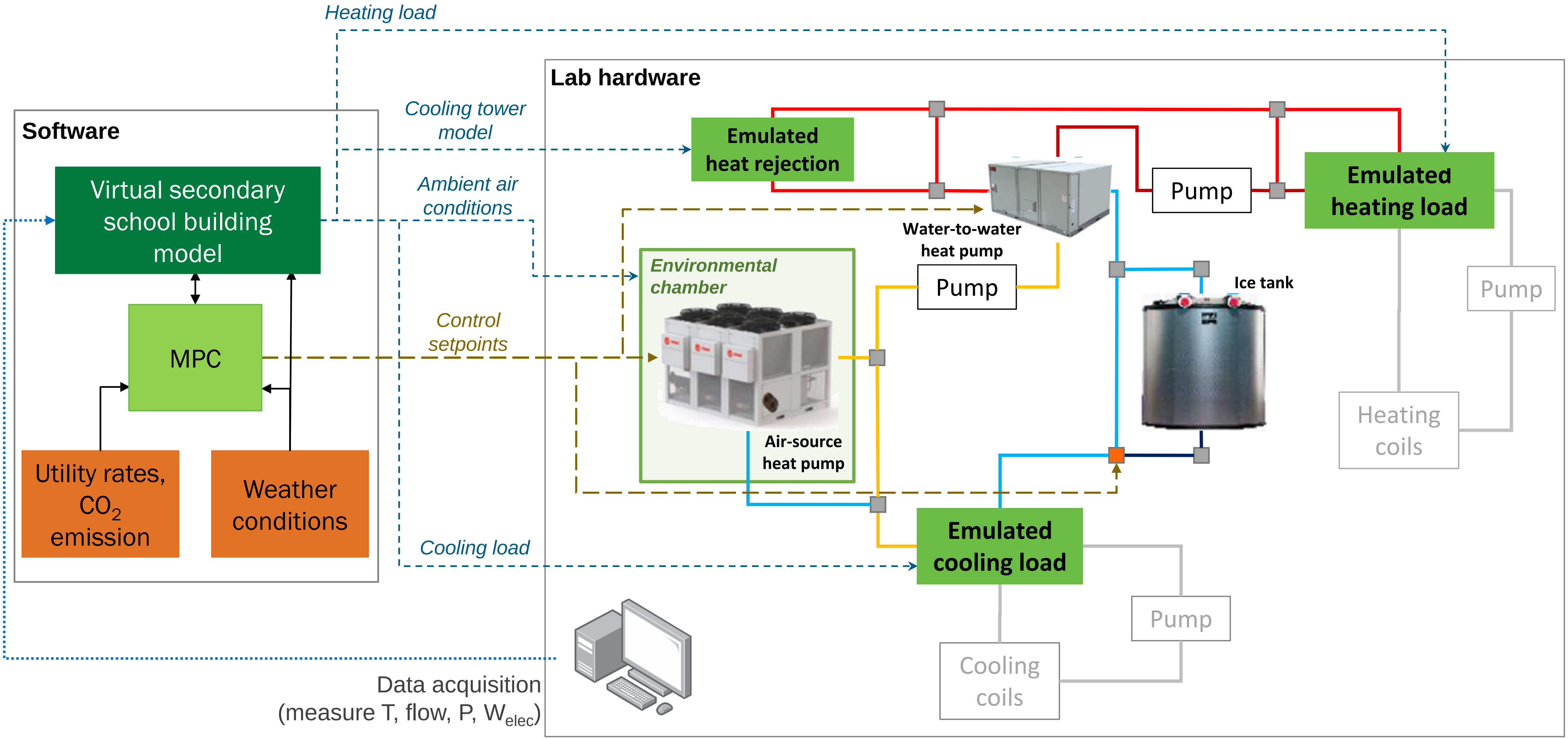


Data acquisition
(measure T, flow, P, W_{elec})

Performance will be measured while responding to emulated, realistic building loads



Model predictive controller will send control setpoints to equipment based on predicted building loads, utility rates, and grid CO_2 emissions profiles



Status summary and future work

- Completed three months of this 36-month project
- Modeling and design tasks will be largely complete midway through the project (months 1-18)
- Experimental tasks will take place the second half of the project (months 18-36)
- During the project, we will work with our advisory group to determine possible field demonstration site(s) for a potential follow-on project

Thank You

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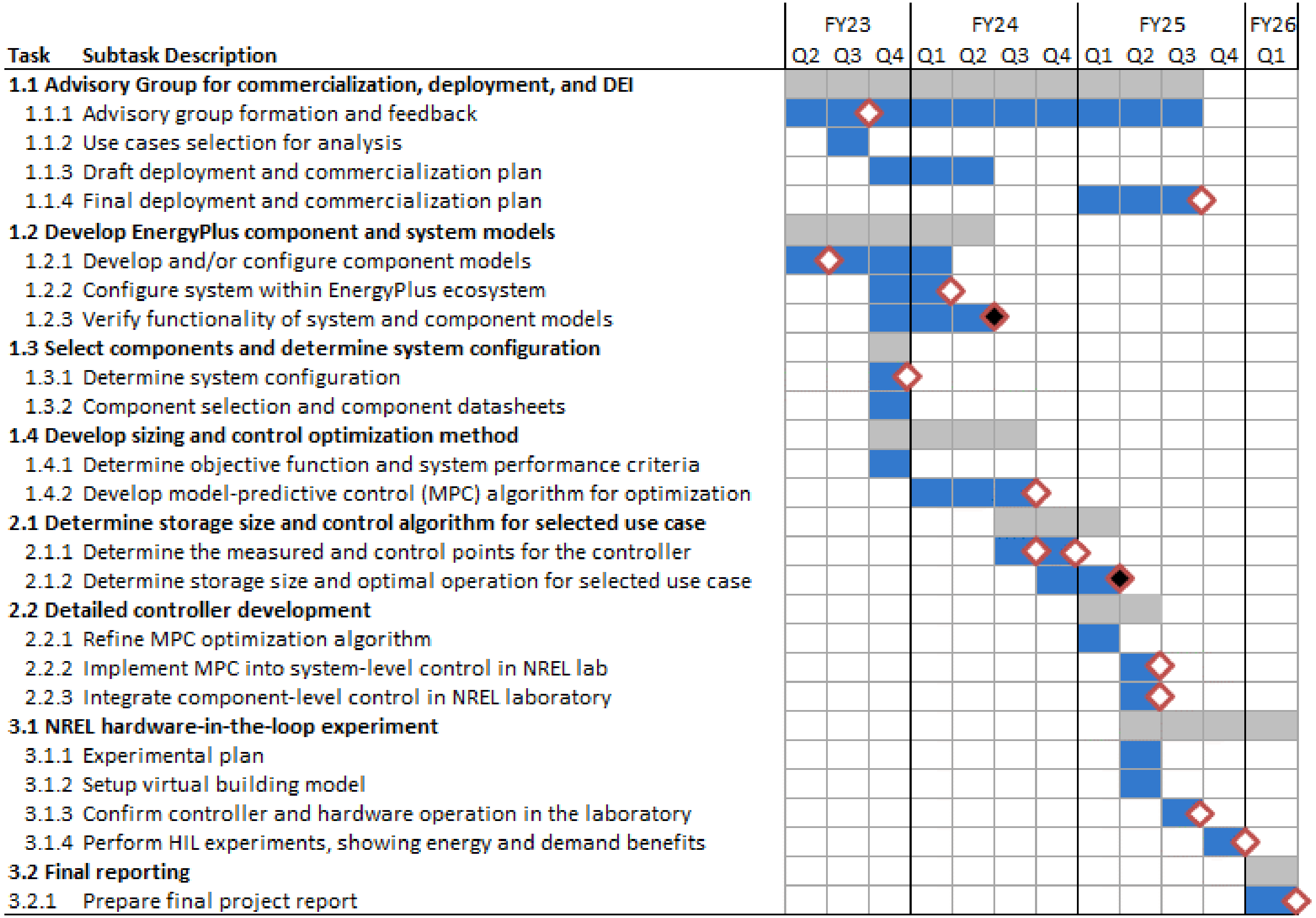
REFERENCE SLIDES

Project Execution – tasks and Gantt chart



Task	Subtask Description	FY23			FY24				FY25				FY26
		Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1
1.1	**Advisory Group for commercialization, deployment, and DEI**	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
1.1.1	Advisory group formation and feedback	🟦	🟦◇	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦		
1.1.2	Use cases selection for analysis		🟦										
1.1.3	Draft deployment and commercialization plan			🟦	🟦	🟦							
1.1.4	Final deployment and commercialization plan								🟦	🟦	🟦◇		
1.2	**Develop EnergyPlus component and system models**	▨	▨	▨	▨	▨							
1.2.1	Develop and/or configure component models	🟦◇	🟦	🟦	🟦								
1.2.2	Configure system within EnergyPlus ecosystem			🟦	🟦◇								
1.2.3	Verify functionality of system and component models			🟦	🟦	🟦◆							
1.3	**Select components and determine system configuration**			▨									
1.3.1	Determine system configuration			🟦◇									
1.3.2	Component selection and component datasheets			🟦									
1.4	**Develop sizing and control optimization method**			▨	▨	▨	▨						
1.4.1	Determine objective function and system performance criteria			🟦									
1.4.2	Develop model-predictive control (MPC) algorithm for optimization				🟦	🟦	🟦◇						
2.1	**Determine storage size and control algorithm for selected use case**						▨	▨	▨				
2.1.1	Determine the measured and control points for the controller						🟦◇	🟦◇					
2.1.2	Determine storage size and optimal operation for selected use case							🟦	🟦◆				
2.2	**Detailed controller development**								▨	▨			
2.2.1	Refine MPC optimization algorithm								🟦				
2.2.2	Implement MPC into system-level control in NREL lab									🟦◇			
2.2.3	Integrate component-level control in NREL laboratory									🟦◇			
3.1	**NREL hardware-in-the-loop experiment**									▨	▨	▨	▨
3.1.1	Experimental plan									🟦			
3.1.2	Setup virtual building model									🟦			
3.1.3	Confirm controller and hardware operation in the laboratory										🟦◇		
3.1.4	Perform HIL experiments, showing energy and demand benefits											🟦◇	
3.2	**Final reporting**												▨
3.2.1	Prepare final project report												🟦◇

◇ Milestone

◆ Go/No-Go decision point

Project Execution – milestones, deliverables, and Go/No-go decision points

M	Date	Milestone Description	Method to Verify Measurable Result
Complete			
1.1	FY23Q2	Component model implementation plan selected	1-page document describing plan such that it can calibrated to Trane data and integrates with EnergyPlus .idf
Current and future work			
1.2	FY23Q3	Advisory group formation complete	Advisory group member selection complete and meeting cadence established
1.3	FY23Q4	System configurations determined for further analysis	System configurations determined for each selected use case.
1.4	FY24Q1	System configuration in EnergyPlus complete	Model results show complete system configuration operates according to chosen use case
Go/No-Go 1 (FY24Q2): Functionality of system and component models are verified. Modeled scenario showing at least 10% energy savings and 25% load reduction (prior to optimization).			
2.1	FY24Q3	MPC algorithm development complete	Control algorithm results confirming functionality based on the chosen objective function for the determined use case
2.2	FY24Q4	Controller measurement and control point determination complete	Documented measurement and control point list for future laboratory integration
Go/No-Go 2 (FY25Q1): Optimal system size and controller operation determined for chosen use case. Compare modeled performance to target of >20% energy savings and >50% peak demand reduction			
3.1	FY25Q2	MPC algorithm integration with system control for laboratory experimentation complete	Communication test documenting controller integration within CBRI HIL experiment network
3.2	FY25Q2	Component level control integration for laboratory experimentation complete	Communication test documenting successful component integration within CBRI HIL experiment network
3.3	FY25Q3	MPC controller and hardware operation confirmation complete	Complete end-to-end test documenting successful integration of system components, MPC controller, and virtual use case building model within CBRI HIL experiment network
3.4	FY25Q3	Finalize commercialization plan	Deployment and commercialization plan document including list of possible demonstration sites complete
3.5	FY25Q4	Hardware-in-the-Loop experimentation complete	Experiment results showing system operation and integrated supervisory control achieves 20% energy savings and 50% peak demand reduction
3.6	FY26Q1	Report out complete	Draft conference papers or journal articles ready for submission

Project logic model

OBJECTIVES

- Enable load flexibility from ice storage in summer and winter
- Improve heat pump performance in cold climates
- Determine optimal control strategy to minimize costs and CO2 emissions
- Ensure flexible heat pump technologies are deployed equitably

ACTIVITIES

- Explore system configurations through modeling for Heat Pump + Ice Storage system
- Develop method for sizing and optimal control of Heat Pump + Ice Storage system
- Demonstrate the controller and system with realistic loads and grid signals (laboratory HIL experiment)

OUTPUTS

- Control and optimal sizing method for ice storage for central heating and cooling systems
- Modeling results for Heat Pump + Ice Storage system, with 20% energy savings and 50% demand reduction
- Measured system performance demonstrating efficiency, load shifting potential, and optimal control

OUTCOMES

- Model data showing the benefits of the technology
- Trane to start commercializing this technology
- Path for deploying grid-connected heat pump systems to a diverse set of buildings, with support from utility incentives

IMPACT

- Up to 20% reduction in energy use for central heat pumps used for space heating
- 50% lower peak demand from central heat pump systems for both cooling and heating
- Grid-connected storage providing resiliency and flexibility for heating and cooling

Team

Trane Technologies:

Trane is supporting this project through:

- Providing equipment datasheets for modeling
- Co-developing two of the custom python models with NREL
- Developing a commercialization and deployment plan for this technology
- Modifying NREL's existing equipment, and updating the controls software, to enable both heating and cooling operation

Advisory Group (to date):

Brian Benson, Senior Design Engineer, Horwitz, Inc.
Energy Outreach Colorado (1 member)
Minnesota Center for Energy and the Environment (2 members)
Mark MacCracken, VP CALMAC, Trane Technologies
Shannon Oliver, Manager of Energy & Sustainability, Adams 12 Five Star Schools
John Pantzke, Business Development and Energy Services Supervisor, Stearns Electric Association
John Schneider, Product Portfolio Manager, Xcel Energy
Kevin Scott, Product Developer, Xcel Energy
Andy Steiner, Sr. Mechanical Engineer, KBSO Consulting
Cody Williams, Energy Solutions Engineer, Xcel Energy

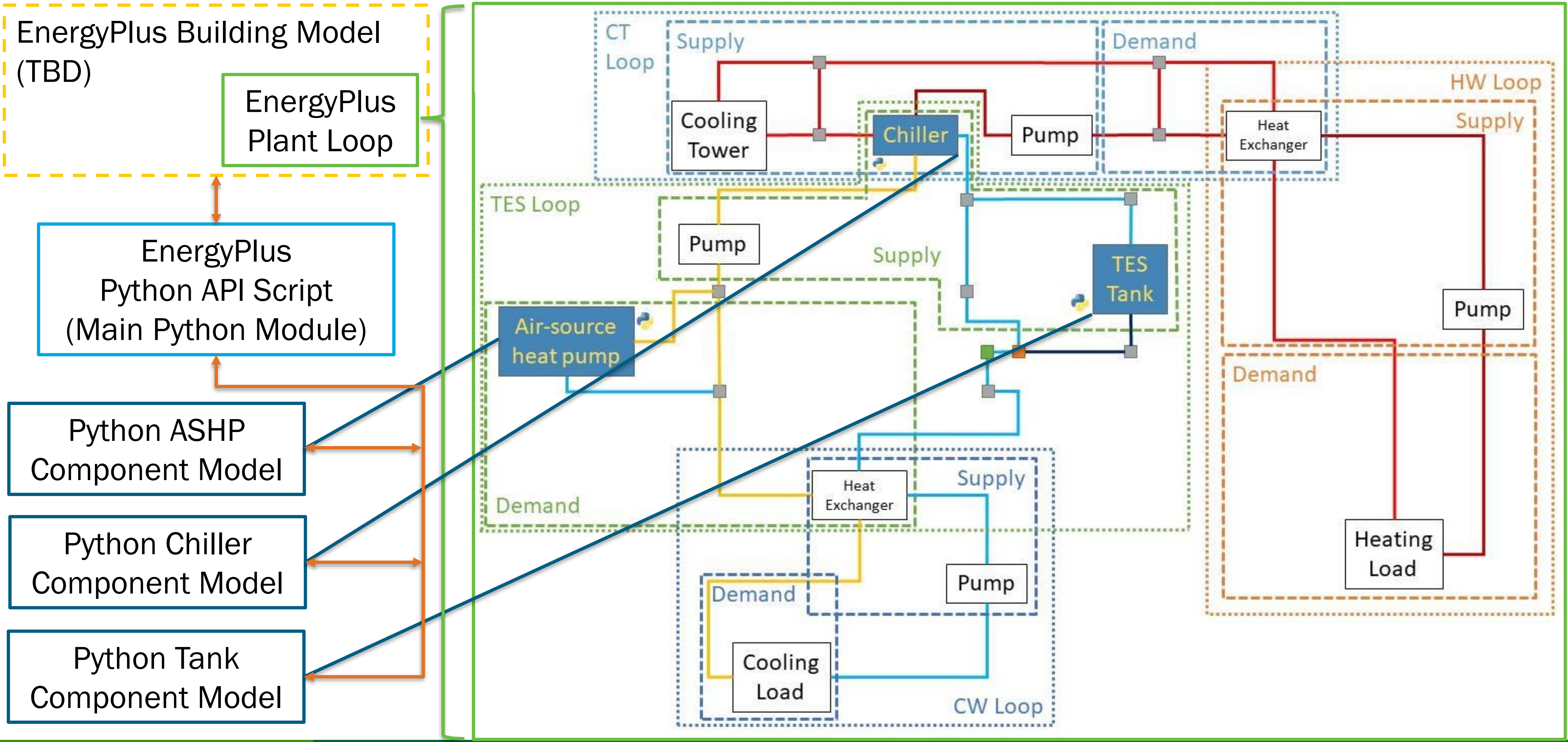
Progress – Advisory Group


Dennis Schroeder, NREL

- **Advisors engaged** to date include:
  - **School districts** serving disadvantaged students
  - **NGOs** providing need-based energy efficiency assistance
  - **HVAC design engineers**
  - **Large utility** professionals
  - **Electric co-op** professionals
  - **Equipment manufacturer** engineers and sales team

- **Feedback trends** to date include:
  - Equipment is typically **replaced upon failure**, and replacement is **like for like**
  - Designer, contractor, owner, maintenance staff must be **comfortable with and confident in the technology**
  - Schools require **year-round conditioning** and prioritize reliability and thermal comfort
  - **Long capital cycles** characterize school funding
    - Upfront costs can be covered by bonds, but ongoing costs can be more challenging to cover
  - Proposals capturing **total cost of ownership** can clarify future cost balancing of higher upfront costs
  - **Not yet common** to have customers **working toward sustainability or electrification goals**

Detailed system schematic



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EnergyPlus Plant Loop

EnergyPlus Python API Script (Main Python Module)

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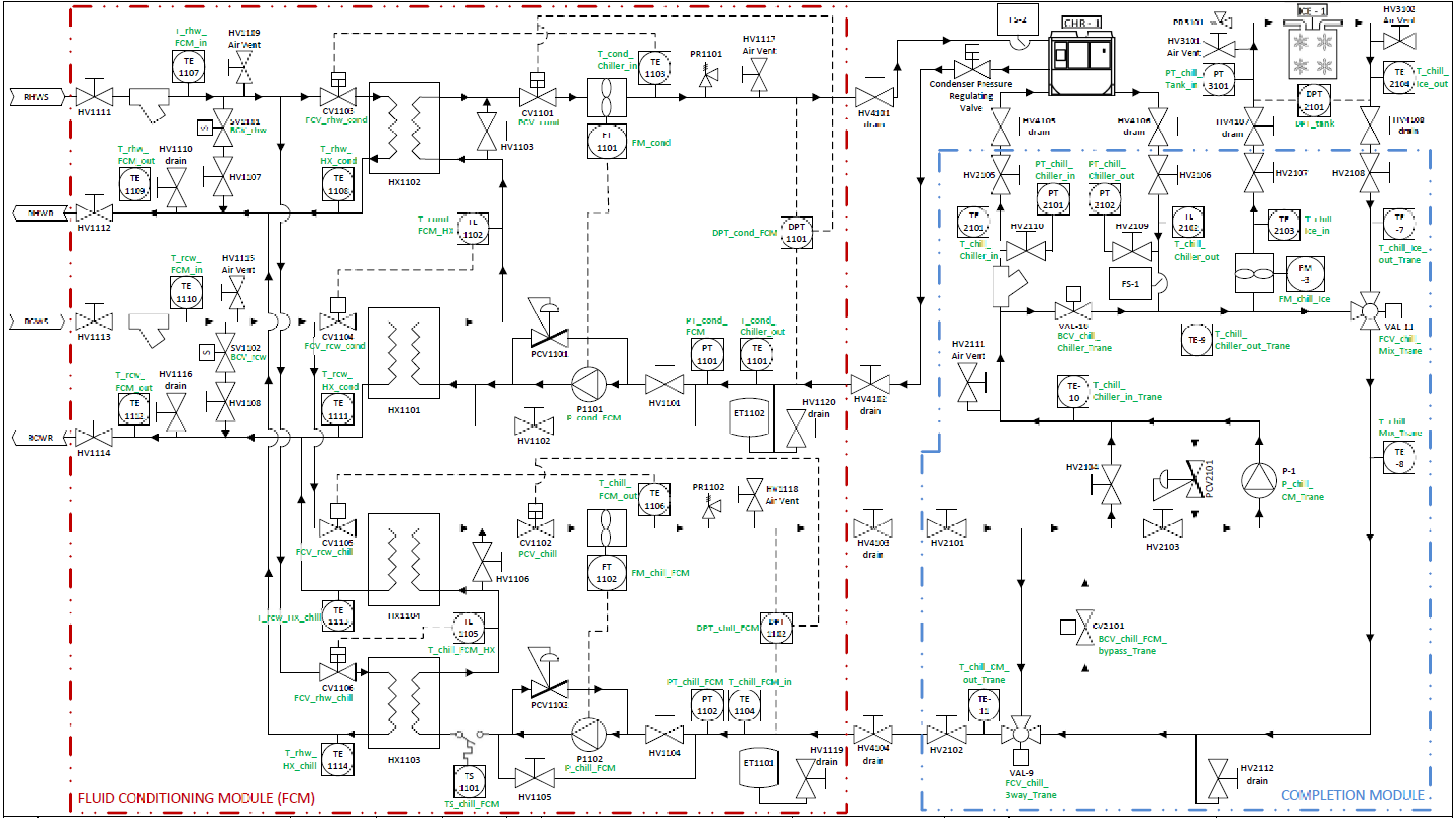
Python Chiller Component Model

Python Tank Component Model


RHWS
HV1111
T_rhw_FCM_in
TE 1107
HV1109 Air Vent
SV1101
BCV_rhw
CV1103
FCV_rhw_cond
HX1102
HV1103
CV1101
PCV_cond
T_cond_Chiller_in
TE 1103
FT 1101
FM_cond
PR1101
HV1117 Air Vent
RHWR
HV1112
T_rhw_FCM_out
TE 1109
HV1110 drain
HV1107
T_rhw_HX_cond
TE 1108
T_cond_FCM_HX
TE 1102
DPT_cond_FCM
DPT 1101
RCWS
HV1113
T_rcw_FCM_in
TE 1110
HV1115 Air Vent
SV1102
BCV_rcw
CV1104
FCV_rcw_cond
HX1101
PCV1101
P1101
P_cond_FCM
HV1101
PT_cond_FCM
PT 1101
T_cond_Chiller_out
TE 1101
ET1102
HV1120 drain
HV1102
RCWR
HV1114
T_rcw_FCM_out
TE 1112
HV1116 drain
HV1108
T_rcw_HX_cond
TE 1111
CV1105
FCV_rcw_chill
HX1104
HV1106
CV1102
PCV_chill
T_chill_FCM_out
TE 1106
FT 1102
FM_chill_FCM
PR1102
HV1118 Air Vent
T_rcw_HX_chill
TE 1113
TE 1105
T_chill_FCM_HX
DPT_chill_FCM
DPT 1102
CV1106
FCV_rhw_chill
HX1103
PCV1102
P1102
P_chill_FCM
HV1104
PT_chill_FCM
PT 1102
T_chill_FCM_in
TE 1104
ET1101
HV1119 drain
T_rhw_HX_chill
TE 1114
TS 1101
TS_chill_FCM
HV1105
FLUID CONDITIONING MODULE (FCM)
FS-2
CHR - 1
Condenser Pressure Regulating Valve
HV4101 drain
HV4102 drain
HV4103 drain
HV4104 drain
HV4105 drain
HV4106 drain
HV4107 drain
HV4108 drain
PR3101
HV3101 Air Vent
PT_chill_Tank_in
PT 3101
ICE - 1
DPT 2101
DPT_tank
HV3102 Air Vent
TE 2104
T_chill_Ice_out
HV2105
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PT 2101
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TE 2103
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TE -7
T_chill_Ice_out_Trane
FS-1
FM -3
FM_chill_Ice
VAL-10
BCV_chill_Chiller_Trane
TE-9
T_chill_Chiller_out_Trane
VAL-11
FCV_chill_Mix_Trane
HV2111 Air Vent
TE-10
T_chill_Chiller_in_Trane
T_chill_Mix_Trane
TE -8
HV2104
PCV2101
P-1
P_chill_CM_Trane
HV2101
HV2103
CV2101
BCV_chill_FCM_bypass_Trane
T_chill_CM_out_Trane
TE-11
HV2102
VAL-9
FCV_chill_3way_Trane
HV2112 drain
COMPLETION MODULE