PNNL-30028

Implementation Plan for Combined Heat and Power Systems VOLTTRON Controller

Performance Monitoring and Real-Time Commissioning Algorithm Verification

June 2020

N Fernandez
S Katipamula

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

DISCLAIMER

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from
the Office of Scientific and Technical
Information,
P.O. Box 62, Oak Ridge, TN 37831-0062
www.osti.gov
ph: (865) 576-8401
fox: (865) 576-5728
email: reports@osti.gov

Available to the public from the National Technical Information Service
5301 Shawnee Rd., Alexandria, VA 22312
ph: (800) 553-NTIS (6847)
or (703) 605-6000
email: info@ntis.gov
Online ordering: http://www.ntis.gov

PNNL-30028

Implementation Plan for Combined Heat and Power Systems VOLTTRON Controller

Performance Monitoring and Real-Time Commissioning Algorithm Verification

June 2020

N Fernandez
S Katipamula

Prepared for
the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99354

Executive Summary

Building-integrated cooling, heating, and power (CHP) systems are more efficient than conventional systems at providing local power and thermal energy, and favorable fuel prices are bound to spur their increased adoption. However, to realize the full benefit of the CHP systems, we must ensure persistence of energy efficient operations. Much of inefficiency in the current building operations can be eliminated by use of automated performance monitoring (PM), real-time commissioning verification (CxV) and automated fault detection and diagnostic (AFDD) tools. These automated tools can help system operators make intelligent decisions. For example, remote and continuous monitoring of system conditions and performance will enable better management and integration of CHP with existing building systems. Together continuous PM, real-time CxV, and AFDD could alleviate burdens for operations staff, enhance operations and maintenance (O&M), and improve reliability of building and CHP systems.

To address the O&M challenges and to provide a means to maximize the rate-of-return of building-integrated CHP systems, the Building Technologies Office (BTO) within the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE) initiated a project to design, develop, and field test a VOLTTRON™-based supervisory controller and associated open-source algorithms. These algorithms will ensure real-time optimal operation of a building-integrated CHP system, support electric grid reliability, and lead to achieving the goal of clean, efficient, reliable, and affordable next-generation integrated energy system.

A previous report listed the components for which PM, real-time CxV, and AFDD algorithms will be developed, how the algorithms will be tested, and the metrics that will be used to validate the algorithms and their ease of deployment. Deployment of these algorithms in the field will result in a reduction in energy consumption of between 10% and 20% (for both CHP and conventional building systems). This report builds upon the previous report by detailing the process by which PNNL will implement performance monitoring and real-time commissioning algorithms for CHP systems in conjunction with the use of the VOLTTRON CHP economic dispatch agent in host facilities. This report provides further details regarding algorithm testing and validation process.

Testing Process

The January 2020 report (Katipamula et. al. 2020) outlined performance monitoring and real-time commissioning methods that require specific metrics. Testing these methods will require component- and system-level run-time data to calculate the required metrics. Once the data are acquired, testing of the algorithms will be performed using customized coding of the algorithms in a Python script. There are two potential sources of the underlying data. The first are actual run-time data from CHP systems and/or components. This type of data is hard to come by, requiring that CHP sites first maintain a log of the required sensors and then share the data. For some component validation, these data will be available for PNNL campus buildings that have conventional heating, ventilation, and air-conditioning (HVAC) plant systems (boilers and conventional chillers). Previously, a hospital EnergyPlus simulation model was used for virtual testing of the VOLTTRON economic dispatch framework. The same EnergyPlus model will be used to generate time-series virtual sensor data not available from the buildings on PNNL campus for performance monitoring and real-time commissioning validation. This simulated data will also be used to monitor the balance of CHP components and to calculate system-level metrics. The details of data generated from the simulation model and data from real systems are described in more detail in the report (Section 2).

Performance Monitoring

The goal is to design, develop, and test both component and system-level PM algorithms for selected CHP and conventional HVAC systems. Performance monitoring is geared toward trending key variables or performance indicators that give insight into the functioning of a component within a CHP or HVAC system or a system as a whole. These variables can simply be tracked or monitored in a dashboard for informational purposes, rolled up into more complex time-of-use analytics, or used to alert the user when the performance is degraded for a period of time.

Performance monitoring implementation details for the various CHP components is presented in the report (Section 3). The components include prime movers (Fuel Cell, Microturbine, or Reciprocating Engine), electrically driven vapor compression chiller, heat exchanger, waste heat-driven absorption chiller, boiler, battery and thermal energy storage systems, photovoltaic system, and cooling tower. In addition to component level validation, there will also be a few system-level validation metrics. These include fuel utilization factor, value-weighted energy utilization factor, absorption chiller utilization factor, and current fuel expenditure rate.

Real-Time Commissioning

Real-time commissioning refers to a validation of the rated or expected performance of a component or system on manufacturers' data. Real-time commissioning is an exercise that should be performed during the first few months after the device or system is installed and running. This time frame allows for validation of the performance of the system while it is new enough to rule out any performance degradation that may occur over time. The set of validation metrics that can be used for real-time commissioning is likely to be a subset of those used for performance monitoring because it necessarily relies on metrics that are likely to be specified by the manufacturer. An important difference between real-time commissioning and performance monitoring is that the real-time commissioning has to replicate any rated conditions to be valid. This may be done passively, by waiting until conditions sufficiently close to rated conditions happen to occur, or it may be done proactively, for example, by controlling the component or system to setpoints that actively reproduce the rated conditions.

The real-time commissioning process will be developed for the following CHP: microturbine, fuel cell, electrical driven vapor compression chiller, waste heat-driven absorption chiller, boiler, and battery energy storage system.

Acknowledgments

The authors acknowledge the Building Technologies Office (BTO) of the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy for supporting the research and development effort. The authors also acknowledge the valuable guidance from Ms. Erika Gupta, the Sensors and Controls technology development manager at BTO. The authors also acknowledge Amanda Smith and Austin Rogers for technical review of the document and Susan Ennor for technical editing.

Acronyms and Abbreviations

AC	alternating current
AFDD	automated fault detection, and diagnosis
AHU	air-handling units
BAS	Building Automation System
CHP	cooling, heating, and power
COP	coefficient of performance
DC	direct current
DOE	U.S. Department of Energy
EERE	Energy Efficiency and Renewable Energy
EMSL	Environmental and Molecular Science Laboratory
ER	emergency room
HVAC	heating, ventilation and air-conditioning
OR	operating room
PLR	part load ratio
PNNL	Pacific Northwest National Laboratory
SOC	(battery) state of charge
VAV	variable air volume
VFD_{CT}	cooling tower variable frequency drive speed

Nomenclature

Ab_F	absorption chiller utilization fraction
$C_{p,Chw}$	specific heat capacity of chilled water (Btu/lb-°F)
$C_{p,water}$	specific heat capacity of water (Btu/lb-°F)
$CAP_{Bat,Rated}$	rated battery energy storage capacity (kwh)
CF	correction factor for microturbines to account for elevation pressure differences
COP_a	actual chiller coefficient of performance at rated test conditions
$Cost_{Fuel}$	CHP system current expenditure rate for fuel ($)
Δt	recording time interval (s)
ΔSOC	change in battery state of charge
ε_{CT}	cooling tower effectiveness
ε_{HRU}	heat exchanger effectiveness
EUF_{VW}	CHP system value-weighted energy utilization factor
I_T	tilted surface solar incident radiation
K_η	angle incidence modifier for solar calculations
LHV_{Fuel}	lower heating value of the fuel (kBtu/lb)
η_B	boiler efficiency
$\eta_{Bat,R}$	battery roundtrip efficiency
$\eta_{Bat,R,a}$	actual battery roundtrip efficiency at rated test conditions
$\eta_{Bat,R,\ rated}$	battery manufacturer rated roundtrip efficiency
η_{Ch}	battery charge efficiency
$\eta_{CT,elec}$	cooling tower electric efficiency
η_{Dis}	battery discharge efficiency
η_F	CHP system fuel utilization factor
η_G	microturbine or fuel cell generation efficiency
$\eta_{G,a}$	microturbine or fuel cell actual generation efficiency at rated test conditions
$\eta_{G,rated}$	microturbine or fuel cell manufacturer rated efficiency
$\eta_{TS,R}$	thermal energy storage roundtrip efficiency
$P_{Bat,Ch}$	battery charge power (kW)
$P_{Bat,Ch,rated}$	battery charge power at rated test conditions (kW)
$P_{Bat,ch,tol}$	battery charge power tolerance (kW)
$P_{Bat,Dis}$	battery discharge power (kW)
$P_{Bat,dis,tol}$	battery discharge power tolerance (kW)
P_{Ch}	chiller electric power (kW)

$P_{CT,elec}$	cooling tower electric (fan) power (kW)
P_{Elec}	electric power generated by the prime mover (kW)
$P_{Elec,rated}$	manufacturer rated maximum electric power generated by the prime mover (kW)
$P_{elec,corrected}$	microturbine power, correcting for pressure differences caused by elevation (kW)
PLRrated	part load ratio at rated test conditions
PLRtol	part load ratio tolerance in determining if rated test conditions are met
$P_{PV,elec}$	photovoltaic AC electric power generated (kW)
$P_{PV,elec,rated}$	peak site electric power (kW)
$\mathrm{Price}_{\mathrm{Fuel}}$	Fuel price per unit ($)
$Q_{Ab,ChW}$	absorption chiller's cooling output (kBtu/hr)
Q_B	boiler heat output (kBtu/hr)
$Q_{B,Rated}$	boiler rated heat output (kBtu/hr)
Q_{Ch}	chiller cooling output (kBtu/hr)
$Q_{ch,load}$	total chilled water load (kBtu/hr)
$Q_{ch,max}$	actual chiller capacity at rated test conditions (kBtu/hr)
$Q_{Ch,rated}$	chiller rated cooling output (kBtu/hr)
Q_{fuel}	prime mover's fuel energy input (kBtu/hr)
$Q_{HRU,HW}$	heat recovery unit waste heat output (kBtu/hr)
$Q_{TS,ch}$	cooling energy charging the thermal storage tank (Btu/hr)
$Q_{TS,dis}$	cooling energy discharging the thermal storage tank (Btu/hr)
$RH_{a,rated}$	outdoor air relative humidity at rated test conditions (microturbine) (°F)
$RH_{a,tol}$	outdoor rel. humidity tolerance in determining if rated test conditions are met (°F)
SOC_0	battery internal state of charge
ρ_{Fuel}	fuel density (lb/ft^2)
ρ_{Hw}	density of hot water (lb/ft^3)
ρ_{Chw}	density of chilled water (lb/ft^3)
$T_{Ab,Chw,i}$	absorption chiller return chilled water temperature (°F)
$T_{Ab,Chw,o}$	absorption chiller supply chilled water temperature (°F)
$T_{ab,chW,o,rated}$	absorption chiller supply chilled water temperature at rated test conditions (°F)
$T_{ab,chW,o,tol}$	absorption chiller supply chilled water temperature tolerance (°F)
$T_{Ab,CW,i}$	absorption chiller condenser water inlet temperature (°F)
$T_{ab,CW,i,rated}$	absorption chiller condenser water inlet temperature at rated test conditions (°F)
$T_{ab,CW,i,tol}$	absorption chiller condenser water inlet temperature tolerance (°F)

$T_{Ab,HW,i}$	absorption chiller supply hot water temperature (°F)
$T_{ab,HW,i,rated}$	absorption chiller supply hot water temperature at rated test conditions (°F)
$T_{ab,HW,i,tol}$	absorption chiller supply hot water temperature tolerance (°F)
$T_{Ab,HW,o}$	absorption chiller return hot water temperature (°F)
T_{amb}	outdoor air ambient temperature (°F)
$T_{a,rated}$	outdoor air temperature at rated test conditions (multiple components) (°F)
$T_{a,tol}$	outdoor air temp. tolerance in determining if rated test conditions are met (°F)
$T_{B,w,i}$	boiler inlet hot water temperature (°F)
$T_{B,w,o}$	boiler outlet hot water temperature (°F)
$T_{Ch,w,i}$	chiller evaporator water inlet temperature (°F)
$T_{Ch,w,o}$	chiller evaporator water outlet temperature (°F)
$T_{ch,o,rated}$	chiller evaporator water outlet temperature at rated test conditions (°F)
$T_{ch,o,tol}$	chiller evaporator water outlet temperature tolerance (°F)
$T_{CT,w,i}$	cooling tower water inlet temperature (°F)
$T_{CT,w,o}$	cooling tower water outlet temperature (°F)
$T_{cond,i}$	chiller condenser water inlet temperature (°F)
$T_{cond,i,rated}$	chiller condenser water inlet temperature at rated test conditions (°F)
$T_{cond,i,tol}$	chiller condenser water inlet temperature tolerance (°F)
$T_{HRU,ex,i}$	Heat recovery exhaust inlet temperature (°F)
$T_{HRU,ex,o}$	Heat recovery exhaust outlet temperature (°F)
$T_{HRU,w,i}$	Heat recovery water inlet temperature (°F)
$T_{TS,ch,in}$	Thermal storage charge inlet temperature (°F)
$T_{TS,ch,out}$	Thermal storage charge outlet temperature (°F)
$T_{TS,dis,in}$	Thermal storage discharge inlet temperature (°F)
$T_{TS,dis,out}$	Thermal storage discharge outlet temperature (°F)
T_{wb}	Outdoor wet bulb temperature (°F)
Θ_p	tilt of the solar collectors with respect to the horizontal (°)
θ_z	solar zenith angle (°)
φ_p	azimuth of the solar collectors with respect to due south (°)
φ_z	solar azimuth angle (°)
$\dot{v}_{Ab,Chw}$	absorption chiller chilled water volumetric flow rate (gal/min)
$\dot{v}_{B,Fuel}$	boiler fuel input (ft^2/min)
$\dot{v}_{B,w}$	boiler hot water volumetric flow rate (gal/min)
$\dot{v}_{Chw}$	chiller chilled water volumetric flow rate (gal/min)

$\dot{v}_{CT,w}$	cooling tower water volumetric flow rate (gal/min)
$\dot{v}_{Fuel,pm}$	prime mover fuel input (ft^2/min)
$\dot{v}_{HRU,w}$	heat recovery unit volumetric flow rate (gal/min)
$\dot{v}_{TS,ch}$	thermal storage charge water volumetric flow rate (gal/min)
$\dot{v}_{TS,dis}$	thermal storage discharge water volumetric flow rate (gal/min)

Contents

Executive Summary iii
Acknowledgments v
Acronyms and Abbreviations vi
Nomenclature vii
Contents xi
1.0 Introduction 1
1.1 Report Content and Organization 1
2.0 Testing Process 2
2.1 Real Data from PNNL Campus Systems 2
2.2 EnergyPlus Model (Modification of DOE Hospital Model) 2
2.2.1 DOE Prototype Model 2
2.2.2 Modified Hospital Model 6
2.3 Testing the Performance Monitoring Algorithms in Python 7
Example Script: Calculation of heat exchanger effectiveness (as in Section 3.3) 7
3.0 Performance Monitoring 8
3.1 Prime Mover (Fuel Cell, Microturbine, or Reciprocating Engine) 8
3.2 Electrically Driven Vapor Compression Chiller 9
3.3 Heat Exchanger 11
3.4 Waste Heat-Driven Absorption Chiller 13
3.5 Boiler 15
3.6 Battery Energy Storage System 16
3.7 Thermal Energy Storage System 19
3.8 Photovoltaic System 21
3.9 Cooling Towers 22
3.10 System-Level Validation 24
4.0 Real-Time Commissioning 28
4.1 Microturbine 28
4.2 Fuel Cell 29
4.3 Electrical-Driven Vapor Compression Chiller 31
4.4 Waste Heat-Driven Absorption Chiller 32
4.5 Boiler 33
4.6 Battery Energy Storage System 35
5.0 References 37
Appendix A – Solar Angle Calculation A.1

Figures

Figure 2.1. Axonometric projection of the geometry of the DOE hospital prototype................ 3
Figure 2.2. Daily schedules for occupancy, lighting, equipment, and HVAC operations.. 4
Figure 2.3. Average annual electric, chilled water, and hot water building load profiles (Los Angeles and New York).. 5
Figure 2.4. Variation of average electric, chilled water, and hot water building loads on a monthly basis (Los Angeles and New York)... 6
Figure 3.1. Input/output diagram for prime mover performance monitoring algorithms........... 9
Figure 3.2. Input/output diagram for vapor compression chiller monitoring algorithms......... 11
Figure 3.3. Input/output diagram for heat recovery unit monitoring algorithms. 13
Figure 3.4. Input/output diagram for absorption chiller monitoring algorithms....................... 15
Figure 3.5. Input/output diagram for boiler monitoring algorithms. 16
Figure 3.6. Input/output diagram for battery monitoring algorithms. 19
Figure 3.7. Input/output diagram for thermal storage monitoring algorithms. 21
Figure 3.8. Input/output diagram for solar photovoltaics monitoring algorithms. 22
Figure 3.9. Input/output diagram for cooling tower monitoring algorithms............................. 24

Tables

Table 2.1. Breakdown of zones within the DOE hospital prototype. 3

1.0 Introduction

In fiscal year 2017 (FY2017), the Building Technologies Office (BTO) within the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE) initiated a project to develop a VOLTTRON™-based supervisory controller for cooling, heating, and power (CHP) systems. This ongoing effort will address operations and maintenance challenges and enable the best rate-of-return for building-integrated CHP systems. More specifically, the controller and associated open-source algorithms will assure real-time optimal operation and support electric grid reliability. The controller is thus an important step toward achieving clean, efficient, reliable, and affordable integrated energy systems.

The initial focus of the project was to develop an automated economic dispatch software that can be deployed on the VOLTTRON platform. That portion of the work concluded in FY2019 with a successful field test at a CHP site in upstate New York. The purpose of the ongoing effort is to develop performance monitoring, real-time commissioning, and automated fault detection and diagnosis (AFDD) algorithms for selected CHP components. In January 2020, Pacific Northwest National Laboratory (PNNL) provided a report to DOE entitled *Design, Development, and Testing Plan for Energy Efficiency Algorithms Related to Building-Integrated Cooling, Heating, and Power Systems* (Katipamula et. al 2020). That report presented the need for performance monitoring and real-time commissioning and introduced the components and metrics that would be targeted for algorithm development. The current report builds upon the Design, Development and Testing report by detailing the process by which PNNL will implement performance monitoring and real-time commissioning algorithms for CHP systems in conjunction with the use of the VOLTTRON CHP economic dispatch agent in host facilities.

1.1 Report Content and Organization

Section 2 details the process for testing the algorithms, including how real and simulated sensor data from CHP systems and components will be fed into algorithms, developed for testing purposes in Python. Sections 3 and 4 detail the performance monitoring and continuous commissioning algorithms, respectively, in a form that will serve as a guide to programmers developing the Python algorithms.

2.0 Testing Process

The January 2020 report (Katipamula et. al. 2020) outlined performance monitoring and real-time commissioning methods that require specific metrics. Testing these methods will require component- and system-level run-time data to calculate the required metrics. Once the data are acquired, testing of the algorithms will be performed using customized coding of the algorithms in a Python script. There are two potential sources of the underlying data. The first are actual run-time data from CHP systems and/or components. This type of data is hard to come by, requiring that CHP sites first maintain a log of the required sensors and then share the data. For some component validation, these data will be available for PNNL campus buildings that have conventional heating, ventilation, and air-conditioning (HVAC) plant systems (boilers and conventional chillers). A building simulation will be used to obtain data not available from the buildings on PNNL campus. This simulated data will be used to monitor the balance of CHP components and to calculate system-level metrics. The same EnergyPlus model that was used for virtual testing of the VOLTTRON economic dispatch framework will be used to generate time-series virtual sensor data for performance monitoring and real-time commissioning validation.

2.1 Real Data from PNNL Campus Systems

Historical trend data for boilers, chillers, and cooling towers are available from PNNL's Environmental and Molecular Science Laboratory (EMSL) and will be used to validate algorithms specific to those three components. The EMSL central plant consists of five centrifugal, magnetic bearing chillers, which have each been replaced within the last 5 years. Four chillers are sized at 500 T each and the fifth is a smaller 92 T chiller. There are four boilers: two large, conventional boilers sized at 5 mmBtu/hr each and two smaller condensing boilers, sized at 1.88 mmBtu/hr each. There are five cooling towers: three 2-speed and two variable-speed cooling towers. Performance monitoring and real-time commissioning algorithms for conventional chillers, boilers, and cooling towers will be tested using data from these systems. Validating algorithms for other components will rely on simulated data from an EnergyPlus model.

2.2 EnergyPlus Model (Modification of DOE Hospital Model)

The EnergyPlus model represents a hospital that has been modified from the DOE Commercial Prototype Model of a hospital in a way that provides data to support this study. Hospitals are generally good candidates for CHP systems because (1) they have around-the-clock operations, which can facilitate 24/7 operation of prime movers (fuel cells, microturbines, and reciprocating engines), and (2) they are critical facilities that require backup power in the event of a grid outage. These two factors help justify the initial costs of the prime mover. The around-the-clock operation can also prevent frequent shutdowns and restarts, facilitating incorporation of fuel cells, which have slow ramp rates.

2.2.1 DOE Prototype Model

The DOE hospital model (DOE 2018) represents a six-story building (including a basement), totaling 241,413 ft^2 of total floor area. Figure 2.1 reveals an axonometric projection of the building shape, showing the size and location of windows. The overall window-wall area is 16%. Windows are conceptually double-paned and are modeled with a U-factor of 3.04 W/m^2-K and solar heat gain coefficient of 0.428. The floor-to-floor height is 14 ft, except in the basement, where it is 8 ft. Exterior walls are 8” mass (concrete) with insulation, and roofs are built-up with a roof membrane, insulation, and metal decking. The U-factor for the exterior walls is 0.698 W/m^2-K, except in patient rooms, where the U-factor of the walls is 0.511 W/m^2-K. The roof U-factor is 0.358 W/m^2-K.

Table 2.1. shows a breakdown of the zone types within the building, including the floor area and the average density of plug loads and lighting within zones that fall into each category. The total (average) plug load density building-wide is 2.22 W/ ft^2 and the lighting power density is 1.08 W/ ft^2. Thermostat setpoints building-wide are set to 70°F for heating and 75°F for cooling. Those setpoints remain constant year-round. Figure 2.2 shows the daily (weekday and weekend) schedules for key operations within the building, including lighting, equipment, people (occupancy), HVAC operation schedules, and minimum outdoor air damper schedules.

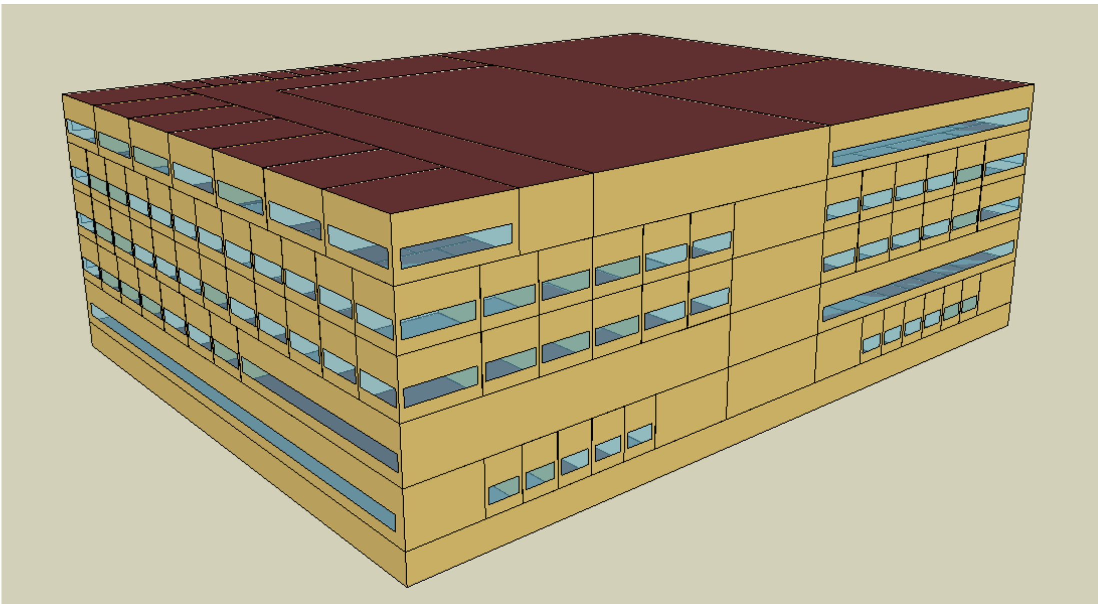

Figure 2.1. Axonometric projection of the geometry of the DOE hospital prototype.

Table 2.1. Breakdown of zones within the DOE hospital prototype.

Zone Type	Area (ft^2)	Plug and Process (W/ft^2)	Lighting (W/ft^2)
Operation/Exam/Lab	36,413	4.02	1.31
Lobby	77,945	1.13	1.34
Office	6,898	1.00	1.00
Patient Rooms	20,393	2.00	0.70
Cafeteria	17,494	13.36	1.07
Corridor	42,035	0.00	1.00
Basement	40,235	0.75	1.00
Total	**241,413**	**2.22**	**1.08**

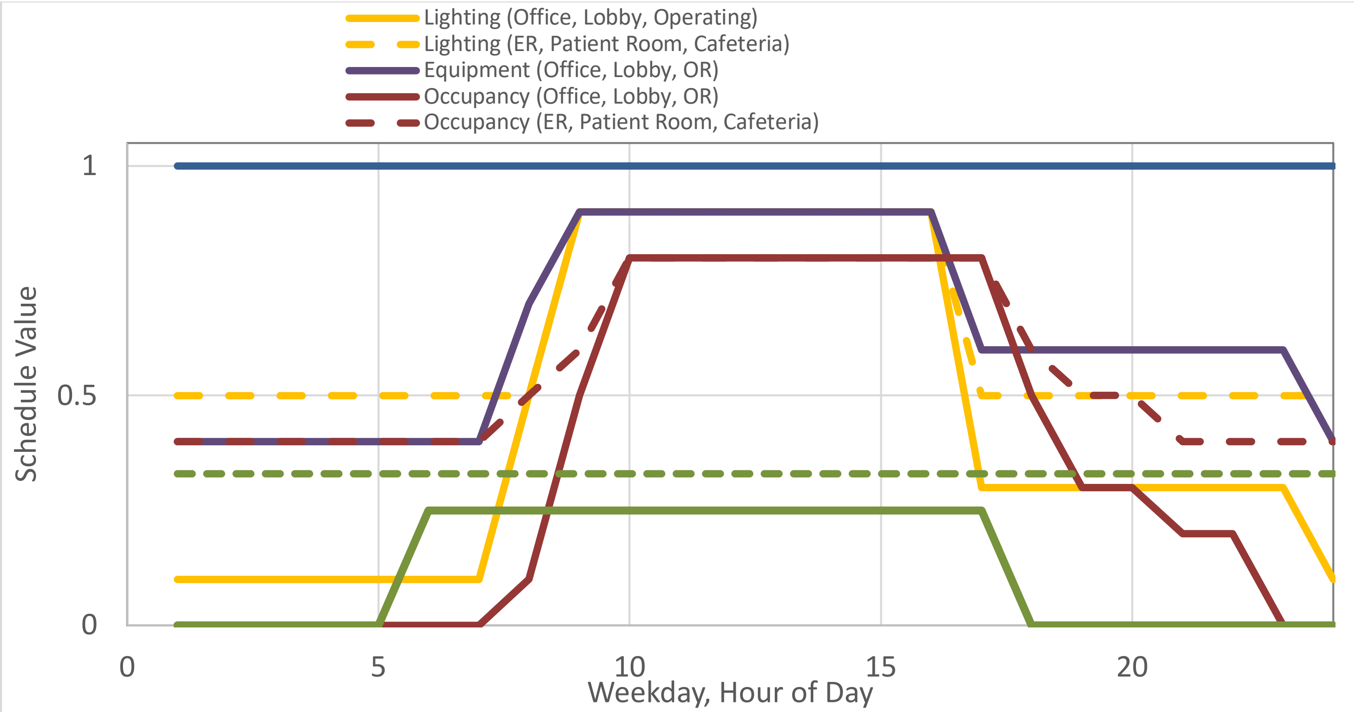

Figure 2.2. Daily schedules for occupancy, lighting, equipment, and HVAC operations.

There are seven separate variable air volume (VAV) air-handling units (AHUs) and one constant air volume (CAV) unit in the hospital model that serve the following distinct zones:

- VAV_1 serves the basement plus offices, corridors and lobbies on the 1st and 2nd floors
- VAV_2 serves offices, corridors and lobbies on the 3rd to 5th floors
- VAV_ER serves the emergency room (ER) wing (exam areas)
- VAV_OR serves operating rooms (ORs)
- VAV_ICU serves intensive care patient rooms
- VAV_PATRMS serves the rest of the patient rooms
- VAV_LABS serve laboratory zones
- CAV_KITCHEN is a CAV unit that serves the cafeteria.

The VAV systems are equipped with airside economizers and hydronic heating and cooling coils. The supply air temperature setpoint is constant at 55°F year-round, and the kitchen CAV has a constant setpoint of 60°F. Zones are all served by VAV boxes that have hydronic reheat coils. Labs, ER, OR, exam rooms, and patient rooms all have minimum VAV airflow fractions of 100% (no variation in airflow rate). Other zones vary between 30% and 52% for minimum airflow fractions.

The building's cooling plant consists of four water-cooled chillers, sized at 400 T, each. The chilled water loop is a primary-secondary loop. The secondary chilled water pump is a variable-speed pump that pumps against 56 ft of head. The primary pump is constant speed and pumps against 16.7 ft of head.

The heating plant consists of six gas-fired boilers, sized at 8 mmBtu/hr each. The hot water loop is variable speed, primary only, with a hot water pump that pumps against 60 ft of head.

Figure 2.3 shows average load profiles for electricity, hot water, and chilled water over the course of an annual simulation using two locations for weather files (Los Angeles, CA and New York, NY). Figure 2.4 breaks down the average loads by month to show the variation in hot water, chilled water, and electricity as a function of the time of the year, and by extension the weather.

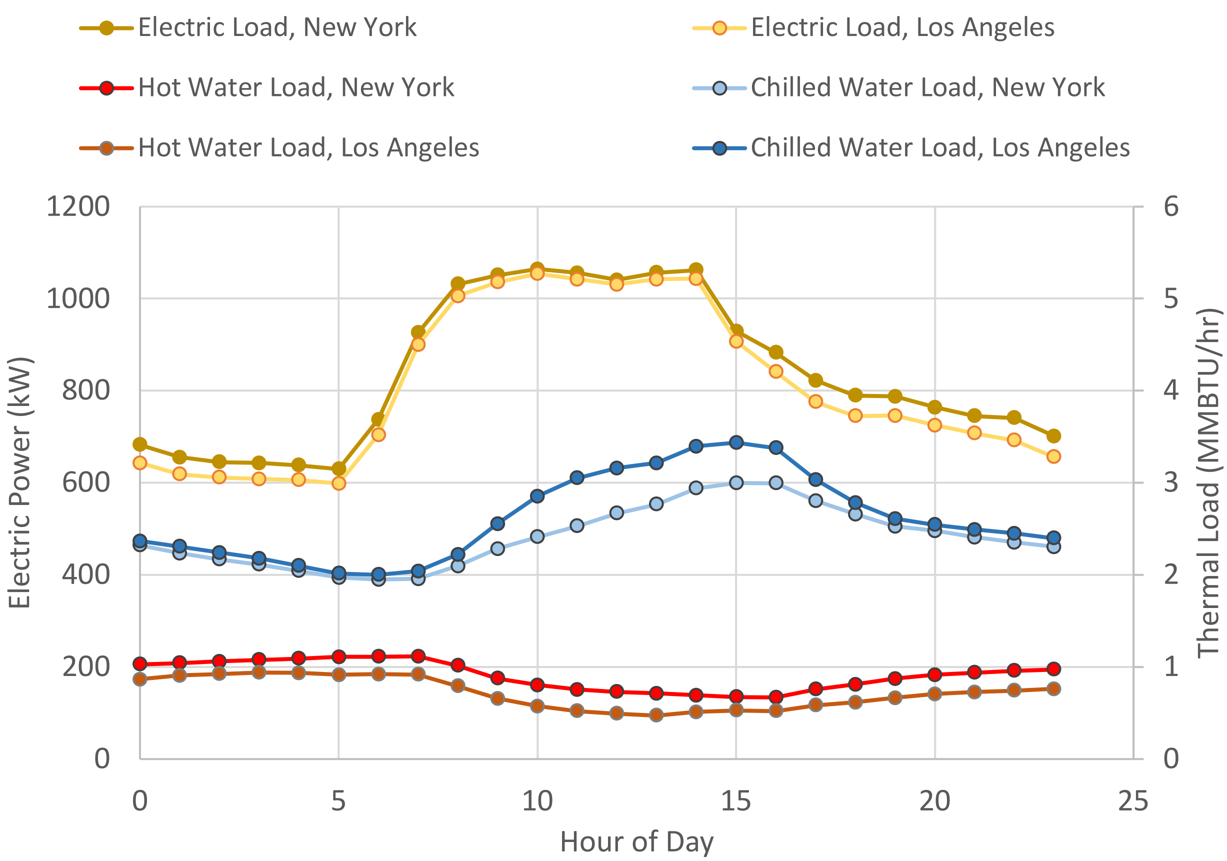

Figure 2.3. Average annual electric, chilled water, and hot water building load profiles (Los Angeles and New York).

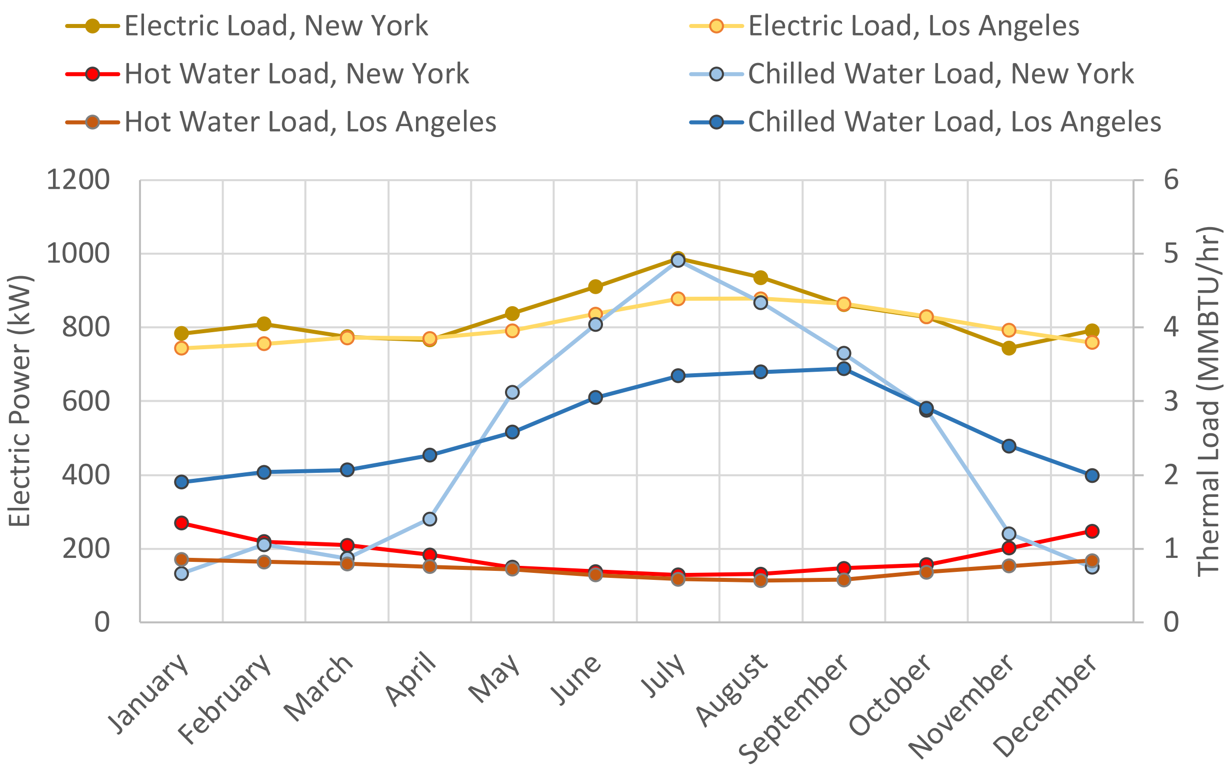

Figure 2.4. Variation of average electric, chilled water, and hot water building loads on a monthly basis (Los Angeles and New York).

2.2.2 Modified Hospital Model

To develop a fully functional model representing an arbitrary configuration of CHP systems that may or may not include a host of prime movers (microturbines, fuel cell generators, reciprocating engines), battery and thermal storage, absorption chillers, and an arbitrary number of boilers and chillers, the hospital prototype was modified to form an “exhaustive” EnergyPlus model that contains all possible components. Then, to model a specific configuration, each of the components that are not included in that configuration can be turned off, by setting availability/operating schedules to 0 and setting design capacities to 0. The following CHP and conventional HVAC plant components are available for inclusion:

- 1 microturbine (500 kW)
- 1 fuel cell (600 kW)
- 1 reciprocating engine (788 kW)
- 1 absorption chiller (62.5 T)
- 1 battery (2,000 kWh storage; 500 kW maximum charge, discharge)
- 1 chilled water thermal storage tank (607 m^3)
- 4 centrifugal chillers (500 T each)
- 6 boilers (8 MBtu/hr each).

The model can be run in one of two ways: as a standalone energy model in EnergyPlus, or through co-simulation with EnergyPlus, using the optimal dispatch algorithms. Running the model in the standalone generates virtual performance data for validation of performance monitoring and real-time commissioning algorithms in Python. Dispatch commands can be set as needed in the standalone model to highlight the use of certain subsystems for component-level validation or to exercise multiple components in targeted ways for system-level validation.

2.3 Testing the Performance Monitoring Algorithms in Python

A series of Python-based scripts will be used to validate the performance monitoring and real-time commissioning algorithms. The general process will involve encoding the algorithms, then processing real or simulated data from components or systems through those Python scripts, obtaining the results of the performance monitoring, and verifying that the results make sense. The Python scripts are anticipated to have the following characteristics:

- Sensor validation – ongoing analysis of incoming sensor data to validate that the sensor has not failed, and is not reading a value that is outside of reasonable bounds
- Steady-state detection criteria – where necessary, a determination that the component or system is in steady state and its performance is ready to be validated
- Core algorithm/equation governing performance metric
- Tracking of the core algorithm in terms of its relationship to important and relevant independent variables. The performance of most components and systems may vary normally (not due to degradation or failure) because of changing conditions.

Example Script: Calculation of heat exchanger effectiveness (as in Section 3.3)

```
# heat recovery exhaust inlet temperature [C]
T_HRU_ex_i = 250

# heat recovery exhaust outlet temperature [C]
T_HRU_ex_o = 100

# heat recovery water inlet temperature [C]
T_HRU_w_i = 40

# heat exchanger effectiveness

   epsilon_HRU = (T_HRU_ex_i - T_HRU_ex_o) / (T_HRU_ex_i - T_HRU_w_i)
```

3.0 Performance Monitoring

The goal is to design, develop, and test both component and system-level PM algorithms for selected CHP and conventional HVAC systems. Performance monitoring is geared toward trending key variables or performance indicators that give insight into the functioning of a component within a CHP or HVAC system or a system as a whole. These variables can simply be tracked or monitored in a dashboard for informational purposes, rolled up into more complex time-of-use analytics, or used to alert the user when the performance is degraded for a period of time. In this section, performance monitoring implementation details for the various CHP components is presented.

3.1 Prime Mover (Fuel Cell, Microturbine, or Reciprocating Engine)

The primary metric to track for the prime movers is the generation efficiency (η_G). This metric can be tracked for informational and trending purposes as well as for tracking of performance degradation. The sensor tracking the electric power generated (P_{Elec}) should also be monitored and trended, because it is useful for inclusion in power flow graphics and analytics. The prime mover's fuel energy input, Q_{fuel} should also be tracked for the same reasons, using the following equation:

$$Q_{fuel} = \rho_{Fuel}\dot{v}_{Fuel,pm}LHV_{Fuel} \cdot 60\frac{min}{hr}$$

where ρ_{Fuel} is the density of the fuel [lb/ft^2], in most cases natural gas, LHV_{Fuel} (kBtu/lb) is the lower heating value of the fuel, and $\dot{v}_{Fuel,pm}$ is the prime mover fuel input flow rate (ft^2/m). Details for the η_G metric are provided below, and an overview of required inputs and outputs is depicted in Figure 3.1.

Metric: Generation efficiency (η_G)

Sensor Validation: Electric power generated (P_{Elec}), fuel input ($\dot{v}_{Fuel}$).

- P_{Elec} should be flagged for a bad sensor if the reading is below 0, or more than 20% above the rated electric power of the generator.
- $\dot{v}_{Fuel}$ should be flagged for a bad sensor if the reading is below 0, if the value remains constant during operation as P_{Elec} changes by more than +/- 10%, or if $\dot{v}_{Fuel}$ is greater than $\frac{1.5P_{Elec,rated}}{\rho_{Fuel}LHV_{Fuel}}$.

Steady-State Detection:

- Wait at least 1 hour after system startup.
- After that point, record generation efficiency whenever the rate of change of $P_{Elec}/P_{Elec,rated}$ with respect to time (determined through linear regression over a prior 10-minute window) is below 10%/hour.

Equation:

$$\eta_G = \frac{P_{Elec}}{\rho_{Fuel}\dot{v}_{Fuel}LHV_{Fuel} \cdot 60\frac{min}{hr} \cdot 0.293\frac{kW}{kBtu/hr}}$$

Independent variables: Part load ratio, ambient temperature.

Performance validation recording/reporting:

1. Record real-time performance every minute (not less frequently than every five minutes).
2. Determine a "threshold A" fraction of real-time efficiency readings (e.g., 50%) that are below normal performance by a "threshold B" (e.g., 0.04) over a one-day window. Normal performance should be determined via multiple regression or machine learning algorithms compared to a baseline data set established earlier (e.g., 1st year after setup of monitoring)

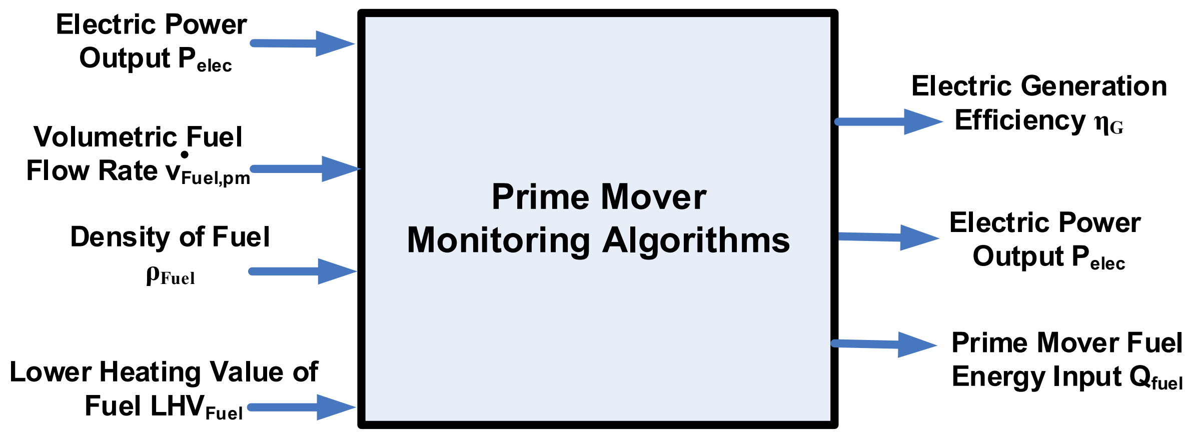

Figure 3.1. Input/output diagram for prime mover performance monitoring algorithms.

3.2 Electrically Driven Vapor Compression Chiller

The primary metric to track in regard to vapor compression chillers is the coefficient of performance (COP). This metric can be tracked for informational and trending purposes as well as for tracking of performance degradation. The sensor tracking the electric power consumed by the chiller (P_{Ch}) and the chiller cooling output (Q_{Ch}) should also be monitored and trended. P_{Ch} can be used for CHP system power flow tracking, while Q_{Ch}, when summed across all the chillers, is the building's chilled water load (demand) and may be used in other analytics. Details for the COP metric are provided below, and an overview of required inputs and outputs for all monitoring points is depicted in Figure 3.2.

Metric: Coefficient of performance (COP)

Sensor Validation:

- Chiller power consumption (P_{Ch}) should be flagged for a bad sensor if the reading is below 0, or if the power reading (In kW) is more than 3.5 times higher than the rated chiller cooling output (in tons).

- Evaporator water inlet temperature ($T_{Ch,w,i}$) should be flagged for a bad sensor if the reading is below 32° F (except for chillers generating chilled glycol water for ice storage), above 70°F during steady-state operating conditions, or above 100°F at any time.
- Evaporator water outlet temperature ($T_{Ch,w,o}$) should be flagged for a bad sensor if the reading is below 32°F (except for chillers generating chilled glycol water for ice storage), above 70°F during steady-state operating conditions, or above 100°F at any time.
- Evaporator water volumetric flow rate ($\dot{v}_{Chw}$) should be flagged for a bad sensor if the reading is below 0 or if the volumetric flow rate (in gallons per minute) is more than 20% higher than the chiller's primary pump rated flow rate (if available).

Steady-State Detection:

- Wait at least 20 minutes after system startup.
- After that point, record generation efficiency whenever the rate of change of $Q_{Ch}/Q_{Ch,rated}$ (also referred to as the chiller part load ratio or PLR) with respect to time (determined through linear regression over a prior 10-minute window) is below 10%/hour.

Equation:

$$COP = \frac{Q_{Ch}}{P_{Ch}} = \frac{\dot{v}_{Chw}\rho_{Chw}C_{p,Chw}\left(T_{Ch,w,i} - T_{Ch,w,o}\right) \cdot \frac{ft^2}{7.48\ gal} \cdot \frac{60\ min}{hr} \cdot 0.000293\,\frac{kW}{Btu/hr}}{P_{Ch}}$$

where ρ_{Chw} is the density of water (62.4 lb/ft^3 unless a glycol-water mixture is used) and $C_{p,Chw}$ is the specific heat of water (1.001 Btu/lb-°F unless a glycol-water mixture is used). Both can be approximated as constants.

Independent variables: Chiller PLR, $T_{Ch,w,o}$, condenser water inlet temperature (cooling tower outlet temperature; $T_{cond,i}$).

Performance validation recording/reporting:

1. Record real-time performance every minute (not less frequently than every 5 minutes).
2. Determine a threshold fraction "threshold A" of real-time COP readings that are below normal performance by a "threshold B" (e.g., 0.5) over a 1-day window. Normal performance should be determined via multiple regression or machine learning algorithms compared to a baseline data set established earlier (e.g., 1st year after setup of monitoring)

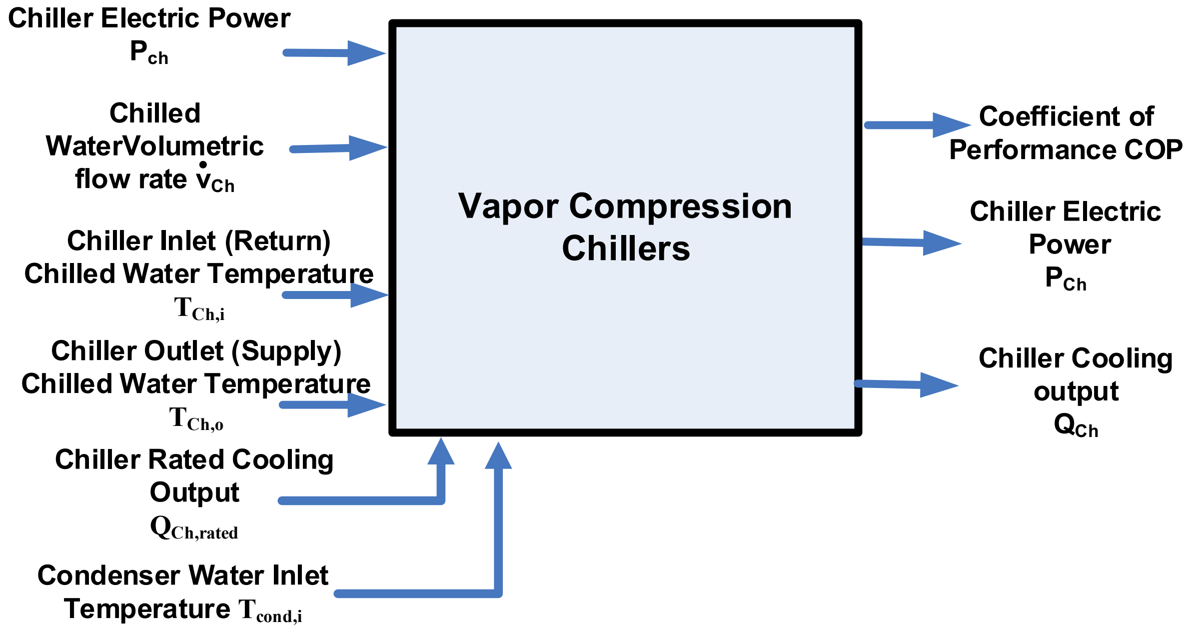

Figure 3.2. Input/output diagram for vapor compression chiller monitoring algorithms

3.3 Heat Exchanger

<u>**Metric**</u>**: Effectiveness (ε_{HRU})**

<u>Sensor Validation</u>:

- Heat recovery exhaust inlet temperature ($T_{HRU,ex,i}$) should be flagged for a bad sensor if the reading is below 200° F when the prime mover is running or over 600°F.
- Heat recovery exhaust outlet temperature ($T_{HRU,ex,o}$) should be flagged for a bad sensor if the reading is below 100° F when the prime mover is running or over 600°F.
- Heat recovery water inlet temperature ($T_{HRU,w,i}$) should be flagged for a bad sensor if the reading is below 70° F or above 212°F.
- Heat recovery water outlet temperature ($T_{HRU,w,o}$) should be flagged for a bad sensor if the reading is below 70° F or above 212°F
- Heat recovery water flow rate ($\dot{v}_{HRU,w}$) should be flagged for a bad sensor if the reading is below 0 or if the value is above 20 gallons per minute but does not change value in over 4 hours.
- Heat recovery exhaust gas flow rate ($\dot{v}_{HRU,ex}$) should be flagged for a bad sensor if the reading is below 0 or if the value is above 2 cfm but does not change value in over 4 hours.

<u>Steady-State Detection</u>:

- Wait at least 20 minutes after prime mover startup.
- After that point, record heat exchanger effectiveness whenever the rate of change of $T_{HRU,ex,i}$ with respect to time (determined through linear regression over a prior 10-minute window) is below 10°F/hour.

Equation:

$$\varepsilon_{HRU} = \frac{\dot{v}_{HRU,w}\rho_{HW}C_{p,HW}\left(T_{HRU,w,o} - T_{HRU,w,i}\right) \cdot \frac{ft^2}{7.48\ gal}}{\dot{v}_{HRU,ex}\rho_{ex}C_{p,ex}\left(T_{HRU,ex,i} - T_{HRU,w,i}\right)}$$

In this equation, the specific heat of exhaust gases ($C_{p,ex}$) can be approximated as a constant at 0.284 Btu/lb-F and the density of exhaust gases (ρ_{ex}) can be approximated as a constant at 0.0285 lb/ft^3. ρ_{HW} can be approximated as a constant at 62.2 lb/ft^3.

Independent variables: None.

Performance validation recording/reporting:

1. Record real-time performance every minute (not less frequently than every 5 minutes).
2. Determine a “threshold A” fraction (e.g., 50%) of real-time performance readings that are below normal performance by a “threshold B” (e.g., 0.02) over a 1-day window. Normal performance should be determined via multiple regression or machine learning algorithms compared to a baseline data set established earlier (e.g., 1st year after setup of monitoring)

Metric: Waste Heat Output ($Q_{HRU,HW}$)

Sensor Validation:

- Water flow rate ($\dot{v}_{HRU,w}$) should be flagged for a bad sensor if the reading is below 0, or the value is above 20 gallons per minute but does not change value in over 4 hours.
- Heat recovery water outlet temperature ($T_{HRU,w,o}$) should be flagged for a bad sensor if the reading is below 70° F or above 212°F.

Steady-State Detection: No steady-state detection required.

Equation:

$$Q_{HRU,HW} = \rho_{Hw}\dot{v}_{HRU,w}C_{p,water}(T_{HRU,w,o} - T_{HRU,w,i}) \cdot \frac{ft^2}{7.48\ gal}$$

Independent variables: None.

Performance validation recording/reporting:

1. Record waste heat output every minute (not less frequently than every 5 minutes).
2. This value is used for tracking key heat energy flows within the CHP system, but is for informational and analytical purposes only.

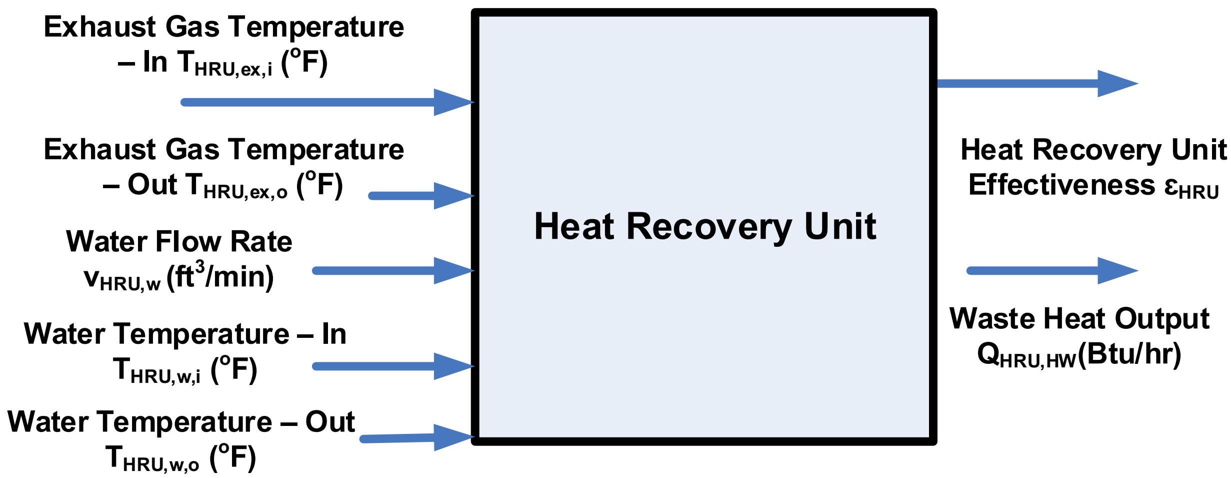

Figure 3.3. Input/output diagram for heat recovery unit monitoring algorithms.

3.4 Waste Heat-Driven Absorption Chiller

Similar to conventional chillers, the primary metric to track in regard to absorption chillers is the coefficient of performance (COP). This metric can be tracked for informational and trending purposes as well as for tracking of performance degradation. The hot water heat input to the absorption chiller ($Q_{Ab,HW}$) as well as the absorption chiller's cooling output ($Q_{Ab,Ch}$) should also be monitored and trended.

$$Q_{Ab,ChW} = \rho_{Chw}\dot{v}_{Ab,Chw}C_{p,water}(T_{Ab,Chw,i} - T_{Ab,Chw,o}) \cdot \frac{ft^2}{7.48\ gal} \cdot \frac{60\ min}{hr}$$

where $T_{Ab,Chw,i}$ is the return chilled water temperature entering the absorption chiller, $T_{Ab,Chw,o}$is the chilled water outlet temperature from the absorption chiller, and $\dot{v}_{Ab,Chw}$ is the volumetric flow rate of chilled water to the absorption chiller.

$$Q_{Ab,HW} = \rho_{w}\dot{v}_{Ab,HW}C_{p,water}(T_{Ab,HW,o} - T_{Ab,HW,i}) \cdot \frac{ft^2}{7.48\ gal} \cdot \frac{60\ min}{hr}$$

where $T_{Ab,HW,i}$ is the supply hot water temperature entering the absorption chiller, $T_{Ab,HW,o}$is the return hot water temperature leaving the absorption chiller, and $\dot{v}_{Ab,HW}$ is the volumetric flow rate of hot water to the absorption chiller.

Details for the COP metric are provided below, and an overview of required inputs and outputs for all monitoring points is depicted in Figure 3.4.

Metric: Coefficient of performance (COP)

Sensor Validation:

- $T_{Ab,Chw,i}$ should be flagged for a bad sensor if the reading is below 32° F, above 70°F during steady-state operating conditions, or above 100°F at any time.
- $T_{Ab,Chw,o}$ should be flagged for a bad sensor if the reading is below 32° F, above 70°F during steady-state operating conditions, or above 100°F at any time.

- $\dot{v}_{Ab,Chw}$ should be flagged for a bad sensor if the reading is below 0, or the value is above 20 gallons per minute but does not change value in over 4 hours.
- $T_{Ab,HW,i}$ should be flagged for a bad sensor if the reading is below 60° F or above 212°F at any time.
- $T_{Ab,HW,o}$ should be flagged for a bad sensor if the reading is below 60° F or above 212°F at any time.
- $\dot{v}_{Ab,HW}$ should be flagged for a bad sensor if the reading is below 0, or the value is above 20 gallons per minute but does not change value in over 4 hours.
- condenser water inlet temperature ($T_{Ab,CW,i}$) should be flagged for a bad sensor if the reading is below 32° F or above 100°F at any time.

Steady-State Detection:

- Wait at least 60 minutes after system startup.
- After that point, record COP whenever the rate of change of $Q_{Ab,ChW}/\ Q_{Ab,ChW,rated}$ (also referred to as the absorption chiller part load ratio, or PLR) with respect to time (determined through linear regression over a prior 10-minute window) is below 10%/hour.

Equation:

$$COP = \frac{Q_{Ab,ChW}}{Q_{Ab,HW}} = \frac{\dot{v}_{Ab,Chw}\rho_{Chw}C_{p,Chw}\left(T_{Ab,Chw,i} - T_{Ab,Chw,o}\right)}{\dot{v}_{Ab,HW}\rho_{Hw}C_{p,Hw}\left(T_{Ab,HW,o} - T_{Ab,HW,i}\right)}$$

where ρ_{Hw} is the density of the hot water in the generator (slightly different from ρ_{Chw}, based on its higher temperature) and $C_{p,Hw}$is the specific heat of the generator water. Both can be approximated as constants.

Independent variables:

Part load ratio (PLR), $T_{Ab,Chw,o}$, $T_{Ab,CW,i}$, $T_{Ab,HW,i}$, where $T_{Ab,CW,i}$ is the absorption chiller wondenser water inlet temperature.

Performance validation recording/reporting:

1. Record real-time performance every minute (not less frequently than every 5 minutes).
2. Determine a threshold fraction of real-time performance readings that are below normal performance by a threshold (e.g., 0.05) over a 1-day window. Normal performance should be determined via multiple regression or machine learning algorithms compared to a baseline data set established earlier (e.g., 1st year after setup of monitoring).

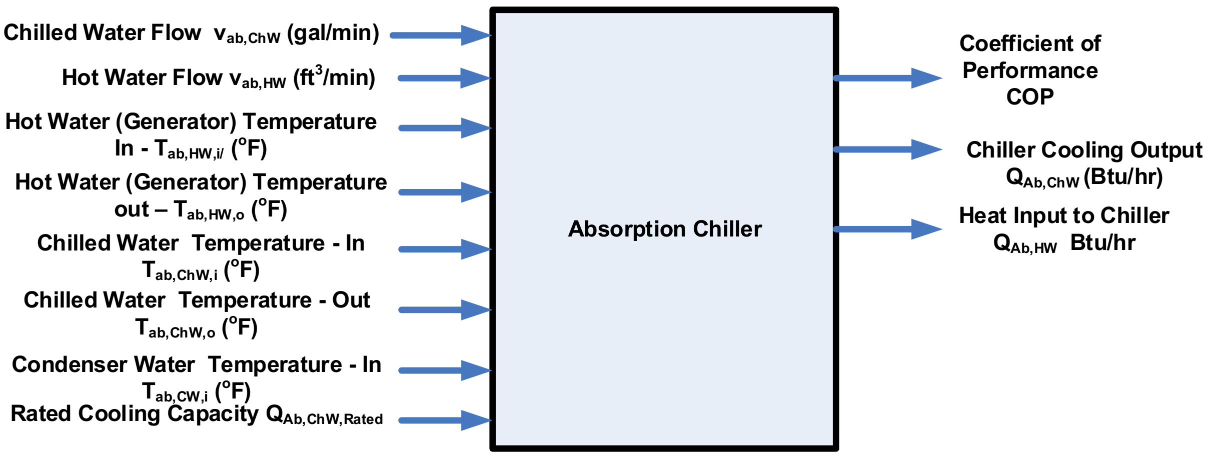

Figure 3.4. Input/output diagram for absorption chiller monitoring algorithms.

3.5 Boiler

The primary metric to track for boilers is the efficiency (η_B). This metric can be tracked for informational and trending purposes as well as for tracking of performance degradation. The heat output from the boiler (Q_B) should also be monitored for informational and graphical purposes.

$$Q_B = \rho_{Hw}\dot{v}_{B,w}C_{p,water}(T_{B,w,o} - T_{B,w,i}) \cdot \frac{ft^2}{7.48\ gal}$$

where $\dot{v}_{B,w}$ is the hot water flow rate through the boiler, $T_{B,w,i}$ is the boiler inlet hot water (return) temperature, and $T_{B,w,o}$ is the outlet hot water (supply) temperature.

Details for the boiler efficiency metric are provided below, and an overview of required inputs and outputs for all monitoring points is depicted in Figure 3.5.

Metric: Boiler efficiency (η_B)

Sensor Validation:

- Boiler gas flow rate ($\dot{v}_{B,Fuel}$) should be flagged for a bad sensor if the reading is below 0, if the value remains constant during operation as Q_B changes by more than +/- 10%, or if $\dot{v}_{B,Fuel}$ is greater than $\frac{1.5Q_{B,Rated}}{\rho_{Fuel}LHV_{Fuel}}$.
- $T_{B,w,i}$ should be flagged for a bad sensor if the reading is below 60° F or above 212°F at any time.
- $T_{B,w,o}$ should be flagged for a bad sensor if the reading is below 60° F or above 212°F at any time.
- $\dot{v}_{B,w}$ should be flagged for a bad sensor if the reading is below 0, or the value is above 20 gallons per minute but does not change value in over 4 hours.

Steady-State Detection:

- Wait at least 20 minutes after system startup.

- After that point, record η_B whenever the rate of change of $Q_B/\ Q_{B,Rated}$ (also referred to as the boiler part load ratio, or PLR) with respect to time (determined through linear regression over a prior 10-minute window) is below 10%/hour.

Equation:

$$\eta_B = \frac{\dot{v}_{B,w}\rho_{Hw}C_{p,Hw}\left(T_{B,w,o} - T_{B,w,i}\right)}{\rho_{Fuel}\dot{v}_{B,Fuel}LHV_{Fuel}} 1$$

Independent variables: PLR, $T_{B,w,i}$

Note that $T_{B,w,i}$ is required for condensing boilers and not for conventional boilers, but can be used for both as a default.

Performance validation recording/reporting:

1. Record real-time performance every minute (not less frequently than five minutes).
2. Determine a "threshold A" fraction of real-time performance readings (e.g., 50%) that are below normal performance by a threshold (e.g., 0.04) over a 1-day window.

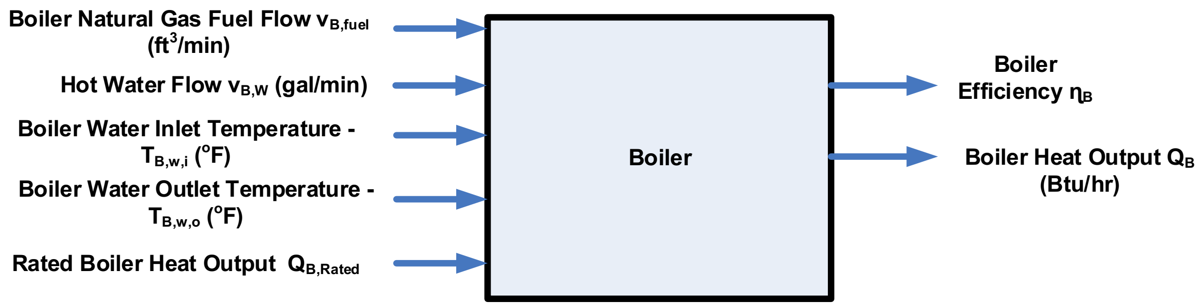

Figure 3.5. Input/output diagram for boiler monitoring algorithms.

3.6 Battery Energy Storage System

There are three performance metrics that can potentially be tracked with regard to batteries: charge efficiency (η_{Ch}), discharge efficiency (η_{Dis}), and roundtrip efficiency ($\eta_{Bat,R}$). Note that the formulations for charge and discharge efficiency as performance validation metrics using the available sensors rely on the assumption that, as the battery's capacity degrades, the state of charge (SOC) remains relatively fixed. In other words, the peak SOC does not get re-scaled to be 100% even as the battery's ability to store charge is degraded. If this is not valid, the roundtrip efficiency metric will be the best choice for identifying degradation. In addition to these three-performance metrics, the battery's charge and discharge power ($P_{Bat,Ch}$ and $P_{Bat,Dis}$)

[1] Note that the use of a volumetric flow to calculate gas heat content at a given lower heating value assumes that the volumetric flow being measured is at standard temperature and pressure. This may be a reasonable assumption for most sites; however, for better accuracy, actual cubic feet per minute may need to be converted to standard cubic feet per minute according to the equation:

$$SCFM = ACFM \left(\frac{P}{14.7}\right)\left(\frac{519}{T}\right)$$

where P is the gas pressure in psi, and T is the gas temperature in degrees Rankine (°R=460+°F).

should also be tracked for monitoring CHP system power flows. No steady-state detection is required for battery performance metrics.

Details for the three battery efficiency metrics are provided below, and an overview of required inputs and outputs for all monitoring points is depicted in Figure 3.6.

Metric: Charge efficiency (η_{Ch})

Sensor Validation:

- Battery state of charge (SOC) should be flagged as a faulty sensor if the value is below 0 or greater than 1.05.
- Battery charge power meter ($P_{Bat,Ch}$) should be flagged as a faulty sensor if the value remains the same, even as SOC increases by more than 0.05.

Equation:

$$\eta_{Ch} = \frac{\Delta SOC * CAP_{Bat,Rated}}{\Sigma P_{Bat,Ch} \Delta t}$$

where ΔSOC is the change in SOC compared to a previous time and positive indicates an increase in battery charge; $CAP_{Bat,Rated}$ is the battery's rated capacity.

Independent variables: SOC (average), $P_{Bat,Ch}$ (average value during charge cycle).

Performance validation recording/reporting:

1. Record SOC and P_{Ch} at time intervals (Δt) ranging from 10 seconds to 1 minute.
2. Every 10 minutes take the following steps:
   a. Over the past 30 minutes, first validate that ΔSOC (SOC at the end of the 30 minutes minus SOC at the beginning of the 30 minutes) is above a minimum threshold (e.g., 0.02) and that P_{Ch} has always been positive during the entire 30 minutes (battery has not switched from charging to discharging, which would invalidate the efficiency calculation).
   b. Sum across all recording intervals within the 30-minute period: the product of P_{Ch} and Δt (for the summation in the denominator of the η_{Ch} equation).
3. Determine a threshold reduction compared to normal efficiency (e.g., 4%). Performance degradation can be reported based on the results of a single charge cycle. Normal performance should be determined via multiple regression or machine learning algorithms compared to a baseline data set established earlier (e.g., 1st year after setup of monitoring).

Metric: Discharge efficiency (η_{Dis})

Sensor Validation (In addition to those called out in the charge efficiency metric):

- The battery discharge power meter ($P_{Bat,Dis}$) should be flagged as a faulty sensor if the value remains the same, even if the SOC decreases by more than 0.05.

Equation:

$$\eta_{Dis} = \frac{-\Delta SOC * CAP_{Bat,Rated}}{\Sigma P_{Bat,Dis}\Delta t}$$

Independent variables: SOC (average), $P_{Bat,Dis}$ (average).

Performance validation recording/reporting:

1. Record SOC and P_{Dis} at time intervals (Δt) ranging from 10 seconds to 1 minute.
2. Every 10 minutes, take the following steps:
   a. Over the past 30 minutes, first validate that ΔSOC (SOC at the end of the 30 minutes minus SOC at the beginning of the 30 minutes) is below a minimum threshold (e.g., -0.02) and that P_{Dis} has always been positive during the entire 30 minutes (battery has not switched from charging to discharging or other scenarios that would invalidate the measurement).
   b. Sum across all recording intervals within the 30-minute period: the product of P_{Ch} and Δt (for the summation in the denominator of the η_{Ch} equation).
3. Determine a threshold reduction compared to normal efficiency (e.g., 4%). Performance degradation can be reported based on the results of a single discharge cycle. Normal performance should be determined via multiple regression or machine learning algorithms compared to a baseline data set established earlier (e.g., 1st year after setup of monitoring).

Metric: Roundtrip efficiency ($\eta_{Bat,R}$)

This metric uses the same sensors as the charge and discharge efficiency metrics and no additional sensor validation is required.

Equation:

$$\eta_{Bat,R} = \frac{\Sigma P_{Bat,Dis}\Delta t}{\Sigma P_{Bat,Ch}\Delta t} \text{ (referenced against constant SOC; see below)}$$

Independent variables: $P_{Bat,Ch}$ (average), $P_{Bat,Dis}$ (average).

Performance validation recording/reporting:

1. The battery beginning a discharge cycle (switching from charge to discharge or from disuse to discharge) will initiate a single validation of roundtrip efficiency. Note, however, that the validation cannot be completed until the SOC returns to the SOC at the time the discharge cycle was initiated.
2. Note the SOC at the start of the discharge cycle (SOC_0).
   a. Record $P_{Bat,Ch}$ and $P_{Bat,Dis}$ at a time interval (Δt) ranging from ten seconds to one minute. Keep a running total of the product of $P_{Bat,Ch}$ and Δt as well as a running total of the product of $P_{Bat,Dis}$ and Δt.
   b. Wait for the SOC to decrease during the discharge cycle by at least a threshold (ex - 0.1).
   c. Evaluate $\eta_{Bat,R}$ when the SOC returns to SOC_0.

d. Determine a threshold drop in roundtrip efficiency for performance degradation (ex 0.04). This can be reported based on deviation during a single charge/discharge cycle. Normal performance should be determined via multiple regression or machine learning algorithms compared to a baseline data set established earlier (e.g., 1st year after setup of monitoring).

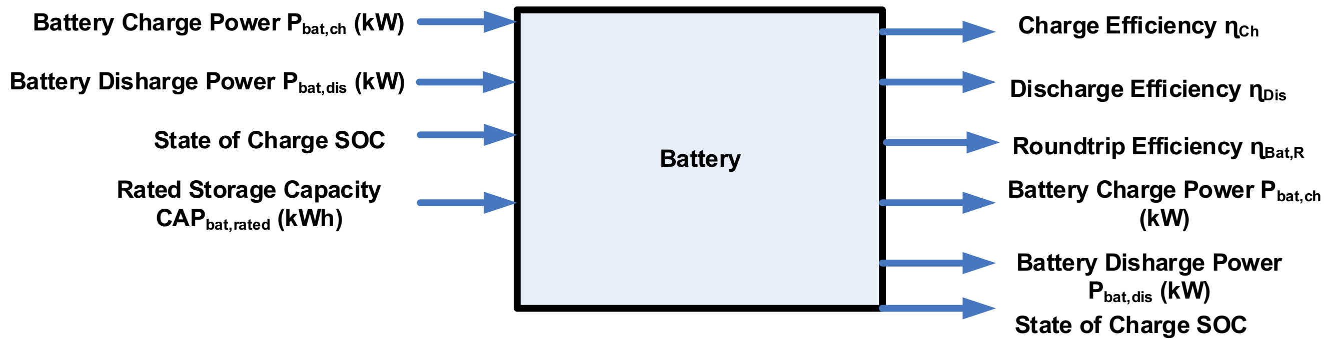

Figure 3.6. Input/output diagram for battery monitoring algorithms.

3.7 Thermal Energy Storage System

The primary metric to track for chilled water thermal energy storage systems is the roundtrip efficiency ($\eta_{TS,R}$). This metric can be tracked for informational and trending purposes as well as for tracking of performance degradation. The cooling energy charging the thermal storage tank ($Q_{TS,Ch}$), the cooling energy discharging from the thermal storage tank ($Q_{TS,Dis}$), and the thermal storage state of charge (SOC_{TS}) should also be tracked for monitoring cooling energy flows and understanding the remaining capacity of the storage tank. SOC_{TS} is expected to be a sensor value available from the thermal storage tank (internally calculated by the thermal storage management system). $Q_{TS,Ch}$ and $Q_{TS,Dis}$ are described below:

$$Q_{TS,ch} = \rho_w \dot{v}_{TS,ch} C_{p,water}(T_{TS,ch,out} - T_{TS,ch,in}) \cdot \frac{ft^2}{7.48\ gal} \cdot \frac{60\ min}{hr}$$

$$Q_{TS,dis} = \rho_w \dot{v}_{TS,dis} C_{p,water}(T_{TS,dis,in} - T_{TS,dis,in}) \cdot \frac{ft^2}{7.48\ gal} \cdot \frac{60\ min}{hr}$$

where

$T_{TS,ch,in}$ = the thermal storage charge inlet temperature,
$T_{TS,ch,out}$ = the charge outlet temperature,
$T_{TS,dis,in}$ = the thermal storage discharge inlet temperature,
$T_{TS,dis,out}$ = the thermal storage discharge outlet temperature,
$\dot{v}_{TS,ch}$ = the chilled water charge flow rate, and
$\dot{v}_{TS,dis}$ = the chilled water discharge flow rate.

Details for the roundtrip efficiency metric are provided below, and an overview of required inputs and outputs for all monitoring points is depicted in Figure 3.7.

Metric: Thermal storage roundtrip efficiency ($\eta_{TS,R}$)

Sensor Validation:

- $T_{TS,ch,in}$ should be flagged as a faulty sensor if the value is below 32°F (except for ice storage systems), above 70°F when the charging pump is running, or above 100°F at any time.
- $T_{TS,ch,out}$ should be flagged as a faulty sensor if the value is below 32°F (except for ice storage systems), above 70°F when the charging pump is running, or above 100°F at any time.
- $T_{TS,dis,in}$ should be flagged as a faulty sensor if the value is below 32°F (except for ice storage systems), above 70°F when the discharging pump is running, or above 100°F at any time.
- $T_{TS,dis,out}$ should be flagged as a faulty sensor if the value is below 32°F (except for ice storage systems), above 70°F when the discharging pump is running, or above 100°F at any time.
- $\dot{v}_{TS,dis}$ should be flagged for a bad sensor if the reading is below 0, or the value is above 20 gallons per minute but does not change value in over 4 hours.
- $\dot{v}_{TS,ch}$ should be flagged for a bad sensor if the reading is below 0, or the value is above 20 gallons per minute but does not change value in over 4 hours.
- SOC_{TS} should be flagged as a faulty sensor if the value is below 0 or greater than 1.05.

Equation:

$$\eta_{TS,R} = \frac{\Sigma(T_{TS,dis,in} - T_{TS,dis,out})\dot{v}_{TS,dis}\ \Delta t}{\Sigma(T_{TS,ch,out} - T_{TS,ch,in})\dot{v}_{TS,ch}\ \Delta t}\ \text{(referenced against constant SOC}_{TS}\text{)}$$

Independent variables: $T_{TS,ch,in}$

Performance validation recording/reporting:

1. The thermal storage tank beginning a discharge cycle (switching from charge to discharge or from disuse to discharge) will initiate a single validation of roundtrip efficiency. Note, however, that the validation cannot be completed until the SOC_{TYS} returns to the SOC_{TS} at the time the discharge cycle was initiated.
2. Note the SOC_{TS} at the start of the discharge cycle ($SOC_{TS,0}$).
3. Record sensor variables at time interval (Δt) ranging from 10 seconds to 1 minute. Keep a running total of the product of $(T_{TS,dis,in} - T_{TS,dis,out}), \dot{v}_{TS,dis}$, and Δt as well as a running total of the product of $(T_{TS,ch,out} - T_{TS,ch,in}), \dot{v}_{TS,ch}$, and Δt.
4. Wait for the SOC_{TS} to decrease by at least a threshold (e.g., -0.1) during the discharge cycle.
5. Evaluate $\eta_{TS,R}$when the SOC_{TS} returns to SOC_0. If the entire cycle does not complete in 24 hours, the validation should be discarded.
6. Determine a threshold drop in roundtrip efficiency for performance degradation (e.g., 0.04). This can be reported based on deviation during a single charge/discharge cycle. Normal performance should be determined via multiple regression or machine learning algorithms compared to a baseline data set established earlier (e.g., 1st year after setup of monitoring).

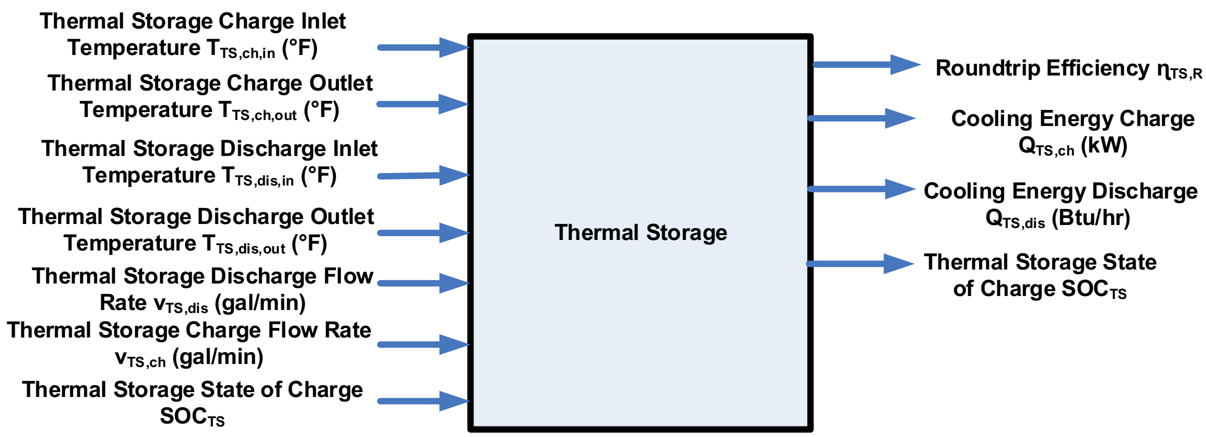

Figure 3.7. Input/output diagram for thermal storage monitoring algorithms.

3.8 Photovoltaic System

For photovoltaic systems, the AC power generated is the most important metric to track. Power generation can be degraded by dirty collectors, aging photocells, and potential problems with the DC/AC inverter. Power generation from the photovoltaics is important to track, regardless of available sensors, however, if the tilted surface (at the angle of the collectors) incident solar radiation is measured onsite, it is possible to perform performance validation on the solar panels to detect degradation as well. Details for the power generation metric are provided below, and an overview of required inputs and outputs for all monitoring points is depicted in Figure 3.8.

Metric: AC power generated ($P_{PV,elec}$)

Required sensors: Ambient temperature (T_{amb}), tilted surface solar incident radiation (I_T).

Independent variables: I_T and T_{amb} (if available onsite)

Equation: Baseline data can be collected to train the following regression equation (determine constants a, b, and c):

$$P_{elec} = a.I_T.K_\eta + b.I_T.K_\eta.T_a + c.(I_T.K_\eta)^2$$

where K_η is an angle incidence modifier, defined as $K_\eta = 1 - 0.1 \times (1/\cos\theta_i - 1)$,
where

$$\cos\theta_i = \sin\theta_s \sin\theta_p \cos(\phi_s - \phi_p) + \cos\theta_s \cos\theta_p$$, and

Θ_p = the tilt of the solar collectors with respect to the horizontal
φ_p = the azimuth of the solar collectors with respect to due South
θ_z = the solar zenith angle
φ_z = the solar azimuth angle.

Calculating the solar azimuth and zenith angles is relatively complex and is described in Appendix A.

Performance validation recording/reporting:

1. Collect baseline data over a 1-year period. Use a multiple regression to calculate the values of the coefficients a, b, and c, then hard code those coefficients into the equation for $\mathrm{P_{elec}}$.
2. For better accuracy, baseline values for a, b, and c can be determined monthly (e.g., different values for a, b, and c apply to different months of the year).
3. During this baseline period, also define a peak site electric power, $P_{PV,elec,rated}$, as the maximum value for $P_{PV,elec}$ in the baseline data.
4. After the 1-year baseline period,
   a. Collect data over a 1-week time frame.
   b. Determine a "threshold A" fraction (e.g., 50%) of P_{elec}/ $P_{elec,rated}$ readings that are below normal performance by a "threshold B" (e.g., 0.05) over a 1-day window. Normal performance should be determined via multiple regression or machine learning algorithms compared to a baseline data set established earlier (e.g., 1st year after setup of monitoring).

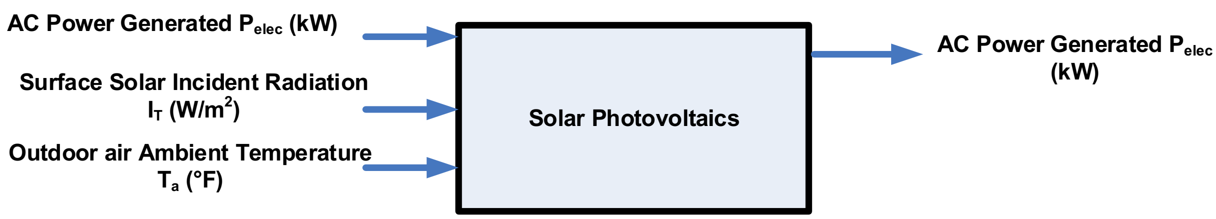

Figure 3.8. Input/output diagram for solar photovoltaics monitoring algorithms.

3.9 Cooling Towers

For cooling towers, two performance metrics are tracked: the cooling tower effectiveness ($\boldsymbol{\varepsilon_{CT}}$) and the cooling tower electric efficiency ($\eta_{CT,elec}$). The cooling tower electric efficiency requires measurement of cooling tower fan power consumption $P_{CT,elec}$. This sensor value should also be monitored for analytics detailing overall CHP system power flows.

ε_{CT} and $\eta_{CT,elec}$ are detailed below, and an overview of required inputs and outputs for all monitoring points is depicted in Figure 3.9.

Metric: Cooling tower effectiveness ($\boldsymbol{\varepsilon_{CT}}$)

Sensor Validation:

- Cooling tower water inlet temperature ($T_{CT,w,i}$) should be flagged as a faulty sensor if the value is below 32°F or above 100°F at any time.
- Cooling tower water outlet temperature ($T_{Ct,w,o}$) should be flagged as a faulty sensor if the value is below 32°F or above 100°F at any time.
- Outdoor wet bulb temperature (T_{wb}) should be flagged as a faulty sensor if the value is above the outdoor air temperature, or less than half of the outdoor air temperature (when both are in units of °F).

Steady-State Detection:

- Wait at least 20 minutes after system startup.
- After that point, record ε_{CT} whenever the rate of change of cooling tower fan variable frequency drive (VFD_{CT}) speed (determined through linear regression over a prior 10-minute window) is below 10%/hour.

Equation:

$$\varepsilon_{CT} = \frac{T_{CT,w,i} - T_{CT,w,o}}{T_{CT,w,i} - T_{wb}}$$

Independent variables: VFD_{CT}, cooling tower water flow rate ($\dot{v}_{CT,w}$; if the flow is variable).

Time frame for performance validation:

1. Record real-time performance every five to-ten minutes
2. Determine a "threshold A" fraction of real-time performance readings (e.g., 50%) that are below normal performance by a "threshold B" (.e.g., 0.04) over a one-day window. Normal performance should be determined via multiple regression or machine learning algorithms compared to a baseline data set established earlier (e.g., 1st year after setup of monitoring).

Metric: Cooling tower electric efficiency ($\eta_{CT,elec}$)

Sensor Validation:

- Cooling tower water flow rate ($\dot{v}_{CT,w}$) should be flagged as a faulty sensor if the value is below 0.
- Cooling tower electricity consumption ($P_{CT,elec}$) should be flagged as a faulty sensor if the value is below 0, or if the value does not change as the cooling tower fan VFD speed changes by more than +/-10%.

Steady-State Detection:

- Wait at least 20 minutes after system startup.
- After that point, record $\eta_{CT,elec}$ whenever the rate of change of the cooling tower fan variable frequency drive (VFD_{CT}) speed (determined through linear regression over a prior 10-minute window) is below 10%/hour.

Equation:

$$\eta_{CT,elec} = \frac{\rho_w \, C_{p,w} \, \dot{v}_{CT,w}(T_{CT,w,i} - T_{CT,w,o}) \cdot \frac{ft^2}{7.48\ gal} \cdot \frac{60\ min}{hr} \cdot 0.000293 \frac{kW}{Btu/hr}}{P_{CT,elec}}$$

Note that this "efficiency" is expected to be much greater than 1.

Independent variables: VFD_{CT}, $\dot{v}_{CT,w}$.

Performance validation recording/reporting:

1. Record real-time performance every minute (not less frequently than five minutes).
2. Determine a "threshold A" fraction of real-time performance readings (e.g., 50%) that are below normal performance by a "threshold B" (e.g., 0.2) over a 1-day window. Normal performance should be determined via multiple regression or machine learning algorithms compared to a baseline data set established earlier (e.g., 1st year after setup of monitoring).

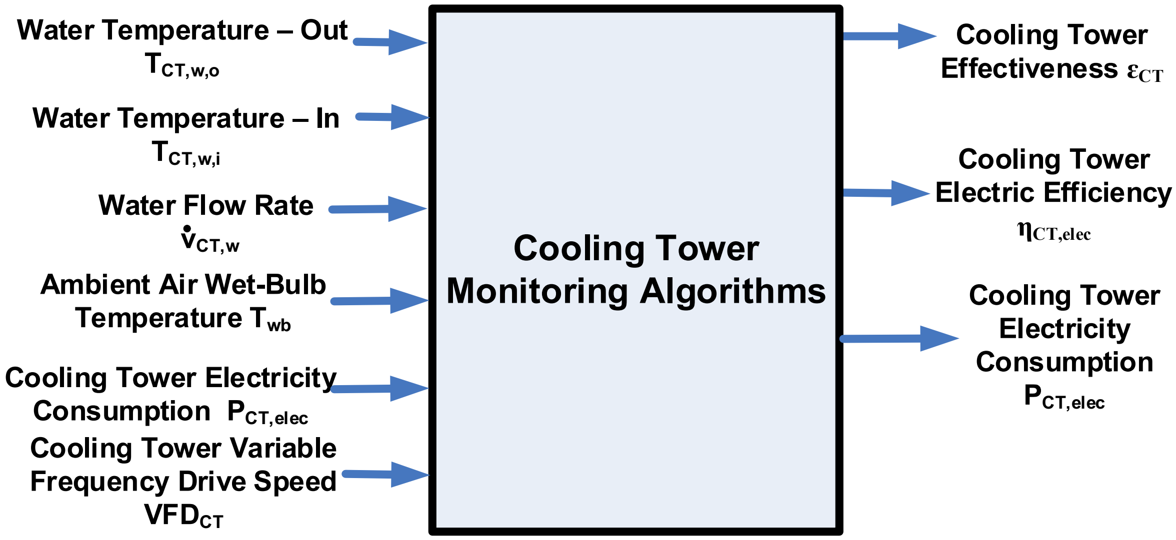

Figure 3.9. Input/output diagram for cooling tower monitoring algorithms.

3.10 System-Level Validation

Four metrics are used to perform validation of the CHP system performance as a whole: the fuel utilization factor (η_F), the value-weighted energy utilization factor ($\boldsymbol{EUF_{VW}}$), the absorption chiller utilization fraction ($\boldsymbol{Ab_F}$), and the current expenditure rate for fuel ($\boldsymbol{Cost_{Fuel}}$l). This section defines these metrics and describes how they should be used to perform system-level validation.

While component-level validation typically indicates a degradation in performance likely related to a fault or degradation in intrinsic capabilities, system-level validation is more likely to uncover issues related to control or dispatch of the components, unless the system-level performance degradation is paired with component-level performance problems, in which case pairing the two can allow for identifying the system-level impacts of component-level performance problems.

Note that system-level validation algorithms make use of the same sensors already addressed for component-level validation, and thus, sensor validation is neglected for these metrics to avoid duplication of effort.

<u>Metric</u>: Fuel utilization factor (η_F)

This metric quantifies what fraction of the fuel directed to the prime movers is used for productive purposes (rather than rejected as waste heat). The productive uses include the electricity generated by the prime mover and the heat delivered to the hot water loop via the heat recovery unit.

Required sensors:

- Prime mover electric power generated (P_{Elec})
- Prime mover fuel flow ($\dot{v}_{Fuel,pm}$)
- Heat recovery unit water inlet temperature ($T_{HRU,w,i}$)
- Heat recovery unit water outlet temperature ($T_{HRU,w,o}$)
- Heat recovery unit water flow rate ($\dot{v}_{HRU,w}$).

Equation:

$$\eta_F = \frac{P_{Elec} + \rho_w \dot{v}_{HRU,w} C_{p,water}(T_{HRU,w,o} - T_{HRU,w,i}) \cdot \frac{ft^2}{7.48\ gal} \cdot 0.293 \frac{kW}{kBtu/hr}}{\rho_{Fuel}(\dot{v}_{Fuel,pm}) LHV_{Fuel} \cdot 60 \frac{min}{hr} \cdot 0.293 \frac{kW}{kBtu/hr}}$$

Performance validation recording/reporting:

1. Wait one hour after prime mover startup.
2. Record η_F at a regular time interval, Δt in both a daily database and a weekly database.
3. Stop recording η_F if the prime movers are not operational.
4. Report the average value of η_F in daily and weekly summaries to the user, using the average value of η_F in each database:

$$\overline{\eta_F} = \frac{\sum \eta_F dt}{\Delta t}.$$

Metric: Value-weighted energy utilization factor (EUF_{VW})

This metric helps to refine the fuel utilization factor by applying value weights ($V_{elec}, V_{HW}, V_{fuel}$) to the energy streams. While assigning values to electricity and natural gas may be straightforward (equal to current prices for electricity and natural gas from the utility), assigning a value to hot water requires a more subjective judgment/process.

Required sensors:

- Prime mover electric power generated (P_{Elec})
- Prime mover fuel flow ($\dot{v}_{Fuel,pm}$)
- Heat recovery unit water inlet temperature ($T_{HRU,w,i}$)
- Heat recovery unit water outlet temperature ($T_{HRU,w,o}$)
- Heat recovery unit water flow rate ($\dot{v}_{HRU,w}$).

Equation:

$$EUF_{VW} = \frac{P_{Elec} V_{elec} + \rho_w \dot{v}_{HRU,w} C_{p,water}(T_{HRU,w,o} - T_{HRU,w,i}) V_{HW} \cdot \frac{ft^2}{7.48\ gal} \cdot 0.293 \frac{kW}{kBtu/hr}}{\rho_{Fuel}(\dot{v}_{Fuel,pm}) LHV_{Fuel} V_{Fuel} \cdot 60 \frac{min}{hr} \cdot 0.293 \frac{kW}{kBtu/hr}}$$

Performance validation recording/reporting:

1. Wait one hour after prime mover startup.

2. Record EUF_{VW} at a regular time interval, Δt in both a daily database and a weekly database.
3. Stop recording EUF_{VW} if the prime movers are not operational.
4. Report the average value of EUF_{VW} in daily and weekly summaries to the user, using the average value of EUF_{VW} in each database:

$$\overline{EUF_{VW}} = \frac{\sum EUF_{VW} dt}{\Delta t}$$

<u>Metric</u>: Absorption chiller utilization fraction (Ab_F)

This metric helps to determine how effectively waste heat is being used for cooling, as opposed to conventional chiller operation. The metric determines the total fraction of generated chilled water-cooling energy provided by the absorption chiller.

<u>Required sensors</u>:

- Absorption chiller evaporator water outlet temperature ($T_{ab,w,o}$)
- Absorption chiller evaporator water inlet temperature ($T_{ab,w,i}$)
- Absorption chiller evaporator water flow rate ($\dot{v}_{ab,w}$)
- Chiller water inlet temperature ($T_{Ch,w,i}$)
- Chiller water outlet temperature ($T_{Ch,w,o}$)
- Chiller volumetric flow rate – all chillers ($\dot{v}_{Ch}$).

<u>Equation:</u>

$$Ab_F = \frac{\rho_w \dot{v}_{ab,w} C_p (T_{ab,w,i} - T_{ab,w,o})}{\rho_w \dot{v}_{ab,w} C_p \left(T_{ab,w,i} - T_{ab,w,o}\right) + \rho_w \dot{v}_{Ch} C_p \left(T_{Ch,w,i} - T_{Ch,w,o}\right)}$$

Ab_F is not very informative as an instantaneous value; a time-averaged value is more useful.

<u>Independent Variables</u>: Total chilled water load

$$Q_{ch,load} = \rho_w \dot{v}_{ab,w} C_p \left(T_{ab,w,i} - T_{ab,w,o}\right) \cdot \frac{ft^2}{7.48\ gal} + \rho_w \dot{v}_{Ch} C_p \left(T_{Ch,w,i} - T_{Ch,w,o}\right) \cdot \frac{ft^2}{7.48\ gal}$$

<u>Performance validation recording/reporting</u>:

1. Wait 20 minutes after any chiller starts up (vapor compression or absorption) after all have been off.
2. Record Ab_F at a regular time interval, Δt in both a daily database and a weekly database.
3. Stop recording Ab_F if all chillers are not operational.
4. Report the average value of Ab_F in daily and weekly summaries to the user, using the average value of Ab_F in each database:

$$\overline{Ab_F} = \frac{\sum Ab_F \Delta t}{\Delta t}.$$

- Report the average value of Ab_F as a function of the total chilled water load ($Q_{ch,load}$) via scatter plot or bin analysis (average values of Ab_F in discrete and regularly spaced “bins” of $Q_{ch,load}$).

Metric: Current fuel expenditure rate ($\boldsymbol{Cost_{Fuel}}$)

This metric indicates the rate of expenditure of funds on fuel for the CHP plant.

Equation:

$$Cost_{fuel} = \rho_{Fuel}\dot{v}_{Fuel,pm}LHV_{Fuel}\mathrm{Price}_{\mathrm{Fuel}}$$

Required sensors:

- Prime mover fuel flow rate ($\dot{v}_{Fuel,pm}$).

Performance validation recording/reporting:

Record the calculated instantaneous fuel cost value and the value for the real-time monitoring/dashboard.

4.0 Real-Time Commissioning

Real-time commissioning refers to a validation of the rated or expected performance of a component or system on manufacturers' data. Real-time commissioning is an exercise that should be performed during the first few months after the device or system is installed and running. This time frame allows for validation of the performance of the system while it is new enough to rule out any performance degradation that may occur over time. The set of validation metrics that can be used for real-time commissioning is likely to be a subset of those used for performance monitoring because it necessarily relies on metrics that are likely to be specified by the manufacturer. An important difference between real-time commissioning and performance monitoring is that the real-time commissioning has to replicate any rated conditions to be valid. This may be done passively, by waiting until conditions sufficiently close to rated conditions happen to occur, or it may be done proactively, for example, by controlling the component or system to setpoints that actively reproduce the rated conditions.

4.1 Microturbine

Metrics: Rated efficiency (η_G at rated conditions)

Rated Capacity (P_{elec} at rated conditions)

- Prompt user for their microturbine's specific rated efficiency ($\eta_{G,rated}$) and rated capacity ($P_{elec,rated}$).
- Allow the user the option to select "passive testing only" or "active testing."

Rated Test Conditions (ISO Conditions; unless stated otherwise by the manufacturer):

- Ambient (outdoor air) temperature $T_{a,rated}$ = 59°F
- Ambient (relative humidity) $RH_{a,rated}$ = 60%
- Part load ratio (PLR_{rated}) = 100%

Passive Testing Algorithm:

1. Wait for steady-state conditions to be reached:
   a. Wait at least 1 hour after microturbine startup.
   b. After that point, wait until the rate of change of $P_{Elec}/\ P_{Elec,rated}$ with respect to time (determined through linear regression over a prior 10-minute window) is below 10%/hour.
2. After steady state has been reached, validate that each of the following conditions is met:
   - Condition 1: $T_{a,rated} - T_{a,tol} <= \mathbf{T_a} <= T_{a,rated} + T_{a,tol}$; recommended value for $T_{a,tol}$ is 3°F.
   - Condition 2: $RH_{a,rated} - RH_{a,tol} <= \mathbf{RH_a} <= RH_{a,rated} + RH_{a,tol}$; recommended value for $T_{a,tol}$ is 5%.
   - Condition 3: $\mathbf{PLR} >= PLR_{rated} - PLR_{tol}$; recommended value for PLR_{tol} = 0.01.

Active Testing Algorithm:

1. Validate that each of the following conditions is met:
   - Condition 1: $T_{a,rated} - T_{a,tol} <= \mathbf{T_a} <= T_{a,rated} + T_{a,tol}$; recommended value for $T_{a,tol}$ is 3°F.

- Condition 2: $RH_{a,rated}$ - $RH_{a,tol}$ <= $\mathbf{RH_a}$ <= $RH_{a,rated}$ + $RH_{a,tol}$; recommended value for $T_{a,tol}$ is 5%.

2. If conditions under Step 1 (immediately above) are met, command the microturbine to the full rated power (PLR = 100%). Wait until steady-state conditions are met, then:
   a. Wait at least 1 hour after microturbine startup.
   b. After that point, wait until the rate of change of $P_{Elec}/\ P_{Elec,rated}$ with respect to time (determined through linear regression over a prior 10-minute window) is below 10%/hour.

<u>Passive and Active Testing (completion of algorithms)</u>:

1. For P_{elec}, when Conditions 1 and 2 have been met, create a new variable called $P_{elec,corrected}$:
   a. If the elevation of the site is below 1,765 ft, $P_{elec,corrected}$ = P_{elec}
   b. If the elevation of the site is greater than 1,765 ft

$$P_{elec,corrected} = P_{elec} * CF$$
$$CF = [0.0000497Elevation + 0.9122].$$

2. For each recording timestep for which Conditions 1 and 2 have been met, record $\boldsymbol{\eta_G}$ and $P_{elec,corrected}$ in a real-time commissioning database.
3. Complete the real-time commissioning when either
   - 100 entries for each of $\boldsymbol{\eta_G}$ and $P_{elec,corrected}$ are recorded in the database, or
   - 12 months have passed since real-time commissioning was enabled.
4. Define the actual microturbine efficiency ($\boldsymbol{\eta_{G,a}}$) as the average value of $\boldsymbol{\eta_G}$ in the database.
5. Define the actual microturbine capacity ($P_{elec,\max}$) as the average value of $P_{elec,corrected}$ in the database.
6. Create the following report messages to the user:
   a. "The rated efficiency listed for Microturbine #[x] was [$\eta_{G,rated}$]. A real-time commissioning process has been completed for this system. The actual efficiency at rated conditions has been determined to be [$\boldsymbol{\eta_{G,a}}$]."
   b. **If the site elevation is below 1765 ft:** "The rated capacity listed for Microturbine #[x] was [$P_{elec,rated}$]. A real-time commissioning process has been completed for this system. The actual capacity at rated conditions has been determined to be [$P_{elec,\max}$]."
   c. **If the site elevation is above 1765 ft:** "The rated capacity listed for Microturbine #[x] was [$P_{elec,rated}$]. A real-time commissioning process has been completed for this system. The actual capacity at rated conditions has been determined to be [$P_{elec,\max}$], however, due to the elevation of your site, the maximum capacity that Microturbine #[x] can output at your site is [$\frac{P_{elec,\max}}{CF}$]."

4.2 Fuel Cell

Metrics: Rated efficiency ($\boldsymbol{\eta_G}$ at rated conditions)

Rated Capacity ($\boldsymbol{P_{elec}}$ at rated conditions)

- Prompt user for their microturbine's specific rated efficiency ($\eta_{G,rated}$) and rated capacity ($P_{elec,rated}$).
- Allow the user the option to select "passive testing only" or "active testing."

Rated Test Conditions (ISO Conditions; unless stated otherwise by the manufacturer):

- Ambient (outdoor air) temperature $T_{a,rated}$ = 77°F.
- Part load factor (PLR_{rated}) = 100%.

Passive Testing Algorithm:

1. Wait for steady-state conditions to be reached:
   a. Wait at least 1 hour after fuel cell startup.
   b. After that point, wait until the rate of change of $P_{Elec}/\ P_{Elec,rated}$ with respect to time (determined through linear regression over a prior 10-minute window) is below 10%/hour.
2. After steady state has been reached, validate that each of the following conditions are met:
   a. $T_{a,rated} - T_{a,tol} <= \mathbf{T_a} <= T_{a,rated} + T_{a,tol}$; recommended value for $T_{a,tol}$ is 3°F.
   b. **PLR** >= $PLR_{rated} - PLR_{tol}$; recommended value for PLF_{tol} = 0.01.

Active Testing Algorithm:

1. Validate that $T_{a,rated} - T_{a,tol} <= \mathbf{T_a} <= T_{a,rated} + T_{a,tol}$; recommended value for $T_{a,tol}$ is 3°F.
2. Command the microturbine to the full rated power (PLF = 100%). Wait until steady-state conditions are met:
   a. Wait at least 1 hour after fuel cell startup.
   b. After that point, wait until the rate of change of $P_{Elec}/\ P_{Elec,rated}$ with respect to time (determined through linear regression over a prior 10-minute window) is below 10%/hour.

Passive and Active Testing (completion of algorithms):

1. For each recording timestep for which steps 1 and 2 (in either the passive or active testing algorithm) have been met, record $\boldsymbol{\eta_G}$ and P_{elec} in a real-time commissioning database.
2. Complete the real-time commissioning when either
   - 100 entries for each of $\boldsymbol{\eta_G}$ and P_{elec} are recorded in the database, or
   - 12 months have passed since real-time commissioning was enabled.
3. Define the actual fuel cell efficiency ($\boldsymbol{\eta_{G,a}}$) as the average value of $\boldsymbol{\eta_G}$ in the database.
4. Define the actual fuel cell capacity ($P_{elec,\max}$) as the average value of P_{elec} in the database.
5. Create the following report messages to the user:
   a. "The rated efficiency listed for Fuel Cell #[x] was [$\eta_{G,rated}$]. A real-time commissioning process has been completed for this system. The actual efficiency at rated conditions has been determined to be [$\boldsymbol{\eta_{G,a}}$]."

b. "The rated capacity listed for Fuel Cell #[x] was $[P_{elec,rated}]$. A real-time commissioning process has been completed for this system. The actual capacity at rated conditions has been determined to be $[P_{elec,\max}]$."

4.3 Electrical-Driven Vapor Compression Chiller

Metrics: Rated COP (COP at rated conditions)

Rated Capacity (Q_{ch} at rated conditions)

- Prompt user for their chiller's specific rated COP (COP_{rated}) and rated capacity ($Q_{Ch,rated}$).
- Allow the user the option to select "passive testing only" or "active testing."

Rated Test Conditions (ASHRAE/ANSI/AHRI/ISO Standard 13256; unless stated otherwise by the manufacturer):

- Leaving evaporator water temperature $T_{ch,o,rated}$ = 44.6°F.
- Condenser entering water temperature $T_{cond,i,rated}$ = 86°F.
- Part load ratio (PLR_{rated}) = 100%.

Passive Testing Algorithm:

1. Wait for steady-state conditions to be reached:
   a. Wait at least 20 minutes after chiller startup.
   b. After that point, wait until the rate of PLR with respect to time (determined through linear regression over a prior 10-minute window) is below 10%/hour.
2. After steady state has been reached, validate that each of the following conditions are met:
   a. $T_{ch,o,rated} - T_{ch,o,tol} <= \mathbf{T_{ch,o}} <= T_{ch,o,rated} + T_{ch,o,tol}$; recommended value for $T_{ch,o,tol}$ is 1°F.
   b. $T_{cond,i,rated} - T_{ond,i,tol} <= \mathbf{T_{cond,i}} <= T_{cond,i,rated} + T_{cond,i,tol}$; recommended value for $T_{cond,i,tol}$ is 2°F.
   c. **PLR** >= PLR_{rated} - PLR_{tol}; recommended value for PLR_{tol} = 0.01.

Active Testing Algorithm:

1. Wait until the chiller is fully loaded (**PLR** >= PLR_{rated} - PLR_{tol}; recommended value for PLR_{tol} = 0.01).
2. Command the condenser water temperature setpoint to 86°F and the chilled water temperature setpoint to 44.6°F in the Building Automation System (BAS). Wait for steady-state conditions:
   a. Wait until the condenser water temperature reaches the condenser water temperature setpoint within a programmed tolerance:

      $T_{cond,i,rated} - T_{ond,i,tol} <= \mathbf{T_{cond,i}} <= T_{cond,i,rated} + T_{cond,i,tol}$; recommended value for $T_{cond,i,tol}$ is 2°F.
   b. Wait until the chilled water temperature reaches the chilled water temperature setpoint within a programmed tolerance:

      $T_{ch,o,rated} - T_{ch,o,tol} <= \mathbf{T_{ch,w,o}} <= T_{ch,o,rated} + T_{ch,o,tol}$; recommended value for $T_{ch,o,tol}$ is 1°F.

Passive and Active Testing (completion of algorithms):

1. For each recording timestep for which steps 1 and 2 (in either the passive or active testing algorithm) have been met, record $\boldsymbol{COP}$ and Q_{ch} in a real-time commissioning database.
2. Complete the real-time commissioning when either
   - 100 entries for each of $\boldsymbol{COP}$ and Q_{ch} are recorded in the database, or
   - 12 months have passed since real-time commissioning was enabled.
3. Define the actual chiller COP ($\boldsymbol{COP_a}$) as the average value of $\boldsymbol{COP}$ in the database. Define the actual chiller capacity ($Q_{ch,max}$) as the average value of Q_{ch} in the database.
4. Create the following report messages to the user:
   a. "The rated COP for Chiller #[x] was $[COP_{rated}]$. A real-time commissioning process has been completed for this system. The actual efficiency at rated conditions has been determined to be $[\boldsymbol{COP_a}]$."
   b. "The rated capacity listed for Chiller #[x] was $[Q_{ch,rated}]$. A real-time commissioning process has been completed for this system. The actual capacity at rated conditions has been determined to be $[Q_{ch,\max}.]$."

4.4 Waste Heat-Driven Absorption Chiller

Metrics: Rated COP (COP at rated conditions)

Rated Capacity ($Q_{ab,chW}$ at rated conditions)

- Prompt user for their absorption chiller's specific rated COP (COP_{rated}) and rated capacity ($Q_{ab,chW,rated}$).
- Allow the user the option to select "passive testing only" or "active testing."

Rated Test Conditions (Air Conditioning, Heating, and Refrigeration Institute Standard 560-2000; unless stated otherwise by the manufacturer):

- Leaving evaporator water temperature $T_{ab,chW,o,rated}$ = 44°F.
- Condenser entering water temperature $T_{ab,CW,i,rated}$ = 85°F.
- Hot water (generator) entering temperature $T_{ab,HW,i,rated}$ = user input, determined from manufacturer's data.
- Part load ratio (PLR_{rated}) = 100%.

Passive Testing Algorithm:

1. Wait for steady-state conditions to be reached:
   a. Wait at least 20 minutes after absorption chiller startup.
   b. After that point, wait until the rate of PLR with respect to time (determined through linear regression over a prior 10-minute window) is below 10%/hour.
2. After steady state has been reached, validate that each of the following conditions are met:
   a. $T_{ab,chW,o,rated} - T_{ab,chW,o,tol} <= \mathbf{T_{ab,chW,o}} <= T_{ab,chW,o,rated} + T_{ab,chW,o,tol}$; recommended value for $T_{ab,chW,o,tol}$ is 1°F.

b. $T_{ab,CW,I,rated}$ - $T_{ab,CW,i,tol}$ <= $\mathbf{T_{ab,CW,i}}$ <= $T_{ab,CW,i,rated}$ + $T_{ab,CW,i,tol}$; recommended value for $T_{ab,CW,i,tol}$ is 2°F.

c. $T_{ab,HW,i,rated}$ - $T_{ab,HW,i,tol}$ <= $\mathbf{T_{ab,HW,i}}$ <= $T_{ab,HW,i,rated}$ + $T_{ab,HW,i,tol}$; recommended value for $T_{ab,HW,i,tol}$ is 4°F.

d. **PLR** >= PLR_{rated} - PLR_{tol}; recommended value for PLR_{tol} = 0.01.

Active Testing Algorithm:

1. Wait until the absorption chiller is fully loaded (**PLR** >= PLR_{rated} - PLR_{tol}; recommended value for PLR_{tol} = 0.01).
2. Command the condenser water temperature setpoint to $T_{ab,CW,i,rated}$, the chilled water temperature setpoint to $T_{ab,chW,o,rated}$, and the hot water inlet temperature to $T_{ab,HW,i,rated}$. Wait for steady-state conditions:
   a. Wait until the condenser water temperature reaches the condenser water temperature setpoint within a programmed tolerance: $T_{ab,CW,i,rated}$ - $T_{ab,CW,i,tol}$ <= $\mathbf{T_{ab,CW,i}}$ <= $T_{ab,CW,i,rated}$ + $T_{ab,CW,i,tol}$; recommended value for $T_{ab,CW,i,tol}$ is 2°F.
   b. Wait until the chilled water temperature reaches the chilled water temperature setpoint within a programmed tolerance: $T_{ab,chW,o,rated}$ - $T_{ab,chW,o,tol}$ <= $\mathbf{T_{ab,chW,o}}$ <= $T_{ab,chW,o,rated}$ + $T_{ab,chW,o,tol}$; recommended value for $T_{ab,chW,o,tol}$ is 1°F.
   c. Wait until the hot water temperature reaches the hot water inlet temperature setpoint within a programmed tolerance: $T_{ab,HW,i,rated}$ - $T_{ab,HW,i,tol}$ <= $\mathbf{T_{ab,HW,i}}$ <= $T_{ab,HW,i,rated}$ + $T_{ab,HW,i,tol}$; recommended value for $T_{ab,HW,i,tol}$ is 4°F.

Passive and Active Testing (completion of algorithms):

1. For each recording timestep for which steps 1 and 2 (in either the passive or active testing algorithm) have been met, record $\boldsymbol{COP}$ and $Q_{ab,chW}$ in a real-time commissioning database.
2. Complete the real-time commissioning when either
   - 100 entries for each of $\boldsymbol{COP}$ and $Q_{ab,chW}$ are recorded in the database, or
   - 12 months have passed since real-time commissioning was enabled.
3. Define the actual chiller COP ($\boldsymbol{COP_a}$) as the average value of $\boldsymbol{COP}$ in the database.
4. Define the actual chiller capacity ($Q_{ab,chW,max}$) as the average value of $Q_{ab,chW}$ in the database.
5. Create the following report messages to the user:
   a. "The rated COP for Absorption Chiller #[x] was $[COP_{rated}]$. A real-time commissioning process has been completed for this system. The actual efficiency at rated conditions has been determined to be $[\boldsymbol{COP_a}]$."
   b. "The rated capacity listed for Absorption Chiller #[x] was $[Q_{ab,chW,rated}]$. A real-time commissioning process has been completed for this system. The actual capacity at rated conditions has been determined to be $[Q_{ab,chW,\max}]$."

4.5 Boiler

Metrics: Rated efficiency (η_B at rated conditions)

Rated Capacity (Q_B at rated conditions)

- Prompt user for their boiler's specific rated efficiency ($\eta_{B\ rated}$) and rated capacity ($Q_{B,rated}$).
- Allow the user the option to select "passive testing only" or "active testing."

Rated Test Conditions (.AHRI.) Standard 1500; unless stated otherwise by the manufacturer):

- Hot water temperature $T_{B,HW,o,rated}$ = 180°F (non-condensing boilers); 120°F (condensing boilers)
- Part load ratio (PLR_{rated}) = 100%.

Passive Testing Algorithm:

1. Wait for steady-state conditions to be reached:
   a. Wait at least 20 minutes after boiler startup.
   b. After that point, wait until the rate of PLR with respect to time (determined through linear regression over a prior 10-minute window) is below 10%/hour.
2. After steady state has been reached, validate that each of the following conditions are met:
   a. $T_{B,HW,o,rated} - T_{B,HW,tol} <= \mathbf{T_{B,HW,o}} <= T_{B,HW,o,rated} + T_{B,HW,o,tol}$; recommended value for $T_{B,HW,o,tol}$ is 4°F.
   b. **PLR** >= PLR_{rated} - PLR_{tol}; recommended value for PLR_{tol} = 0.01.

Active Testing Algorithm:

1. Wait until the boiler is fully loaded (**PLR** >= PLR_{rated} - PLR_{tol}; recommended value for PLR_{tol} = 0.01).
2. Command the boiler water temperature setpoint to $T_{B,HW,o,rated}$ in the BAS. Wait until the hot water temperature reaches the hot water temperature setpoint within a programmed tolerance: $T_{B,HW,o,rated} - T_{B,HW,tol} <= \mathbf{T_{B,HW,o}} <= T_{B,HW,o,rated} + T_{B,HW,o,tol}$; recommended value for $T_{B,HW,o,tol}$ is 4°F.

Passive and Active Testing (completion of algorithms):

1. For each recording timestep for which steps 1 and 2 (in either the passive or active testing algorithm) have been met, record $\boldsymbol{\eta_B}$ and Q_B in a real-time commissioning database.
2. Complete the real-time commissioning when either
   - 100 entries for each of $\boldsymbol{\eta_B}$ and Q_B are recorded in the database, or
   - 12 months have passed since real-time commissioning was enabled.
3. Define the actual boiler efficiency ($\boldsymbol{\eta_{B,a}}$ as the average value of $\boldsymbol{\eta_B}$ in the database.
4. Define the actual boiler capacity ($Q_{B,max}$) as the average value of Q_B in the database.
5. Create the following report messages to the user:
   a. "The rated efficiency for boiler #[x] was [$\boldsymbol{\eta_{B_{rated}}}$]. A real-time commissioning process has been completed for this system. The actual efficiency at rated conditions has been determined to be [$\boldsymbol{\eta_{B,a}}$]."

b. "The rated capacity listed for Boiler #[x] was [$Q_{B,rated}$] A real-time commissioning process has been completed for this system. The actual capacity at rated conditions has been determined to be [$Q_{B,\max}$]."

4.6 Battery Energy Storage System

Metric: Roundtrip Efficiency ($\eta_{Bat,R}$ at rated conditions)

- Prompt user for their battery's rated roundtrip efficiency ($\eta_{Bat,R,\ rated}$) and the rated charge/discharge power ($P_{Bat,Ch,rated}$).
- Allow the user the option to select "passive testing only" or "active testing."

Passive Testing Algorithm:

1. The battery beginning a discharge cycle (switching from charge to discharge or from disuse to discharge) will initiate a single validation of roundtrip efficiency. Note, however, that the validation cannot be completed until the SOC returns to the SOC at the time the discharge cycle was initiated.
2. Note the SOC at the start of the discharge cycle (SOC_0).
   a. Record $P_{Bat,Ch}$ and $P_{Bat,Dis}$ at a time interval (Δt) ranging from 10 seconds to 1 minute. Keep a running total of the product of $P_{Bat,Ch}$ and Δt as well as a running total of the product of $P_{Bat,Dis}$ and Δt.
   b. Wait for the SOC to decrease during the discharge cycle by at least a threshold e.g., 0.3).
   c. After the SOC returns to SOC_0, validate that each of the following conditions are met:
      - $P_{Bat,Ch,rated}$ - $P_{Bat,ch,tol}$ <= $\overline{P_{Bat,Ch}}$ <= $P_{Bat,Ch,rated}$ + $P_{Bat,ch,tol}$; Recommended value for $P_{Bat,ch,tol}$ is 0.5 kW
      - $P_{Bat,Ch,rated}$ - $P_{Bat,dis,tol}$ <= $\overline{P_{Bat,Dis}}$ <= $P_{Bat,Ch,rated}$ + $P_{Bat,dis,tol}$; Recommended value for $P_{Bat,dis,tol}$ is 0.5 kW
   d. If conditions under Step 2c are met, evaluate $\eta_{Bat,R}$ when the SOC returns to SOC_0 and record the value in a real-time commissioning database.
3. Complete the real-time commissioning when either
   - five entries for each of $\eta_{Bat,R}$ are recorded in the database, or
   - 12 months have passed since real-time commissioning was enabled.
4. Define the actual battery roundtrip efficiency ($\eta_{Bat,R,a}$) as the average value of $\eta_{Bat,R}$ in the database.
5. Create the following report message to the user:
   a. "The rated battery roundtrip efficiency for the battery storage system was [$\eta_{Bat,R}$]. A real-time commissioning process has been completed for this system. The actual roundtrip efficiency at rated conditions has been determined to be [$\eta_{Bat,R,a}$]."

Active Testing Algorithm:

1. Wait for the user to schedule or initiate a real-time commissioning cycle for the battery.

2. Command the battery to charge until the SOC reaches 90% and record SOC_0 = 90%. If the SOC is already above 90%, record SOC_0 = the current SOC.
3. Command a discharge of the battery at a rate of $P_{Bat,Ch,rated}$. Continue discharging until the SOC reaches 30%. Record $P_{Bat,Dis}$ at a time interval (Δt) ranging from 10 seconds to 1 minute. Keep a running total of the product of $P_{Bat,Dis}$ and Δt.
4. Command a charge of the battery at a rate of $P_{Bat,Ch,rated}$. Continue charging until the SOC reaches SOC_0. Record $P_{Bat,Ch}$ at a time interval (Δt) ranging from 10 seconds to 1 minute. Keep a running total of the product of $P_{Bat,Ch}$ and Δt.
5. Evaluate $\eta_{Bat,R}$ when the SOC returns to SOC_0. Record the value as $\eta_{Bat,R,a}$.
6. Create the following report message to the user:
    a. "The rated battery roundtrip efficiency for the battery storage system was [$\eta_{Bat,R}$]. A real-time commissioning process has been completed for this system. The actual roundtrip efficiency at rated conditions has been determined to be [$\eta_{Bat,R,a}$]."

5.0 References

This list contains sources cited in the main narrative and in the appendix.

Katipamula, S., N. Fernandez, AD Smith, AP Rogers. 2020. Design, Development, and Testing Plan for Energy Efficiency Algorithms Related to Building-Integrated Cooling, Heating, and Power Systems. PNNL-XXXX, Pacific Northwest National Laboratory, Richland, Washington.

Duffie, J.A. and Beckman, W.A. 2006. Solar Engineering of Thermal Processes. 3rd Edition, Wiley, Hoboken, NJ.

U.S. Department of Energy. (2018). Retrieved April 24, 2020, from https://www.energycodes.gov/development/commercial/prototype_models

Appendix A – Solar Angle Calculation

The sun's position in the sky can be defined by two angles:

1. zenith angle (θ_s)

$$\cos\theta_s = \cos\lambda\cos\delta\cos\omega + \sin\lambda\sin\delta \tag{A.1}$$

2. azimuth angle (ϕ_s)

$$\sin\phi_s = \frac{\cos\delta\sin\omega}{\sin\theta_s} \tag{A.2}$$

where λ= latitude of location and δ = solar declination, which can be calculated according to Equation (A.3). ω is the solar hour angle, defined according to Equation (A.3), where n is the day of the year, counting from January 1 and t_{sol} is the solar time.

$$\sin\delta = -\sin 23.45^\circ \times \cos\frac{360^\circ \times (n+10)}{365.25} \tag{A.3}$$

$$\omega = (t_{\text{sol}} - 12\,\text{h}) \times 15^\circ \tag{A.4}$$

A flat plane is specified in terms of the zenith angle (or tilt angle from the horizontal) θ_p and azimuth ϕ_p of the surface normal (positive for orientations west of south). The solar incidence angle, θ_i (equal to the angle between normal of plane and line to sun) for **stationary planes** is defined as

$$\cos\theta_i = \sin\theta_s\sin\theta_p\cos(\phi_s - \phi_p) + \cos\theta_s\cos\theta_p \tag{A.5}$$

Expressions for different types of trackers requiring periodic or continuous adjustments can be found in the literature (see for example, Duffie and Beckman 2006). In the case of horizontal **N-S one-axis trackers** with continuous adjustment (a rather common mounting type):

$$\cos\theta_i = (\cos^2\theta_s + \cos^2\delta.\sin\omega)^{1/2} \tag{A.6}$$

All solar angles calculations should be based on solar time. Three quantities are relevant when specifying time of the day at a specified location:

- Standard time t_{std} of the time zone of the specified location is defined by the reference value of the longitude. For instance, in the contiguous United States, the reference meridians for the time zones are 75°W for Eastern, 90°W for Central, 105°W for Mountain, and 120°W for Pacific standard times. The standard time is the watch time when daylight savings time is not followed.

- Local civil time $t_{civ,loc}$ is the time at the specific location in question. A constant correction is needed which accounts for the difference in longitude between the reference meridian and the local meridian. Because one full cycle of a day corresponds to 360° longitude, each degree corresponds to

$$\left(\frac{24 \text{ h x } 60 \text{ min}}{360^0}\right) = \frac{1}{15} \text{ h} = 4 \text{ min}.$$

  In most parts of the world, clocks are set to the same time within a time zone covering approximately 15° of longitude (although the boundaries may be quite irregular).

- Daylight savings time needs to be corrected for when appropriate.

Another source of deviation between solar time and local civil time is due the *equation of time* E_t. It is a function of the time of year and can be approximated by

$$E_t = 9.87 \times \sin 2B - 7.53 \times \cos B - 1.5 \times \sin B \quad (\text{min}) \tag{A.7}$$

with

$$B = 360^\circ \times \frac{n-81}{364} \quad \text{for } n\text{th day of year} \tag{A.8}$$

Solar time t_{sol} is related to standard time t_{std}:

In hours:

$$t_{\text{sol}} = t_{\text{std}} \pm \frac{L_{\text{std}} - L_{\text{loc}}}{15^\circ/\text{h}} + \frac{E_t}{60 \text{ min/h}} \tag{A.9}$$

In minutes:

$$t_{\text{sol}} = t_{\text{std}} \pm 4' \times (L_{\text{std}} - L_{\text{loc}}) + E_t \tag{A.10}$$

where L_{std} and L_{loc} designate the longitudes (in degrees) of the time zone and the location, respectively. The plus (+) sign is to be used for locations west of Greenwich and the negative (-) sign for locations east of Greenwich. In regions with daylight saving time, one has to subtract 1 hour from daylight saving time to obtain t_{std} during the summer half of the year.

Pacific Northwest National Laboratory

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354
1-888-375-PNNL (7665)

www.pnnl.gov