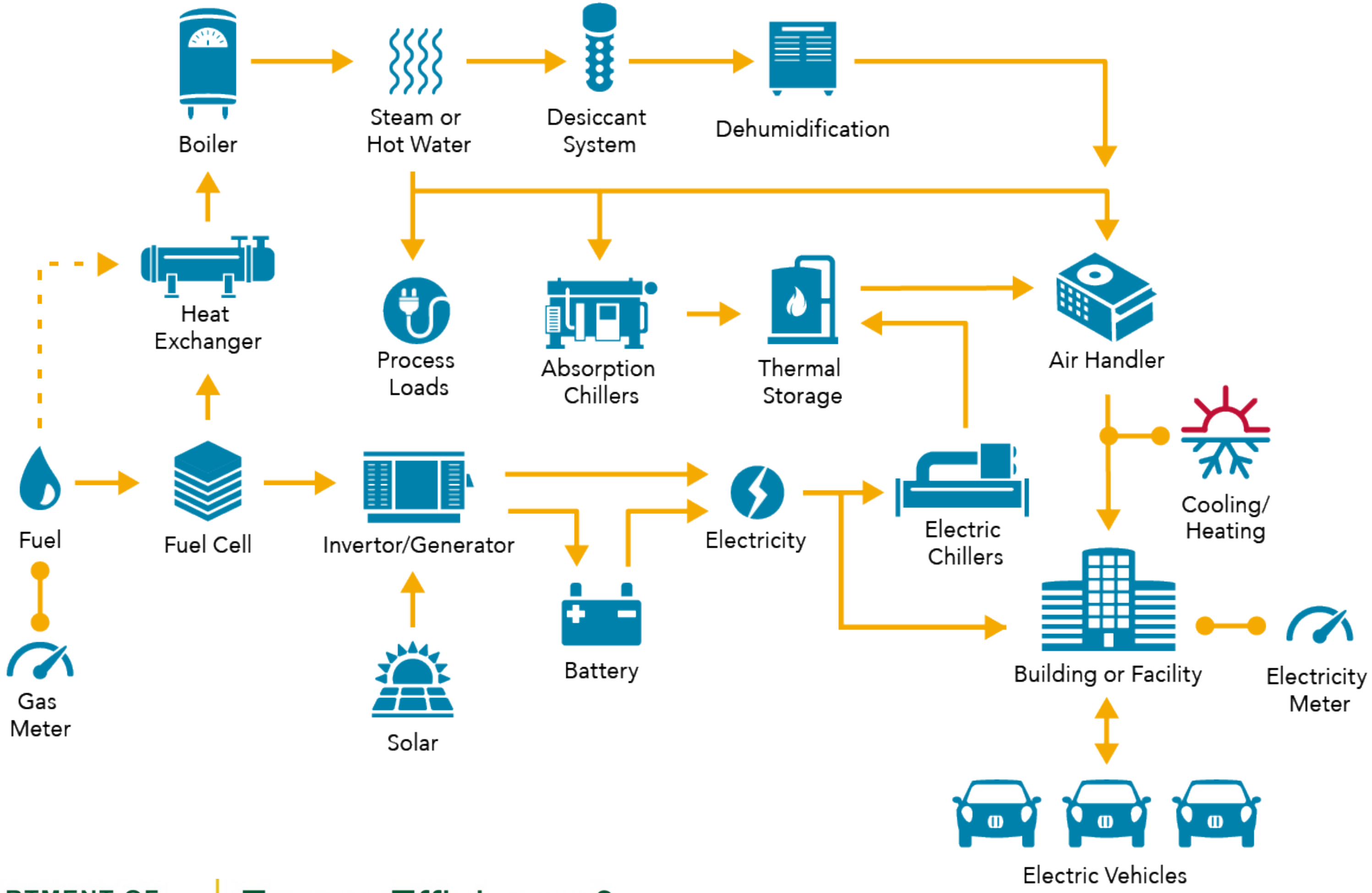
VOLTTRON™ Controller for Economic Dispatch

Maximize Return-on-Investment, and Improve Energy Efficiency and Grid Reliability

2017 Building Technologies Office Peer Review



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Project Summary

Timeline:

Start Date: March 31, 2016

Planned End Date: December 31, 2018

Key Milestones

1. Test algorithms with offline data (3/31/17)
2. Develop integrated software for field testing (9/30/17)
3. Field validation; update controller (12/31/18)

Budget:

Total DOE $ to Date: $0.292M (FY16); $1.458M (FY17);

Total Overall DOE $: $2.75M

Key Partners:

Pacific Northwest National Laboratory (PNNL)
Oak Ridge National Laboratory (ORNL)
Arizona State University (ASU)
Washington State University (WSU)

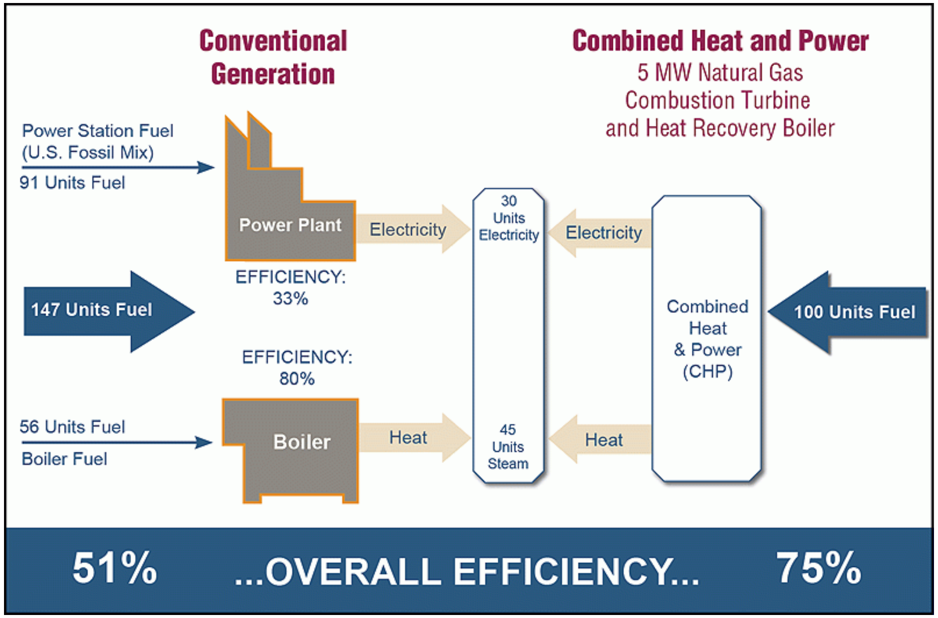
Project Goal:

Design, develop, field test and validate a VOLTTRON™ controller for economic dispatch.

This multi-purpose economic dispatch and control tool and associated open-source algorithms will ensure real-time optimal operation of buildings, increase electric grid reliability, and lead to the goal of a clean, efficient, reliable, and affordable next generation integrated energy system.

Purpose and Objectives: Problem Statement

- Today, economic benefit from **combined cooling, heating and power** (CCHP) systems is **often not fully realized** because of lack of integrated dispatch and control solution
- Distributed renewable energy is increasing and operation of heating, ventilation, and air conditioning system is lacking



https://www.epa.gov/chp/chp-benefits

- These facts underscore the need for a **real-time control system with algorithms that integrate transactive market signals**, monitored performance data, and risk preferences

Purpose and Objective: Goal and Solution

- Primary goal is to provide a general procedure for formulating an economic dispatch in a commercial building for optimal day-ahead scheduling and realizing optimal real-time operation
  - Secondary goal: performance monitoring, automated fault detection and diagnostics (AFDD) and automated continuous commissioning (ACCx)

- **Objective Function:** Minimizing total energy cost, emissions, or other objectives
- **Constraints:**
  - Operational ranges
  - Relationships between components' states and energy-use
  - Relationships between components' control variables/states
  - Relationships between components' states, static and dynamic
- **Solution:**
  - Fully functional economic dispatch tool intended for building-integrated CCHP system to maximize ROI and improving energy efficiency and grid reliability
  - Optimal 24-hour schedules (on/off states, temperature set points, etc.) for all the controllable IES (CCHP and conventional) components

Purpose and Objectives: Target Market and Audience

- Target market = larger commercial and institutional buildings that integrate CCHP
- Total primary energy consumption of these buildings is approximately 8 Quads
- **Potential energy savings = 2 to 3 Quads**
- Audience = commercial building owners and energy service providers, or building operators serving the buildings
  - A target audience could be the light industrial sector
- **Minimize operating cost and maximize return-on-investment and improved grid reliability**
- **Support transactive controls**

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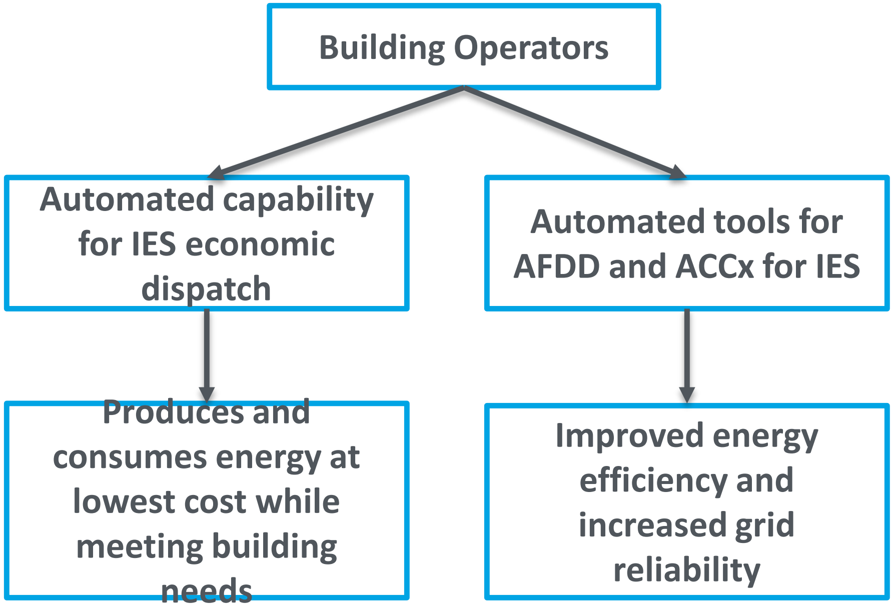
Purpose and Objectives: Impact of Project

- Deliver VOLTTRON-compatible real-time control algorithms packaged as a fully functional toolkit
  - Supervisory control and generalized economic dispatch
  - Short-term weather and load forecasting
  - Management of short-term imbalance between local generation and demand
  - Performance monitoring, automated fault detection, and diagnostics(AFDD)
  - Automated continuous commissioning (ACCx)



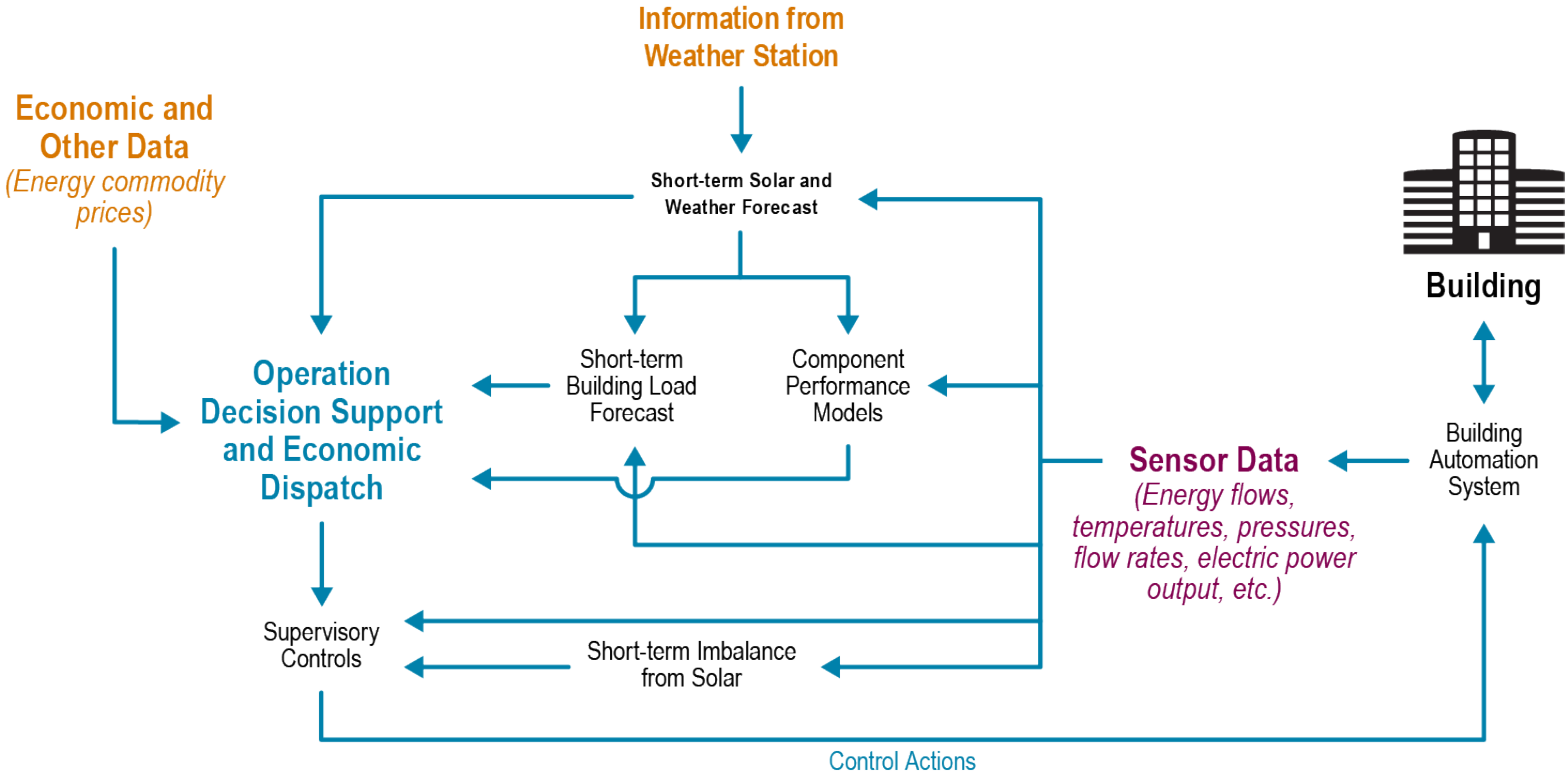
- **Short-term (immediate):** Open-source economic dispatch and performance monitoring software for IES
- **Medium-term (<3 years)**: One or more energy service providers commercialize the software and offer that as a service to their customers
- **Long-term (>3 years):** Software operational in at least 25 sites

Approach

- **Development of Models:**
  - Weather forecast models to predict solar irradiation to better manage and integrate solar PV onsite
  - Inverse empirical models for forecasting electric and thermal loads
  - Performance models for prime movers, heat recovery heat exchangers, absorption and vapor compression chillers, boilers, and other HVAC equipment
- **Development of Algorithms:**
  - Combining component models, develop generalized economic dispatch and supervisory control algorithms for day-ahead and shorter-term IES operations
  - AFDD and ACCx for ensuring performance
- **Testing and Deployment:**
  - Algorithms coded in Python programming using open-source libraries and deployed on the VOLTTRON™ platform-hosted controller

The economic dispatch and supervisory control software will be deployed on the versatile and secure VOLTTRON™ distributed control platform hosted on a low-cost (<$200) hardware and Integrated with existing building automation system

Approach: Economic Dispatch Process



Approach: Key Issues and Distinctive Characteristics

Key Issues

Enable next-generation CCHP/IES thru design, development, testing, and validation of algorithms deployed using VOLTTRON. The resulting capability will:

- **Address** various **technical and economic** barriers to IES
- **Accelerate adoption** of IES by providing improvements that **minimize operational cost and maximize return-on-investments (ROI)**
- **Improve energy efficiency in buildings, grid reliability, and renewables integration**

Distinctive Characteristics

Generalized **open source optimization framework** that can be **automatically configured to any combination of systems** present in a building

- Modular software design, so default algorithms/models can be replaced with user defined
- Software will include default parameters for the component models; however, software includes **adaptive elements** to **learn and update** parameters
- **Leveraging past and current work to support project objectives**

Progress and Accomplishments

- Adapted weather and solar generation forecast models
- Developed and tested of inverse models for building thermal and electric load and for HVAC systems performance prediction
- Developed economic dispatch and supervisory control algorithms
- Adapted algorithms to mitigate short-term loss of power from renewables or load forecast error
- Converted all models to Python and documented them
- Testing of all algorithms with offline data nearly complete

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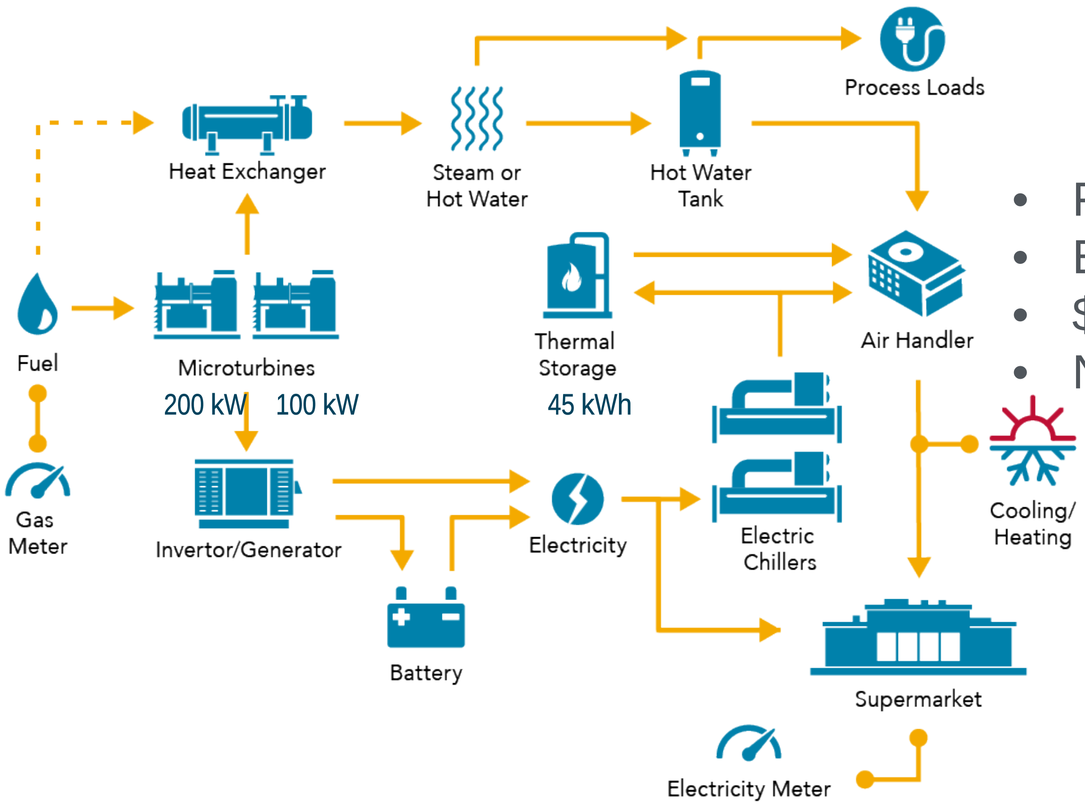
Economic Dispatch Process

- At midnight on each day, building’s PV generation, electricity load, and thermal load are forecasted for the next 24 hours
- Hot water provided by boiler and/or micro-turbine with a heat recovery unit
- Chilled water provided by absorption chiller or vapor compression chiller
- An optimization problem is formulated for all controllable components for the next 24 hours
- Component models are used to estimate performance of individual components
- Hourly set points (control commands) determined after solving the optimization problem
- At 1 a.m., set points are changed in the building automation system according to the solution
- New forecast for the next 24 hours is made at 1 a.m. (repeating bullet one); a new optimization problem is formulated based on current states and optimal set points are recomputed for the next 24 hours

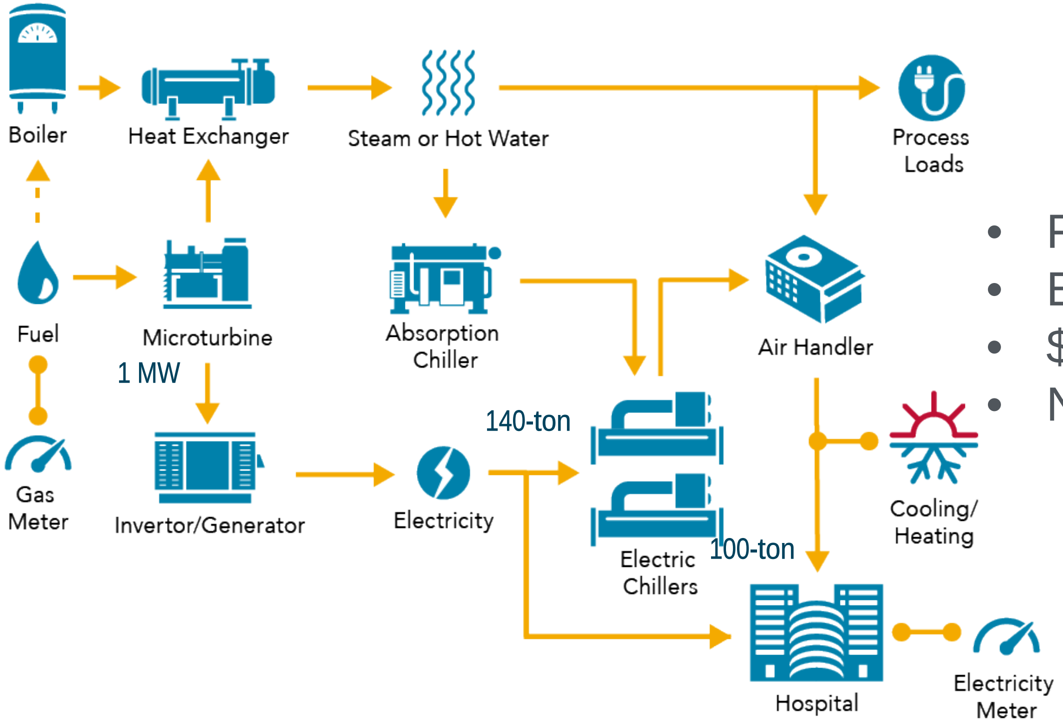
Demonstrative Use Case – Supermarket in Phoenix



- Fuel rate: $4 per mmBTU
- Electric rate: $0.06/kWh off peak,
- $0.14/kWh on-peak (noon to 8 p.m.)
- Not annual simulation

- Optimized compared to manual dispatch will result in around 10% cost savings
- Additional benefits not quantified, could improve grid reliability; AFFD and ACCx will ensure persistence of equipment operations leading to additional cost savings

Demonstrative Use Case – Hospital in Phoenix



- Fuel rate: $4 per mmBTU
- Electric rate: $0.06/kWh off peak,
- $0.14/kWh on-peak (noon to 8 p.m.)
- Not annual simulation

- Optimized compared to manual dispatch will result in around 36% cost savings
- Additional benefits not quantified, could improve grid reliability; AFFD and ACCx will ensure persistence of equipment operations leading to additional cost savings

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Project Integration and Collaboration

Project Integration:

- Actively engaged energy service providers
  - Will deploy the software at one or more sites to test and validate the algorithms
  - Working with energy service providers who are potential users and commercializes of the software will help accelerate adoption of the tools developed in the project

Partners, Subcontractors, and Collaborators:

Partner	Role
PNNL (Lead)	Development of optimization framework, VOLTTRON deployment, testing
ASU	Developed solar weather forecast, solar generation forecast, and selected component models
WSU	Developed selected component models, testing and validation of optimization approach
ORNL	Will help in testing in year two

Communications: The project team has identified a number of potential papers and publications that will be presented at conferences or published in research journals

Next Steps and Future Plans

- Finish offline testing and validation of the algorithms and component models and document them
  - The tests will be done using historical data for typical days in fall and spring, as well as peak summer and winter

- Start development of performance monitoring, continuous commissioning, automated fault detection and diagnostic algorithms, and integrated software for field testing

- Identify field site to enable testing in FY18
  - Will subsequently lead to test result evaluations and updating of the controller

REFERENCE SLIDES

Project Budget

Project Budget

Variances: No variances

FY2017 Cost to Date: Cost to date in FY2016 totaled $292K. Cost through February 2017, totals $197K. $98K is currently committed to ASU/WSU.

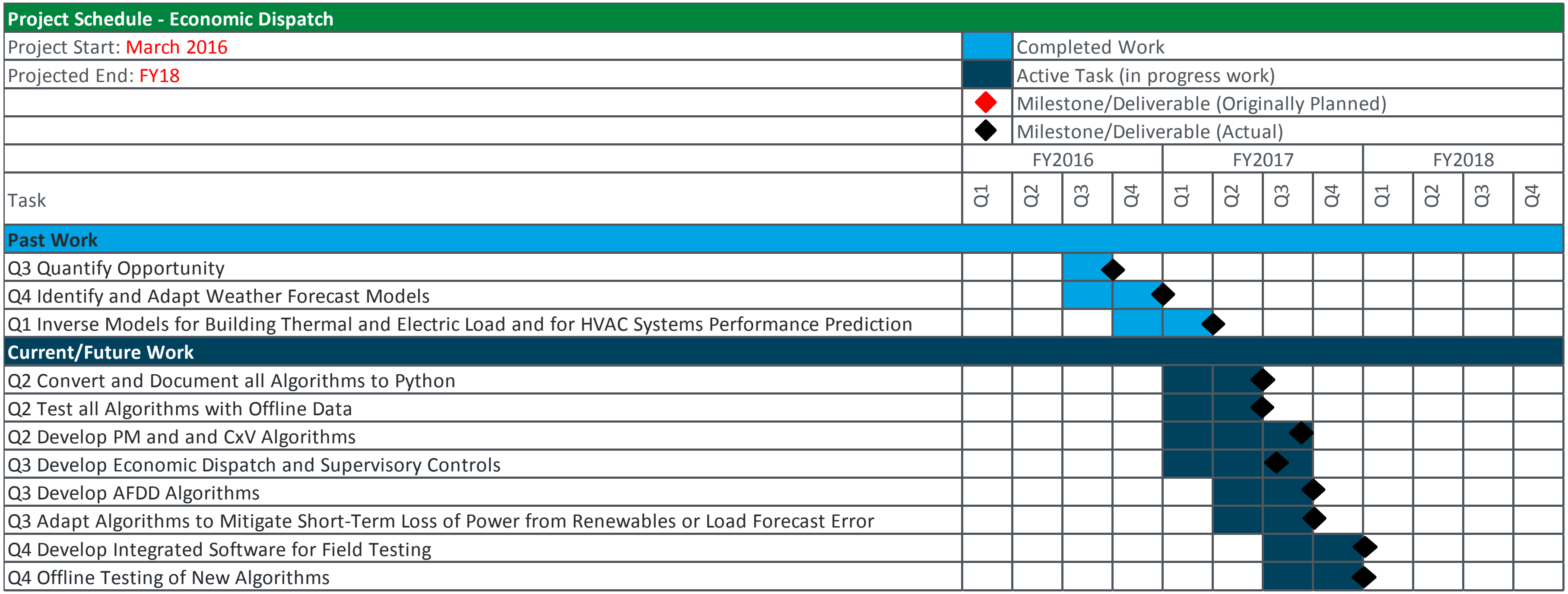
Additional Funding: None.

Budget History					
FY2016 (past)		FY2017 (current)		FY2018 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$1,000K	$0K	$750K	$0K	$1,000K	

Project Plan and Schedule

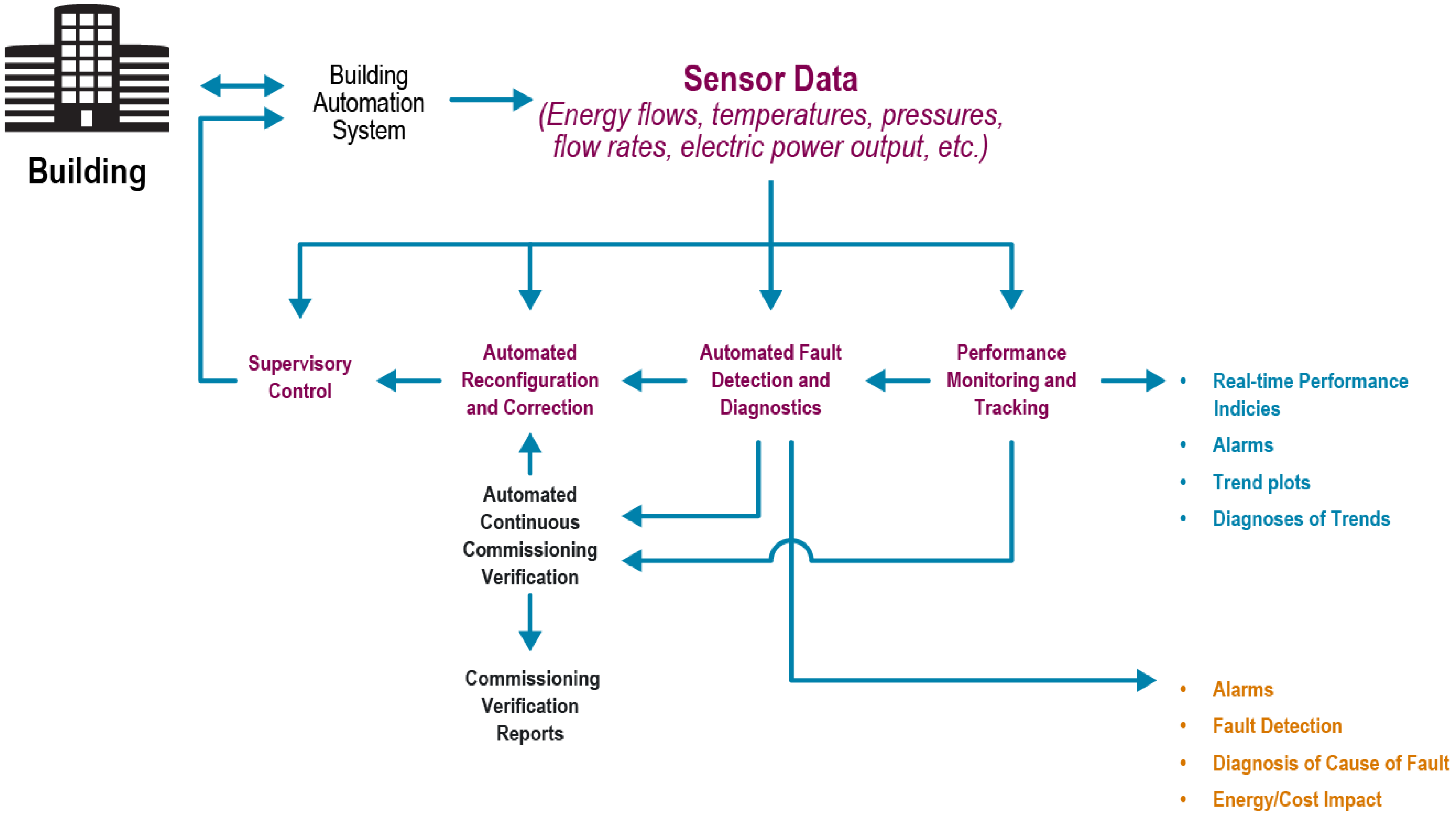
Describe the project plan including:

- Project started in March 2016 and is scheduled for completion with field testing and validation in December 2018
- Schedule and Milestones (see table below)
- All milestones and deliverables are on track
- Go/no-go decision points: Successful testing of all algorithms with offline data
- Current and future work: Described in the main presentation



Project Schedule - Economic Dispatch												
Project Start: March 2016	🟦	Completed Work										
Projected End: FY18	⬛	Active Task (in progress work)										
	♦	Milestone/Deliverable (Originally Planned)										
	◆	Milestone/Deliverable (Actual)										
	FY2016				FY2017				FY2018			
Task	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
Q3 Quantify Opportunity			🟦◆									
Q4 Identify and Adapt Weather Forecast Models			🟦	🟦◆								
Q1 Inverse Models for Building Thermal and Electric Load and for HVAC Systems Performance Prediction				🟦	🟦◆							
Current/Future Work												
Q2 Convert and Document all Algorithms to Python					⬛	⬛◆						
Q2 Test all Algorithms with Offline Data					⬛	⬛◆						
Q2 Develop PM and and CxV Algorithms					⬛	⬛	⬛◆					
Q3 Develop Economic Dispatch and Supervisory Controls					⬛	⬛	⬛◆					
Q3 Develop AFDD Algorithms						⬛	⬛◆					
Q3 Adapt Algorithms to Mitigate Short-Term Loss of Power from Renewables or Load Forecast Error						⬛	⬛◆					
Q4 Develop Integrated Software for Field Testing							⬛	⬛◆				
Q4 Offline Testing of New Algorithms							⬛	⬛◆				

Approach: Energy Efficiency Process



Building

Building Automation System

Sensor Data

(Energy flows, temperatures, pressures, flow rates, electric power output, etc.)

Supervisory Control

Automated Reconfiguration and Correction

Automated Fault Detection and Diagnostics

Performance Monitoring and Tracking

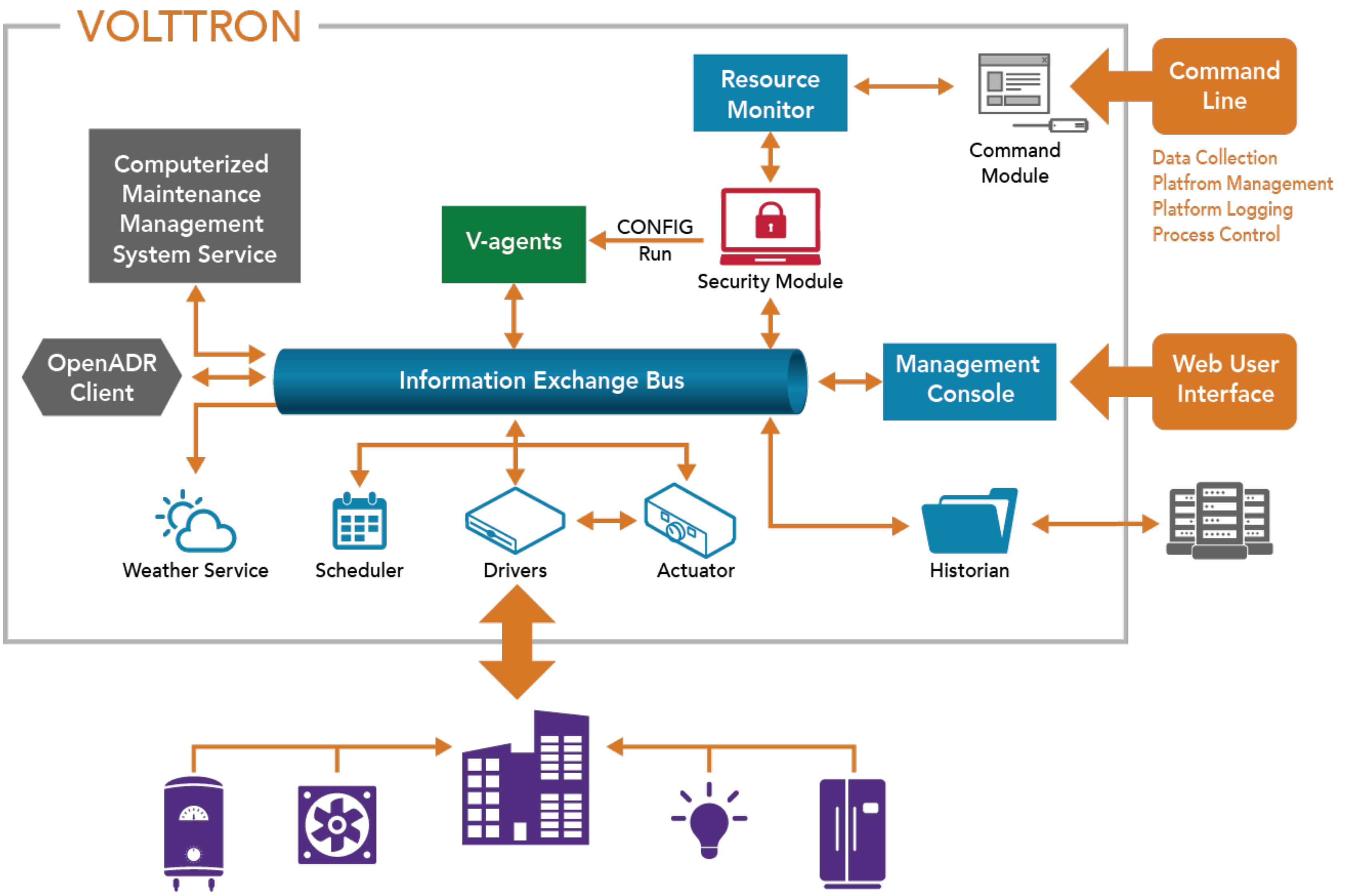
- Real-time Performance Indicies
- Alarms
- Trend plots
- Diagnoses of Trends

Automated Continuous Commissioning Verification

Commissioning Verification Reports

- Alarms
- Fault Detection
- Diagnosis of Cause of Fault
- Energy/Cost Impact

Inside VOLTTRON™



VOLTTRON

Resource Monitor

Command Module

Command Line

Data Collection
Platfrom Management
Platform Logging
Process Control

Computerized Maintenance Management System Service

V-agents

CONFIG
Run

Security Module

OpenADR Client

Information Exchange Bus

Management Console

Web User Interface

Weather Service

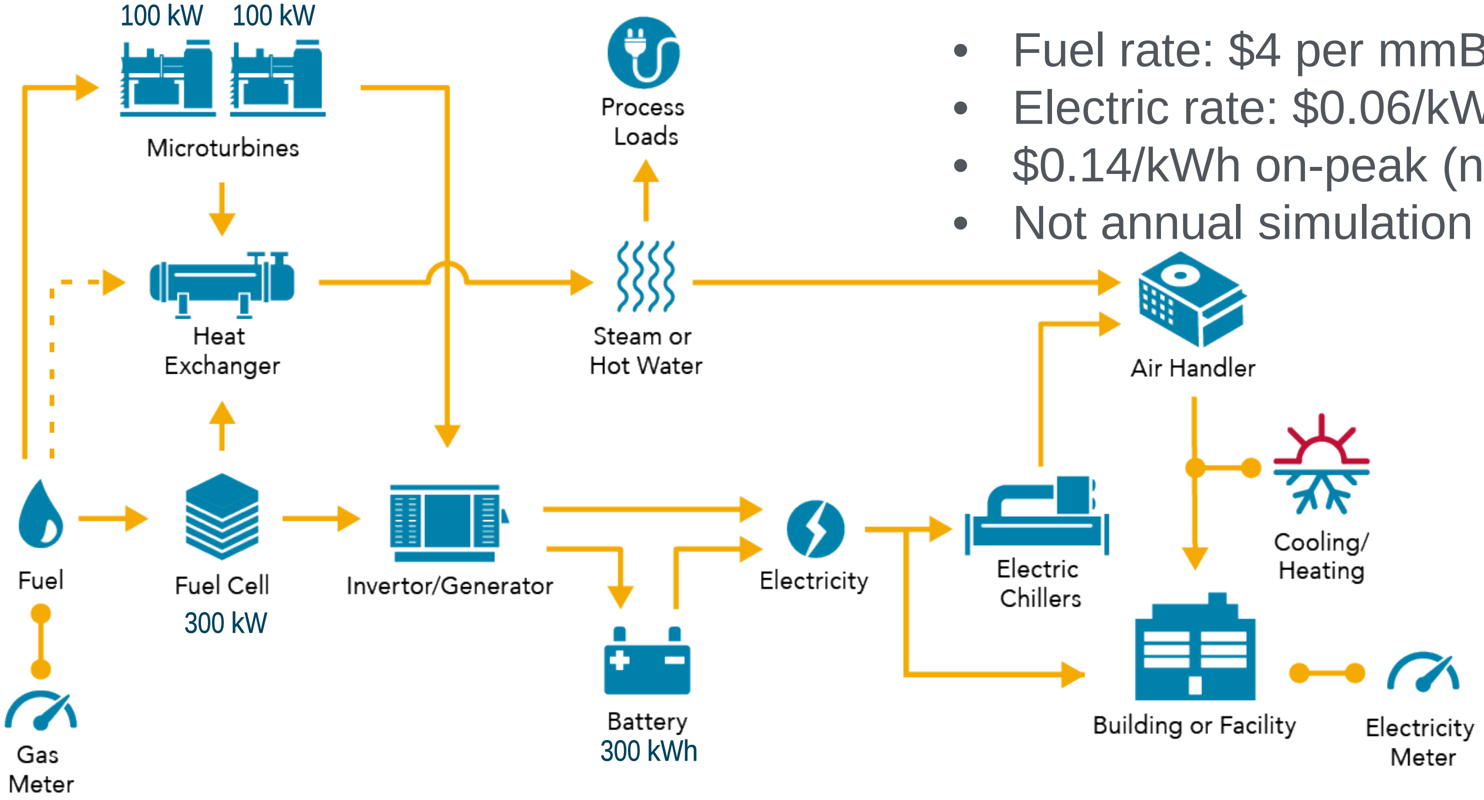
Scheduler

Drivers

Actuator

Historian

Demonstrative Use Case – Medium Office in Phoenix



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CCHP System Components Model Details

Model	Type/ Description	Inputs	Outputs	Regression-Based Training
Prime Mover	Part-load electrical efficiency curves	Actual and rated power output (kW), fuel flow (ft^3/min), rated efficiency	Electrical efficiency	Yes
Heat Recovery Unit	Physical Heat Exchanger Model: NTU-Effectiveness	Exhaust fluid inlet temp (˚C) and mass flow (kg/s), water inlet temp (˚C) and mass flow (kg/s)	Water outlet temp(C), Heat Recovered (W)	Yes: Heat Exchanger Effectiveness
Absorption Chillers	Part-load performance curve	Rated thermal heat input (Btu/hr), actual and rated thermal cooling load (Btu/hr), actual and rated condenser water inlet temp. (˚C)	Thermal heat input (Btu/hr)	Yes
Electric Chillers	Part-load performance curve	Rated power input (kW), actual and rated thermal cooling load (Btu/hr), condenser water inlet temp. (˚C) , condenser water inlet temp. at rated condition (˚C)	Power input (kW)	Yes
Boilers	Part-load performance curve	Rated fuel energy input (Btu/hr), actual and rated boiler heat output (Btu/hr)	Fuel energy input (Btu/hr)	Yes

CCHP System Components Model Details (Cont.)

Model	Type/ Description	Inputs	Outputs	Regression-Based Training
Fuel Cell	Physical Model: Blower, heat exchangers, reformer, electrochemical stack, post-combustor, and recirculation valves. Linear and non-linear models.	Electric power request, ambient air conditions.	Net DC electric power out, fuel consumption, exhaust temperature and flow rate.	None
mGT	Physical/Empirical Model: Empirical compressor/turbine maps used, physical components include heat exchangers, combustor, shaft, and plenum volume. Linear and non-linear models.	Electric power request, ambient air conditions.	Net AC electric power out, fuel consumption, exhaust temperature and flow rate.	Yes: calibrated to Capstone C65 test data

Solar PVs Model Details

Component	Type/ Description	Inputs	Outputs	Regression-Based Training
Inverter model	Simple efficiency curve multiplier	Electric power (DC)	Electric power output (AC)	None
Diffuse solar radiation model	Black-box polynomial model	Latitude (degree), Refer time zone longitude (degree), Location longitude (degree), Day of the year, Standard time, Total horizontal radiation I (W/m^2)	Diffuse radiation (W/m^2)	Yes
Solar radiation on plane of array (I_T) - Uses HDKR anisotropic sky model	Physical Model	Latitude (degree), Refer. time zone longitude (degree), Location longitude (degree), Zenith angle of plane (degree), Azimuth of plane (degree), PV mounting code*, Reflectivity of ground, Day of the year, Standard time, Total horizontal radiation (W/m^2), Diffuse radiation (W/m^2)	Plane of array radiation (W/m^2)	None

* 1 for ground-mounted and 0 for roof-mounted systems

Solar PVs Model Details (Cont.)

Component	Type/ Description	Inputs	Outputs	Regression-Based Training
PV cell temp. prediction	Physical Model	Plane of arrays radiation (W/m^2), Ambient temperature (˚C), NOCT	Cell temp. (˚C)	None
PV power prediction-G&R Model	Semi-empirical Model	Plane of arrays radiation (W/m^2), Ambient temperature (˚C), Latitude (degree), Refer. time zone longitude (degree), Location longitude (degree), Day of the year, Standard time	Electric power output (DC)	Yes
PV power prediction-modified Evans model	Semi-empirical Model	Plane of arrays radiation (W/m^2), Cell temperature (˚C), Cell temp. at rated condition (˚C)	Electric power output (DC)	Yes