PNNL-NorthWrite Small Business Voucher Project (3.2.4.38; New Start July 2016)

2017 Building Technologies Office Peer Review

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Michael Brambley, michael.brambley@pnnl.gov
Pacific Northwest National Laboratory (PNNL)

Project Summary

Timeline:

Start date: July 15, 2016

Planned end date: July 31, 2018

Key Milestones

1. Fault detection and diagnostic (FDD) and sensor suitcase opportunity algorithms fully documented; 2017-01-31
2. FDD and opportunity algorithm testing and validation completed; 2017-09-29
3. All algorithms implemented; 2018-03-30

Budget:

Total DOE Project $ to Date:

- DOE: $300K
- Cost Share: $200K

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Key Partners:

PNNL
NorthWrite Inc.

Project Outcomes:

1. Enable NorthWrite to deploy three sets of algorithms that provide fault detection and diagnostics for small commercial buildings, realizing additional whole-building energy savings of 5% to 10%*
2. Test results will validate algorithm performance and sensitivity to selectable values of parameters
3. Dissemination of algorithm documentation will enable deployment by other companies.

The algorithms were developed in prior work by PNNL and LBNL in research supported by BTO

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*Savings will be higher for buildings that have not already implemented energy-efficiency measures (~10% to 15%).

Purpose and Objectives

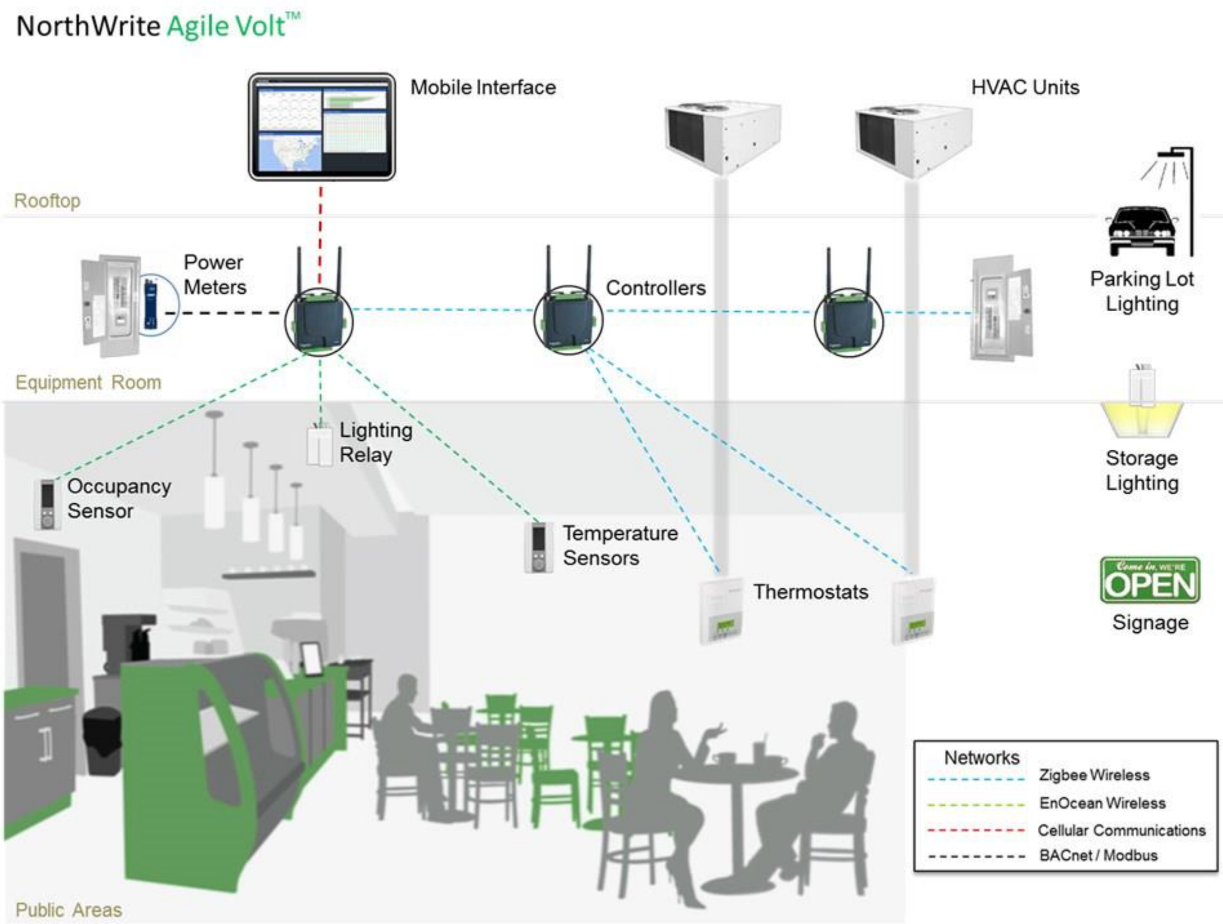
Problem Statement

- Deployment rate for new algorithms is limited by the ease of use
- Deployers (e.g.,. NorthWrite) need:
  - More documentation than descriptions of the core algorithms—pseudocode, code, evidence of algorithm validity and performance
  - Test cases and data for verifying the correctness of their software code
  - Technical support for deployment--selecting values for adjustable parameters and interpreting unexpected results during initial use

Objectives

- Enable NorthWrite to implement three sets of algorithms that provide fault detection and diagnostics for small commercial buildings
- Validate algorithm performance through tests on two specially equipped and instrumented representative RTUs set up for this purpose at PNNL
- Provide technical support to NorthWrite interpreting unexpected results and other issues during commercial deployment
- Disseminate project results broadly

SBV Applicant & Commercial Partner, NorthWrite Inc.



Objective: Uses advanced energy analytics, communications, computing power, data management, and business process to provide functionality for small commercial buildings – maximizing energy efficiency while minimizing cost

Platform: Wireless hardware integrated with cloud-based oversight

Outcome: Provide automated energy and load management to small building owners at a fraction of the cost of traditional building automation systems

Other features:
- Guaranteed energy cost reduction
- No upfront, out of pocket cost
- 10-25% drop in long-term energy costs
- Mobile apps for remote management

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Target Market and Impact of Project

Target Market:

- Small commercial buildings (less than 50,000 ft^2) with packaged rooftop air conditioners and heat pumps
- Building owners and facility managers
- Energy service providers

Impact of Project:

1. Outputs/Final Products: Documented, tested, and field demonstrated fault detection and diagnostic algorithms for rooftop packaged HVAC systems ready for adoption in the small commercial buildings sector.
2. Measuring impact
    a. Near-term outcomes (up to 1 year after project): The energy savings resulting from NorthWrite's use of the algorithms—measured by NorthWrite as increases in savings across projects with vs. without algorithms
    b. Intermediate outcomes (1-3 years after project): Adoption of algorithms by national account companies and utility programs
    c. Long-term outcomes (3 years+ after project): Large-scale adoption of algorithms in the small commercial building space

Approach and Key Issues

Approach: Through development of documentation, validating performance through testing on physical equipment, and providing technical assistance in software coding and during deployment, enable the industry applicant, NorthWrite, and other companies to deploy fault detection, diagnostic, and energy savings opportunity identification algorithms for small commercial buildings.

- Document data needs of each algorithm
- Document the algorithms in pseudocode
- Test algorithms on RTU test apparatus to characterize algorithm performance and validate recommended values for adjustable parameters
- Technically support NorthWrite in its coding of algorithms for Cloud implementation
- Verify NorthWrite software with test data and cases
- Provide technical assistance in initial field use of algorithms—help with unexpected results
- Document and disseminate all results, including lessons learned in providing technical support for software coding and field deployment

Approach and Key Issues

Key Issues:

- Constraints on and diversity of the sensed data available on RTUs in the field
- Adding sensors to RTUs is costly and resisted by users—installation labor, some costly sensors, data communication cost, data storage cost (for Cloud storage)
- Long sampling times for sensor data on many legacy RTUs— 5 and 15 minute sampling intervals will not support several algorithms
- Algorithm performance needs to be characterized over a range of conditions—carefully selecting test conditions is critical
- Values recommended for adjustable parameters in algorithms need to be validated
  - thresholds in algorithms (e.g., number of samples in averages, time steps for air-side steady state, number of short cycling detections to alert user)

Effect of Sensor Availability

Controller	Point Name	Description	Used by Algorithms
Advanced Controller Points	Serial_Communical_Setting	Communications Protocol	
	OB_status	Demand Response Status	
	VFD_speed	Supply fan VFD speed, expressed in Hertz	✓
	SS_MART	extra space temperature sensor	
	System_Fault_Code	Fault code information (multi-variable)	
	Status_of_Current_Mode	RTU Status	✓
	Cooling_Load	cooling demand	✓
	Heating_Load	heating demand	✓
	Supply_Air_Temperature	RTU discharge-air temperature	✓
	Outdoor_Air_Temperature	Outdoor air temp	✓
	Outdoor_Air_Damper	damper position	✓
	CO2_Parts_Per_Million	Carbon Dioxide (ppm)	
Tstat Points	CoolingCPH	cooling cycles per hour	
	CoolingStages	# of Stages of Cooling	
	Deadband	Deadband between heating and cooling	
	Demand Control	Demand response control to stat	
	Demand Control Status	Demand response status from stat	
	FanControl		
	FanMode	mode== auto, on, off	
	GFanStatus	Fan Status (on or off)	✓
	HeatingCPH	heating cycles per hour	
	HeatingStages	# of stages of heating	
	OccCommand	occupancy command	
	OccCoolSetpoint	Occupied cooling temperature set point	
	OccHeatSetpoint	Occupied heating temperature set point	
	RoomTemp	Space temperature (room with Tstat)	✓
	SystemModeRTU	mode== cooling, heating, auto (both)	✓
	W1Status	heating status stage 1	✓
	W2Status	heating status stage 2	✓
	Y1Status	cooling status stage 1	✓
	Y2Status	cooling status stage 2	✓
Additional Sensor	RTU submeter	RTU total power	✓

Algorithms Supported

Tstat Points: 4

- Thermostat setbacks not enabled for unoccupied hours
- Over-cooling or over-heating during occupied hours
- Heating and cooling set points too close together (I think)
- Under-conditioning during occupancy

Advanced Controller Points + Tstat Points: 13

All points: All 18

Distinctive Characteristics

Distinctive Characteristics: These algorithms and services they support target small commercial buildings under 50,000 ft^2, which represent 94% of all U.S. commercial buildings and 40% of the total commercial floor area

- The project targets small commercial buildings with relatively low energy expenditures, payback periods limited to 3 years and often less, and constraints on availability of capital for investment
- Assists companies offering energy-efficiency services to small commercial buildings in increasing energy savings and lowering costs
- Focuses on operational improvements rather than retrofits
- Leverages three sets of algorithms developed in previous BTO projects and focuses on meeting needs to accelerate deployment
- One set of algorithms was adapted from the Sensor Suitcase, which was developed by PNNL and LBNL for small commercial building retro-commissioning and included in ESource's "Top 22 Technologies and Trends of 2014"

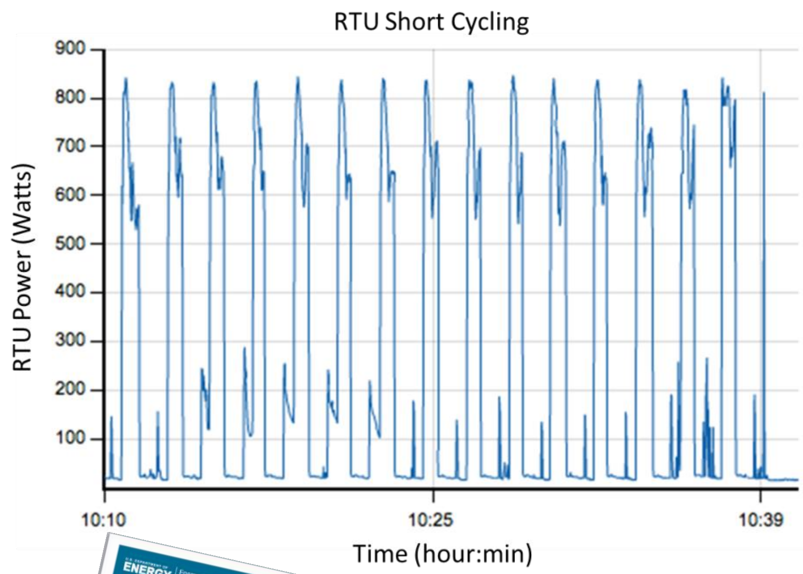
Rooftop Unit Fault Detection Algorithms

Sensor Suitcase Opportunity Algorithms

1. Thermostat setbacks not enabled for unoccupied hours
2. Over-cooling or over-heating during occupied hours
3. Heating and cooling setpoints too close together
4. Under-conditioning during occupied hours
5. RTU short cycling
6. Under-use of air-side economizing

Fault Detection and Diagnostics (FDD) Algorithms

7. Air-side temperature sensor faults
8. Determine if the outdoor-air damper is modulating
9. Isolating an air-side temperature sensor fault
10. RTU is economizing when it should not
11. RTU is not economizing when it should
12. RTU is using excess or insufficient outdoor air for ventilation

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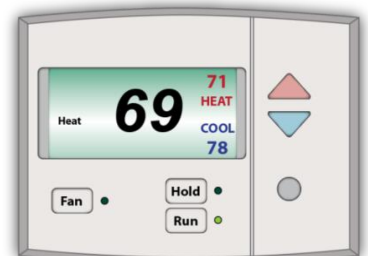
PNNL-23790

Rooftop Unit Embedded Diagnostics: Automated Fault Detection and Diagnostics (AFDD) Development, Field Testing and Validation

September 2015

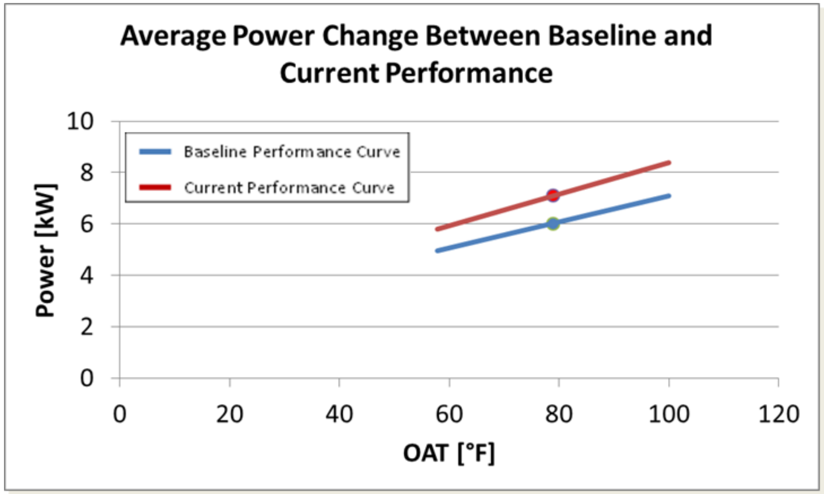
Prepared for the U.S. Department of Energy
By:
S Katipamula
W Kim
R Lutes
RM Underhill
Pacific Northwest National Laboratory

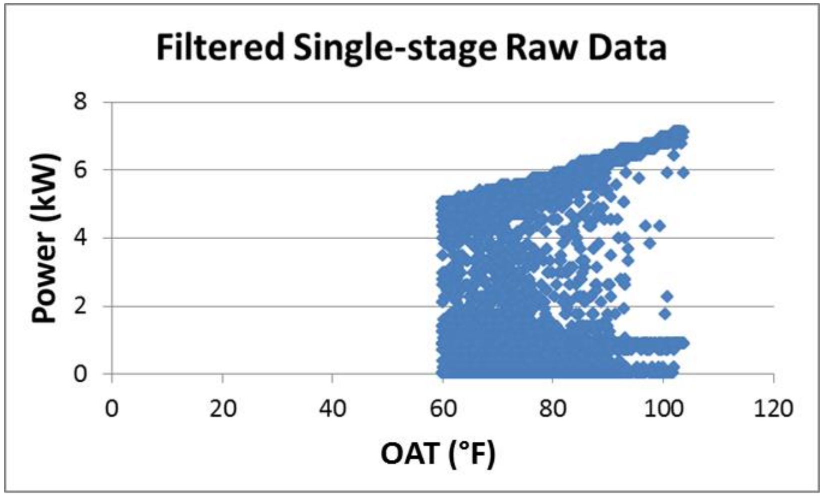


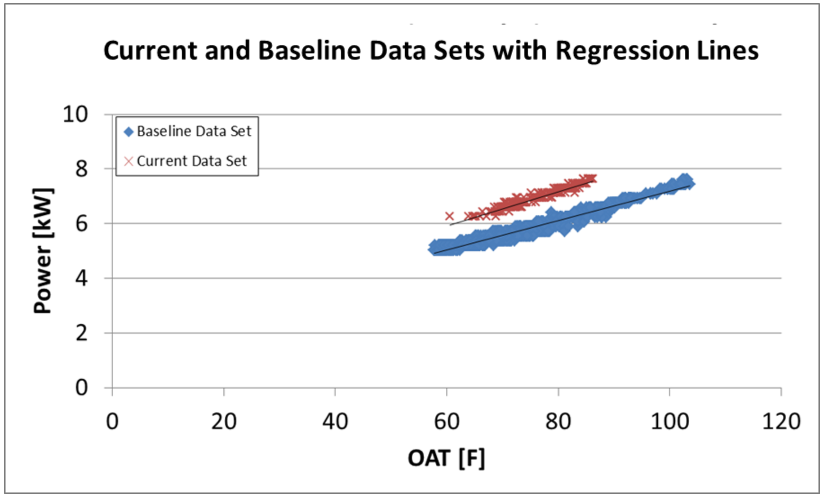
Rooftop Unit Diagnostic Algorithms

Smart Monitoring and Diagnostic System (SMDS)

13. Detect degradation in the vapor compression cycle cooling performance
14. Detect compressor short cycling
15. Compressor operating continuously
16. RTU runs continuously
17. RTU always off
18. RTU cycles with compressor only







Progress and Accomplishments

Accomplishments:

- Sensor suitcase opportunity algorithms fully documented – December 2016
- Fault detection and diagnostic algorithms fully documented – January 2017

Market Impact:

- 26% (5.1 quads primary/year) of commercial building primary energy use is consumed in buildings with floor areas of 50,000 ft^2 and less that are conditioned by packaged air-conditioners and heat pumps (CBECS 2012)
- Savings targeted by algorithms: 5% to 10% of whole-building energy use, on average, for NorthWrite; **10% to 15% for buildings on which no previous actions were implemented**
- Technical potential savings: **~0.64 quad (primary)/year**--based on 12.5% savings
- By 2020, 5% market penetration of algorithms would yield savings of 32 trillion Btu (source)/year

Awards/Recognition:

- One set of algorithms used in this project come from the Sensor Suitcase, which has been
  - Included in ESource's "Top 22 Technologies and Trends in 2014"
  - Selected as 1 of 8 projects in the UC Berkeley Haas School of Business Clean Tech 2 Market Program

Validation of Algorithms

Summary of Testing and Validation Process

Algorithms will be validated by testing them on an RTU test bed at PNNL in which the fault each algorithm is intended to detect is implemented for its tests. The algorithms will be tested applied to RTU data offline or in real time online in a sequence of tests over ranges of operating conditions.

Tests will be performed to:

- Validate that each algorithm successfully detects the fault targeted and/or identify the range of conditions over which the algorithm successfully detects the fault
- Validate that each algorithm does not detect a fault when no fault exists in the RTU and/or identify the conditions over which the algorithm incorrectly detects a fault when none is present
- Quantify the limits of detectability for algorithms that detect faults that have variations in fault severity
- Examine the effects of values of key parameters in the algorithms to support selection of recommended values

Time Frame for Testing

- Late spring through Fall 2017

Validation of Algorithms

Major Steps in the Testing Process:

- Design tests for validating each of the algorithms, including detailed specification of conditions for each test
- Create the fault or condition in a test RTU that an algorithm is intended to detect
  - Some faults have severities and the limits of detectability will be identified in tests
- Establish the specified operating conditions for the test
- Test whether the algorithm successfully detects the fault under the specific conditions established
  - Algorithms not relying on interactions between the algorithm and the RTU during fault detection will be tested in two steps:
    1) data collection during RTU operation under specified conditions
    2) offline application of the algorithms to the data
  - Algorithms that interact with the RTU for fault detection will be tested online as the RTU operates
- Retest under the range of conditions established in the design of the test by repeating the process under all the conditions specified
- Analyze the test data to establish the range of conditions (if applicable) under which the algorithm performs successfully—generally, success will be indicated by the algorithm detecting the fault created in the RTU

Lessons Learned

- The data points available on RTUs and data acquisition systems installed on them vary significantly limiting the fault detection algorithms that can be supported

  Actions:

  – Adapted algorithms where possible to use surrogate variables (e.g., zone temperature for return-air temperature and RTU discharge air temperature for mixed-air temperature when the compressor is off)

  – Clearly identified and will document the data requirements for each algorithm

- Many RTUs and data acquisition systems on them collect data at time intervals incompatible with fault detection algorithms

  Action:

  – All algorithms are compatible with 1-minute data sampling intervals. Have identified and will document algorithms compatible with 5-minute sampling intervals.

- The cost of providing monitoring and diagnostic services and the uncertainty in savings tend to limit willingness to invest in additional sensing

  Action:

  – Plan to work with NorthWrite to show the value of adding selected sensors (e.g., RTU power sensor for SMDS algorithms)

Project Integration and Collaboration

Project Integration: PNNL has been and will work directly with NorthWrite in all phases of the project (planning, documentation, implementation and validation) to ensure successful transition of the algorithms

Partners, Subcontractors, and Collaborators:

- PNNL – original developer of algorithms
- NorthWrite, Inc. – Small business partner
    - Established priorities for algorithms
    - Providing data from operating customer RTUs
    - Software coding in Cloud platform
    - Field deployment as part of service to customers

Communications:

Upcoming:

- Web accessible documentation of the algorithm pseudocode
- Seminars highlighting all aspects of the project
- A report or technical paper on the algorithms and test results

Next Steps and Future Plans

NorthWrite near-term actions:

- Begin implementing algorithms in Cloud platform
- Collect more data from existing RTUs in the field for PNNL

PNNL near-term actions:

- Develop plans for testing the algorithms on the RTU testbed at PNNL
- Modify existing algorithm documentation to meet additional needs NorthWrite identifies
- Begin documenting the Smart Monitoring and Diagnostic System (SMDS) algorithms (third set)

REFERENCE SLIDES

Project Budget

Project Budget: $300K total DOE budget and $200K in-kind cost share.

Variances: NorthWrite priorities for the algorithms in order are Sensor Suitcase, FDD, and SMDS. Completion of the Sensor Suitcase Opportunity algorithms was moved to December 2016 in place of Milestone 1, Completion of the AFDD algorithms was moved to January 2017, and Milestone 1 (Completion of SMDS algorithms) was moved to May 2017. These milestone date changes were driven NorthWrite's prioritization of the algorithms for implementation in the order Sensor Suitcase Algorithms, AFDD algorithms, and SMDS algorithms.

Cost to Date: As of the end of Feb. 2017, of the $300K total lab project budget, $103K had been spent.

Additional Funding: In-kind cost share from NorthWrite, Inc.

Budget History					
FY 2016 (past)		FY 2017 (current)		FY 2018 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$32K	$0K	$174K	$137K	$94K	$63K

Project Plan and Schedule

Task	Months After Project Start																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	8/16	9/16	10/16	11/16	12/16	1/17	2/17	3/17	4/17	5/17	6/17	7/17	8/17	9/17	10/17	11/17	12/17	1/18	2/18	3/18	4/18	5/18	6/18	7/18
Task 1: Smart Monitoring and Diagnostic System (SMDS) Testing, Validation, and Implementation Support																								
Task 1.1: Exploration and Development of SMDS Enhancement for Variable-Speed																								
Task 1.2: Prepare Documentation of SMDS Methodology																								
Milestone 1: SMDS Documentation Completed										Δ														
Task 1.3: Testing and Validation of SMDS Method																								
Milestone 3: SMDS Testing and Validation Completed															Δ									
Milestone 4: SMDS SMART milestone: SMDS shown in laboratory tests to detect RTU performance degradation for refrigerant charges deficiencies (i.e., low charge) greater than 25% with a false positive rate of less than 2%.																Δ								
Task 1.4: Technical Support to NorthWrite for Completing SMDS in the Cloud																								
Task 1.5: End-to-End Testing of NorthWrite Cloud SMDS Implementation																								
Task 1.6: SMDS User Training Support																								
Task 2: Identification, Testing, Validation, and Implementation Support for RTU FDD Algorithms																								
Task 2.1: Characterization and Prioritization of FDD Algorithms																								
Task 2.2: FDD Algorithm Documentation																								
Milestone 2: FDD Algorithms Documented						Δ																		
Task 2.3: Testing, Validation, and Performance Characterization of FDD Algorithms																								
Milestone 5: FDD and Opportunity Algorithms Testing and Validation Completed														Δ										
Task 2.4: FDD Algorithm Refinement (where required based on testing results)																								
Milestone 6: Economizer fault detection algorithms shown in laboratory tests to detect faults with a false positive rate of less than 5%.																	Δ							
Task 2.5: Technical Support to NorthWrite for Cloud Implementation of FDD Algorithms																								
Task 2.6: End-to-End Testing of NorthWrite Cloud Implementation of FDD																								
Task 3: Selection, Testing, Validation, and Implementation for Small Building Energy Savings Opportunity Identification Algorithms																								
Task 3.1: Characterization and Prioritization of Opportunity Identification Algorithms																								
Task 3.2: Identification Algorithm Documentation																								
Milestone 10: Documentation for Opportunity Identification Algorithms Completed					Δ																			
Task 3.3: Non-RTU Algorithms Testing, Validation, Performance Characterization, and Refinement (where required based on testing results)																								
Task 3.4: RTU-Specific Algorithms Testing, Validation, Performance Characterization, and Refinement (where required based on testing results)																								
Milestone 7: Opportunity SMART milestone: Algorithm for RTU short-cycling (excess compressor on/off operation) shown in laboratory tests to detect short cycling faults with a false positive rate of less than 2%.														Δ										
Task 3.5: Technical Support to NorthWrite for Cloud Implementation of Opportunity Algorithms																								
Milestone 8: All Algorithms Implemented																			Δ					
Task 3.6: End-to-End Testing of Cloud Implementation of Opportunity Identification Algorithms																								
Task 4: Field Deployment Technical Support																								
Milestone 9: Final Presentation to DOE																								Δ