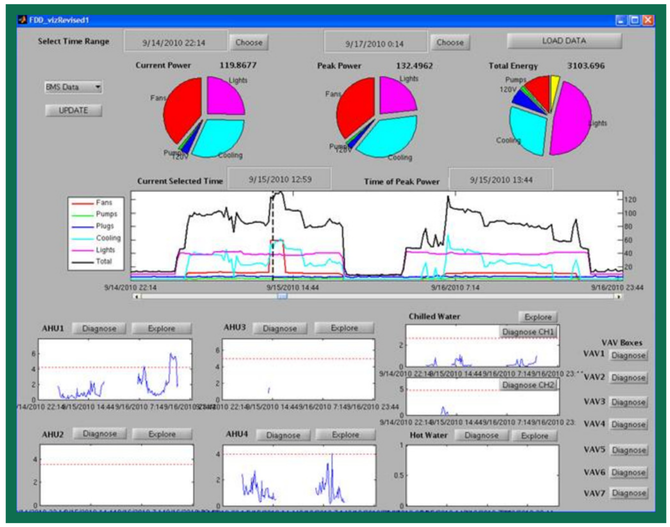
ESTCP
Cost and Performance Report

(EW-200929)



Automated Continuous Commissioning of Commercial Buildings

October 2011

ESTCP

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

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ACRONYMS AND ABBREVIATIONS

AHU	Air Handling Unit
ANSI	American National Standards Institute
API	Application Programming Interface
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BACnet	Building Automation and Control Networks
BCVTB	Building Control Virtual Test Bed
BLCC	Building Life Cycle Cost
BMS	Building Management System
BTU	British Thermal Unit
CHW	chilled water
CO_2	carbon dioxide
DB	database
DDC	direct digital control
DEM	digital energy meter
DoD	Department of Defense
DOE	Department of Energy
ECIP	Energy Conservation Investment Program
EEMCS	Extended Energy Management and Control System
EIS	Energy Information Systems
EMCS	Energy Management and Control System
ESTCP	Environmental Security Technology Certification Program
EW	Energy and Water
FDD	fault detection and diagnostics
FFSC	Fleet and Family Support Center
GUI	graphical user interface
HVAC	heating, ventilation and air conditioning
ISDN	Integrated Services Digital Network
ISO	Industry Standard Object
LBNL	Lawrence Berkeley National Laboratory
MMBTU	One Thousand British Thermal Units
MILCON	Military Construction
NMCRS	Navy Marine Corps Relief Society

ACRONYMS AND ABBREVIATIONS

NOAA	National Oceanic and Atmospheric Administration
PACRAT	Performance and Continuous Re-Commissioning Analysis Tool
PC	personal computer
RH	relative humidity
SIR	savings to investment ratio
SPB	simple pay back
SQL	structured query language
UTRC	United Technologies Research Center
VAV	variable air volume

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1.0 EXECUTIVE SUMMARY

The Department of Defense (DoD) is the largest single user of energy in the United States, representing 0.8% of the total US energy consumed and 78% of the energy consumed by the Federal government. Approximately 70% of the DoD electricity use is consumed by its buildings and facilities. The energy policy for DoD is being guided by the Energy Policy Act of 2005, Executive Order 13423 [1], and the Energy Independence and Security Act of 2007 to ensure a 30% energy reduction by 2015. Increasing existing DoD facility energy efficiency offers the largest opportunity for reducing DoD energy consumption. Building energy systems often consume 20% more energy than is necessary due to system deviation from the design intent. Identifying the specific sources and root causes of energy waste in buildings can be challenging largely because energy flows are generally invisible and because of the diversity of potential problems. To help address this challenge, the United Technologies Research Center (UTRC) in partnership with the Lawrence Berkeley National Laboratory (LBNL) proposed to demonstrate an automated, model-based, whole-building performance monitoring system at two DoD sites in partnership with Naval Station Great Lakes. The system continuously acquires performance measurements of heating, ventilation and air conditioning (HVAC) and lighting usage from the existing Energy Management and Control System (EMCS) augmented by additional sensors as required. (The system could also acquire water usage data, but this was not of interest at the selected demonstration sites.) The system compares these measurements in real time to reference simulation models that either represent the design intent for each building or have been calibrated to represent acceptable performance. The comparison enables identification and quantification of sub-optimal performance, identification of the conditions under which sub-optimal performance occurs, a means to compare alternative corrective actions using whole building metrics, and finally a means to validate improved performance once corrective actions have been taken. The study has also supported the development of best practice guides that outline procedures to ensure that a new facility's HVAC, lighting, and water distribution systems are operating properly and to correct faulty existing systems.

The goal of this project was to demonstrate a whole-building performance monitoring and anomaly classification system in two DoD buildings. The specific objectives of the project were to demonstrate a model-based whole-building monitoring system and establish its ability to:

- Identify, classify, and quantify building energy and water (EW) consumption deviations from design intent or an optimum,
- Support classification and identification of root causes of such deviation,
- Support recommendations for corrective actions,
- Quantify and prioritize the economic, energy, and water value for corrective actions, and demonstrate that the building performance improves, ideally to its design intent, following implementation of corrective actions.

The following energy faults were detected and diagnosed from the demonstration sites. These faults would waste more than 20 to 30% energy annually at the building level on two demonstration sites. Some faults would also cause issues related to thermal comfort.

- <u>Economizer faults</u>: too much outside air intake during non-economizer modes,
- <u>Lighting faults</u>: lights on during unoccupied hours,
- <u>Plug load faults</u>: excessive plug load due to occupant behaviors,
- <u>Chiller faults</u>: chiller was off when commanded on due to control issues. These faults cause the Air Handling Unit (AHU) discharge air temperatures and room temperatures to deviate from their respective setpoints. This causes building thermal comfort issues.

The overall performance evaluation for the automated continuous commissioning system and a few highlights from the demonstration are summarized as follows:

- A real-time model-based whole-building performance monitoring and energy diagnostics tool using EnergyPlus has been developed and demonstrated at Naval Station Great Lakes.
- A framework for whole-building, simulation-based energy diagnostics has been established and demonstrated. Fault detection and diagnostics (FDD) algorithms based on statistical process control methods such as T2 and Q statistics have been tested.
- A visualization dashboard for building performance energy monitoring and energy diagnostics has been developed and deployed in two real buildings. This dashboard provides an effective way for building facility managers to perform building performance decision-making.
- Currently, the instrumentation cost is relatively high. The largest components are the equipment and installation costs related to submetering and the on-site weather station. It is possible and reasonable to eliminate the on-site weather station by using weather data from the internet or an existing weather station on the base. There is a need for additional research efforts to establish cost-effective submetering.
- The facility team at the demonstration site found the energy usage visualization tool to be helpful as it enabled them to monitor impacts of control changes they made on energy consumption.
- Faults and issues identified by the automated continuous commissioning tool were valued by the facility team because the tool provided additional visibility into the building operation that was not provided by the existing building management system (BMS). This additional information allowed the facility team to identify previously unknown operational issues and prioritize their maintenance actions.
- Internet access is critical for both cost reduction and tool development.
- Building as-built drawings, control submittals, operation and maintenance records are very important to develop the energy models.
- It is desirable to have a centralized BMS on the base, so the facility team member can remotely access the automated continuous commissioning system sitting in each building. Ideally, only one PC is needed to host the automated continuous commissioning system in the centralized BMS.

- Considering different scenarios of instrumentation cost, the typical simple pay back (SPB) for the automated continuous commissioning system is between 2.65 and 6.43, while the typical system savings to investment ratio (SIR) is between 1.13 and 2.75.

1.1 BACKGROUND

Executive Order 13423 [1] and the Energy Independence and Security Act of 2007 (Title IV Subtitle C) require that United States federal agencies improve energy efficiency and reduce greenhouse gas emissions by 30% by 2015 relative to a 2003 baseline. It also requires water consumption to be reduced by 2% annually, beginning in 2008 and running through 2015, for a total reduction of 16% relative to a 2007 baseline. At some point in the future, similar goals for greenhouse gases may be formalized. Reducing the amount of EW wasted by HVAC; lighting; and water systems can achieve much of this goal. These systems often consume 20% more energy than is necessary to meet occupant comfort and indoor air quality requirements largely due to system deviation from design intent [2]. HVAC systems present the most problems, particularly air distribution systems, and common correctional measures focus on modifications to control systems [3].

Identifying the specific sources and root causes of water and energy waste in particular buildings can be challenging, largely because energy flows and water usage are invisible and because of the diversity of potential problems. A crucial barrier is the lack of data or information at sufficient detail (due to lack of measurement systems or difficulty in acquiring such data) to isolate abnormal changes in load conditions or anomalous equipment operations. Moreover, even if problems are identified, it can be difficult to prioritize a set of corrective actions because it can require comparison of performance among diverse functional elements of a building. Similarly, establishing limits of performance (meaning a quantification of how much energy is being wasted relative to a physical optimum, constraint or design intent), and also identification of the factors limiting waste reduction is a challenge. For example, HVAC energy consumption can be reduced through cool-roof technology that reflects and emits near-infrared radiation but the maximum achievable savings are limited by physics and should be quantified to compare against alternative measures to reduce HVAC energy consumption. Also, once actions have been taken, it can be a challenge to validate that they have achieved the desired effect because conditions before and after the action may have changed.

To help address these challenges, the UTRC in partnership with LBNL proposed to demonstrate an automated, model-based, whole-building performance monitoring system at two DoD sites in partnership with the Navy. The system continuously acquires performance measurements of HVAC and lighting usage from the existing EMCS augmented by additional sensors as required (The system could also acquire water usage data, but this was not of interest at the selected demonstration sites.). The system compares these measurements in real time to reference simulation models that either represent the design intent for each building or have been calibrated to represent acceptable performance. The comparison enables identification and quantification of sub-optimal performance, identification of the conditions under which sub-optimal performance occurs, a means to compare alternative corrective actions using whole building metrics, and finally a means to validate improved performance once corrective actions have been taken. The study has also supported the development of best practice guides that outline procedures to ensure that a new facility's HVAC, lighting, and water distribution systems are operating properly and to correct faulty existing systems. Such procedures have been developed already combining domain expertise, measurements, and functional testing for variable air volume (VAV) systems, package boilers, chillers, exhaust systems, and hydronic systems [4]. Finally, the system is based on open-source, publicly available software that can be run on personal computers (PCs).

The system features three innovations relative to existing EMCS technologies and methodologies. First, it employs an integrated, whole-building simulation model that provides subhourly calculations of HVAC, lighting, and water system energy consumption, taking into account the dynamic interactions among the building envelope, airflow, weather, internal loads, building usage, equipment, and controls. Detrimental interactions among these systems (particularly air distribution) can cause elevated energy consumption and identification and analysis of such problems are beyond the scope of both existing FDD and EMCS technologies. Second, the system features optimal estimation of zonal heating and cooling loads. The internal sensible and latent heat gains, and external envelope loads are not easily measured directly, but are important in the analysis of abnormal behavior. Providing estimates of zonal loads will help operators and facility managers identify causes of excessive energy consumption and poor comfort and thereby help prioritize corrective actions. Third, the system makes use of data mining algorithms to automatically identify and quantify whole-building performance deviations and learn over time to differentiate acceptable versus unacceptable performance. The system offers two additional advantages: the simulation model enables isolation of whole-building performance deviation – not only identification of a pre-defined, rule-based set of equipment faults - and it provides a means to evaluate the energy and economic value of alternative corrective actions. Finally, the model can compute equivalent greenhouse gas emissions assuming source fuel type is known. A conference paper [5] describing the system has been prepared and will be presented in November, 2011.

1.2 OBJECTIVES OF THE DEMONSTRATION

The goal of this project was to demonstrate a whole-building performance monitoring and anomaly classification system in two DoD buildings. It was originally planned that these buildings would be at two separate facilities; however, a number of logistical difficulties at the facilities considered initially led to implementation in two separate buildings at the same facility - Naval Station, Great Lakes, IL.

The ultimate goal is to reduce energy consumption, peak electric demand, and water use in DoD buildings by providing actionable information to facility managers and building operators. Based on the energy savings achieved from two DoD demonstration sites (>30% energy consumption reduction in Building 7230 and >20% reduction in Building 26), we expect to identify corrective actions that would reduce energy consumption by 15 to 20% per site but in an incremental manner consistent with the reductions required under both the Energy Independence and Security Act of 2007 and Executive Order 13423. With annual DoD expenditures of $2.5B on facility energy consumption, the savings potential can be up to $0.5B if the technology is applied across all DoD facilities. More conservatively, assuming the technology can be applied to only 10% of DoD facilities which are known to have direct digital control (DDC) capabilities, deployment would result in $50M of *annual* expenditure savings over the next three to five years. At the same time, the thermal comfort in DoD buildings would be improved to result in increased occupant productivity. Further, because the technology includes an energy model of each building, an additional benefit is to provide a means to quantify and prioritize alternative corrective actions, improving the long-term capital planning process.

The software environment demonstrated in this project (Figure 1) integrates real-time building measurements and real-time weather data with a simulation model, data mining, and anomaly detection algorithms. The computer simulation "reference model" represents the design intent of the building and includes HVAC, lighting, internal process loads, and water consumption. The existing EMCS and supplemental instrumentation measures parameters such as on/off status, temperatures, relative humidity (RH), power, and water flows. Data mining and anomaly detection algorithms identify and classify deviation from design intent.

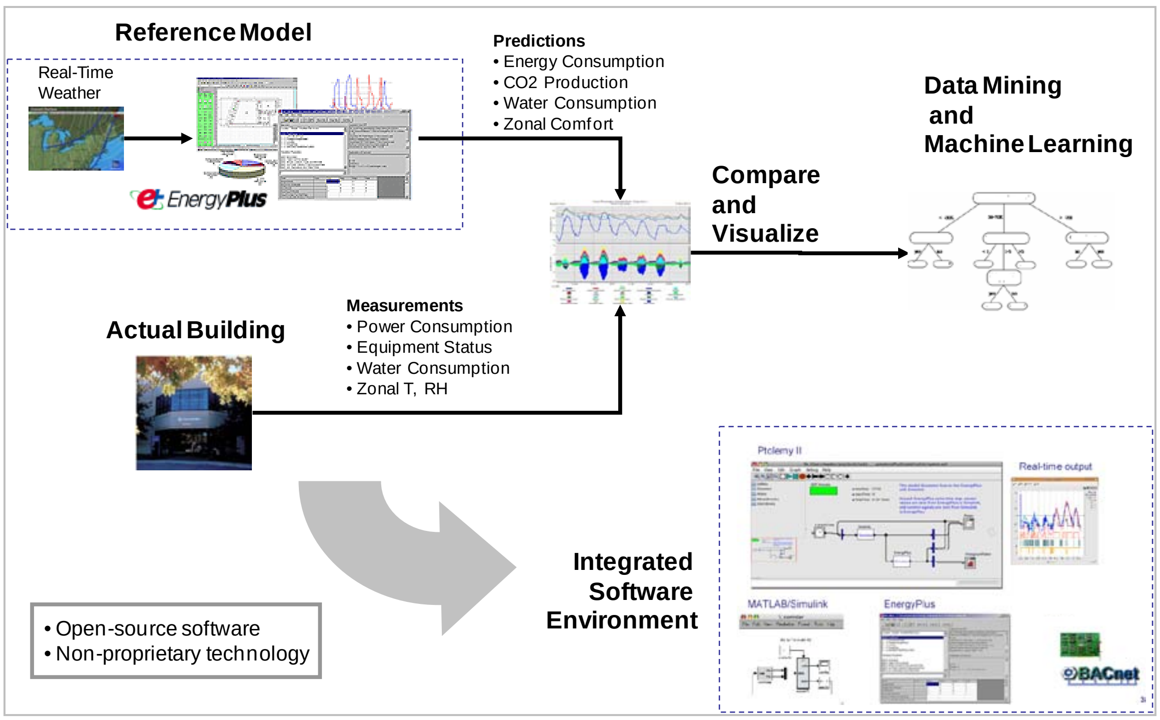

Figure 1. Automated Continuous Commissioning System.

1.3 REGULATORY DRIVERS

Executive Order 13423 [1] and the Energy Independence and Security Act of 2007 (Title IV Subtitle C) require that U.S. federal agencies improve energy efficiency and reduce greenhouse gas emissions by 30% by 2015 relative to a 2003 baseline. It also requires water consumption to be reduced by 2% annually, beginning in 2008 and running through 2015, for a total reduction of 16% relative to a 2007 baseline.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY/METHODOLOGY OVERVIEW

The implemented technology is a dynamic, model-based, whole-building performance monitoring system that compares measured performance metrics to those generated by a physics-based reference model representing "design intent" or expected performance. The system is depicted in Figure 2.

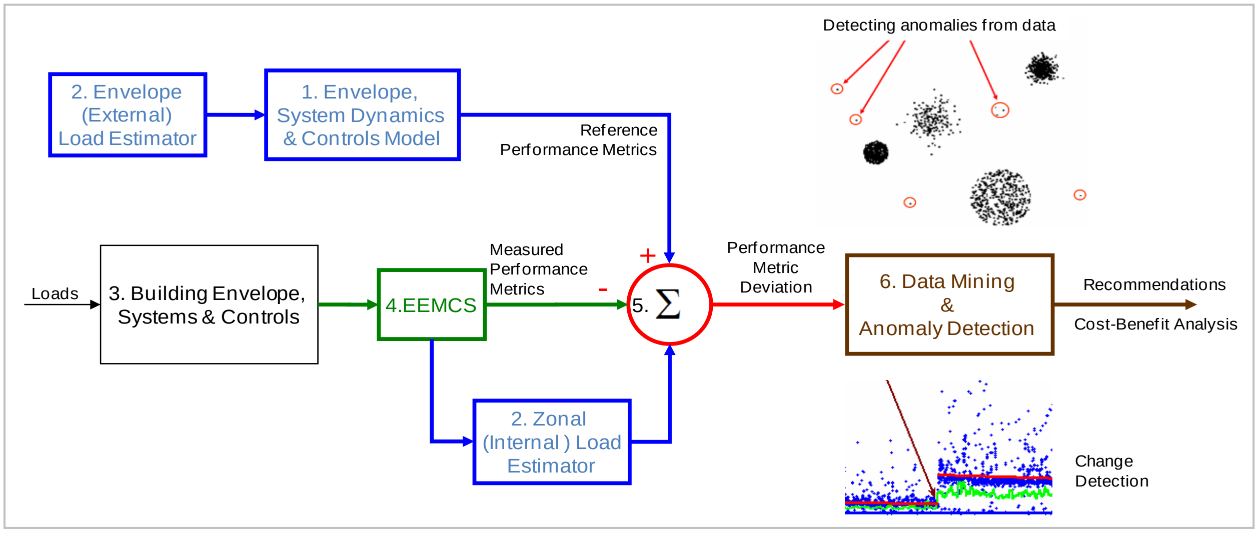

Figure 2. Diagram of the Performance Monitoring System.

The software system integrates and compares the output from an EnergyPlus building simulation model to measurements to detect deviations from design intent.

The key elements of the system are as follows:

- **Building Reference Model.** A whole-building EnergyPlus simulation model representing the desired performance of the envelope, HVAC, lighting, water, and control systems. EnergyPlus [6] is an open-source whole-building simulation program developed by the Department of Energy (DOE). It models heating, cooling, lighting, and ventilating processes, as well as water usage in buildings and includes many innovative simulation capabilities such as time steps of less than one hour, modular systems, multizone airflow, thermal comfort, water use, and natural ventilation. The model can also represent "plug" loads including computers and calculates both the direct electrical energy consumption and the effects of heat gains on the HVAC system. The model takes as input a description of the building (e.g., geometry, materials, roof type, window type, shading geometry, location, orientation), its usage and internal heat loads, and the HVAC system description, and then computes the energy flows, zonal temperatures, airflows, and comfort levels at sub-hourly intervals for periods of days to years.

- **Load Estimator.** Heating and Cooling Loads are defined as heat flow through the building envelope (external loads) or generation of heat at sources within the building zones (internal loads). External loads include the effects of weather (temperature, humidity, wind, solar radiation) and resulting envelope heat transfer including outside air infiltration. Internal loads include the heat gains due to occupancy, plug loads (e.g., computers) and building usage (e.g., process loads). External loads must be either measured or estimated and applied as inputs to the Reference Model. Real-time weather measurements near each site are used for this purpose [7]. These estimates are compared to locally measured values of weather for validation purposes. Separately, zonal loads are estimated using available measurements and compared with the design intent represented by the Reference Model. The load estimator essentially is a complement to the Reference EnergyPlus model.
- **Building Envelope and Systems.** This represents the physical building, the envelope, HVAC, lighting, and water systems – the physical plant.
- **Extended Energy Management and Control System (EEMCS).** This consists of the building control system, together with the additional sensors required to determine key performance metrics. Additional sensors include electrical power submetering, fluid flow meters, and temperature sensors to determine thermal energy flow rates. Measurement of electrical input and thermal output enables the monitoring of chiller efficiency, for example. Installation of permanent instrumentation connected to the EMCS ensures that the benefits of the additional performance monitoring capability are available to base personnel over the long-term. The existing Siemens APOGEE™ control system was expanded to provide data acquisition for the additional sensors and to interface to a new PC that provides a host for the simulation model and the data mining, anomaly detection, and data visualization software.
- **Integrated Software Environment.** Represented by the Σ symbol in Figure 1, this is a software environment and supporting signal processing integrated with the EEMCS and Reference Model such that the Reference Model outputs can be automatically assimilated with and compared to measurements. This software system is built upon the Building Control Virtual Test Bed (BCVTB) [8], an open source software platform developed by LBNL for integration of EEMCS data and a range of energy modeling software tools including EnergyPlus. The BCVTB makes use of Ptolemy II [9], an open source software environment for combining heterogeneous modeling and simulation tools (developed at the University of California Berkeley). Ptolemy II is programmable, which enables comparisons of building data with building reference model outputs and also implementation of Data Mining algorithms. The system outputs information in the form of a data table and graphs as shown in Figure 1.
- **Data Mining and Anomaly Detection.** Algorithms that take measured and reference data as input and process the data to classify operational patterns, detect outliers or changes, and identify faults. There are two main elements: Data Classification and Anomaly Detection. Data Classification and domain expertise has been used together to identify variables that describe the state of the system (a feature space) using methods such as cluster analysis. Anomaly detection addresses both sudden changes (e.g., a fault) and gradual trends (e.g., slowly developing water or air leaks). The system outputs alarms in the form of a text report, which are explained using graphs.

The software system integrates EnergyPlus using the open-source software platform Ptolemy II [9]. The system enables the integration with the EEMCS and also scripting and signal processing within the Ptolemy II environment.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

This system differs from existing Energy Information Systems (EIS) in the following ways:

- Existing systems do not provide a means to compare actual performance to design intent. This system augments an existing EMCS with additional sensors and uses a whole building reference model and diagnostic software to make performance deviations visible.
- Existing systems neither provide a viable means to quantify the value of performance degradations, nor a methodology to quantify the value of corrective actions. This system employs a physics-based, calibrated energy model that is useful to ascertain the magnitude of performance deviations and also for estimating the economic value of corrective actions.
- Compared to purely rule-based technologies such as Performance and Continuous Re-Commissioning Analysis Tool (PACRAT) [10], this system uses a physics based, whole-building energy model together with data mining such as clustering, change detection, and other data mining techniques for rigorous diagnosis.

The technical risks and the corresponding mitigations are summarized as follows:

- The model calibration may be insufficient to discern differences between actual and desired building performance. An extensive and comprehensive sensitivity study is being used to characterize the behavior of the model. For selected outputs of interest (e.g., total electricity consumption at the whole building level, etc.), the most influential input parameters are identified and further tuned by either hand or by automated optimizations.
- The corrective actions required to address faulty operation or other deficiencies identified by the tool may require modifications to building systems that are outside the scope of this contract or substantial capital expenditures that are beyond the means of this contract. Mitigation efforts will focus on modifications to the control system that are realizable with minimal effort, and also on relatively simple fixes to the HVAC or lighting systems that fall within the expertise of the team and local facility staff.
- The system compares baseline performance to post-corrective action. The comparison must be done under equivalent conditions (e.g., weather, usage) to be meaningful. Efforts have been made to ensure the baseline is generated for similar weather and occupancy conditions - in fact, the model based approach ensures this.
- The relatively high implementation cost is the major limitation from this technology. The largest components are the equipment and installation costs related to submetering and the on-site weather station. It is possible and reasonable to eliminate on-site weather station by using weather data from the internet or existing weather station on the base.

- A deployment concern about this technology is the skill level required to install and maintain the system. Another challenge is the efficient generation of simulation models of existing buildings from limited, often paper-based, design and as-built documentation. The current development of a comprehensive graphical user interface (GUI) for EnergyPlus by a team led by LBNL [11] will make a number of different aspects of modeling buildings, including existing buildings, simpler, faster and less prone to error.

3.0 PERFORMANCE OBJECTIVES

The majority performance objectives were met during the demonstration. The exceptions include all the objectives related to water systems. Based on the site visit and review with the facility manager at Naval Station Great Lakes, water conservation is not viewed as a significant issue for buildings at Naval Station Great Lakes. The assessment of performance objective is summarized in the table below:

Table 1. Performance objectives.

Performance Objective	Metric	Data Requirements	Success Criteria[1]	Results
Quantitative Performance Objectives				
Reduce building energy consumption (Energy) & greenhouse gas emissions (carbon dioxide [CO_2])	Building total electric consumption (kWh/[ft^2-yr]) and peak demand (kW) Building total steam consumption (therm/[ft^2-yr]) and peak demand Building total equivalent CO_2 emissions (kg)	Metering data for building electric and steam usage Building simulation data for equivalent CO_2 emissions	>10% reduction in building total energy consumption and related costs (over baseline) >15% reduction in building peak demand energy and related costs (over baseline) >10% reduction in building total equivalent CO_2 emissions (over baseline)	>30% reduction in building total energy consumption and related costs (over baseline) >30% reduction in building peak demand energy and related costs (over baseline) >30% reduction in building total equivalent CO_2 emissions (over baseline)
Reduce HVAC equipment specific energy consumption (Energy)	Chiller (kW/ton) AHU (kW/ton) Fan (kW/CFM) Pump (kW/gpm)	Sub-metering data for HVAC equipment	>10% reduction in overall HVAC equipment specific energy consumption (over baseline)	> 20% reduction in overall HVAC equipment specific energy consumption (over baseline)
Reduce building loads (Energy)	Lighting loads (kWh) Plug loads (kWh)	Sub-metering data for lighting and plug loads	5-10% reduction in lighting and plug loads and related costs (over baseline)	>20% reduction in lighting and plug loads and related costs (over baseline)
Building model validation	Building overall energy consumption (kWh/ft^2-yr) HVAC equipment energy consumption (kW)	Metering data for building electric and gas usage Sub-metering data for HVAC equipment	Overall building energy consumption accuracy within +/- 15% HVAC equipment energy consumption accuracy within +/- 10%	Overall building energy consumption accuracy within +/- 10% HVAC equipment energy consumption accuracy within +/- 10%

Table 1. Performance objectives. (continued)

[1] Success criteria related to building and HVAC equipment energy consumption have been assessed using both model-based simulations and actual energy measurements. Note: only those recommended energy fault corrective actions implemented by DoD facilities during the execution of this project could be assessed using actual energy measurements.

Performance Objective	Metric	Data Requirements	Success Criteria[1]	Results
Automated continuous commissioning system payback[2]	Simple payback time SIR (Savings-to-Investment Ratio) NPV (Net Present Value)	Cost to install and implement advanced building energy management system Savings from using advanced building energy management system	Simple payback time is less than 5 year[3] SIR is greater than 2.1. NPV is greater than 0	SPB is between 2.65 and 6.43 SIR is between 1.13 and 2.75
Qualitative Performance Objectives				
Ease of use	Ability of an energy manager and/or facility team skilled in the area of building energy modeling and control to use the technology	Feedback from the energy manager and/or facility team on usability of the technology and time required to learn and use	An energy manager and/or facility team skilled in HVAC able to do automated commissioning of building with some training	The user interface was refined based on feedback from facility team. The refined interface was well received
Energy fault identification, classification and prioritization	Ability to detect, classify and prioritize (based on energy impact) building faults	Building measured data Building simulation data	Energy manager and/or facility team able to detect , classify and prioritize (based on energy impact) building faults by comparing simulated building performance (design intent or optimal) against measured building performance	The system allows direct comparisons of energy consumption at multiple levels by providing deviations between the measurements and reference simulation models that either represent the design intent or have been calibrated to represent acceptable performance. Also, the system flags faulty behavior via anomaly scores. This information enables the facility team to prioritize faults based on energy impacts from simulation models.

[2]This payback success criterion is only applied to the case when the only retrofits considered are those that do not involve major equipment retrofits

[3]DoD Energy Managers Handbook http://www.wbdg.org/ccb/DOD/DOD4/dodemhb.pdf

Table 1. Performance objectives. (continued)

Performance Objective	Metric	Data Requirements	Success Criteria[1]	Results
Energy fault corrective action prioritization	Ability to prioritize energy fault corrective actions based on energy impact	Building measured data Building simulation data	Energy manager and/or facility team able to prioritize energy fault corrective actions by comparing the simulated building energy impact benefits for each fault corrective action alternative against the simulated or measured baseline building energy performance	By comparing the simulated building energy impact benefits, the system enables the facility team to prioritize the fault corrective action.
Automated continuous commissioning system robustness	Percentage of faults classified correctly	Building energy/water faults identified/ classified by automated continuous commissioning system	80% of faults identified are classified correctly (during 3 month demonstration period)	All faults that were detected and reported to the facility managers have been validated. Of the faults reported during the demonstration period, more than 80% have been identified and classified correctly based on feedback from the facility teams.

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4.0 SITE DESCRIPTION

The implementation of this system depends on the existing building control system communication capability. It is desirable that the existing EMCS should support open communication protocols such as Building Automation and Control Networks (BACnet), LonWorks, or Modbus. Another criterion for site selection is whether the building is undergoing a major renovation or has the renovation plan in the near future because this technology is intended to apply to buildings that are relatively stable.

Based on these criteria, two buildings at Naval Station Great Lake were selected as the demonstration site for this automatic continuous commissioning system.

4.1 FACILITY/SITE LOCATION AND OPERATIONS

4.1.1 Building 7230

The first identified demonstration site is Building 7230, the Naval Atlantic Drill Hall, at Naval Training Center, Great Lakes, IL. It is a two-storey facility with a drill deck, office, and administrative rooms. The gross area of this building is approximately 69,218 ft^2. Figure 3 shows the outlook and the location of this building schematically with a map (Building 7230 is identified with a yellow star on the map).

Figure 3. Location of Building 7230.

4.1.2 Building 26

The second identified demonstration site is Building 26, Fleet and Family Support Center (FFSC)/Navy Marine Corps Relief Society (NMCRS), at Naval Training Center, Great Lakes, IL. It is a two-storey office building with basement. The gross area of this building is approximately 37,000 ft^2. Figure 4 shows the outlook and the location of this building schematically and with a map (Building 26 is identified with a yellow star on the map).

Figure 4. Location of Building 26.

4.2 FACILITY/SITE CONDITIONS

4.2.1 Building 7230

The Drill Hall HVAC system consists of four airside systems and two separate waterside systems. The Drill deck is supplied by two VAV air handling units with heating and cooling capability. Operation of these units depends on the occupancy of the Drill deck space. Double-walled sheet metal ductwork with a perforated liner and drum louvers distribute the air throughout the space. The office and administrative area is served by one VAV air handling unit with VAV terminal units (with hot water reheat). The Classroom is served by one VAV air handling unit. The chilled water (CHW) system consists of two 100-ton air-cooled rotary-screw type chillers with fixed-speed primary pumping and variable-speed secondary pumping. Heating is supplied from the existing base-wide steam system through a steam-to-water heat exchanger. The hot water serves unit heaters, VAV box reheating coils, and air handling unit heating coils. There is an instantaneous stream-to-domestic hot water generator for domestic hot water service. The server room and communication service room are served by dedicated split systems.

4.2.2 Building 26

The Building 26 HVAC system consists of two airside systems and two separate waterside systems. The office and administrative area on the first and second floors is served by two VAV AHU with VAV terminal unit (with hot water reheat) heating and cooling capability. These AHUs have both heating and cooling capability. Operation of these units depends on the occupancy of the building. The CHW system consists of one 54.5-ton air-cooled rotary-screw type chillers with fixed-speed primary pumping. Heating is supplied from the existing base-wide steam system through a steam-to-water heat exchanger. The hot water serves unit heaters, VAV box reheating coils, and air handling unit heating coils. The communication service room is served by one dedicated split system. Electric unit heater and baseboard are used to provide heating to stairwells and restrooms.

A distributed DDC control system, APOGEE™ Insight by Siemens Building Technologies is installed in both buildings. This system monitors all major environmental systems. Building electric and water meters will be read by the DDC system. Operator workstations provide graphics with real-time status for all DDC input and output connections.

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5.0 TEST DESIGN

5.1 CONCEPTUAL TEST DESIGN

The technology has been demonstrated at the Naval Station Great Lakes facility. The demonstration was carried out in two phases:

- Phase 1: Models were constructed and calibrated based on as-built drawings and other reference material. Building instrumentation was deployed and data collected. An off-line comparison between model predictions and building measured data was performed to identify potential corrective actions that will improve building performance.
- Phase 2: The building reference model and data mining / anomaly detection algorithms were integrated using the BCVTB, and a real-time performance assessment was conducted.

A networked Siemens APOGEE™ DDC)system monitors all major lighting and environmental systems in Building 7230 and Building 26. Operator workstations provide graphics with real-time status for all DDC input and output connections.

Additional metering was installed to calibrate models and accurately measure energy consumption to validate results. It is important to emphasize that most of this instrumentation was required only to validate results. Deployment of this technology beyond the first two demonstration sites should require significantly less additional instrumentation. For Building 7230, the added-on sensors instrumentation include a digital energy meter (DEM)-electrical for chiller, a matched pair of supply and return CHW temperature sensors, a pyranometer, and aspirated wet and dry bulb temperature sensors for the weather station. These sensors were integrated into the Siemens EMCS, and a BACnet server was installed to enable information to flow to a computer located within the building. This computer is hosting the BCVTB, the reference EnergyPlus model and the information system.

5.2 BASELINE CHARACTERIZATION

Two baseline models were developed, to serve two different purposes:

5.2.1 Existing Operation Baseline Model

The existing operation baseline model refers to a whole-building EnergyPlus simulation model that represents the current building operational practice. The model takes as input a description of the building (e.g., location, orientation, geometry, shading, envelope material, and construction), weather, lighting and plug load profile, occupancy, HVAC system sequence of operation and water usage. It then computes the building energy consumption for HVAC system, lighting and plug loads and water consumption at the time step of a fraction of an hour (typically 15 minutes).

The building description was obtained from the design documentation and the as-built drawings. In cases where some information is not available, either an on-site investigation or an empirical estimate would used to determine these parameters. The HVAC system sequence of operation was obtained by combining the information from the control design documents, existing EMCS programming and interviews with the building operators and Siemens control engineers. The weather data, including solar irradiation, outside air temperature and RH and wind speed and direction were collected from the augmented on-site weather station. The lighting and plug load profiles were obtained from the additional building level sub metering. If sub metering is not available, a onetime measurement along with occupancy profile can be used to determine the lighting and plug load profile. The real occupancy profiles were estimated based on a one time investigation during a typical weekday. Real-time load profiles were assessed using a load estimator [12]. A model-based estimation approach was used here to provide real-time estimates of internal loads at multiple scales within the building. The estimation was built upon a reduced-order building model from the building thermal network and real-time data (e.g., temperatures, airflow rates) from the EEMCS, with considerations for sensor noise and model uncertainties.

After the initial model was built, a calibration process was applied to match the simulation results with the measured data by tuning the model input data. Detailed about the proposed automated calibration procedure can be found from the final report.

This model has two major functions: 1) to analyze and prioritize corrective action alternatives and 2) to quantify the building performance impact following implementation of the corrective actions.

5.2.2 Design Intent Baseline Model

The design intent baseline model represents the design intent/desired performance of the building. The design intent and operation models share the same model inputs for building information and weather data but differ in the description of the HVAC system operation, lighting and plug load profile, and water usage. In the design intent baseline model, the HVAC sequence of operation stand for the initial design intent or the desired performance that the facility management team is attempting to achieve based on the capability of existing equipment. The lighting and plug load profile in the design intent baseline model signifies an “ideal” performance that has only minimum lighting and plug loads on during unoccupied hours and lighting and plug loads proportional to the occupancy profile during occupied hours. The water usage is strictly proportional to the occupancy profile at all times.

By comparing to the measured data, the design intent baseline model was applied to identify and quantify the building energy consumption deviations from design intent or desired performance.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

5.3.1 Instrumentation and Monitoring

The automatic continuous commissioning system continuously acquires performance measurements of HVAC, lighting, and water usage from the existing building EMCS augmented by additional sensors/meters as required.

Additional instrumentation is required to provide run-time model inputs, calibrate models and accurately measure energy consumption to validate results. It is important to emphasize that most of this instrumentation is required only to validate results and deployment of this technology beyond the first two demonstration sites should require significantly less additional instrumentation. The measurements related to run-time weather inputs are outdoor dry bulb temperature, outdoor RH, direct normal solar radiation, diffuse solar radiation, and wind speed and direction. Modern buildings equipped with the EMCS commonly have the outdoor dry bulb temperature and RH measurements available, while the measurements, such as wind speed and direction, direct normal solar radiation, and diffuse solar radiation, are not typically available. Those missing measurements should be installed according to the manufacturers' instructions or industry standards.

The additional measurements required to track key performance metrics are electrical power submetering and thermal energy consumption for cooling and heating. The submetering of the electrical power should be able to measure the whole building electrical power and separate the lighting electrical power, plug load electrical power and HVAC equipment electrical power. The measurement accuracy of the submetering for electricity and thermal energy refers to Specifications Guide for Performance Monitoring Systems (http://cbs.lbl.gov/performance-monitoring/specifications/).

5.3.2 Performance Monitoring System PC Server

The overall system schematic diagram is shown in Figure 5. The PC server running the proposed system is located in the same building location as the PC running the EMCS. The required building performance data is collected through the existing EMCS and then made accessible to the energy diagnostics system through a BACnet gateway.

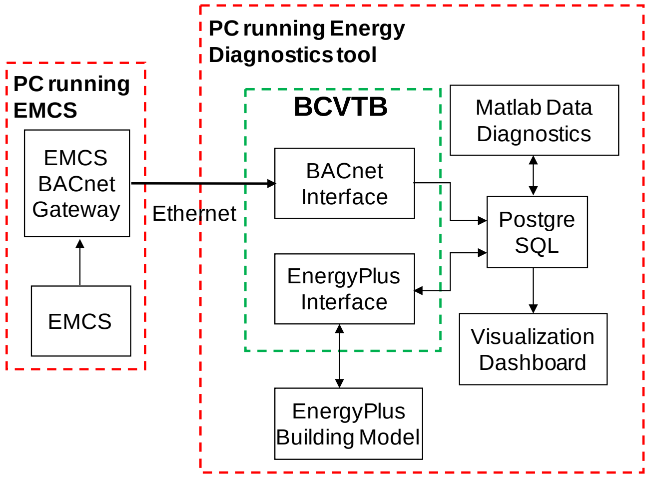

Figure 5. System schematic diagram.

Within the BCVTB, there are two modules necessary to achieve the proposed functional requirements. The BACnet module is used to acquire the relevant building performance data from the EMCS BACnet interface through an Ethernet connection. The sampling interval is 5 minutes. The data then is transferred to the Postgre structured query language (SQL) database (DB). The EnergyPlus module establishes the communication between the BCVTB and an external pre-built EnergyPlus model that represents the design/optimal building performance. The EnergyPlus simulation time-step is 15 minutes. The EnergyPlus module receives the relevant real time data (e.g., weather data) and executes the external EnergyPlus reference model. The EnergyPlus output results then are passed back to the PostgreSQL DB. The Matlab Data Diagnostic tool applies data mining and anomaly detection methods to identify building faults using building measurements and building EnergyPlus reference model predictions data stored in the PostgreSQL DB. The Visualization dashboard is the user interface to demonstrate the results as well as to display the real-time building performance data. It should be noticed that the BCVTB, EnergyPlus building model, the Matlab Data Diagnostic and DB software are all running in the background and not visible to the user.

5.4 OPERATIONAL TESTING

The Automated Continuous Commissioning system runs as an application on a PC at each of the two demonstration buildings. The BCVTB runs as a background application on this PC to automatically invoke the different Automated Continuous Commissioning functional modules (BACnet, data base, EnergyPlus, data mining). A visual user interface application is available on the PC desktop. This user interface application allows the facility team to plot the real-time comparison between building energy consumption data and the EnergyPlus model output. The user interface application also allows the facility team to conduct real-time comparisons of the reference model output to the building measurements, and to automatically identify which building performance metrics are anomalous and how corrective actions should be prioritized.

5.5 SAMPLING PROTOCOL

The existing Siemens APOGEE™ EMCS collects all the building performance data, including the additional measurement data for this project. The data communication within the APOGEE™ system is accomplished by Siemens proprietary protocol. In order to acquire the relevant data for this demonstration project, an APOGEE™ BACnet interface was installed. This BACnet interface allows the existing Siemens EMCS to exchange data with the external BCVTB environment using the BACnet protocol.

BACnet is a communication protocol for BACnet. It is an American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), American National Standards Institute (ANSI), and Industry Standard Object (ISO) standard protocol. BACnet was designed to allow communication of building automation and control systems for applications such as heating, ventilating, and air-conditioning control, lighting control, access control, and fire detection systems and their associated equipment. The BACnet protocol provides mechanisms for computerized building automation devices to exchange information, regardless of the particular building service they perform.

5.6 SAMPLING RESULTS

Table 2 lists summary information regarding the data collected in this project. All the data are included, in Excel csv format, in the CD delivered with the final report.

Table 2. Building data facts.

Building	Data Points	Sampling Frequency	Duration	Measurement Variables
Building 7230	688	5 minutes	04/12/2010 to October 2011	Temperatures, water flow rates, air flow rates, damper/valve positions, duct pressure, setpoints, control outputs (command)
Building 26	1062	5 minutes	03/03/2011 to October 2011	

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6.0 PERFORMANCE ASSESSMENT

The performance of the automated continuous commissioning system has been assessed against the performance objectives listed in Table 1 in Section 3.0. The last column in Table 1 also summarizes the assessment for all the performance objectives. The summary of the identified savings and payback is provided in Table 3.

Table 3. Summary of selected energy savings strategies and associated payback.

Selected Energy Savings Strategies	Simulation- Based Savings (%) Compared With Current Operation	Annual Savings In $*	Simple Payback**	Building
Lighting system (occupancy based lighting control)	-23.14% (Total electricity)	$6,542	Less than 2 months	Drill Hall
Reduce AHU1/2 outside air intake in the non-economizer mode	-40.49% (Total steam)	$4,418	Less than 1 month	Drill Hall
AHU1/2 operation mode (operate AHU1/2 in parallel)	-2.06% (Total electricity) -31.21% (Fan electricity)	$582	No initial cost	Drill Hall
Reduce plug load	-40.67%(Plug electricity) -22.32%(Total electricity)	$4,119	No initial cost	Building 26

*Assume (1) $0.069 per kWh for the electricity; (2) $8.7 per One Thousand British Thermal Units (MMBTU) for the steam
** Only consider the capital cost required to implement these energy savings strategies.

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7.0 COST ASSESSMENT

7.1 COST MODEL

A cost model for the automatic continuous commissioning tool is provided in Table 4. Since the demonstration served as a proof-of-concept, particular attention was given to the instrumentation selection so that the model output uncertainties that arise from the uncertainties of these measurements can be minimized. The high quality instrumentation used in the project is required only to validate results and deployment of this technology beyond the two demonstration sites could use less expensive instrumentation. It is expected that similar system performance could be achieved by using fewer sensors/meters as well as less expensive sensors.

Table 4. Cost model for the automated continuous commissioning tool.

Cost Element	Data Tracked during the Demonstration	Estimated Costs ($)	
		Bldg 7230	Bldg 26
Hardware capital costs	Estimates made based on component costs for demonstration	41,055	49,123
Installation costs	Labor and material required to install	34,868	28,934
Consumables	Estimates based on rate of consumable use during the field demonstration	N/A	N/A
Facility operational costs	Reduction in energy required vs. baseline data	N/A	N/A
Maintenance	Frequency of required maintenance Labor and material per maintenance action	One day per year ($1000)	One day per year ($1000)
Hardware lifetime	Estimate based on components degradation during demonstration	0	0
Operator training	Estimate of training costs	One day ($1000)	One day ($1000)

[1]Detailed list of materials and analytical costs provided in Final Report

7.1.1 Hardware Capital Costs

The hardware capital costs are mainly attributed to the additional instrumentation, which is required to provide run-time model inputs, calibrate models and do energy performance diagnosis. An EMCS with BACnet gateway is a requirement for implementing the technology. In cases where the BACnet gateway is absent and needs to be provided, additional cost is incurred. The measurements related to run-time weather inputs are outdoor dry bulb temperature, outdoor RH, direct normal solar radiation, diffuse solar radiation, wind speed and direction. The additional measurements required to track key performance metrics are electrical power submetering and thermal energy consumption for cooling and heating. The submetering of the electrical power should be able to measure the whole building electrical power and separate the lighting electrical power, plug load electrical power, key HVAC equipment (e.g., chiller) and total HVAC equipment electrical power.

7.1.1.1 Additional Weather Station

Pyranometer: Pyranometers are not typically used in the building industry and most of the pyranometers available on the market only measure the global (total) solar radiation. However, separation of the global solar radiation into the direct beam and the diffuse solar components is required to simulate the building performance properly in the whole building simulation program. The chosen pyranometer was the only off-the-shelf product that can measure the total solar radiation and diffuse solar radiation when the project started. A newly available product has no moving parts and is more compact compared to the chosen pyranometer with about half of the cost. However, this product only outputs global solar radiation and diffuse solar radiation and the user has to derive the beam solar radiation from these two measurements. Nevertheless, this product has the potential to reduce the major component of the cost of the weather station.

Temperature and RH sensor: Outside air temperature and humidity are weather variables with the most influence on the performance of typical commercial buildings. Modern buildings equipped with an EMCS commonly have the outdoor dry bulb temperature and RH measurements available. They can be used directly by the technology. However, care needs to be taken to ensure that existing sensors are calibrated and properly located to provide reasonable measurements.

Wind speed and direction sensor: The wind speed and direction will affect the building external convective heat transfer coefficient as well as the infiltration rate and will impact the building energy performance. Most available products on the market should satisfy this need for the technology implementation.

When deploying the technology, there are a few options that can be considered for cost reduction:

- If internet access is available, we will choose to use the data from the National Oceanic and Atmospheric Administration (NOAA) website directly without installing the weather station. If the internet access is not available, as is the case at Naval Station Great Lakes, then a weather station has to be installed. Using real time weather data is very important for any building simulation program used in this application.
- Multiple buildings on one campus will be able to share one weather station with the necessary network setup. It is possible that this kind of network setup (e.g., centralized BMS) is not available for some campuses.

7.1.1.2 Additional Submetering

The cost associated with the submetering is very site-specific and presents the highest variability. The number of electric power meters needed to disaggregate. The end-uses can be as few as four or greater than ten. The number of electric power meters needs be determined by reviewing the electrical as-built drawings and through an on-site investigation. The instrumentation for the thermal energy measurement needs to be determined on a site-by-site basis, e.g., electromagnetic vs. turbine flow meter, hot water measurement vs. steam measurement. If long straight pipe sections are available, a more cost effective turbine flow meter will be sufficient. Otherwise, a magnetic flow meter is needed. If district heating or cooling is present, the need for chiller electric power measurement and boiler fuel measurement can be eliminated.

7.1.1.3 Other Costs

A dedicated PC to host the software needed by the technology is needed. Most products on the market are adequate. A BACnet gateway is required only if the EMCS is not BACnet compatible.

7.1.2 Installation Cost

The installation cost is highly dependent on the required instrumentation. As mentioned above, the instrumentation requirements are very site-specific, and so, therefore, is the installation cost. For example, due to the roof access requirement for installing the weather station on Building 7230, the installation cost was higher than that for Building 26, even though the equipment to be installed was similar.

7.2 COST DRIVERS

Section 7.1 discussed some of the cost drivers. Several site-specific characteristics that will significantly impact cost are highlighted here:

- **Networking capability for campus applications.** If networking is available to allow sharing of the weather station, only one weather station is needed.
- **Electrical system layout.** A good electrical system design needs significantly fewer electric power meters to disaggregate the end-uses.
- **Cooling and heating distribution system.** If a long straight main pipe is not available, multiple British Thermal Unit (BTU) meters need to be installed on the piping branches to obtain the total.

7.3 COST ANALYSIS AND COMPARISON

The Military Construction (MILCON) Energy Conservation Investment Program (ECIP) template in the NIST Building Control Virtual Test Bed (BLCC) program [13] is used to calculate the SPB and SIR for the automated continuous commissioning system in Building 7230 and Building 26. Table 2 provides details of savings opportunities from both buildings. We also assume there will be ~$1,000 savings per year per building for operation and maintenance costs due to the fact that the system down-time could be reduced and the facility team could better prioritize their work orders. The following assumptions are used:

- $0.069/kWh for electricity and $8.7 /MMBTU for steam
- No demand charge
- Real discount rate of 3%
- Inflation rate of 1.2%

A few different capital cost scenarios (Table 5 for Building 7230, Table 6 for Building 26) were proposed after the analysis of current capital cost structure. Figure 6 illustrates the capital cost structure for both demonstration buildings. The high quality instrumentation used in the project is required only to validate results and deployment of this technology beyond the two demonstration buildings could use less expensive instrumentation. Also, the materials (i.e., sensors and meters) and installation costs are highly dependent on specific site and buildings (e.g., roof access requirement etc). Therefore, it is reasonable to assume different capital cost scenarios.

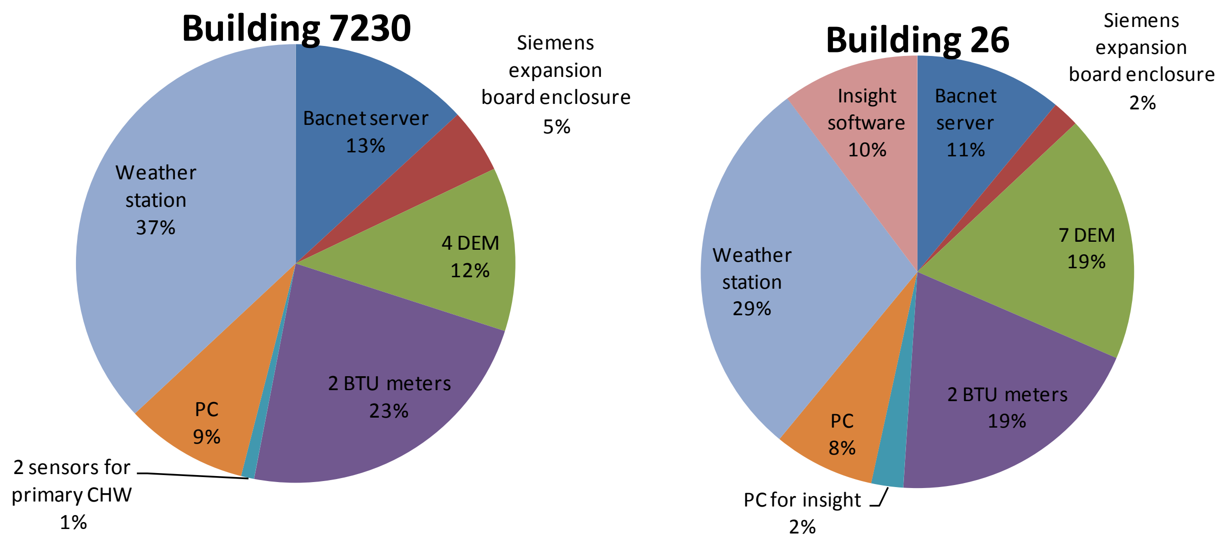

Figure 6. Pie chart plot of capital cost structure for Building 7230 and Building 26.

The following assumptions are used for different capital cost scenarios:

- If the building has a native BACnet BMS, then BACnet server will not be needed.
- If there is a PC available, then a PC will not be needed.
- If the weather information can be accessed from the internet or an existing weather station on the base, then the on-site weather station will not be needed.
- If the building has BMS software, then the BMS software (e.g., the Insight software used in Building 26) will not be needed.
- The installation cost reduction is linearly related to the material cost reduction.
- To effectively use the automated continuous commissioning system, submetering is necessary. The lighting faults (Building 7230) and plug load issues (Building 26) could not have been identified without the submeters installed in this project.

The SPB and SIR in different capital cost scenarios for the automated continuous commissioning system demonstrated in the Great Lakes are summarized in Tables 7 and 8.

Table 5. Different capital cost scenarios for Building 7230.

SCENARIO 1 Full capital cost ($75,923)	SCENARIO 2 78% of capital cost ($59,220)	SCENARIO 3 63% of capital cost ($47,831)	SCENARIO 4 41% of capital cost (31,128)
• BACnet server • Control vendor expansion board enclosure • 4 DEM • 2 BTU meters • 2 sensors for primary CHW • PC • Weather station	• Control vendor expansion board enclosure • 4 DEM • 2 BTU meters • 2 sensors for primary CHW • Weather station • (BACnet server and PC are removed)	• BACnet server • Control vendor expansion board enclosure • 4 DEM • 2 BTU meters • 2 sensors for primary CHW • PC • (Weather station is removed)	• Control vendor expansion board enclosure • 4 DEM • 2 BTU meters • 2 sensors for primary CHW • (BACnet server, PC and weather station are removed)

Table 6. Different capital cost scenarios for Building 26.

SCENARIO 1 Full capital cost ($78,057)	SCENARIO 2 71% of capital cost ($55,420)	SCENARIO 3 69% of capital cost ($53,859)	SCENARIO 4 40% of capital cost ($31,223)
• BACnet server • Control vendor expansion board enclosure • 7 DEM • 2 BTU meters • PC for insight • PC • Weather station • Insight software	• BACnet server • Control vendor expansion board enclosure • 7 DEM • 2 BTU meters • PC for insight • PC • Insight software • (Weather station is removed)	• Control vendor expansion board enclosure • 7 DEM • 2 BTU meters • Weather station • (BACnet server, PC and Insight software are removed)	• Control vendor expansion board enclosure • 7 DEM • 2 BTU meters • (BACnet server, PC, Insight software and weather station are removed)

Table 7. Cost analysis results for Building 723 demonstration.

	SCENARIO 1 Capital Cost	SCENARIO 2 78% of Capital Cost	SCENARIO 3 63% of Capital Cost	SCENARIO 4 41% of Capital Cost
First year savings:	$11,799	$11,799	$11,799	$11,799
Simple payback period (in years)	6.43	5.02	4.05	2.65
SIR	1.13	1.45	1.80	2.75

Table 8. Cost analysis results for Building 26 demonstration.

	SCENARIO 1 Capital Cost	SCENARIO 2 71% of Capital Cost	SCENARIO 3 69% of Capital Cost	SCENARIO 4 40% of Capital Cost
First year savings:	$4019	$4019	$4019	$4019
Simple Payback Period (in years)	19.42	13.79	13.40	7.77
SIR	0.37	0.53	0.54	0.93

Currently, most of the faults identified in Building 26 are related to thermal comfort rather than energy consumption. For example, due to control problems, there were times when the chiller was actually switched off when had been commanded on, so the building consumed less energy than expected but the room temperatures were not being maintained. The economic impact from occupant productivity due to lower thermal comfort is not quantified here because it is beyond the scope of this project. Based on an ASHRAE study [14] on the life cycle of a building, initial construction cost is about 2% and operational and energy cost is about 6%, while occupancy cost accounts for about 92%. The automated continuous commissioning system is able to identify issues related to thermal comfort to help address productivity problems.

8.0 IMPLEMENTATION ISSUES

This section includes discussions of the implementation issues in the areas of instrumentation, modeling and software, diagnostics, and visualization.

8.1 INSTRUMENTATION

All the instrumentation is standard commercial off-the-shelf products. The recommended measurement accuracies for the power meters and thermal meters are given in *A Specifications Guide for Performance Monitoring Systems* [15]. Since the pyranometer used to measure the beam and diffuse solar radiation is not commonly used in the HVAC industry, a particular mechanical contractor may not be familiar with the installation and commissioning of the sensor. Therefore, technical assistance from the manufacturer on the installation and commissioning of the pyranometer is highly recommended.

If the EMCS is not a 'native' BACnet system, a BACnet gateway will be required to implement the technology. Care is needed when setting up the BACnet gateway. The change of value (COV) for updating the measurement for the weather station, power meters and thermal meters should be as small as possible while not overloading with the BMS communication network.

Currently, the instrumentation cost is relatively high. The largest components are the equipment and installation costs related to submetering and the on-site weather station. It is possible and reasonable to eliminate the on-site weather station by using weather data from the internet or an existing weather station on the base. There are some ongoing research efforts for cost-effective submetering.

8.2 MODELING AND SOFTWARE

The data obtained from the instrumentation is delivered to the software platform. The components of the software platform include the BCVTB, the DB, the DB Application Programming Interface (API), EnergyPlus and Matlab. The software platform also includes utilities for configuring the communication connections between the software platform elements. Examples of the software platform data flow are:

- from the BACnet interface to the BCVTB
- the same data from the BCVTB to the DB
- data from the DB to the BCVTB
- the same data from the BCVTB to EnergyPlus
- data from EnergyPlus to the BCVTB
- the same data from the BCVTB to the DB
- data from the DB to Matlab
- data from Matlab to the BCVTB

For this project, the implementation of all these communication interfaces was such that they have to be maintained manually. Thus, if changes in the system, such as addition of measured points or change in input or output variables of a calculation, are frequent, the maintenance of the system could become cumbersome. The next generation system would limit any manual changes to a single location, with the changes automatically propagating to the rest of the system.

Matlab was used in this project as the platform for calculation and visualization. For a technology demonstration project, the use of Matlab is appropriate. For broader deployment, existing Matlab code can be compiled and distributed as an executable program. In other words, the automated continuous commissioning system can be deployed on computers without Matlab.

The Matlab-based visualization is available only on the local machine (i.e., it is a "thick client"). The next generation system would utilize a web-based visualization tool.

A customized version of EnergyPlus was used in Building 7230 to override the weather data. This feature has now been incorporated in the official release of EnergyPlus.

8.3 DIAGNOSTICS AND VISUALIZATION

8.3.1 Model Development and Debugging using Remote Access

We encountered significant challenges in the development and testing of the FDD tool because of remote access problems. Network security constraints prevented us from having broadband access to the PCs at Great Lakes. An Integrated Services Digital Network (ISDN) line was set up to access the computer at Building 7230 but there were configuration issues in the initial period which prevented us from having remote access. Also, given the nature of data collection where data were being uploaded to the DB in real-time from the Siemens BACnet system, we were unable to simulate a similar set-up offline. In the case of Building 26, there was no possibility of remote access.

This presented a significant challenge for coding and debugging. Team members could do efficient debugging only while visiting the site. This made it harder for the team to troubleshoot and fix complex and unforeseen issues with the code.

We recommend that remote access be granted for developers implementing similar systems at other sites.

Using this Automated Continuous Commissioning Tool currently requires the installer to have the following skills:

- **Create an EnergyPlus model.** EnergyPlus, developed by DOE, is a whole building energy simulation program that engineers, architects, and researchers use to model EW use in buildings. Modeling the performance of a building with EnergyPlus enables building professionals to optimize the building design to use less EW. DOE regularly provides training on how to use EnergyPlus. Also, the Appendices B and C provide detailed descriptions of EnergyPlus model for demonstration buildings used in the project. The current development of a comprehensive GUI for EnergyPlus by a team led by LBNL [11] will make a number of different aspects of modeling buildings, including existing buildings, simpler, faster and less prone to error.

- **Use the BCVTB.** The BCVTB is an open source software platform for building data acquisition, and the integration of real time data and EnergyPlus model. The BCVTB makes use of Ptolemy II [8], an open source software environment for combining heterogeneous modeling and simulation tools. A detailed description of the steps required to use the BCVTB is provided in the final report.

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APPENDIX A

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