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Building Monitoring System and Preliminary Results for a Retrofitted Office Building

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1. ABSTRACT

Existing commercial buildings in the United States consumed 18.42 quadrillion Btus of primary energy in 2008 which amounts to 18.4% of all energy consumed and 78% of all electricity in the United States (DOE 2011). The U.S. Energy Information Administration's Commercial Buildings Energy Consumption Survey (EIA 2011) shows a flat energy consumption profile between 1983 and 2003 indicating no real improvement in the aggregate commercial building stock. Buildings less than 100,000 square feet account for 65% of the commercial building floor space (EIA 2011). These buildings fall into three general categories: privately owned, state owned or federally owned and they can be either owner occupied or tenant occupied.

According to a recent report, only 25 percent of small building owners plan to make energy efficiency improvements (IFMA 2009). The current state of the building retrofit market incorporates disparate modeling tools that generally do not take into account utility bills, are expensive to populate with data and provide a wide bandwidth of results. Equipment, subsystems, sensors and controls are designed as discrete solutions to narrow problems, and performance is more a matter of meeting individual rating standards than integrated building load profiles. Finally, the construction industry itself is structurally fragmented leading to suboptimal results.

Given the preceding, one can only conclude deep energy efficiency retrofits of average existing buildings will be multifaceted and challenging. This paper will explore The Energy Efficient Buildings Hub (EEB Hub) commercial building testbed program designed to:

- provide researchers with detailed existing building level performance and indoor environmental quality data
- develop and/or validate existing and new building load models
- assess dynamic control systems
- examine current energy auditing practices and develop new strategic asset management practices
- validate building integrated technology performance

2. INTRODUCTION

Figure 1 presents the dispersion of actual building energy results versus the model predicted results for some of the nation's recent and best buildings. This is clear and convincing evidence that the complex nature of building design and operation is not fully understood. The situation is more complex when focusing on the nation's existing building stock of small and medium sized building that have been in operation for a number of years.

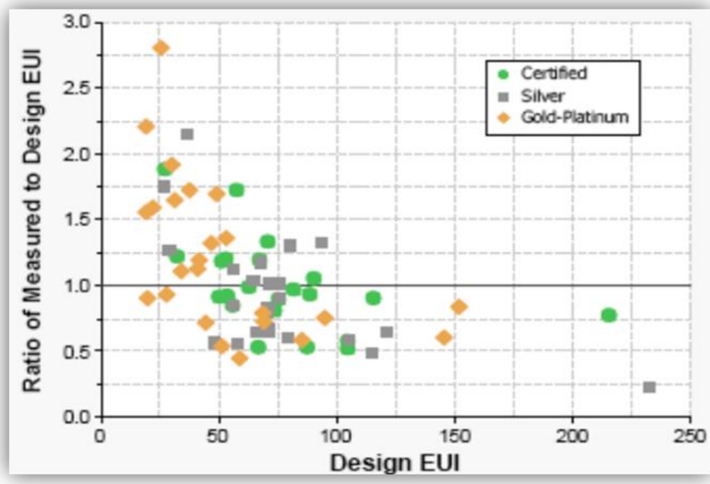

Figure 1. Measured EUI versus Design EUI (Frankel et al. 2008)

Improving energy load modeling for existing buildings requires a closer look at real building performance and providing researchers with enough time-sequenced data to calibrate existing models and develop and validate new models that will be easy to use and more accurate.

Model predictive controls, distributed controls, wireless controls and automated/human hybrid control schemes are all in various stages of development and commercialization. Testing these various approaches in controlled field experiments is an important endeavor in moving deep energy retrofits forward as studies that control improvements alone can account for 15% to 25% (Roth et al. 2005) energy efficiency improvement.

ASHRAE Level II Energy Survey and Engineering Analysis (energy audit) is an important point to begin the process of energy retrofit market transformation. This is a key touch point between the customer (purchaser of an energy conservation measure "ECM") and the industry professional. If audits are not deemed reliable, they will not be used. If audits are too time consuming or expensive, they will not be used. The EEB Hub's assessment of ASHRAE Level II audits within the region reveals a significant breadth of capabilities, results, recommendations and credibility.

The building commissioning literature, targeted building equipment and systems surveys, and anecdotal information suggest the widespread existence of building equipment and system faults. In this context, faults denote deviations from intended building equipment and systems performance. A significant volume of literature suggests that retro-commissioning of existing buildings typically reduces total building annual energy consumption by 5% to 20%, with higher values (up to 30%) in some buildings. Confirmed data cost/benefits of retro-commissioning and other ECMs is critical for market transformation.

Building energy components (walls, roofs, windows, HVAC equipment, sensors, controls, etc.) are generally viewed as discrete elements within a retrofit. Approaching existing building retrofits holistically, similar to airplane design engineering approaches, focuses on the impact that one component or subsystem upgrade has on the whole system performance. An equally important issue is that a discrete change today strategically impacts future energy retrofit design choices. The systems performance approach requires a radical change in equipment selection wherein selection is based on whole building performance metrics rather than component efficiencies. Achieving significant energy efficiency improvements in existing buildings will require a fundamentally new approach to retrofit design.

The EEB Hub Building test-bed program including Building 101 and other buildings at the Navy Yard, as well as, other buildings in the region will compile significant data with the intent of improving building energy modeling, building level control systems, building energy auditing practices, retro-commissioning and other ECMs, and implementation of integrated technology solutions.

This paper will present the details and the intent of the instrumentation currently deployed and operating at Building 101 in the Philadelphia Navy Yard.

3. APPROACH

In order to meet the EEB Hub goals of auditing building energy usage, studying occupant comfort and indoor air quality (IAQ), calibrating and verifying detailed simulation models of the building systems and the impact of any modifications to the building energy system, a comprehensive diagnostic and monitoring instrumentation suite is planned for deployment. On one hand this measuring system is capable of recording the instantaneous and aggregated use of electrical and thermal (gas) energy as well as mass and energy balance of the whole building, and on the other it focuses on adequate and accurate measurements of the air flow, the thermodynamic states (pressure and temperature) of the supply flow, return flow and the monitored zones. This is absolutely essential to establish a "baseline" for the building energy performance, to diagnose faults (deviation from design intent) and to compare different control strategies as and when they are implemented in the building.

3.1 Test Building: Building 101, Philadelphia Navy Yard

Figure 2. Bldg 101 in Philadelphia Navy Yard

The building of interest is the temporary headquarters of the EEB Hub in the Philadelphia Navy Yard – Building 101 (see **Figure 2)**. Built in 1911, this three story masonry office building has 75,000 gross sq ft and 65,000 sq ft of conditioned space. The building is segmented into three wings, each wing being served by a separate Air Handling Unit (AHU) and condensing unit, but with a common boiler. In addition there are two rooftop type units supplying the two wings of the basement separately. The building was renovated in 1999 to serve a single tenant but now is being used by multiple tenants.

The instrumentation described below is designed to provide an energy analysis of the building overall. In addition, more detailed energy and indoor air quality instrumentation was specified for the North Wing of the Second Floor, the location of the EEB Hub offices. The following quantities will be measured for the overall building:

- total electricity and natural gas uses in the overall building,
- heating and cooling capacity delivered by the HVAC equipment to understand the building loads and equipment efficiencies
- local weather conditions near the building
- ventilation flow rates provided to the building as well as the heating and cooling loads
- overall air leakage rates for the building as well as the air flows and leakage rates induced by mechanical systems and natural forces.

For the EEB Hub offices, the following additional quantities will be measured:

- operating conditions, heating and cooling inputs supplied by the Variable Air Volume (VAV) boxes
- supply and return airflows from the space as well as the pressure-induced air flows between this zone and other neighboring spaces and outdoors.
- conduction losses across interior and exterior surfaces as well as solar gains into the space
- internal gains in the space from plug loads and lighting
- occupancy levels with automated real time measurements
- temperature stratification as well as IAQ parameters and environmental conditions at multiple locations in the space

3.2 Instrumentation

Electrical and Natural Gas End Use: Power meters and a datalogger have been installed on the building's main electrical panel to measure power use for the total building, the 277 Volt lighting, the three air handlers and three condensing units. The gas use of the main boiler and the domestic hot water system is also being measured. In addition power meters have been installed in the 277 Volt panel in the basement to further submeter the lights that are located on the 2nd floor North area. These circuits will be submetered to quantify the energy input to this space.

2nd Floor North Electrical Panels: A Veris multi-circuit power transducer that can measure true power on each branch circuit is installed in the electric panels in the 2nd floor electrical room serving both the North and South ends of the building as well as the great room in the middle of the building.

Boiler Room: The total thermal output from the boiler is measured by a BTU meter. The gas input to boiler and heat output is used to determine the boiler efficiency. Similarly, the delivered thermal energy is directly measured for the two domestic hot water (DHW) tanks combined and used with the measured gas-use to estimate overall efficiency. An additional flowmeter is installed to measure recirculation flow and heat loss in the recirculation loop. The runtime and status of the recirculation pump and the burner on each tank and the state of the water heating system are also measured. This is shown in **Figure 3**.

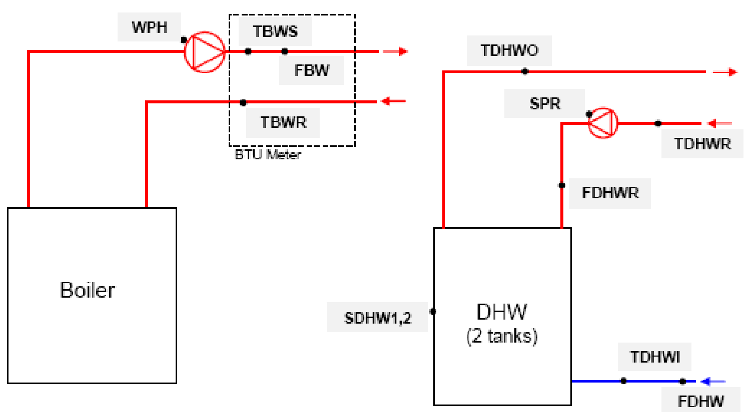

Figure 3. Schematic of Boiler and Domestic Hot Water System

Air Handler Units (AHUs): The building has three AHUs located in the basement. The measurements shown in **Figure 4** are collected for each AHU. AHU3 serves the 2nd floor on the north end of the building, so it will have additional IAQ sensors installed. The sensors are selected to measure air-side capacity psychrometrically. The supply air temperature is measured by a single thermocouple as well as a multi-point reading by the airflow station. In addition, the latent capacity can be confirmed by the measured condensate flow. The status of the two refrigeration circuits is measured along with the liquid refrigerant temperatures into the AHU. The runtime or status of the heating coil is also measured. The amount of fresh air brought into the air handler is to be directly measured so that fresh air loads - sensible and latent - can be determined. CO_2 concentration measurements will confirm the fresh air fraction in the supply air stream. The static pressure entering and leaving the air handler is measured and used with the fan speed and the fan power to develop fan curves for each unit. The pressure drops across the heating/cooling coils and filters will help to break down the pressure drops in the AHU components. One high-quality static pressure sensor with a multiplexed manifold arrangement is used to get all these static pressure measurements.

Condensing Units: The total power of each condensing unit is measured at the main electrical panel. Each condensing unit (CU) has two refrigeration circuits that are dedicated to each compressor. Each compressor has unloaders to provide the required capacity steps. The power use of each compressor is measured. The remaining power use can be associated with the condenser fans. The runtime, or status, of each condenser fan can be tracked along with the runtime and status of the compressor stages, or unloaders, to understand the operating state of the system. The state of the refrigeration system is measured for each compressor by measuring the discharge pressure, the suction pressure, the liquid line temperature, and the suction temperature. From these measurements the saturated suction and condensing temperatures along with the superheat and system sub-cooling can be determined. The liquid line temperatures at the condensing unit can be compared to the liquid temperature at the air handler to assess the magnitude of any heat gain (or loss) in the liquid line **(Figure 5**).

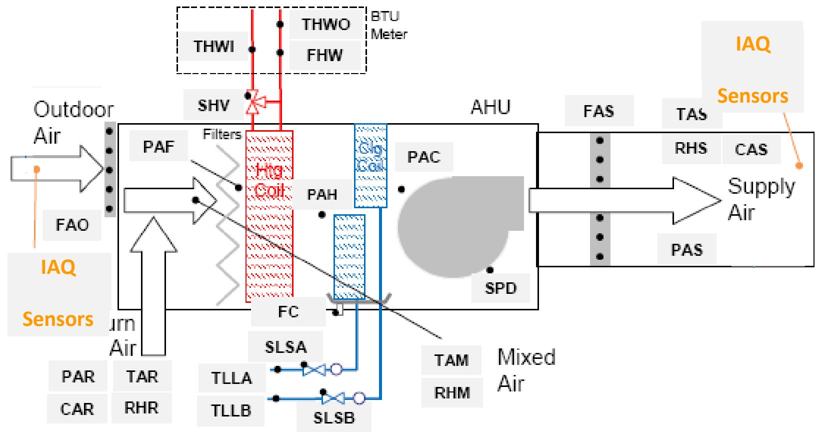

Figure 4. Schematic of typical AHUs (IAQ Sensors for AHU3 only)

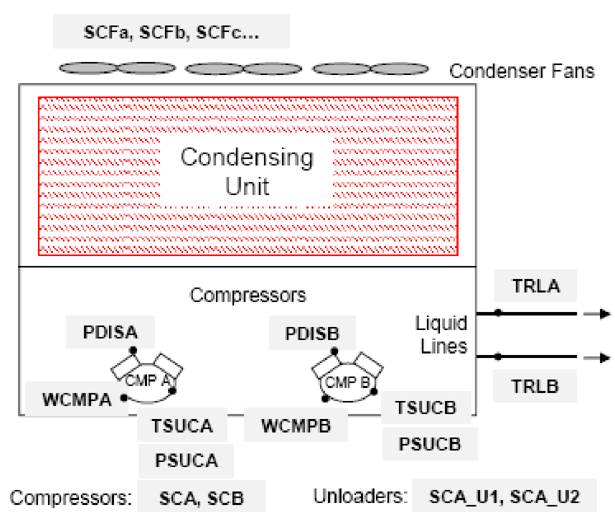

Figure 5. Schematic of Condensing Unit (typical of 3)

VAV Boxes: Each AHU has multiple VAV boxes **(Figure 6)**. The air handlers supply air at a specified air temperature and static pressure. Each VAV box is controlled by a thermostat in the local zone. If more cooling is required the damper in the boxes opens to provide more cold air and then modulates to hold the desired set point. If the space is too cold, then the heating coil is activated and water flowing through the coil modulates to hold the space temperature. The BTU meter measures the heat input; the position of the heating control valve is also recorded. The energy supplied to space on the 2nd floor can be directly determined using the air flow and the enthalpy of the entering air which is measured by the temperature and the dew point.

Portable Carts and Wall Measurements: Two portable carts are being built which measure temperature at multiple levels (6 heights). Each cart also has extendable/retractable poles to measure ceiling temperature and floor temperatures. The carts have a user settable dial (1-10) that identifies to the datalogger the location of the measurements in the space (these ten possible locations are pre-selected and marked on the floor). The humidity is also measured at three locations and CO_2 concentration is measured at one location. The dataloggers communicate wirelessly back to the "master" logger. The wall sensors are located on each orientation of the building's North Wing (East, West, North). Two sensors are located on the inside and one on the outside. The pyranometer is located on the outside wall.

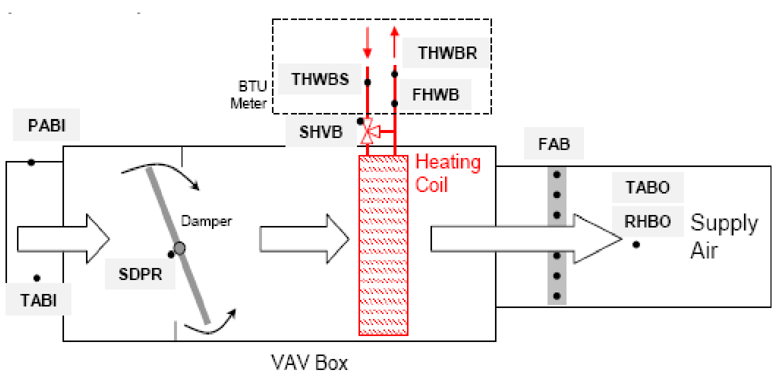

Figure 6. Schematic showing VAV Box measurements

The portable cart is an audiovisual (AV) cart with a vertical pole for holding sensors. The pole offsets at least 6 inches away from the cart to ensure that the free air temperature is sensed. Similarly the ceiling and floor temperatures are deployed or retracted so that the cart can roll to a new location.

Attic and Zone Condition Measurements: The datalogger at the north end of the 2nd floor (near VAV3) is also used to measure the zone pressures, temperatures, and humidities in the basement, 1st floor, 2nd floor, 3rd floor, attic, and stairwell. The pressure transducers and sample lines are installed in the north stairwell and all measurements are made relative to outdoors. The pressure and other conditions in the main lobby or atrium relative to the 2nd floor (using the logger near VAV1 and VAV2) are also measured. A separate logger is located in the attic.

Indoor Air Quality Sensors: The IAQ sensors will measure temperature, humidity, CO, CO_2 TVOCs, and particulates. Sensor locations for the EEB Hub offices are shown in **Figure 7**.

Occupancy Sensors: The number of people entering and leaving the building is measured at the front door as well as the entrances to the North and South Stairwells (3 locations). The number of occupants entering and leaving the 2nd Floor North Space is measured at the Lobby entrance and the North Stairwell (2 locations). Each sensor is a video-based sensor that can provide a count of the inbound and outbound traffic at each location. The traffic count is logged at 15-minute intervals. The XML output file is sent via FTP to the remote servers once per day.

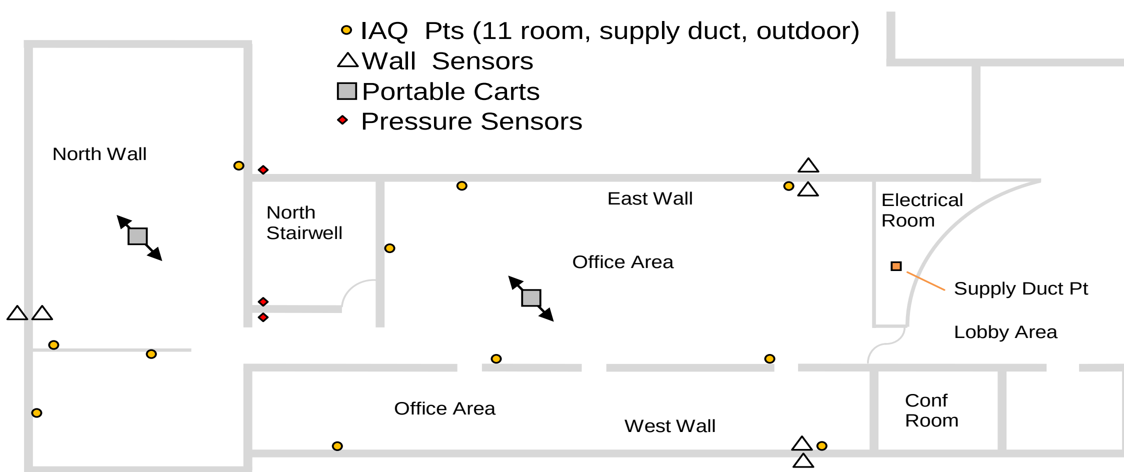

Figure 7. Schematic of In-zone measurements in 2nd Floor, North Wing of Bldg 101

3.3 Data Acquisition

The monitoring system at Building 101 is divided into 13 different data loggers distributed around the building in order to minimize wiring and labor costs. All of these loggers are installed behind a router that connects to the building Ethernet network and the internet via a single IP address. Two types of data loggers were used :

a) A moderately-priced device that reads pulses and analog sensors as well as MODBUS devices (such as power transducers) that are networked on an RS485 twisted pair network. It is used to measure power, read gas meter pulses and it is pre-configured to read various MODBUS BTU meters and power transducers (including the multi-circuit power transducers that are used in the 2ndfloor electrical room to read 126 individual circuits in the electrical panel. It also has MODBUS-based expansion boards that allow it to make measurements at multiple remote locations (such as the multiple condensing units mounted outdoors). This datalogger was used to measure power and gas use in the building as well as the power, status, pressure and temperature measurements on the condensing units.
b) A high accuracy datalogger with flexible programming and various options like the ability to use thermocouples which can accurately read temperatures when differential measurements are the primary concern. It can also be programmed for special purpose tasks such as calculating BTUs from flow and temperatures as well as multiplexing and auto-zeroing a pressure transducer to sample pressures at multiple locations. These loggers can be connected together under a proprietary networking protocol (PakBus) that can be either an RS485 twisted pair or a wireless connection. A datalogger was used for the temperature, humidity, flow, pressure and status measurements on each Air Hander and for the VAV Boxes in the second floor North Zone. Separate loggers were also used for the zone

and envelope measurements as well as the attic readings and the weather station. Two portable carts were also constructed to take temperatures and other environmental conditions in the space.

3.4 Building Leakage Testing

Blower door testing and pressure mapping and other techniques were used to characterize air leakage in the exterior enclosure and between building floors. The goal was to determine overall leakage rates as well as the location and magnitude of leaks in each individual section or zone of the building.

The process encompassed (and in that order):

- Inspecting the building enclosure, floor penetrations, stairwells, elevator shafts, utility chases and demising walls for intentional and unintentional gaps, holes and openings
- Measuring the air leakage rate of the building enclosure using fan pressurization techniques, including total leakage to the exterior as well as the leakage between each floor or zone; HVAC openings - outdoor air intakes, relief hoods and exhaust outlets - were masked for the initial test and then unmasked sequentially to determine the air leakage through each mechanical component
- The floor-to-floor air leakage was measured using “guarded” techniques that maintain the same pressurization on each floor and then systematically take away the pressurization to each area to determine leakage contribution of the connecting walls.
- Pressure mapping during normal HVAC operation established the leakage rates and flow directions
- Infrared cameras and theatrical fog during both pressurization and normal operation were used to understand leakage and flow characteristics.

For the whole building testing the ASHRAE midrise research project test protocol was used (ASHRAE 2011).

4. RESULTS

The detailed building and equipment monitoring instrumentation are currently at various stages of installation and commissioning. The data from the whole building electrical usage, and specifically the consumption by the main HVAC equipment, as well as natural gas consumption, have been logged since November, 2011. In the following, samples from this data and its analysis will be presented.

Figures 8 and **9** show the electrical and gas consumption in the building for the month of February 2012. One can observe the increased level of total electricity usage during a weekday as compared to a weekend, as expected. The lighting power as measured in the LP1 panel is one contributor to the increased usage during a weekday but it does not by itself explain the large difference as the electricity usage by the AHUs and Condensing Units are fairly unchanged over all the days of the week. This by itself is interesting information that points to potential problems with the controls of the AHUs as one expects the schedules (and hence power) to be different between a weekday and weekend. This is further elaborated by **Figure 10** showing the instantaneous power consumption over a typical week. Also one can note that most of the power usage of the HVAC equipment is due to the Air Handlers themselves with very little contribution from the Condensing Units due to the cold weather in the mid-Atlantic region during winter. Almost all of the natural gas consumed is attributable to the boiler with very little being burned in the domestic hot water units, as is usually the case. Data also shows that the power consumption of AHU2 and AHU3 are lower than AHU1 but the reason is not yet well understood as the zone level diagnostics are not yet active. While the integrated total energy consumed by any equipment over the course of a day can mask the instantaneous behavior of the unit, data as shown in **Figure 10** provides conclusive evidence that the total power consumption of the AHUs is fairly steady over weekdays and weekends as well as over the day and night. One would conclude from the data that the control systems that regulate the airflow into the building are not working properly. Indeed, the building operator has verified that the HVAC controls are manually overridden in the building.

Once the installation of the sensors are completed and the monitoring system is commissioned, the instrumentation suite will provide detailed and sufficient data to audit the whole building, monitor the designated zones and identify specific faults and their causes as and when they appear. In addition they will also allow researchers to validate the building energy models and evaluate control system impact.

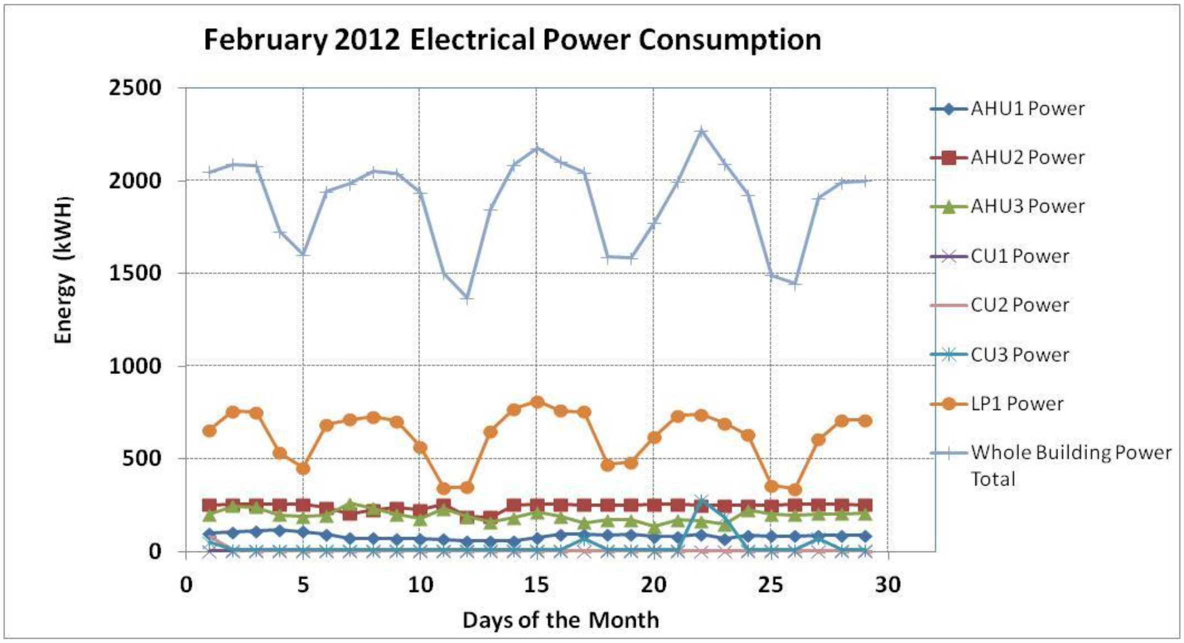

Figure 8. Building 101 Total Electricity Usage and Distribution during February 2012

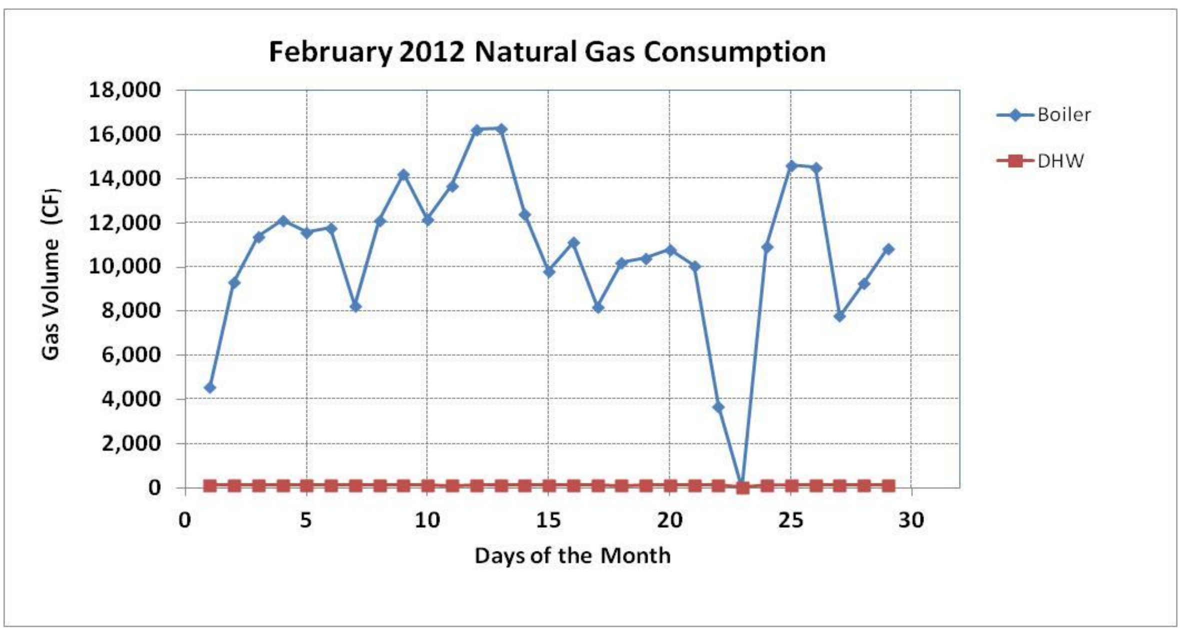

Figure 9. Building 101 Total Gas Usage during February 2012

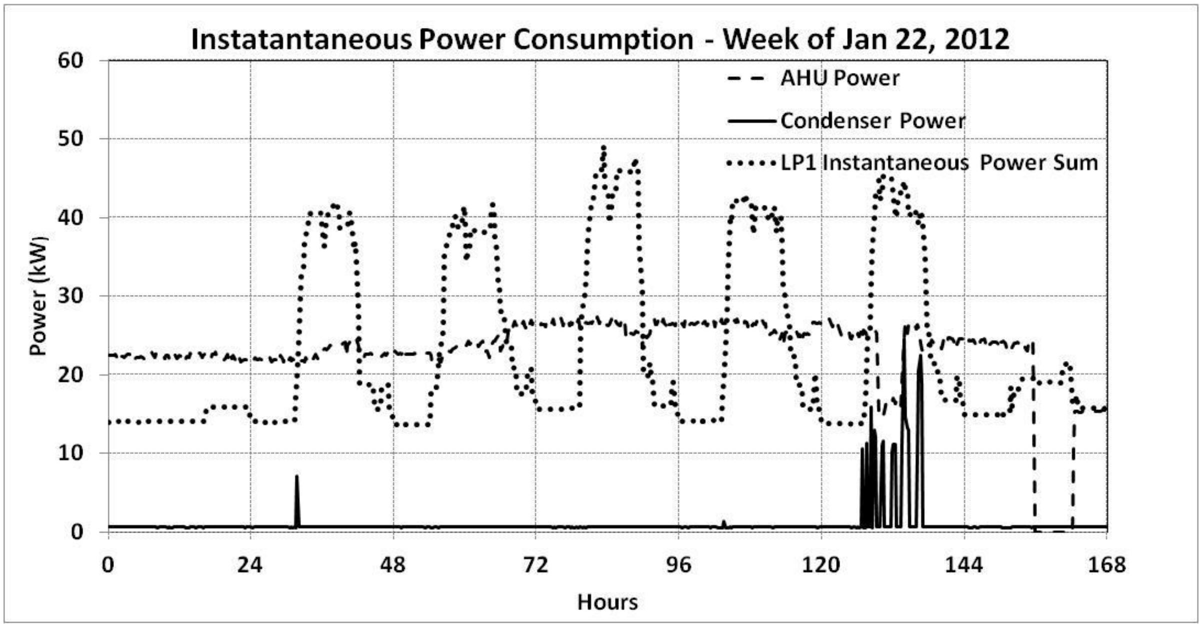

Figure 10. Instantaneous Electrical Loads of Lighting, AHUs and Condensers during a Typical Winter Week

5. CONCLUSION

The objective of this paper was to present an adequate suite of instrumentation that can monitor a building's performance at various levels of complexity – from a gross energy consumption on one end to detailed zone-level energy flow, comfort and air quality. While the instrumentation to monitor the detail states of the zone are not yet commissioned, the electricity and gas usage data at the whole building level is being recorded and important conclusions about the energy efficiency of the building can be drawn from the analysis of this data.

For example, a comparison of actual and predicted energy usage using building simulation tools will show levels of energy efficiency and will alert the building owner about equipment/control system malfunction and requirement for corrective actions. This is important because it demonstrates that even with a limited set of basic electrical and gas flow measurements (data available todate), a building's performance can be evaluated. For building owners, this means that even a modest investment will alert them about any potential areas of inefficiency. The exact corrective action required to fix the problems cannot be identified yet because the investigation of the root cause of the deviation from predicted (or normal) energy usage require more detailed suites of sensors. However in the coming phases of the diagnostic monitoring of the Building 101 those goals will be accomplished.

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