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Measurement and Verification - Retro-Commissioning of a LEED Gold Rated Building Through Means of an Energy Model: Are Aggressive Energy Simulation Models Reliable?

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MEASUREMENT AND VERIFICATION-RETROCOMMISSIONING OF A LEED GOLD RATED BUILDING THROUGH MEANS OF AN ENERGY MODEL: ARE AGGRESSIVE ENERGY SIMULATION MODELS RELIABLE?

A Thesis Presented

by

JUSTIN M. MARMARAS

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
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ABSTRACT

MEASUREMENT AND VERIFICATION OF A LEED GOLD RATED BUILDING THROUGH MEANS OF AN ENERGY MODEL: ARE AGGRESSIVE ENERGY MODELS RELIABLE?

MAY 2014

JUSTIN M. MARMARAS, B.S., UNIVERSITY OF MASSACHUSETTS AMHERST

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Directed by: Professor Dragoljub B. Kosanovic

During the construction of the new 3 story, 25,000+ square foot police station, a decision was made to participate in the LEED program to ensure the building had low operating costs, reduced emissions, conserved water and overall energy. The design of the building includes a primary-secondary ground source heat pump (GSHP) loop, a Dedicated Outside Air System (DOAS) with Energy Recovery Ventilation (ERV) wheel, all controlled by CO_2 monitoring through Demand Control Ventilation (DCV) to supply heat pumps located in each space; all monitored by a Building Automation System (BAS).

The building's future energy performance was predicted through an energy simulation model (ESM) software. Measurement and verification (M&V) was then performed on the building to determine its actual energy performance. Data was collected through the building's electrical meters, the building automation system (BAS), and other techniques to determine discrepancies. Installed electrical submetering along

with ESM results helped identify faults on a subcomponent level. This bottom up approach helped drive a successful retro-commissioning of the building systems reducing energy consumption.

This thesis will detail a methodology for retro-commissioning of underperforming new-construction buildings. Optimization of the building's systems will be facilitated through utilization of the M&V and ESM data. Discussed will be techniques and strategies to benchmark the building's systems, providing utility from the retro-commissioning and M&V results, to determine the value of the ESM. Last will be to discuss and demonstrate the future benefits of utilizing this real-time data to help building operators reduce, manage, and sustain their energy consumption profiles.

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NOMENCLATURE

ESM	Energy Simulation Model
GSHP	Ground Source Heat Pump
DOAS	Dedicated Outside Air System
ERV	Energy Recovery Ventilation
DCV	Demand Control Ventilation
BAS	Building Automation System
HP	Heat Pump(s)
RTU	Roof Top Unit
hp	Horsepower
W	Watt (power)
cfm	cubic feet per minute (air flow)
ft^2	square feet (area)
EWT	Entering Water Temperature (°F)
LWT	Leaving Water Temperature (°F)
WWT	Well water temperature (primary loop) (°F)
COP	Coefficient of Performance
EER	Energy Efficiency Rating
Dp	Differential Pressure
RH	Relative Humidity
MAU	Make-up Air Unit

CHAPTER 1

INTRODUCTION

1.1 LEED Program and Credits

Leadership in Energy and Environmental Design (LEED) is part of the U.S. Green Buildings Council (USGBC) and is a voluntary program that can be implemented into any building construction or renovation to help promote energy efficiency and waste reduction. The program’s participants achieve LEED points through implementing environmental and energy conscious systems and controls for their new or pre-existing buildings. As compared to conventional buildings LEED provides building owners and operators with additional opportunities to address and impact energy consumption while providing a healthier environment for occupants.

LEED has set up guidelines for building owners comprised into several categories that range from Materials & Resources, Indoor Environment Quality, to the Innovation & Design Process in an attempt to promote conservation of resources and reduction of waste. These categories (seven in all) are determined by LEED committees and each category lists the credits and pre-requisites required for completion. The completion of pre-requisites is mandatory for LEED certification while the credits offer suggestions on how to achieve LEED points for certification. To earn a LEED certification, a building must satisfy all pre-requisites and through the LEED credits earn a minimum of 40 out of a possible 110 points (for commercial buildings). The point scale is listed below.

- **Certified** - 40 - 49 Points
- **Silver** - 50 - 59 Points
- **Gold** - 60 - 79 Points
- **Platinum** - 80 + Points

The LEED process and points system is developed, implemented, and maintained by the LEED Steering Committee (LSC), the governing LEED body, along with the Technical Advisory Group (TAG). The LEED pre-requisites and credits help ensure a reduction in waste and pollution from the initial construction to the post-construction phase. This includes the procurement of materials and equipment all the way down to reducing the end use energy and water consumption. Further details on the LEED certification categories, pre-requisites, and specific LEED credits can be found in *LEED for New Construction & Major Renovations Version 2.2* 2005, where the credits are detailed in terms of intent, requirements, and strategies for proper implementation.

Buildings undergoing the LEED process characteristically experience a reduction in waste and energy consumption when compared to conventional code building construction. Although there are some incurred additional costs from the LEED process, a majority of building owners have reported lower annual operating costs, reduction in waste, improved indoor air quality for occupants, along with tax rebates. These savings added up over time can pay for the up-front LEED costs incurred during the initial construction.

For the building that will be focused on throughout this Thesis, attention has been directed towards two specific LEED Energy & Atmosphere credits (EAc) in the Energy and Atmosphere category. They are listed below with their range of possible achievable points along with a generic description.

- **EAc1** – Optimize Energy Performance (1-10 Points)
    - Whole building energy simulation (Option 1)
- **EAc5** – Measurement and Verification (1 Point)
    - Calibrated Simulation Model (Option D)

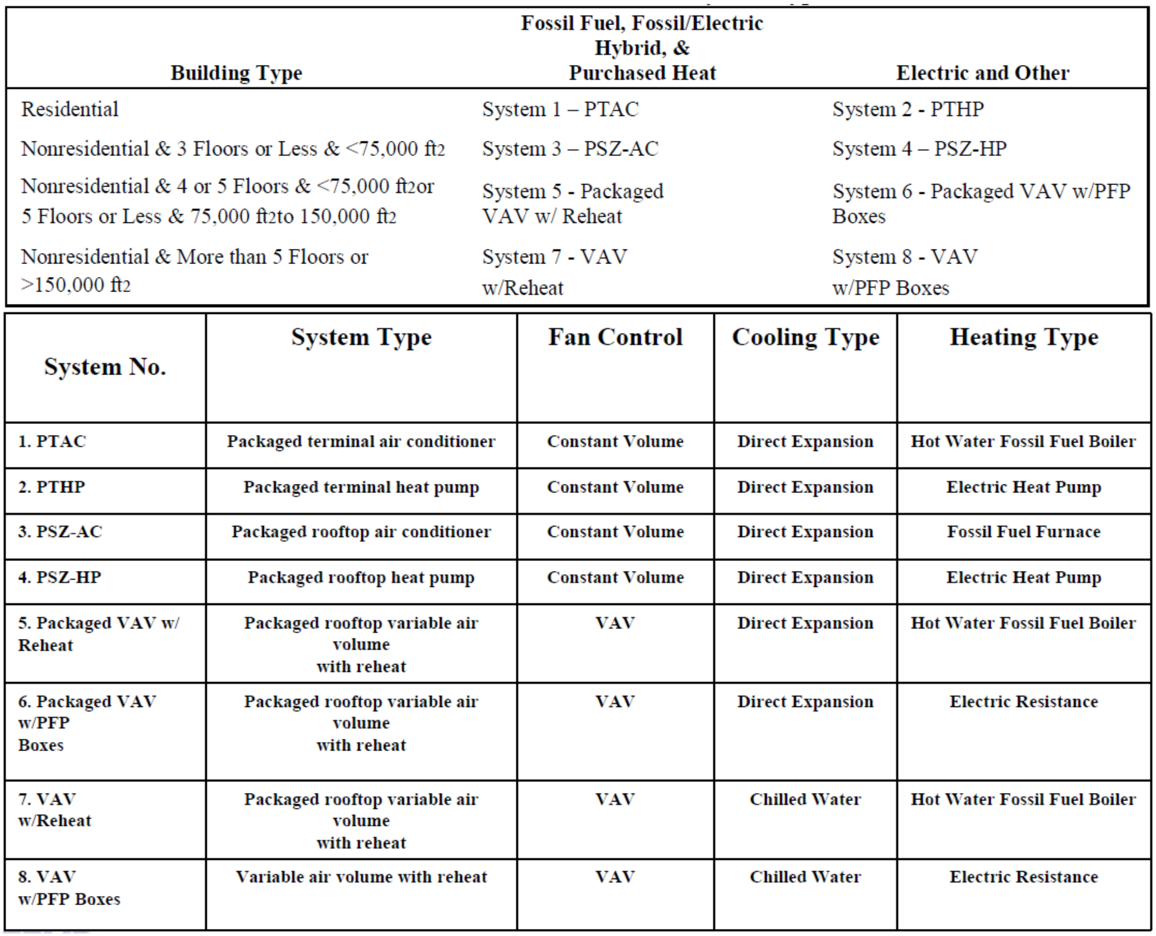
This thesis will utilize the newly constructed LEED gold rated building to determine the overall success of the LEED process as it pertains to these two credits (EAc1 &EAc5). Specifically how the quality of information in the proposed energy simulation model (ESM) can help drive a successful measurement and verification (M&V) process; and also aid in the retro-commissioning of underperforming systems through a bottom up approach. As advanced as LEED buildings tend to be, can their measured energy consumption match that of an aggressive ESM while keeping code and occupants satisfied? Also discussed will be what we can learn from these LEED buildings and the data that is collected during their operation.

1.2 Energy Modeling (EAc1)

The LEED EAc1 credit is achieved by undertaking the whole building energy consumption simulation. This is typically completed through an outside consultant firm that works with the architects and designers. The buildings wall and roof construction, along with the multiple HVAC technologies prescribed within the design documents will be modeled. This will provide an indication of the predicted energy consumption for the building from the proposed ESM.

The proposed energy simulation model (ESM) is performed with an energy simulation software approved by the LEED program. The proposed ESM uses inputs acquired from the designers such as the buildings HVAC equipment, occupancy and equipment operation schedules, along with the building’s prescribed construction materials to simulate how the building and its systems will perform on an hourly basis[10]. The energy simulation program has the ability to use actual or Typical Meteorological Year version 2 (TMY2) weather information comprised of outside dry-bulb air temperature, pressure, humidity, wind speed and direction, and the geographical solar irradiation to calculate the annual energy performance through the DOE-2 engine.

The proposed ESMs annual energy performance is to then be compared to a baseline energy model containing the same building construction and geometry. The proposed ESM must then demonstrate an annual energy consumption improvement from the baseline ESM anywhere from 10.5-42% to achieve the 1-10 points for the EAc1 credit. The number of points achievable is based upon a scale contained in the LEED document. The baseline energy model for LEED and many other buildings is prescribed by ASHRAE Standard 90.1-2004 Appendix G. ASHRAE Standard 90.1 sets the buildings baseline systems based upon the buildings footprint and source fuels. Figure 1.1 below is from the ASHRAE Standard 90.1 which determines the buildings baseline systems based upon residential status and footprint area.



Building Type	Fossil Fuel, Fossil/Electric Hybrid, & Purchased Heat	Electric and Other
Residential	System 1 – PTAC	System 2 - PTHP
Nonresidential & 3 Floors or Less & <75,000 ft2	System 3 – PSZ-AC	System 4 – PSZ-HP
Nonresidential & 4 or 5 Floors & <75,000 ft2 or 5 Floors or Less & 75,000 ft2 to 150,000 ft2	System 5 - Packaged VAV w/ Reheat	System 6 - Packaged VAV w/PFP Boxes
Nonresidential & More than 5 Floors or >150,000 ft2	System 7 - VAV w/Reheat	System 8 - VAV w/PFP Boxes

System No.	System Type	Fan Control	Cooling Type	Heating Type
1. PTAC	Packaged terminal air conditioner	Constant Volume	Direct Expansion	Hot Water Fossil Fuel Boiler
2. PTHP	Packaged terminal heat pump	Constant Volume	Direct Expansion	Electric Heat Pump
3. PSZ-AC	Packaged rooftop air conditioner	Constant Volume	Direct Expansion	Fossil Fuel Furnace
4. PSZ-HP	Packaged rooftop heat pump	Constant Volume	Direct Expansion	Electric Heat Pump
5. Packaged VAV w/ Reheat	Packaged rooftop variable air volume with reheat	VAV	Direct Expansion	Hot Water Fossil Fuel Boiler
6. Packaged VAV w/PFP Boxes	Packaged rooftop variable air volume with reheat	VAV	Direct Expansion	Electric Resistance
7. VAV w/Reheat	Packaged rooftop variable air volume with reheat	VAV	Chilled Water	Hot Water Fossil Fuel Boiler
8. VAV w/PFP Boxes	Variable air volume with reheat	VAV	Chilled Water	Electric Resistance

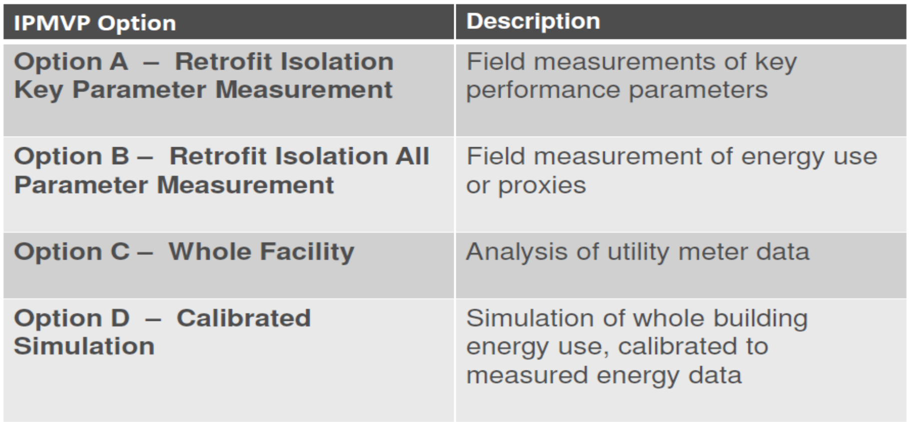
Figure 1.1: ASHRAE Standard 90.1-2004 Appendix G - Table G3.1.1A/B

The baseline ESM submitted for the EAc1 credit should satisfy the applicable mandatory and prescriptive requirements of the ASHRAE Standard 90.1-2004 seen in Figure 1.1. For the proposed and baseline ESMs to be valid for the EAc1 credit, they both must use the same simulation software, weather data input information, energy rates, and receptacle load. The software must also be able to model variations in occupancy, lighting power, miscellaneous power equipment, thermostat set points, and an HVAC system operation at part load performance for 8,760 hours a year for a minimum of ten building zones. Both models are then to be submitted by the consultant firm with documentation detailing energy performance improvement for HVAC systems, list of energy related features, software inputs and output records, end use energy breakdown, times where HVAC couldn’t satisfy the building’s load, and any explanation of errors or assumptions about specific components that could not be modeled properly by the software.

Through the ESMs, detailed hourly data reports specifying the energy consumption for most of the building’s systems can be retrieved. This includes but is not limited to the interior/exterior lighting, internal receptacle loads, heat pump and RTU space heating/cooling loads, pump and fan energy. The hourly data from the ESM and the measured building energy consumption data can be used to determine the ESMs validity. Comparing the ESM data to the building’s actual measured energy consumption will provide insight and identify opportunities that exist within the building to reduce energy consumption. The largest variances in energy consumption can indicate where to focus an energy assessment and help assess feasibility for the retro-commissioning of each system; either through ease of implementation or calculated projected savings.

1.3 Measurement and Verification (EAc5)

The LEED Measurement and Verification (M&V EAc5) credit allows buildings to obtain an extra LEED point by verifying the energy consumption of their building and its systems post-construction; note that M&V results are independent of accomplishing the LEED plaque. During the LEED proposal process there are four options of the M&V plan that can be selected by the building’s owner from the International Performance Measurement and Verification Protocol (IPMVP) Volume 3: *Concepts and Options for Determining Energy Savings in New Construction (2003)* as shown below in Figure 1.2:



IPMVP Option	Description
Option A – Retrofit Isolation Key Parameter Measurement	Field measurements of key performance parameters
Option B – Retrofit Isolation All Parameter Measurement	Field measurement of energy use or proxies
Option C – Whole Facility	Analysis of utility meter data
Option D – Calibrated Simulation	Simulation of whole building energy use, calibrated to measured energy data

Figure 1.2: M&V Options for LEED Credit EAc5

The M&V process is a costly endeavor as qualified consultants are required to carry out the analysis adding more overhead to an already expensive LEED certification. The process should add value to the building's potential future energy consumption and provide insight as to how energy use should trend through various scenarios such as occupation and seasonal loads. If the M&V is not performed then there could be serious issues with the building's energy performance/consumption that may not be identified in a timely fashion. Just because a building has undergone the LEED process doesn't mean it performs as such[21,22,24], as seen in Figure 1.3 below.

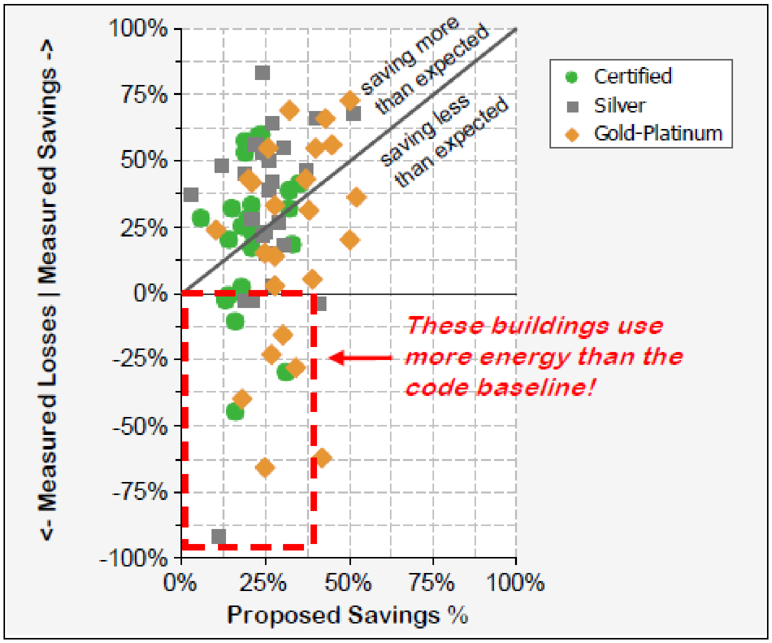


Figure 1.3: Measured vs. Proposed Savings Percentages for LEED Certified Buildings (From NBI/USGBC, Energy Performance of LEED N.C.B., March 2008)

The figure shows post-occupancy M&V results provided to the USGBC compared to the proposed ESM results for a number of LEED certified buildings. This study shows that some LEED buildings do perform better than expected. The figure also shows a significant number of buildings that fell short of the savings that had been proposed; along with the problem of buildings shown to consume more energy than the baseline cases (prescribed by Figure 1). This indicates there are a number of gold and platinum certified LEED buildings that have plaques and consume more energy than a typical baseline code constructed building would of the same size.

The end result of M&V process should be data that provides useful ongoing accountability of the building's energy consumption for the building owner and operator over time[18]. Additionally if individual pieces of equipment and building systems can be monitored, a bottom up approach, deviations associated with specific building functions can be easily recognized and remedied fast. This would direct building operators to specific areas of deficiency where they can focus on just one system and perform corrective actions. This M&V data will hopefully provide use down the road for the building operators, LEED committees, and energy modelers on how they should address specific building types, locations, and HVAC equipment energy consumption for future projects. This will result in more reliable ESMs.

For the LEED M&V credit (EAc5), there are no consequences if the building's energy consumption is shown to exceed the proposed ESM. The point is rewarded to the building; there are no consequences for underachievement or guidelines to help improve performance. There are also no requirements to disclose or share information. So where is the motivation to do the right thing? Who provides the money and expertise after the M&V process to recalibrate/retro-commission the systems so they run as intended and designed? LEED tends to leave this up to the building operator, whose main job and/or priority is typically not the HVAC or the energy management of the buildings systems. Typical building operators are not trained to trouble shoot or commission the newer HVAC technologies and their control sequences. As the industry continues to lean towards green buildings, more sophisticated equipment and controls are going to dominate future building infrastructure in efforts to minimize energy consumption. Will building operators be able to properly understand and troubleshoot these system controls/sequences after designers and commissioners potentially drop the ball? Can reliable proposed ESMs provide assistance? Techniques will be explored to determine what future buildings can gain from EMS data collection in terms of keeping equipment operating properly and minimizing energy consumption.

1.4 Ground Source Heat Pump (GSHP) Theory and Operation

A decision made early in the building design process was the implementation of Ground Source Heat Pump (GSHP) technology. A GSHP system was installed in order to reduce the buildings carbon footprint, greenhouse gas (GHG) emissions, and overall energy usage. GSHP systems typically consist of three main parts; the ground loop, the heat pumps, and the distribution system. These systems are viewed as environmentally responsible, or green, as there is usually no need for combustion of fossil fuels to heat spaces which reduces on site emissions while keeping occupants happy. GSHP systems provide further benefits in terms of energy use, as the heat pumps can provide more useful work than is needed to operate them.

The GSHP ground loop takes advantage of the Earth's neutral ground temperature throughout the year. During the winter the ground is warmer than the outside air due to the heat created within the Earth's crust. This results in a ground temperature the will maintain constant as the outside environment freezes. Inversely, in the summer, the ground is much cooler than the outside air. Cooling of a building or space through heat pumps is achieved by removing the heat in the space. Therefore the ground loop allows for the rejection of the buildings heat during the summer cooling operation.

The heat pump operation can be explained through the Carnot Heat engine. A heat engine uses thermal energy to create mechanical work. Equation 1.1 is the relationship between thermal energy and mechanical energy for a heat engine cycle using the law of conservation of energy. The equation shows that when heat is added to a system, some of that heat energy gets converted over to mechanical work while the rest of the heat is removed (Q_{cold}) and wasted.

$$Q_{heat} = \dot{W} + Q_{cold} \tag{1.1}$$

Figure 1.4 is a basic model for the heat engine and reverse heat engine and shows the relationship between mechanical work and thermal energy.

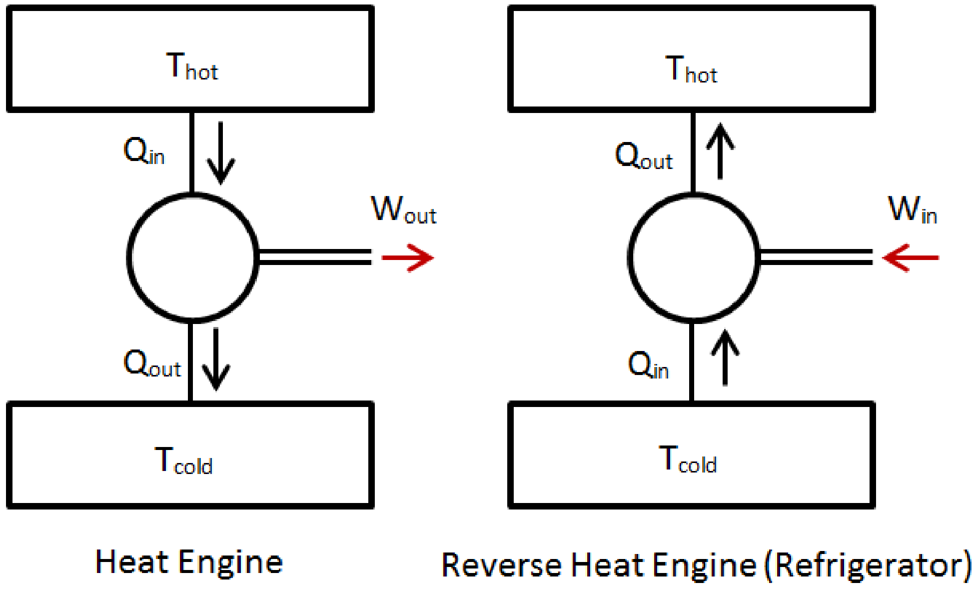


Figure 1.4: Heat Engine and Reverse Heat Engine

A heat pump operates similar to that of a reverse heat engine where mechanical work is done on the system to effectively move heat from a cold reservoir to a hot reservoir through expansion work of a refrigerant (vapor-compression). A heat pump contains three main parts; the evaporator, the condenser, and the compressor. In regards to Figure 1.4, the compressor provides the work for the heat pump while the evaporator and condenser act as the hot and cold reservoirs, depending on operation. The thermodynamic efficiency of the heat pump operation can be determined by Equation 1.2.

$$\eta_{efficiency} = \frac{Work\ Out}{input\ heat} = \frac{\dot{W}}{Q_{heat}} = 1 - \frac{Q_{cold}}{Q_{heat}} \tag{1.2}$$

From the equation we can see that the temperature of the hot and cold reservoirs play a role in the efficiency of the system. With the ground providing a constant temperature reservoir for the building’s GSHP system, part of the system is defined. The internal zones are the other part of the system (reservoir) in which heat will need to be transferred from the ground loop to the building zones and vice versa (depending on building comfort needs).

The distribution to the building zones is the third part of the system where the work done by the ground and heat pumps is then delivered to condition the space to satisfy occupant needs. This is typically accomplished by taking in outside air and conditioning it with the heat pumps to the zone set point conditions. The heat pump then operates with its own refrigeration cycle to produce hot or cold fluid which circulates through a heat exchanger to transfer the energy to the incoming air stream. The waste heat from the heat pumps then gets rejected into the ground loop via the condenser.

The actual energy consumption of the heat pumps is dependent on the operating characteristics of the unit. Heat pump’s energy consumption is characterized by the Coefficient of Performance (COP). The COP is a ratio of the useful output energy of the heat pump and the energy consumed. The higher a heat pump’s COP value, the more energy it can provide per unit of energy consumed; benefitting from the refrigeration cycle. The heat pump’s COP is a function of the conditions on the heat pump; such as air temperature(entering and discharge), and the condenser water temperature provided by the GSHP secondary loop. For heat pumps in heating mode, the warmer the entering condenser water temperature the higher the COP, and vice versa during the cooling operation. This logic will be visited during the retro-commissioning and optimization phase of the Thesis.

In order to optimize the performance of the GSHP system, various parts of the system will be analyzed which will be discussed in detail later in this Thesis. Fluctuating of the GSHP loop temperature and other variables associated with the heat pumps energy consumption can be analyzed to determine what the optimal operating conditions are.

1.5 University of Massachusetts Amherst LEED Gold Rated Police Station

In May 2011, the University of Massachusetts (UMASS) Amherst began operation of its three story, 25,700 ft^2 LEED Gold rated police station on campus. For this LEED gold rated facility an eQUEST 3-64 proposed ESM simulated the whole building and its wide range of HVAC technologies for the EAc1 credit. The buildings HVAC systems include a decoupled primary-secondary ground source heat pump (GSHP) loop in series with a dedicated outside air system (DOAS) roof top unit (RTU). The RTU is rated at 20 tons and is equipped with an energy recovery ventilation (ERV) wheel to capture energy from the building's exhaust stream. The RTU along with the building's heat pumps are all controlled zone by zone through CO_2 monitored demand control ventilation (DCV) scheme and the building automation system (BAS). The building has multiple zones served by over forty individual heat pumps.

The building's proposed wall construction is comprised of a combination of brick, sprayed polyurethane, dense glass gold, and steel studs. The window-to-gross wall ratio is 16% and the roof is lined with R-24 continuous insulation. The windows are double glazed, low-e coating, argon insulated, with gray tint with no shading devices on site. These are all improvements from the ASHRAE 90.1 baseline requirements.

The building, outfitted with multiple electrical submeters, can measure specific types of energy consumption. This enables specific building systems to be excluded from the energy analysis if required; for example lighting, plug loads, etc. All lighting for each floor is on its own submeter along with all of the building's heat pumps and auxiliary loads. Overall six submeters measure lighting, four submeters measure plug loads, and three submeters measure local heat pumps floor by floor (three floors) while a main building electrical meter measures the whole building. With the building's systems being comprised of newer HVAC technologies, the energy performance was assumed to follow the trend of its technologies and be energy efficient. The building provides its HVAC needs through recovering or discharging heat into the ground via the GSHP primary loop. The primary loop then induces the thermodynamic heat loss (or gain) on the GSHP secondary loop to provide adequate cooling and heating fluid for the refrigeration process for all of the local heat pumps and the DOAS RTU, as seen in Figure 1.5.

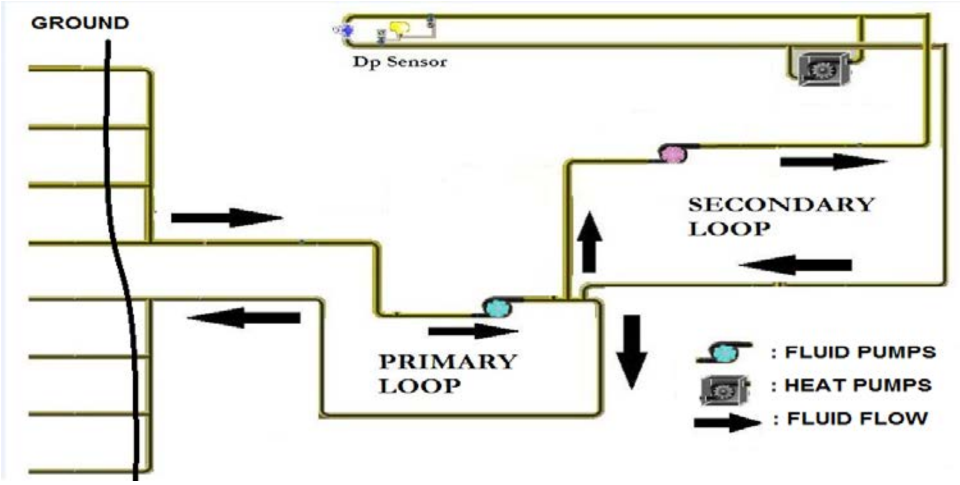


Figure 1.5: Primary-Secondary Heat Pump Loop

The DOAS RTU is supplied with 100% outside air which first travels through an ERV wheel. The wheel recovers enthalpy energy from the exhaust stream, which is characteristically held around 70°F and 50% relative humidity (RH) throughout the year[15], to pre-condition the supply air stream entering the RTU. This provides an efficient way to pre-heat or pre-cool the building's supply air (depending on season). For instance in the winter, incoming outdoor supply air is pre-heated by the wheel while in the summer it is pre-cooled as seen in Figure 1.6 .

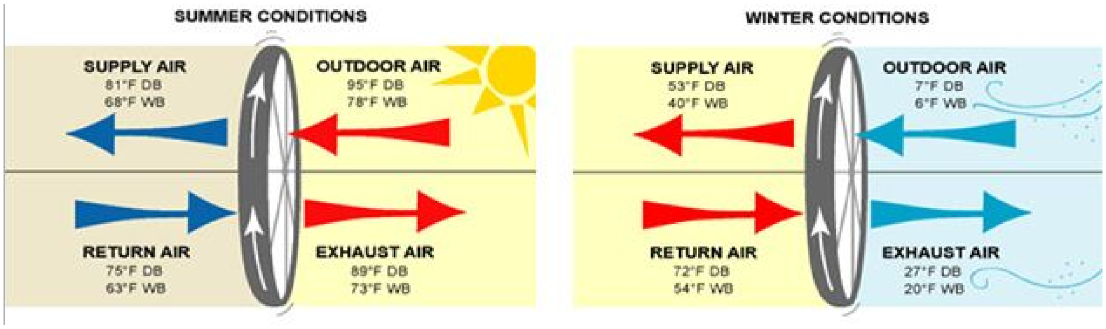


Figure 1.6: Example of ERV Operation

This outside supply air is then further conditioned by the DOAS RTU to a desired discharge air set point temperature and RH by running the RTU compressors. The supply fan speed modulates via a variable frequency drive (VFD) in order to maintain a static pressure set point in the supply duct, while the exhaust fan speed control is a function of the supply fan speed. A screenshot from the BAS shows the actual DOAS RTU and ERV wheel setup and operation with the sensor locations in Figure 1.7 below.

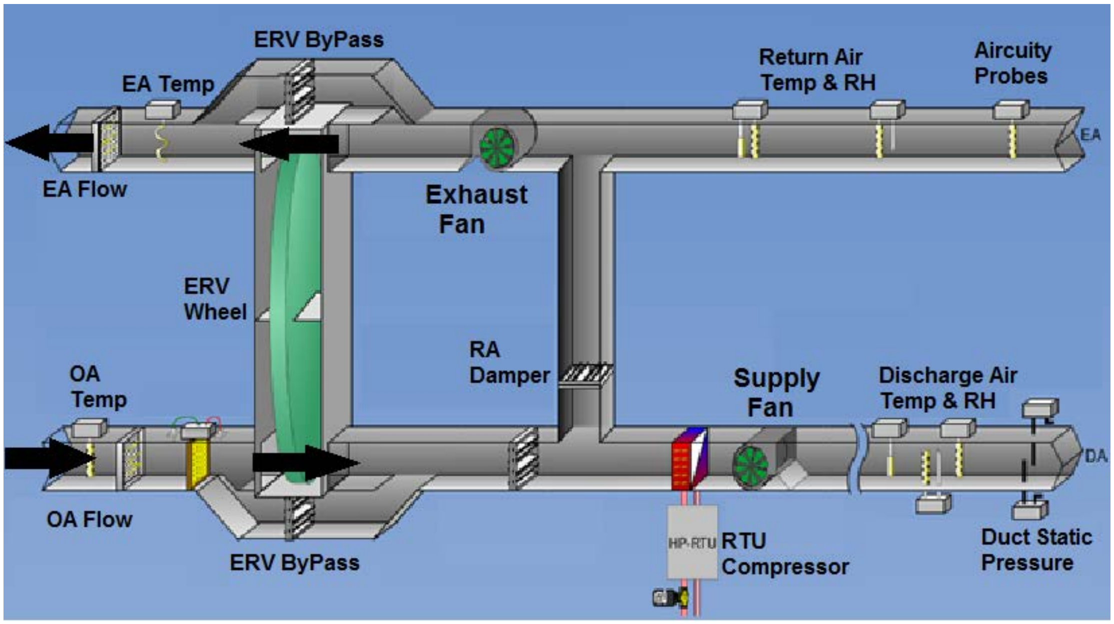


Figure 1.7: Screenshot of DOAS RTU and ERV Wheel Configuration

This outside air conditioned by the ERV wheel and the DOAS RTU compressors then travels through the building via the ductwork into all of the building's zones. Locally zoned heat pumps then have the ability to further condition the supply air to the specific zone's set point needs. The local heat pump and zone duct work typical configuration along with sensor placements and fan location can be viewed in Figure 1.8 below.

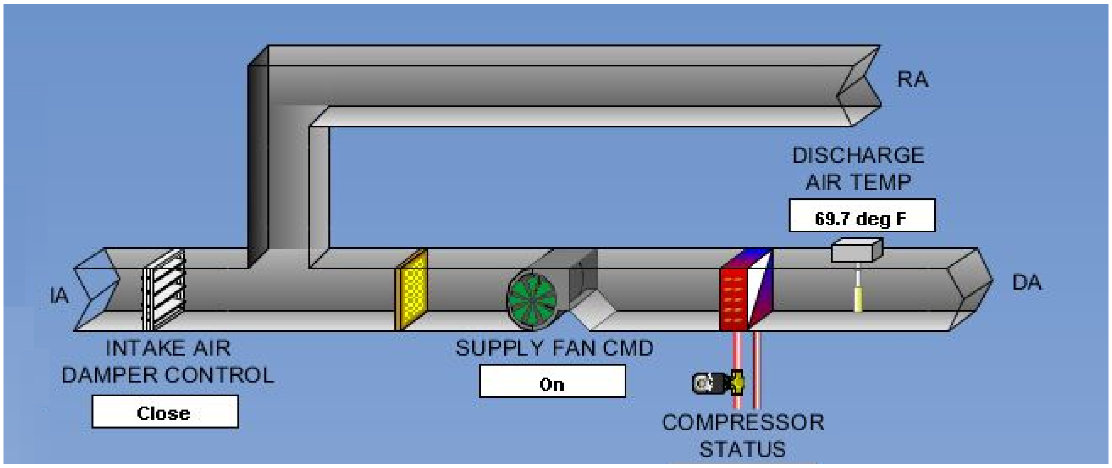


Figure 1.8: Screenshot of Zone Heat Pump and Duct Work Configuration

For this system, it was designed so that the dampers to each zone would close up air tight and only open when fresh air is requested via the CO_2 controlled DCV system. The overall flow of incoming supply air to the RTU is then to be controlled based on the needs of the buildings DCV scheme, which is controlled by an AIRCUITY system which monitors CO_2 levels in all of the zones. This will enable the DOAS RTU supply and exhaust fan to modulate its speed depending on the total building's cfm requirements.

For this LEED gold rated facility an eQUEST 3-64 proposed ESM was used to simulate the whole building and its wide range of HVAC technologies. eQUEST is a Department of Energy (DOE) sponsored tool with a simulation engine derived from the DOE-2 building energy use simulation program. Modelers are required to submit an EAc1 document to UMASS detailing the simulation data, assumptions, and results. The model's proposed energy consumption demonstrated a 45+% percent energy consumption improvement when compared to the baseline energy model prescribed by ASHRAE 90.1 Appendix G where savings were determined by:

$$\text{Energy Savings} = \begin{pmatrix} \text{Projected Baseline} \\ \text{Energy Use} \end{pmatrix} - \begin{pmatrix} \text{Proposed} \\ \text{Energy Use} \end{pmatrix} \qquad (1.3)$$

In order to achieve the maximum of 10 points in the EAc1 credit, the proposed ESM's consumption must have shown a 42% reduction in energy use when compared to the baseline ESM, which was achieved.

The figures below show the ESMs end use energy consumption breakdown month by month for the building's systems, with the building's total annual energy consumption (MWh) in the lower right hand corner; as provided by modelers in the EAc1 Form. Note that there was natural gas usage which will be ignored for the purposes of this analysis (it only serves the hot water heater which is energy star rated and no opportunities exist for energy opportunities). Figure 1.9 shows the baseline energy consumption (552,000 KWh) prescribed by ASHRAE 90.1 Appendix G (2004) and Figure 1.10 which shows the proposed energy consumption (301,000 KWh) determined by the energy modelers working with designers.

Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.10	0.12	0.30	0.98	4.51	7.13	10.61	9.96	5.55	1.67	0.43	0.14	41.52
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	17.59	15.96	12.50	6.89	2.80	0.53	0.40	0.56	1.07	3.96	9.15	15.71	87.13
HP Supp.	9.69	5.84	1.36	0.44	0.06	-	-	-	-	0.12	0.76	2.16	20.43
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	16.60	15.00	16.60	16.07	16.60	16.07	16.60	16.60	16.07	16.60	16.07	16.60	195.48
Pumps & Aux.	0.34	0.29	0.37	0.36	0.23	0.11	0.09	0.10	0.12	0.33	0.37	0.32	3.04
Ext. Usage	5.24	4.38	4.36	3.73	3.43	3.09	3.29	3.68	4.03	4.67	4.95	5.35	50.20
Misc. Equip.	3.85	3.48	3.85	3.98	3.99	3.68	4.00	3.99	3.68	4.00	3.52	3.85	45.85
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	9.13	8.26	9.14	9.51	9.52	8.72	9.53	9.52	8.72	9.53	8.30	9.13	108.99
Total	62.54	53.34	48.49	41.95	41.15	39.33	44.52	44.42	39.23	40.88	43.54	53.27	552.64

Figure 1.9: Baseline Energy Consumption Prescribed by Appendix G

Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.10	0.11	0.25	0.57	1.86	2.71	3.90	3.57	2.11	0.93	0.30	0.14	16.56
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	13.31	11.50	10.01	7.04	4.67	2.34	1.45	1.75	3.04	5.53	8.26	11.16	80.04
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	3.19	2.88	3.19	3.08	3.19	3.08	3.19	3.19	3.08	3.19	3.08	3.19	37.53
Pumps & Aux.	0.89	0.81	0.89	0.85	0.83	0.78	0.80	0.80	0.78	0.86	0.86	0.89	10.05
Ext. Usage	2.82	2.36	2.35	2.01	1.84	1.66	1.77	1.98	2.17	2.51	2.66	2.88	27.02
Misc. Equip.	3.85	3.48	3.85	3.98	3.99	3.68	4.00	3.99	3.68	4.00	3.52	3.85	45.85
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	7.10	6.41	7.07	7.33	7.32	6.72	7.32	7.33	6.73	7.37	6.47	7.12	84.28
Total	31.26	27.54	27.60	24.85	23.71	20.96	22.42	22.61	21.60	24.40	25.16	29.22	301.33

Figure 1.10: Proposed Energy Consumption Prescribed by Energy Modelers

After a couple months, data collection started on the police station and it's systems through the main electrical meter and the installed electrical submeters. The DOAS RTU and the GSHP loop pumps however are not fed to any of the submeters. Therefore additional independent data logging was implemented to determine their specific energy consumption. Before specific systems could be analyzed, it was quickly discovered through the main meter that the actual post-construction building energy performance was not going to satisfy the proposed energy simulation model (ESM) consumption and could possibly exceed it by >70%. A bottom up approach was then implemented and a comparison of the proposed ESM and actual data showed the largest variances existed in the HVAC systems and the plug loads. Further analysis indicated the building was not operating as designed/modeled and was later confirmed with independent metering of equipment through the use of data loggers. The table below shows the results of the initial post-construction measurements for the building's systems extrapolated to annual energy consumption and compared against the proposed energy model consumption predictions:

Table 1.1: Proposed Energy Consumption vs. Measured Post-Construction Energy Consumption

Building Loads	Energy Model Consumption (MWh)	Actual Measured Energy Consumption (MWh)	Percent Extra Energy Consumption
Lighting	111.3	98.2	-11.8%
Recepticle	45.8	93.7	104.6%
Space Heat/Cool	96.6	192.1	98.8%
Pumps/Fans	47.6	153.5	222.5%
Totals	301.3	537.5	78.4%

The M&V process was designed in order to verify proper operation of the building's systems; in this case benchmark against the proposed ESM and determine where opportunities exist to improve or correct their operations. A look at Figure 1.11 below shows where the Police Station initially stands when compared to other buildings going through the LEED M&V process.

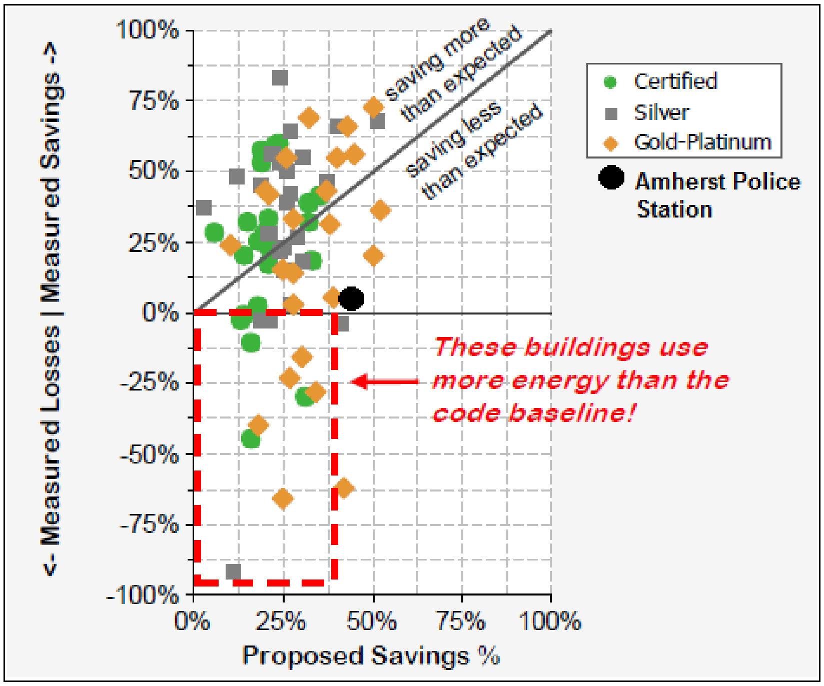


Figure 1.11: Measured vs. Proposed Savings Percentages for LEED Certified Buildings with Amherst Police Station Added

From the figure above, an assumption is made that there should exist opportunities to optimize the building's performance through the aid of the proposed energy model. By understanding how the proposed model simulated the building operation for its systems, an attempt at mirroring the model should accomplish the proposed annual energy consumption through the owner's basis of design (BOD).

In order to analyze the building's energy performance, the M&V Option D "calibrated simulation" from Figure 1.2 was chosen by the building authority to verify how well the building's systems were performing in relation to the proposed ESM data. Due to the facility being installed with a number of electrical submeters and other sensors relevant to the buildings energy consumption, Option D was determined to provide the most value for the building owner and operator. But is the proposed energy model that indicates a 45% reduction in energy consumption from the baseline model too aggressive for this application?

As part of the M&V plan, the main electrical meters along with the buildings installed electrical submeters were monitored and recorded on a monthly to weekly basis. This data was then analyzed to determine any correlation to the simulated energy model. The strategic submetering executed at this building was crucial to the success of the Option D M&V. The building's main meter data does not contain enough detail to separate out end users and successfully perform an M&V systematically from the bottom up. To complete the Option D M&V process, data from the building's meters and the BAS must be recorded, trended, and analyzed for the period of one year post-occupancy. The electrical submeters provide information and details as to how the building consumes energy and when; information obtained from the BAS trends are then analyzed to support the meter readings. A final requirement of the EAc5 M&V credit is to produce a calibrated ESM. The calibrated ESM will use the eQUEST's proposed ESM geometry and building system configuration. An additional requirement of the calibrated ESM will be utilizing actual measured weather data for that specific building location, actual observed operational schedules obtained from the BAS, and equipment loads for the first year of occupancy.

After the first year of post-construction occupancy and the completion of the Option D M&V data collection process, the retro-commissioning process will begin. Through a bottom up approach, modifications to the building’s systems will be implemented accordingly in an attempt to optimize their performance and try to attain the proposed ESMs predicted annual energy consumption, if possible.

1.6 Literature Review

HVAC is an important part of any building’s operation and is directly related to worker productivity and airborne illnesses[31]. As HVAC systems tend to become more efficient and complicated, the operational sequences of these newer technologies are still not fully perfected[32] and plenty of opportunity exists in improving their predicted and actual performance. Many recent publications point to issues such as improper construction, commissioning, sequencing, monitoring, and control in these systems which results in suboptimal energy performance.

This Thesis will discuss the benefits that resulted from going through the LEED process and specifically the Option D M&V process; particularly the value of installed electrical submeters, the BAS, simulated proposed energy model data, and the M&V plan. The proposed energy model along with its aggressive targets were instrumental to the M&V process along with the BAS trend data in determining the performance of all of the building’s HVAC systems. If energy models continue to be a standard and become more reliable, they can add value to buildings carrying out the M&V process by providing a simulated benchmarked energy performance as a guide.

The building considered didn’t perform as simulated, systems put in place through the LEED process helped identify the areas of deficiency and through the aid of the proposed energy model helped to correct them. The underperformance of LEED new construction buildings was realized in a recent publication by USA Today[8] which pointed to multiple LEED schools in the Houston Texas area that are underachieving when compared to expected energy performance predicted by their energy models. In fact LEED schools were being outperformed by other code construction schools; two ranked 155th and 205th out of 239 total schools in energy performance. Utilizing M&V data along with the expected building performance, areas of inefficient energy performance can be identified for those schools; and easily improved considering they are equipped with up to date controls and HVAC technologies.

Brodrick, Cooperman, and Dieckmann[3] show the relationship between energy consumption and electrical submetering in LEED buildings. From their research there exists opportunity in 95-99% of buildings with no current electrical submetering to reduce energy consumption simply by installing submeters and learning where, why, and how their building uses its energy. Along with a BAS, submetering can determine where the power is used and allows for collection of useful data to help understand where opportunities exist to reduce the building’s energy consumption[3]. This idea of electrical submetering on specific systems has been shown to help aid reduce energy use at various facilities and was instrumental for successful M&V process.

Plourde explains how the meters around the facility may not control operations but how they provide vital information and insight on how to maximize the equipment performance[16]. Meter information can allow operators to determine how their buildings use energy; and assess if it's efficient. Plourde also discusses the importance of why design engineers should explain to owners/operators why the BAS information is important and reasons for acting on the information. This will be required to get novice and unskilled building operators information and help them understand how their facility uses energy and possibly engage in continuous commissioning and initiate corrective actions to help reduce and optimize energy consumption for future operation.

Hermann[9] examined BASs and LEED credits to analyze how they directly affect each other. A BAS is not required by LEED but can be effective in gaining LEED M&V credits and benchmarking initial system performance allowing building operators to better maintain their systems. Also having installed electrical submeters directly fed into the BAS, building energy performance trend data can be easily stored in a historian and improvements can be measured year by year to determine energy performance and reduction. The BAS was crucial in determining where energy was being consumed for the building and where to start troubleshooting of the HVAC systems to increase overall efficiency. Through the BAS, any metrics deemed important to the monitoring of energy consumption in the facility can be easily stored and recorded on an hourly, daily, or weekly basis in the historian for future troubleshooting of inefficient systems.

Fisher[6] addresses energy modeling along with the methodology of predicting energy consumption based off $/cfm metrics and how it can lead to trouble. Detailed engineering can help the accuracy of the model but usually is only executed correctly when there is preexisting information about a similar facility from another calibrated simulation, hence benchmarking for modelers. If M&V data was circulated back up to the modelers, energy models may be more accurate and reliable as lessons are learned. Some engineers “casually” choose $/cfm numbers and results can propagate to inaccurate models. With the number of new technologies in place within new construction buildings, energy modelers have to tweak the model software, due to program limitations, to resemble systems such as the ERV. This leads to the model propagating errors within the simulation which leads to an inaccurate energy model target.

In some cases the model could be sound and excess energy use may lie with the construction and commissioning of the building’s systems. For instance, as Feigenbaum[7] showed, the effect leaky ducts can have on energy consumption can be disastrous and could be the result of inadequate commissioning. This can easily cause large discrepancies in predicted HVAC energy use compared to actual measured consumption, especially in DOAS applications. Proper commissioning of the building’s systems would identify areas of concern and assist to reduce issues that lead to inefficient operation.

Brodrick, Roth, and Westphalen[4] explore the impact of building commissioning on the energy performance of the building. The literature suggests that proper commissioning typically reduces annual energy consumption by 5-20% and poor commissioning can lead to inefficient operation. Mills[13] and Tseng[17] both concur spending extra money to hire a commissioning agent that is proficient at new building LEED construction and its systems should save considerable energy/funds in the future. All agree that in the future building commissioning needs to be more rigorous with details spent on energy consumption. The future energy savings experienced will eclipse the extra cost for proper commissioning.

If the building's design, model, and commissioning are all executed correctly and the building performs as designed, the M&V process plays a crucial role in benchmarking the efficient performance. Watson[19] and Chang[5] both agree energy performance benchmarking is crucial to the future of "Green" buildings. A majority of new construction buildings come standard with BAS's and some level of submetering. The information contained within the BAS can be instrumental in determining how efficient a building performs. Suggestions were made to create databases where building energy performance information is readily available. This will benefit the designers/modelers by providing actual data pertaining to a wide range of facilities. Then the introduction of a rating system where buildings with similar functionalities can compare consumption to one another can be implemented. This provides useful feedback to determine if opportunities exist to gain efficiency in specific areas (lighting, plug load, HVAC). Energy modeling in the future can benefit from the benchmarking of new construction systems by providing more accurate/realistic performance metrics about specific systems for modelers to use.

Turner and Frankel[18] examined energy performance of LEED new construction buildings and reported that the M&V process had little impact on the performance of the building. LEED is criticized for not designing the credit in a way that provides useful and usable ongoing data to benchmark the buildings performance. M&V data collection, protocol, and analysis is a large expense and does not provide useful feedback on how to correct or maintain performance. The term benchmark is continuously brought up and needs to be addressed and implemented in order to move forward and help industry learn from the past.

Finally Morrison, Azerbegi, and Walker[14] go into lengths about the benefit of energy models to the M&V process if models are reliable and supported by actual performance data; either from measurement or pre-existing information about similar systems. They point out more feedback is needed about actual building performance and that information shared with the energy modelers will benefit future simulations. They then explain how proper energy models can influence a successful M&V by utilizing the model as a benchmarked performance to compare to, if the model is accurate.

Therefore, calibrating the police station's proposed energy model with actual weather and operational schedule data achieved from the post-construction M&V phase, we expect to see a more accurate model that reflects the measured consumption of the building in its first year of occupancy. If the energy model still doesn't reflect the actual performance of the building, then there could be issues with the modelers' assumptions or the modeling software and how it combines these HVAC systems together for its calculations.

Determining where the variance in actual energy performance originate from will explain if unexpected performance is a result of flawed designs, inept construction or commissioning, improper modeling, or a combination of the above. Further analysis of the many systems in the building will determine if the proposed simulated energy model created through the LEED process is attainable and realistic after achieving the 10 LEED points for a 45% energy reduction. The energy model will be used as a goal for the energy performance of the building and its systems throughout the M&V and retro-commissioning process.

1.7 Objective of Research

The objective of this research is to explore the utility of the EAc1 proposed ESM data and how it can be successfully implemented with the Option D LEED M&V data to provide useful information to building operators. By successfully comparing the data on a component level, retro-commissioning of the underperforming building will be completed in an attempt to try and achieve the predicted energy performance of the proposed ESM. The police station's post-construction measured energy consumption, was benchmarked against the proposed ESM, and showed a large discrepancy. It would benefit industry to take a look and explore the steps that can be taken before, during, and after the M&V process to help building operators and owners understand where and how their building fell short through means of the proposed ESM. Offered in this paper is a protocol on how to optimize the building's underperforming systems through a bottom up approach in an attempt to achieve the proposed eQUEST ESM energy consumption targets.

A retro-commissioning of the building was performed after the first year of occupancy (M&V period) through the guidance of the proposed ESM to determine the models validity. The priority of retro-commissioning tasks will be based on the magnitude of deviation between the measured and proposed ESM consumptions and ease of implementation. A simple Pareto analysis will be utilized to determine which energy efficiency measures (EEMs) should be implemented and in what order during the retro-commissioning. The Pareto Analysis will use specific criteria to weigh the pros of implementing different EEMs to optimized time and resources to successfully retro-commission the building.

The first objective is to identify the variances that exist between the proposed energy model and the building's measured energy consumption. All systems will be analyzed through the building's installed electrical metering, BAS trend data, along with the energy model predictions; and determine urgency for corrective action. With the variety of newer HVAC technologies in the building there was concern about the design intent of these systems, understanding of how they would interact with one another, their sequence of operations, and ultimately how the energy model simulated them.

At the end of the M&V and start of the retro-commissioning process the energy consumption of the building will be drastically reduced when compared to its "out of the box" performance with modifications to still be implemented; but a question remains: Was the simulated energy model too aggressive and was the aggressive energy target achievable? A further look into the LEED process will show flaws in the M&V process; such as no incentives or funds allocated for optimization of the building systems sequences to improve and correct energy efficiency after deficiencies are found. And what levels of expertise are required to optimize the building's up to date systems.

Steps will be taken to simulate the building's actual measured energy consumption through the proposed energy model; utilizing actual measured performance data for each system. This will serve as the Option D M&V "calibrated" energy model. The calibrated model will provide an understanding for why the actual building failed to deliver in terms of energy consumption. It will also question whether the proposed ESM was too aggressive of a design making the energy target unattainable. This information can then be formulated to create a protocol to determine where resources should be spent when this situation occurs again. Through benchmarking the M&V results against the proposed energy model data, existing energy opportunities can be identified and then implemented.

Typically in the past, buildings are analyzed through a top down approach. This looks at the building's overall actual energy consumption compared to an expected total energy consumption that has been previously calculated. Discussed here will be an approach to a bottom up building analysis through the various installed systems with in the building, e.g. the BAS and electrical submeters. This process will allow identification of specific building systems that are out of balance, in terms of energy consumption, quickly and effectively. This will help provide building operators with a systematic approach to correcting potential underperforming building equipped with these systems. The bottom up approach will also provide better benchmarking data and building performance metrics that will aid in future ESM calibrations and database information to help improve industry as a whole.

Lastly will be to offer suggestions for an improved building system that can monitor energy use through the BAS allowing the building operator to monitor and sustain the minimum energy requirement for proper operation. Discussed will be how the data collected through the ESM, the BAS, and the M&V process can be implemented to assist building operators in the future monitor their operations with minimal effort. Allowing building operators to handle all the other issues that come along with supervising a facility.

CHAPTER 2

ENERGY SIMULATION MODEL (ESM): BUILDING SYSTEMS PREDICTED ENERGY PERFORMANCE

2.1 ESM Design Wizard Menus

After initial data collection during the measurement and verification (M&V) process, it was clear the building was to exceed the eQUEST proposed energy simulation model (ESM) targets. The International Performance Measurement and Verification Protocol (IPMVP) Option D process requires a year’s worth of post-occupancy energy data be collected to determine the actual operation of the building. Therefore while measurements and readings were taken early on through the building’s main electrical meters, time was allocated to dissecting the energy simulation model (ESM). This was performed to understand how the proposed ESM simulated the building operations to then compare to the actual building operation.

The eQUEST energy model takes into account information about the building operation to predict energy performance. This includes building geometry, construction materials, building equipment (lighting, plug loads, HVAC), and outside weather patterns (wind speed, solar irradiation, temperature). The ESM requires a variety of inputs about the facility’s building construction and equipment to perform a detailed hourly energy consumption simulation. The ESM analysis requires inputs for all of systems within the building which is achieved through the ESM’s design wizard. Each system in the design wizard has its own independent graphical user interface as shown below in Figure 2.1. A brief description of each toolbar option is provided.

Figure 2.1: eQUEST 3-64 Graphical Interface Screenshot

- **Project and Site** - Building description, Location, Occupancy
- **Building Shell** - Wall and Roof Construction, Windows, Shading
- **Internal Loads** - Lighting, Plug Loads, Equipment Schedules
- **Water-Side HVAC** - GSHP/Pumps/Hot Water Heater Details
- **Air-Side HVAC** - Fan/Heat Pump/Zone Conditions
- **Utility & Economics** - Electric and Fuel Rate Structures

The building's overall energy consumption is calculated with the inputs provided to the design wizard interface within the model. Inputs about the building's systems are dependent upon all of the other wizard's parameters. For example, the building materials specified within the building shell interface will affect how well the building retains heating and cooling loads and can affect the water and air side HVAC. The internal equipment loads and their power draws will dictate how much heat is given off by the operating equipment resulting in less heating in the winter with more cooling in the summer.

The eQUEST toolbar and wizard allows users to address issues related to specific areas in the building through drop down navigation panes. Each parameter can be accessed either through a graphical interface or a spreadsheet layout. The graphical interface allows users to visualize the actual system while providing inputs to the system. There is also a spreadsheet option which allows modelers to view equipment specifications for multiple systems at once, if not all. Within the spreadsheet inputs such as the zones power densities (W/ft^2, W/cfm) or operation schedules can be viewed. Input values within the spreadsheets are denoted with different color types to identify where the value originated from and how it is interacts with the simulation. Some values are prescribed through eQUEST library drop down menus, while others are default values selected during the design phase. Other different color inputs may indicate that there is a linked value, where changing that input will directly affect other parameters within the simulation.

2.2 ESM End Use Energy Types

The eQUEST ESM provides detailed reports that can include up to 13 different end use energy types(depending on the buildings systems). These end use energy consumption types include lighting, fans, pumps, and other systems as seen in the left hand column of the eQUEST ESM output in Figure 2.2.

Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.10	0.11	0.25	0.57	1.86	2.71	3.90	3.57	2.11	0.93	0.30	0.14	16.56
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	13.31	11.50	10.01	7.04	4.67	2.34	1.45	1.75	3.04	5.53	8.26	11.16	80.04
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	3.19	2.88	3.19	3.08	3.19	3.08	3.19	3.19	3.08	3.19	3.08	3.19	37.53
Pumps & Aux.	0.89	0.81	0.89	0.85	0.83	0.78	0.80	0.80	0.78	0.86	0.86	0.89	10.05
Ext. Usage	2.82	2.36	2.35	2.01	1.84	1.66	1.77	1.98	2.17	2.51	2.66	2.88	27.02
Misc. Equip.	3.85	3.48	3.85	3.98	3.99	3.68	4.00	3.99	3.68	4.00	3.52	3.85	45.85
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	7.10	6.41	7.07	7.33	7.32	6.72	7.32	7.33	6.73	7.37	6.47	7.12	84.28
Total	31.26	27.54	27.60	24.85	23.71	20.96	22.42	22.61	21.60	24.40	25.16	29.22	301.33

Figure 2.2: eQUEST 3-64 Output – Energy Consumption by Operation

Although each category has its own function, the change in operation of one can directly affect the performance of another. For example, if lighting is increased, the cooling load would increase to account for the rise in sensible heat given off by the lights and in turn also reduce the space heating requirement for the same reason.

The model has the ability to produce hourly reports on the operation of the HVAC systems and other various zone conditions (temperature set points, air flow to spaces, etc.). The eQUEST's DOE-2 engine simulates the building's equipment and zones on an hour-by-hour basis utilizing weather data, occupancy and equipment schedules, pump and fan load curves, and lighting and plug load density. Most inputs to the model are in relation to a power density, where a metric such as a watt per square foot (W/ft^2) or a watt per cubic feet per minute (W/cfm) is used by the software to calculate energy consumption for varying auxiliary equipment and HVAC system loads respectively. For example, a zone will have a specified airflow in terms of cfm, the W/cfm power density would then indicate how much power is required to provide that air to the space.

2.3 ESM Loads and Schedules

The power density inputs are constant values which rely upon the ESM occupancy and equipment scheduling to determine times of turndown and part load operation. These schedules are based upon fraction input values on an hourly basis. These fractions and the power densities are multiplied hour by hour to run the simulation. The scheduling for the police station considered two cases; a 24 hour operation and a 9 a.m. to 5 p.m. operation. Figure 2.3 shows an example of the eQUEST occupancy(top) and equipment(bottom) schedule screens for the 9am to 5pm weekday operation scheduled zones (observe the projected nighttime turndown between 6:00 P.M. and 8:00 A.M.).

Currently Active Day Schedule: 9-5 Bldg Occup WD

Type: Fraction

Day Schedule Name: 9-5 Bldg Occup WD

Type: Fraction

Hourly Values

Mdnt - 1:	0.0000	ratio	8-9 am:	0.6495	ratio	4-5 pm:	0.6760	ratio
1-2 am:	0.0000	ratio	9-10 am:	0.8717	ratio	5-6 pm:	0.3482	ratio
2-3 am:	0.0000	ratio	10-11 am:	0.8576	ratio	6-7 pm:	0.1486	ratio
3-4 am:	0.0000	ratio	11-noon:	0.6313	ratio	7-8 pm:	0.1025	ratio
4-5 am:	0.0000	ratio	noon-1:	0.5747	ratio	8-9 pm:	0.0990	ratio
5-6 am:	0.0018	ratio	1-2 pm:	0.8434	ratio	9-10 pm:	0.0902	ratio
6-7 am:	0.0284	ratio	2-3 pm:	0.9000	ratio	10-11 pm:	0.0407	ratio
7-8 am:	0.1997	ratio	3-4 pm:	0.8717	ratio	11-Mdnt:	0.0053	ratio

Currently Active Day Schedule: EL3 Bldg InsLt WD

Type: Fraction

Day Schedule Name: EL3 Bldg InsLt WD

Type: Fraction

Hourly Values

Mdnt - 1:	0.0500	ratio	8-9 am:	0.7454	ratio	4-5 pm:	0.7727	ratio
1-2 am:	0.0500	ratio	9-10 am:	0.8854	ratio	5-6 pm:	0.5308	ratio
2-3 am:	0.0500	ratio	10-11 am:	0.9000	ratio	6-7 pm:	0.3465	ratio
3-4 am:	0.0500	ratio	11-noon:	0.9000	ratio	7-8 pm:	0.2792	ratio
4-5 am:	0.0500	ratio	noon-1:	0.9000	ratio	8-9 pm:	0.1638	ratio
5-6 am:	0.0544	ratio	1-2 pm:	0.9000	ratio	9-10 pm:	0.1034	ratio
6-7 am:	0.1117	ratio	2-3 pm:	0.9000	ratio	10-11 pm:	0.0709	ratio
7-8 am:	0.3597	ratio	3-4 pm:	0.8854	ratio	11-Mdnt:	0.0527	ratio

Figure 2.3: eQUEST 3-64 Occupancy and Equipment Schedule Screen Snapshot

These schedules indicate that the model should reflect a decrease in energy consumption during the nighttime and on the weekend (weekend schedule not shown). Below Figure 2.4 is a graph acquired from the eQUEST's hourly report results, showing the building's equipment (miscellaneous equipment) and total end use (whole building) energy consumption obtained from the main electrical meter for a period of one week.

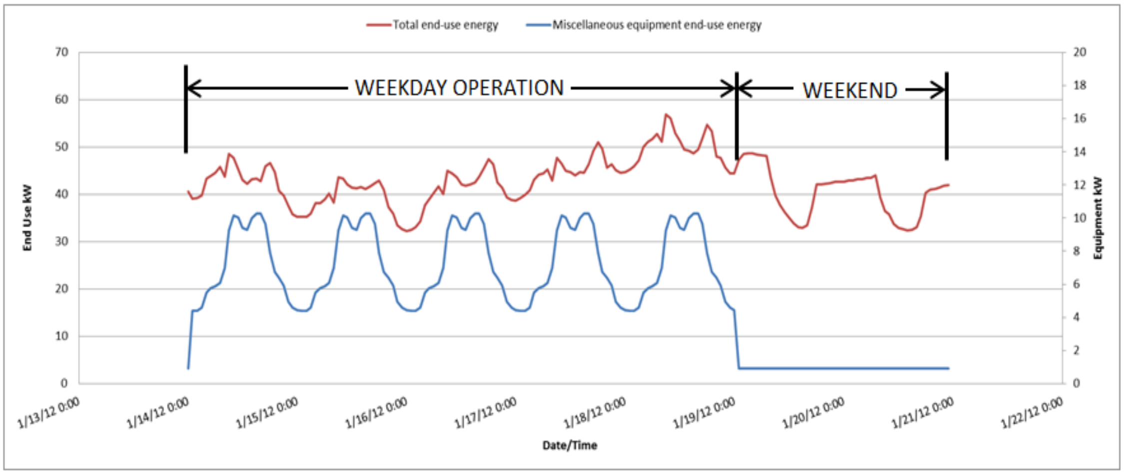


Figure 2.4: eQUEST Total Building Energy + Plug Load Consumption (1 Week)

From Figure 2.4, it is observed that the model assumes a consistent reduction of energy use during the night times and especially on weekends. Readings from the building's actual main electrical meter however indicated little to no change during the nighttime and on the weekends. Figure 2.5 below shows the eQUEST total end use hourly building energy consumption compared to the buildings main electrical meter post-occupancy readings for the first month of operation.

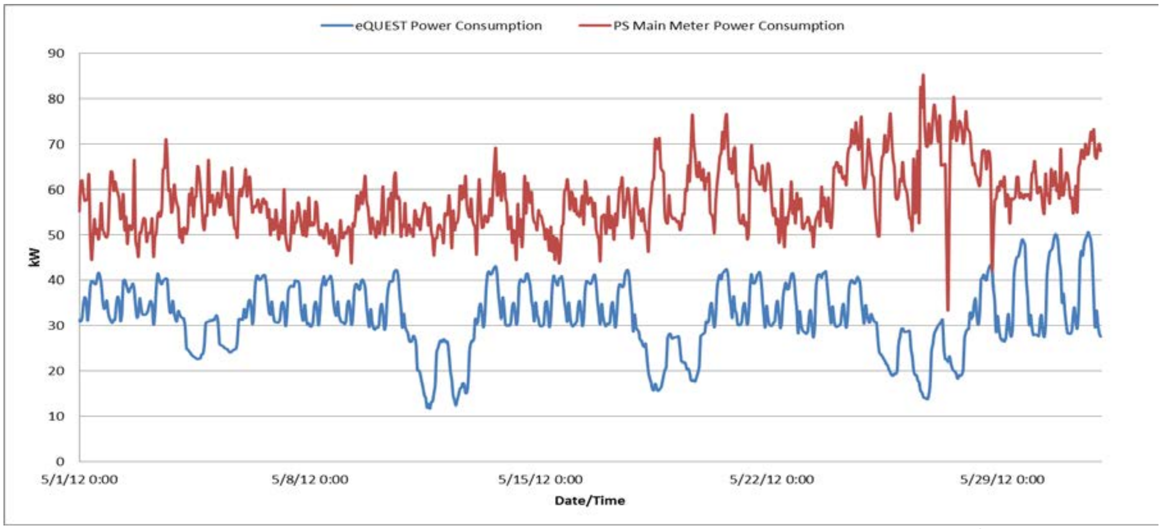


Figure 2.5: ESM Proposed Energy verse Actual Main Meter for 1st Month

From the figure above it is clear that the building's actual energy consumption exceeds the models proposed energy consumption. There is no noticeable change during the nighttime and on the weekends as the proposed ESM predicted. Therefore the eQUEST models proposed occupancy and equipment scheduling were not reflected in the actual operation and occupancy of the building. The lack of turndown during the nighttime and weekends could be a result of unaccounted occupancy within the building or the results of optimistic equipment schedules (where equipment is not cycling off as expected in the building). It was later determined through the building BAS that there was occupancy during the nighttime and weekend that was not reflected in the ESM.

Focus was directed to the eQUEST proposed ESM outputs (Figure 2.2) to see how the building's actual energy consumption would measure up, by end users. This will indicate where attention should be focused within the building and for the calibrated model. Considering that this particular eQUEST simulation output can be broken down into 6 categories (combining space cool and heat together) provides more resolution to the energy consumption problem. By configuring the electrical submeter data into several categories (space conditioning, ventilation/fan energy, pump energy, outside lighting, plug loads, and interior lighting); comparisons of actual measured data and the proposed ESM assumed operation will provide more insight into the building's operation.

CHAPTER 3

M&V MEASUREMENT PROCESS – COLLECTING DATA

3.1 Approach of M&V Data Collection

M&V data collection for this particular LEED building started immediately after occupancy of the facility in mid-2011. The building's electrical submeters along with the Building Automation System (BAS) provided plenty of data and details into building performance. The electrical submeters were not directly fed into the BAS, therefore data was collected on a bi-weekly to monthly basis. Initially in an attempt to benchmark the building systems energy performance, the proposed ESM was determined to provide the reasonable estimation for the targeted energy consumption. The proposed ESM was constructed for this particular building and its systems. Therefore the proposed ESM should aid in determining if the building was operating as designed and whether it achieved estimated reductions in energy consumption. Energy savings should have been realized during unoccupied times as all of the building's equipment can operate efficiently at part load operation. As shown previously in Figure 2.5, from the beginning issues were observed through the main meters which indicated the building's energy consumption was higher than forecasted.

A typical approach to determine whether a building's energy performance is as designed is through the top down approach. A top down approach involves an analysis of the building's total energy consumption (either through the main meter or energy bills) similar to Figure 2.5 and then compare it against some previously determined benchmark. For this particular facility the benchmark was the proposed ESM handed down by the design team and modelers. After one year of data collection, it was obvious from the top down approach that the building’s performance was not as predicted. This can be seen in the first year energy consumption of the building in Figure 3.1. The building’s actual energy performance showed significant deviations when compared to the proposed ESM. The initial measurements taken during the first month continued to propagate which indicates that the building was not going to correct its inefficient performance on its own, it would most likely continue to get worse.

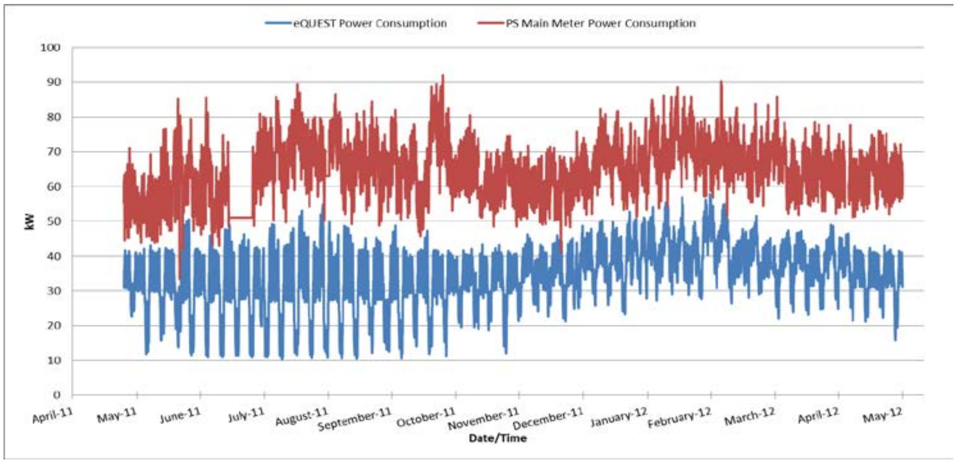


Figure 3.1: ESM Proposed Energy verse Actual Main Electric Meter for 1st Year

Top down approaches are effective for determining a building’s energy performance, but if issues exist it leaves many questions to be answered. The top down approach does not indicate what specific system or systems within the building are responsible for the deviations. There are no indications whether it is the lighting systems or if issues lie with the HVAC operations (comprised of fans, pumps, and compressors). A bottom up approach is required so building operators can get an indication from their measurement and verification (M&V) results where specific issues within the building’s subsystems may lie. A bottom up approach takes on the building’s systems in a component wise or subsystem level and finds faults which are specific to the individual operations of the facility. This eliminates guess work experienced during a top down approach. For a top down approach to be done successfully, consultants would need to come in and take various measurements to find the genesis of deviations. This is costly for the building owner, especially for a facility where funds have already been allocated to the LEED certification process. If a bottom up analysis is appropriate, resulting from installed electrical submeters and a BAS, actions can be taken early to optimize energy consumption. BAS systems along with electrical submeters are becoming common in new construction LEED facilities which make this approach more feasible for the future. This will enable any building operator to perform an energy analysis quickly and easily on their own; eliminating guesswork and the costs associated with outside consultants.

The need to be able to compare the M&V data to the proposed ESM data on a comparative basis is critical to understanding how the building is currently performing; this can potentially benefit industry as a whole in the future. Figure 2.2 (Section 2.1) shows how the proposed ESM model given to owners was broken down into building end use energy type categories. If M&V results are sorted and configured in a manner to allow direct comparisons to the ESM outputs, valuable information can be obtained early. For this particular building this approach was taken. Figure 3.2 demonstrates how the facility was able to take advantage of the installed electrical submeter configuration and the proposed ESM output categories. Both sets of data (M&V and ESM) were grouped into similar energy categories that coincide with similar equipment within the building. The particular energy category grouping in Figure 3.2 is specific for this building and can be implemented in other buildings on a case by case basis. Not all facilities have their electrical submeters configured in this fashion; the configuration of submeters should be handled on an individual basis. Figure 3.2 shows how the ESMs and submeter outputs were broken down into four specific categories that allow for the ESM and submeters to compare data directly. This will provide a bottom up comparison for the data that anyone can understand.

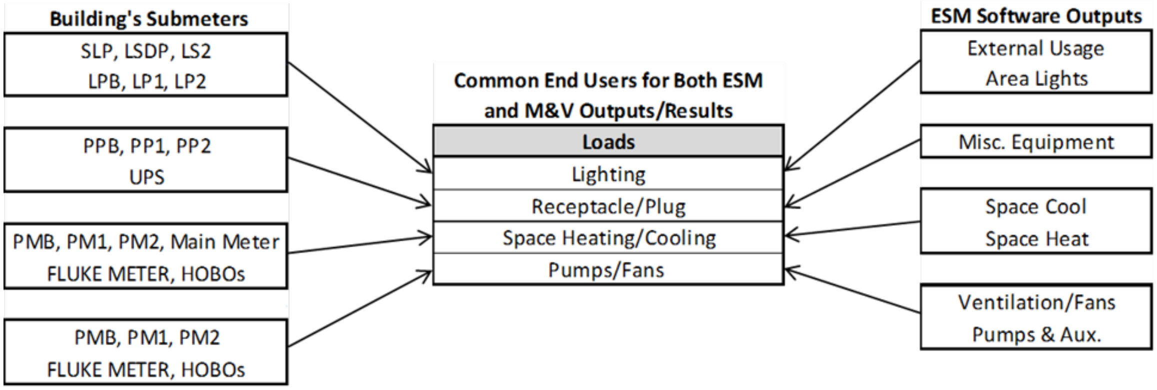


Figure 3.2: Shows how M&V data obtained from electrical submeters can be directly compared to the ESM outputs

Originally the building's electrical submeter and BAS data could not be compared with the ESM outputs. Some minor independent measurements were required in order to compare the data through similar metrics. For example, the DOAS RTU equipment was not metered and was one of the only pieces of equipment not on any of the electrical submeters. Therefore some extra work was essential to determine its specific energy consumption. The summation of all of the building submeters had to be subtracted from the main meter to indicate the performance of the DOAS RTU as seen in Equation (3.1).

$$\text{RTU}_{\text{Power Consumption}} = \text{Main Meter}_{\text{Power Reading}} - \sum\left(\text{Submeter}_{\text{Power Reading}}\right)_{13\text{ submeters}} \quad (3.1)$$

After the first month, the proposed ESM outputs and M&V data were broken down into the subsystems (loads) prescribed by Figure 3.2. The graphical data was revealing to which systems were contributing to the building's excess energy consumption. This shows that the bottom up analysis provides more insight and perspective as to how the building's systems were failing in terms of energy performance.

If the building operator was presented with this type of information early, faults could be detected and addressed in a timely fashion. Some faults if caught early enough could potentially be the responsibility of the commissioning authority (CA). This means the CA could still be responsible for troubleshooting and fixing deficiencies; reducing further costs for the building owner. Figure 3.3 shows the same data, for the first two months, as was shown in Figure 2.5 (Section 2). Now the data has been broken down into the buildings subsystem as prescribed by Figure 3.2 along with calculated percent deviations.

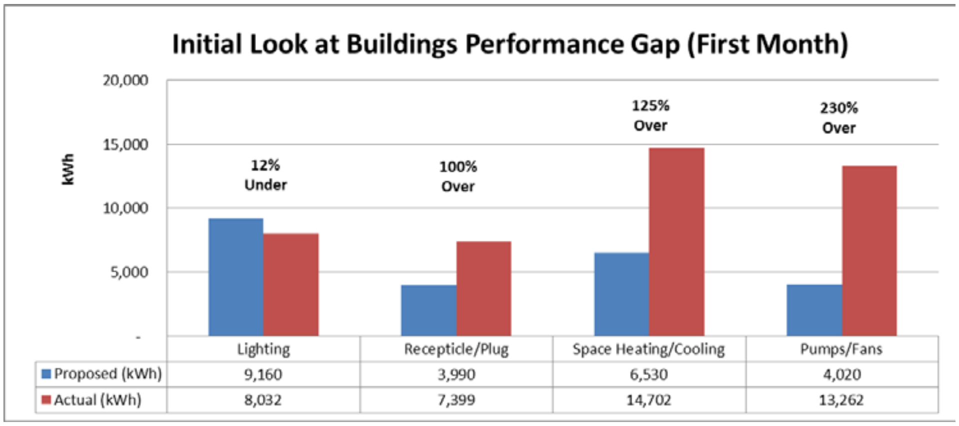


Figure 3.3: Shows Proposed ESM verse M&V Energy consumption Results for the First Month as Prescribed by Figure 3.2

Specific areas that resulted in excess energy consumption within the building can be observed. It is quickly determined that the lighting systems are actually performing better than had been predicted; therefore no time should be allocated to these systems by the building operator. Unfortunately this is not true for the rest of the building’s systems. The building’s plug load is double what was expected. The IPMVP Option D states modelers are not responsible for the determination of plug load energy as the actions of the building occupants who contribute to this load are a large variable. Therefore, time will not be spent on the plug loads for this exercise. The largest deviation is with the building’s fan/pump systems and the HVAC compressors which contribute to the building’s space condition requirements for the zones. The result, the HVAC systems need to be carefully inspected through a bottom up approach.

3.2 Fan and Pump Energy

The fan and pump energy was shown to exceed the predicted energy consumption by over 200% (Figure 3.3). From the proposed ESM and the initial M&V data, specific pieces of fan and pump equipment within the building need to be identified to determine which of the two systems is contributing more to the constant excess energy consumption. Due to the building size it only operates a few pumps. Three (three) hp pumps run continuously at part load with a power draw that was calculated to not be a significant portion of the fan/pump energy. This drove a process of breaking down the fan/pump end use energy category into two subsections; one for fans and one for pumps. Fans were considered the top priority due to their installed capacity, large power draw, and operation time (when compared to the pumps).

3.3 Fan Energy

The ventilation and fan energy is comprised of several different units within the building which include the DOAS RTU and 41 locally zoned heat pumps (HPs). The DOAS RTU contains one 10 hp supply fan and one 7.5 hp exhaust fan which both run continuously throughout the year to provide minimum air requirement to the building spaces. The 41 heat pumps (HPs) each have one fan ranging in sizes from 0.1-0.5 hp, depending on the size of the respective HP. The main source of fan power draw is the DOAS RTU supply and exhaust fans. They run continuously to circulate outside air through the building to satisfy the building zone loads. A look into the proposed ESMs hourly report data indicated that the model assumed a constant part-load power draw for the RTU supply and exhaust fan for the entire year; nighttime and weekends. The EAc1 form (Appendix A) submitted to the building owners by the modeling firm indicated in the narrative that the program was not able to model the variable frequency drive (VFD) operation on the RTU fans. Therefore, an average operating part-load was calculated for the proposed ESM through VFD fan power curves. An assumption was made about the annual average power draw of the fans to account for the varying loads it would encounter. The software then modeled a constant volume fan for the simulation at a constant part load operation.

After determining how the ESM simulated the DOAS RTU supply and exhaust fan power; the BAS was used to investigate the RTU's operation to try and locate the root of the inefficient operation. The electrical submeters do not include the RTU so its consumption was determined through Equation (3.1) (Section 3.1). Due to the data only providing the DOAS RTUs total energy, independent measurements were taken using a FLUKE 41B Power Analyzer to single out the fans power draw. A Fluke 41B reads the three phase current, voltage, and power factor to calculate an equipment's instantaneous power draw. The Fluke 41b along with HOBOware data loggers were able to collect data which will be used to calculate the DOAS RTUs power draw and energy performance. The data loggers only have the ability to capture the equipment's current draw, thus the need to use it with the Fluke together (to obtain correct power factor and voltage). Both pieces of equipment can be viewed in Figure 3.4.

Figure 3.4: Images of the Fluke 41B and HOBOWare Data Logger used for Independent Measurements

To determine the power draw of just the RTU supply and exhaust fans, the Fluke meter was placed directly on the main feed to the DOAS RTU. The DOAS RTU electrical panel only serves the DOAS RTU which is comprised of the supply and exhaust fan as well as the unit’s two scroll compressors. The two scroll compressors operate a refrigeration cycle to condition (heat or cool) incoming air. The unit also supplies the ERV wheel which operates a 0.1 hp motor considered negligible to the overall building energy consumption.

$$\mathrm{RTU}_{\text{Total Power}} = \mathrm{RTU}_{\text{Fan Power (Supply and Exhaust)}} + \mathrm{RTU}_{\text{Compressor Power(x2)}} + \mathrm{ERV}_{\text{wheel}} \quad (3.2)$$

The BAS was instrumental in determining the DOAS RTU fan power by utilizing an ability to remotely lock out the compressor operation. This allowed only the fans to run (the ERV wheel’s tenth hp motor power consumption is considered negligible). Figure 3.5 below shows the results for one week where the RTU compressors are allowed to run a few days before they were locked out to determine the fans power draw.

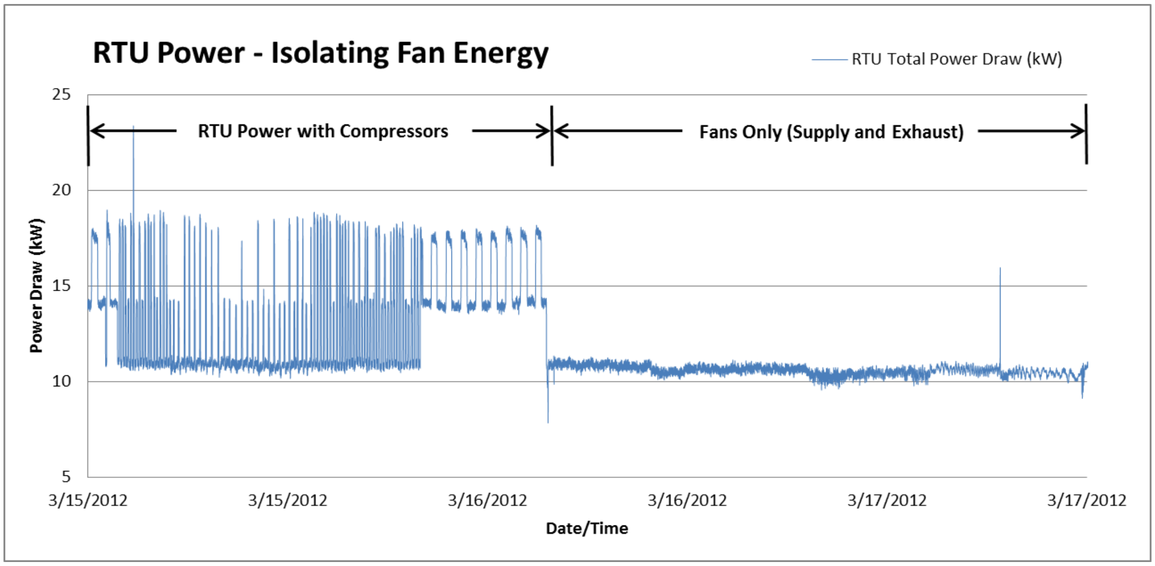


Figure 3.5: RTU Energy Profile With and Without Compressors

Below Table 3.1 shows the proposed ESMs assumed DOAS RTU fan power consumption obtained from the software's hourly reports compared to measurements. The power draw data was extrapolated to determine the annual energy consumption and calculated excess annual energy consumption. Note, the power consumption for the supply and exhaust fan was averaged over a time period larger than what is shown in Figure 3.5, thus the discrepancy between the figure and table values.

Table 3.1: RTU Supply and Exhaust Fan Power and Energy Consumption

RTU LOAD	Average Power	Annual Energy (Extrapolated)
eQUEST Model	4.2 kW	36,792 kWh
Fluke Measurement	9.9 kW	86,724 kWh
Variance	5.7 kW	49,932 kWh

This indicates that there could either be an issue with the ESMs assumed fan power consumption or with the building's post-construction operation. The fact that the RTU energy is over double of what was proposed by the model shows there is a need to address this piece of equipment.

Investigating the other contributors of fan energy in the building is next. All 41 local heat pumps are equipped with their own supply air fan as shown in Figure 1.7

(Section 1.3). After analyzing each of the building's zone operations through the BAS it was observed that all of the local heat pump fans run continuously all year long to circulate air. The proposed ESM inputs were analyzed and indicated an anticipated reduction in HP fan energy when zones were unoccupied, which was not observed. According to the manufacturer, the heat pump fans have two settings; **ON**: run continuously at all times, or **AUTO**: only run when the heat pump compressor is operating. Continuous heat pump fan operation is not part of the BOD and was not assumed by the proposed ESM. The heat pumps model, size, quantity, fan load, run hours and auto-operation run hours can be observed in Table 3.2 below.

Table 3.2: Building Heat Pump Fan Information

Heat Pump(HP) Model	Size of HP (Tons)	Number of Units	Fan Size (hp)	Current Operation (Runtime Hours)	Auto Operation (Runtime Hours)
RSH 007	0.5	9	0.10	78,840	7,455
RSH012	1	9	0.10	78,840	16,871
RSH018	1.5	10	0.17	87,600	19,374
RSH024	2	10	0.25	87,600	13,138
RSH036	3	3	0.50	26,280	3,947
TOTALS	-	41	-	359,160	60,785

Table 3.2 indicates the number of hours that all of the different HP fan types are currently running (Current Hours of Runtime) as compared with the runtime hours obtained for the HP compressor operations, which would indicate the AUTO operational hours. It is observed that there are a significant number of hours that the heat pump fans would not be running had they been programmed to the auto mode. This is a major source of energy consumption adding to the building's inefficient operation. Calculations for the actual HP fans energy consumption can be seen in Table 3.3. Also calculated was the energy consumption assumed if the HP fans ran only when the compressors were

running, showing a significant decrease in energy consumption if this control was adopted.

Table 3.3: Building Heat Pump Fan Analysis

Heat Pump(HP) Model	Size of HP (Tons)	Number of Units	Fan Size (hp)	Current Operation (Runtime Hours)	Auto Operation (Runtime Hours)	Current Operation Consumption (kWh)	Auto Operation Consumption (kWh)
RSH 007	0.5	9	0.10	78,840	7,455	4,705	445
RSH012	1	9	0.10	78,840	16,871	4,705	1,007
RSH018	1.5	10	0.17	87,600	19,374	8,888	1,966
RSH024	2	10	0.25	87,600	13,138	13,070	1,960
RSH036	3	3	0.50	26,280	3,947	7,842	1,178
TOTALS	-	41	-	359,160	60,785	39,210	6,555

Therefore the fan data collected during the M&V indicates opportunities exist in the HP fan operation as well. For the building retro-commissioning and calibration of the ESM discussed later, adjustments to the HP fan operation will need to be addressed.

3.4 Pump Energy

To determine the building's actual pumping energy as compared to the proposed ESM data, the BAS was utilized. The building's pumps are limited to a few different systems; one is the GSHP primary-secondary loop that provides water flow to the RTU and local heat pumps, another is the radiation hot water pumps that provide baseboard water heating in the winter. The four GSHP primary-secondary loop pumps are all equivalent size while the radiation hot water (HW) pumps are of a smaller size. The energy consumption for the pumps was calculated utilizing the BAS trend information along with some independent submetering. Note that the HW baseboard pumps only run to serve spaces when temperature is below 65°F.

The GSHP primary-secondary loop data obtained through the BAS provides details on how the pumps are currently operating. The GSHP fluid is the main driver for the HVAC technologies where the entering water temperature (EWT) to the DOAS RTU and heat pumps dictates the performance of the equipment. Below, Figure 3.6 shows a BAS screenshot of the GSHP primary-secondary loop schematic and locations of the various sensors for which data will be trended and analyzed to determine system performance.

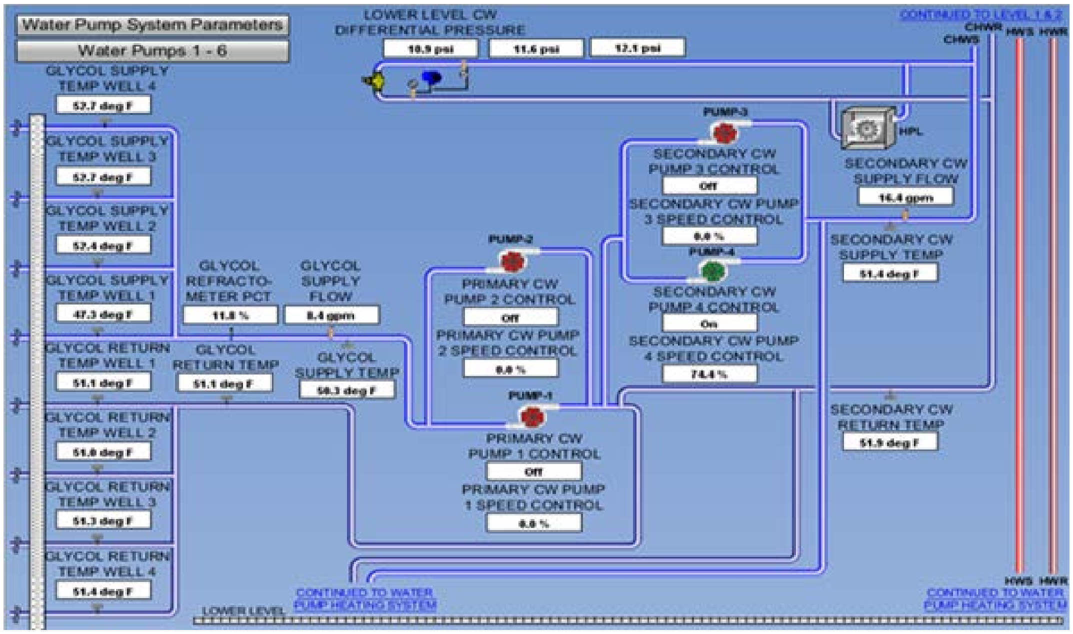


Figure 3.6: Primary-Secondary Loop BAS Screenshot

As shown in Figure 3.6 there are two pumps (P-1 & P-2) on the primary loop and two pumps (P-3 & P-4) on the secondary loop. All four pumps are Bell and Gossett 2-1/2x2-1/2x7 models drawing three hp each providing one hundred twenty gallons per minute at forty feet of head. First task was to analyze and determine the speed and load at which the GSHP primary-secondary loops operate. This will give an indication as to how much power the pumps draw and their energy consumption over the year; it will also provide insight to their sequence of operation. Table 3.4 below shows the results of the data analysis on the GSHP primary-secondary pumps through the BAS.

Table 3.4: GSHP Primary-Secondary Pumps Operation

Percentage of Time Pumps Spend at Each Speed Interval				
% Speed	P-1	P-2	P-3	P-4
100%	16.9%	17.6%	1.1%	1.1%
90-99%	1.0%	1.2%	6.8%	6.6%
80-89%	0.5%	0.6%	40.2%	39.3%
70-79%	0.6%	0.6%	51.4%	51.2%
60-69%	1.0%	0.7%	0.2%	0.2%
50-59%	2.5%	1.1%	-	-
40-49%	2.4%	2.3%	-	-
30-39%	5.1%	5.0%	-	-
20-29%	9.7%	8.1%	-	-
0%	60.3%	62.9%	0.4%	1.7%
Totals	100.0%	100.0%	100.0%	100.0%

From Table 3.4, P-1 and P-2 (primary loop) appear to be off a majority of the time, resulting in the primary loop pumps not running for part of the year. While P-3 and P-4 (secondary loop) run between 70-89% of their rated maximum speed throughout the whole year to help provide zone conditioning. This is due to the building's constant HVAC load. The secondary loop is allowed to run independently of the primary loop taking advantage of zones conditions that require cooling while others simultaneously require heating; known as "balanced" loads within the building or California heat pump design. The sequence allows the secondary pump loop to float between design temperatures of 40-75°F and the primary pumps only to run when the secondary loops EWT is outside that range. This results in the primary pumps P-1 and P-2 to be off 23% of the time during the year and their tendency to ramp up to 100% speed when called to operate.

Due to the GSHP loop pumps not being on the installed submeters, a Fluke 41b and a HOBOWare data logger were employed to determine the power draw and later the energy consumption on the GSHP pump P-4. Due to the pumps sequence of operation they run in parallel at all times at a matched speed, therefore Pump P-3 is assumed to consume the same power as P-4 at all times. Figure 3.7 below shows a power versus speed curve for the P-4 and P-3 pumps along with a curve fit equation used to calculate the pumps annual energy draw through use of the BASs pump speed trends.

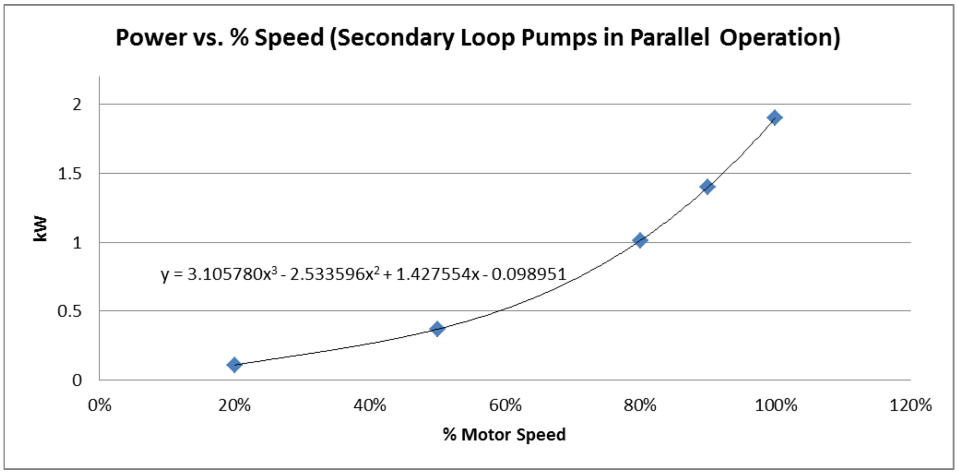


Figure 3.7: GSHP P-4 and P-3 Power Consumption versus Speed

From Figure 3.7 and Table 3.4, the annual energy consumption for the secondary loop pumps can be calculated using the 3rd order polynomial fit calculated for the data set. Below Table 3.5 shows the results for pumps P-3 and P-4 annual energy consumption.

Table 3.5: GSHP Secondary Pumps P-3 & P-4 Annual Energy Consumption

Percentage of Time Pumps Spend at Each Speed Interval			Power Calculations (kWh)	
% Speed	P-3	P-4	P-3	P-4
100%	1.1%	1.1%	186	177
90-99%	6.8%	6.6%	964	939
80-89%	40.2%	39.3%	4,115	4,024
70-79%	51.4%	51.2%	3,726	3,716
60-69%	0.2%	0.2%	8	9
50-59%	-	-	0	0
40-49%	-	-	0	0
30-39%	-	-	0	0
20-29%	-	-	0	0
0%	0.4%	1.7%	0	0
Totals	100.0%	100.0%	8,999	8,865
	TOTALS		**17,864 kWh**	

The proposed ESM (Figure 2.2) predicted the total annual pump energy to be 10,500 kWh. When compared to just the GSHP secondary loop pumps, it is clear the total pump energy will exceed the proposed ESM pumping energy. To calculate the actual total pump energy, the GSHP primary pumps and hot water baseboard pump energy consumption will be considered. Another issue found in the pumping system, not explained in the basis of design (BOD), was the operation for pumps P-3 and P-4 which ran in parallel at matched speeds. This operation will be investigated later during the retro-commissioning process.

The building GSHP loop primary pumps (P1 & P2) were also analyzed to determine how much energy they consumed over the year. Through the BAS, the operation for the primary pumps was obtained. The data was collected and trended in a spreadsheet in order to determine their operation. It was observed that both pumps did run throughout the year, but never at the same time. Below Table 3.6 shows the annual run hours for each of the primary loop pumps along with a summation of their total run time as a percentage of the entire year. Notice that even though each pump may be off for almost 60% of the year, the primary loop pumps water 77% of the year.

Table 3.6: GSHP Primary Pumps P-1 & P-2 Annual Run Operation

	Speed Range and Percent Operation the Primary Pumps Run (Annually)												
Pump	**0%**	**1-9%**	**10-19%**	**20-29%**	**30-39%**	**40-49%**	**50-59%**	**60-69%**	**70-79%**	**80-89%**	**90-99%**	**100%**	**Totals**
Primary Pump (P1)	60%	0.1%	0.1%	9.7%	5.1%	2.4%	2.5%	1.0%	0.6%	0.5%	1.0%	16.9%	100.0%
Primary Pump (P2)	63%	0%	0.1%	8.1%	5.0%	2.3%	1.1%	0.7%	0.6%	0.6%	1.2%	17.6%	100.0%
Overall Operation	22.8%	0.2%	0.2%	17.8%	10.1%	4.7%	3.6%	1.7%	1.1%	1.0%	2.2%	34.5%	100.0%

To determine the power consumption for the primary pumps at each of their respective operating speeds, the pump affinity laws were implemented. Figure 3.8 graphs the relationship between pump motor power consumption as a function of its speed. The pump affinity laws state that the power draw for a pump motor is directly proportional to the cube of the pump speed. Therefore if the pump speed is reduced to 50% of its maximum speed, its power will be reduced to 12.5% of its rated input power. This reduction in power must also consider the loss in efficiency experienced through the variable frequency drive (VFD) on the motor. This relationship is shown in Figure 3.8. The efficiency curves for VFDs are determined by the manufacturers through laboratory tests and the graph shown was obtained from the Department of Energy (DOE) Motor Tip Sheet #11(2008).

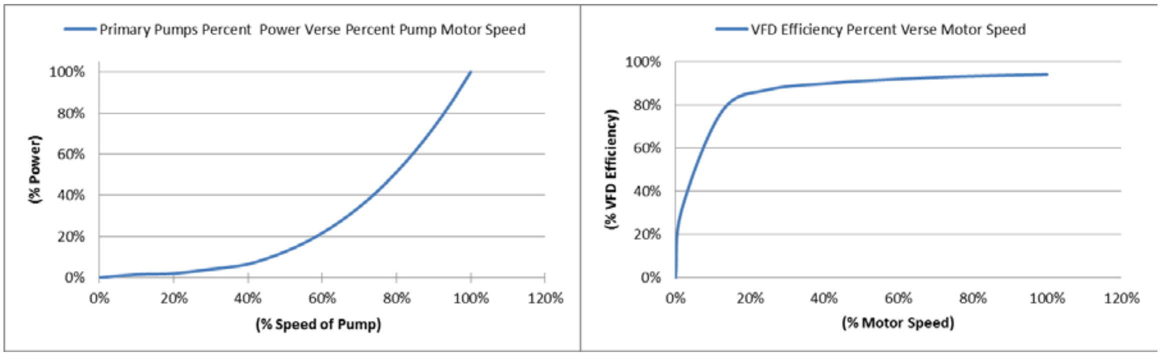


Figure 3.8: GSHP P1-2 Motor Efficiency and VFD Efficiency Curves

With these curves and information obtained from the BAS, the power and overall energy consumption for the primary loops can be determined as shown in Table 3.7.

Table 3.7: GSHP Primary Pumps P-1 & P-2 Annual Energy Consumption

Pump Speed	% Time at Speed	% of Rated Motor Power	VFD Efficiency	Pump Power (kW)	Pump Energy (kWh)
100%	34.5%	100%	94%	2.38	7,193
90-99%	2.2%	73%	94%	1.74	335
80-89%	1.0%	51%	93%	1.23	110
70-79%	1.1%	34%	93%	0.82	82
60-69%	1.7%	22%	92%	0.54	80
50-59%	3.6%	13%	90%	0.32	102
40-49%	4.7%	6%	90%	0.15	62
30-39%	10.1%	5%	88%	0.13	112
20-29%	17.8%	4%	87%	0.10	161
10-19%	0.2%	2%	79%	0.06	1
1-9%	0.2%	2%	20%	0.17	3
0%	22.8%	0%	0%	0.00	0
Totals	100.0%	-	-	-	8,240

This methodology was used to determine the energy consumption of the baseboard water heater pumps (P5 & P6). These pumps were also shown to not run simultaneously. These pumps are smaller than the primary-secondary loop pumps and are only rated for 0.5 hp each. The VFD's used for the HW baseboard pump system is assumed to operate with the same efficiencies as shown in Figure 3.8. Small motors tend to have similar VFD efficiency performance curves and are an adequate estimation for calculating actual energy consumption. Table 3.8 shows the results for the baseboard water heating pumps run times and energy calculations.

Table 3.8: Baseboard Heater Pumps P-5 & P-6 Annual Energy Consumption

Speed Range of the Baseboard Heater Pumps with Energy Calculations (Annually 8,760 Hours)

Pump Speed	% Time at Speed	% of Rated Motor Power	VFD Efficiency	Pump Power (kW)	Pump Energy (kWh)
100%	24.5%	100%	94%	0.40	852
90-99%	15.4%	73%	94%	0.29	391
80-89%	11.2%	51%	93%	0.20	201
70-79%	2.7%	34%	93%	0.14	33
60-69%	0.0%	22%	92%	0.09	0
50-59%	0.0%	13%	90%	0.05	0
40-49%	0.1%	6%	90%	0.02	-
30-39%	0.1%	5%	88%	0.02	-
20-29%	0.1%	5%	86%	0.02	-
10-19%	0.0%	0%	79%	0.00	-
1-9%	0.0%	0%	20%	0.00	-
0%	45.9%	0%	0%	0.00	-
Totals	100%	-	-	-	**1,476**

3.5 Space Heating and Cooling Energy

A majority of the space cooling and heating energy use was obtained from the electrical submeters which monitored the building's 41 heat pumps (HPs) on a floor by floor basis. A total of three electrical submeters measured all of the building HP energy. Due to the submeter configuration also containing the HPs fan energy, some independent calculations were made. The only energy associated with the heat pumps that did not relate to the heating and cooling load were the heat pump fans discussed in Section 3.2. The summation of all HP fan energy consumption calculated in Table 3.3 was then subtracted from the building's electrical submeters for the HPs. This task was simplified as the fans were found to run 24/7 all year round at a constant speed (due to no variation in the DOAS RTU fan control).

The other source of heating/cooling energy is contributed by the RTU compressors which are used to pre-condition the incoming supply air before it is sent downstream to the local heat pump units. The DOAS RTU energy was determined by subtracting the summation of all of the electrical sub meters from the main meter as shown earlier in Equation (3.1). The RTU compressor energy was then calculated from the RTU energy along with the data collected from independent metering of the DOAS RTU. To single out the RTU compressor energy from the total energy measured on the DOAS RTU, as shown in Figure 3.5, subtracted the fan load from the overall energy consumption of the DOAS RTU will result in the RTU compressor energy. Notice, independent metering of one piece of equipment resulted in energy consumption data for two types of systems, compressors and fans. Figure 3.9 shows the method by which the DOAS RTU compressor energy consumption is determined. By integrating the fan energy consumption and subtracting from the integral of the overall DOAS RTU energy consumption, the specific energy required by the RTU compressors can be determined explicitly.

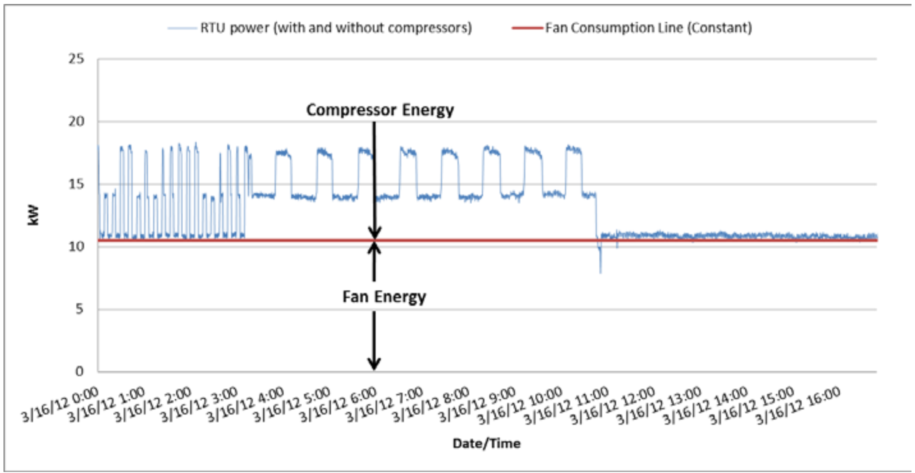


Figure 3.9: Method of Determining DOAS RTU Compressor Energy

Therefore the energy consumption for all of the building’s compressors can be found in Table 3.9 below.

Table 3.9: Calculated Building Overall Compressor Energy

Equipment	Annual Energy Consumption (Electrical Submeter Reading) (kWh)	Calculated Fan Energy (kWh)	Annual Compressor Energy (heat/cool) (kWh)
DOAS RTU	177,646	86,724	90,922
HPs (41)	140,372	39,210	101,162
Totals	318,018	125,934	192,084

3.6 Lighting and Plug Load Energy

The M&V process for the lighting and plug load energy consumption is a straight forward process. Figure 3.2 shows that there were electrical submeters specifically installed to measure the building’s lighting and plug load. Unlike the previous sections, there was no need for independent metering of any equipment to single out the energy consumption for these two end users. Obtaining the data associated with the annual energy consumption was easily identified directly from the electrical submeter readings. This was convenient and demonstrates how effective a bottom up approach could be to the M&V process if proper meters are in place. If buildings in the future were mandated to include this form of electrical submetering, there could be valuable information obtained early on by the building operator which would expedite the M&V and the retro-commissioning process. Resulting in a wider range of energy efficient and properly maintained buildings.

Issues with excessive plug load consumption at the facility were also found. This is not considered a result of an improper energy model as any deviations in the actual energy consumption is deemed a result of the occupants of the building; a variable that is not easily modeled. As the energy consumption shows such a significant deviation, the building operator could potentially make occupants aware of the habits that they have developed and explain the significance it has on the overall building energy footprint. These deviations could arise from building occupants having mini refrigerators, unit heaters at their desks, not turning off equipment when not in the office and other various circumstances.

3.7 M&V Findings and Results

The initial top down analysis indicated that large discrepancies existed in what the designers and modelers anticipated verses the actual energy consumption of the LEED building. Due to the systems installed, the M&V process was expedited due to the electrical submeters and the BAS. By proceeding with a bottom up approach to the M&V process, deficiencies were found on an equipment level relatively early and allowed for a more accurate representation of how the building was actually performing. As the early analysis predicted, the fan energy displayed the greatest discrepancy and issues were immediately located within the DOAS RTU and the local heat pump fans operation. When compared to that of the proposed ESMs predicted operations, an actual number was able to be placed on the underperforming systems giving building operators a target to try and achieve in terms of energy consumption and management. Therefore the ESM outputs and M&V data provide valuable information for analyzing building system performance.

Further investigation of the proposed ESM indicated that issues weren’t just associated with power consumption of pumps and fans, but instead the operations and control sequences for the systems. For example, the ESM demonstrated no consideration in the model for the heat pump fan energy that was shown to run continuous all year. The

HP COP also didn’t include the fan energy which would have only accounted for HP fan energy used when the compressors are on. Calculations shown in Table 3.3 determine the variance between the “on” and “auto” annual run hours and energy consumption respectively. There is opportunity to minimize and sustain the building energy consumption in the future with this data. This provides a value for the proposed ESM and M&V data for the building operator to use in the future, which has been considered a flaw by some in the LEED process.

Additional issues with the GSHP secondary loop pumps were observed. The two pumps on the secondary loop ran continuously all year long in parallel operation. The design documents did not specify any additional flow needs that would require both pumps to operate in parallel at all times. Further analysis of these pumps will be performed later on in the Thesis to determine whether or not the opportunity exists to run just one of the pumps. This would result in another energy efficiency measure (EEM) that could be simply executed by the building operator through the BAS.

Determination of the plug loads and lighting energy consumption proved to be the simplest part of the M&V process as they were both individually submetered. Electrical submeters were configured to capture only their respective profiles on a floor by floor basis. If other systems in the building were metered in this fashion, M&V process could be performed possibly in house simply and effectively by building operators to optimize the building performance. In the future if mandates or regulations placed on newer buildings to include this form of electric submetering, building owners and operators would benefit financially from the energy savings and the ease of monitoring the systems. If owners requested regulations on submetering in buildings it will lead to better benchmarking and analysis and could benefit the industry as a whole; while keeping a tight grasp on the nation’s energy footprint. Once all the building data is clearly understood, automated procedures can then be explored to set off alarms when variances exist to assist with managing energy use.

After the first year of post-construction occupancy within the building, final readings were taken off of the electrical meters. Figure 3.10 shows the annual totals for the actual building energy consumption as broken down into lighting, plug load, space conditioning, and fan/pump energy compared to the proposed ESM. Building performance deficiencies by system are easily recognizable. Figure 3.10 also includes a graphical representation of the monthly consumption for each system which shows that these issues existed from the start of post-occupancy and could have been identified very early on if needed.

Figure 3.10: First Year Post-Occupancy Data – Annual and Monthly

Table 3.10 below is an even more in depth look at how the building's systems had performed. Two more categories were added to the previous model where the fan and pump energy have been separated along with interior and exterior lighting. This was achieved due to the independent metering performed on those systems.

Table 3.10: ESM verse Actual Energy Consumption by Energy Type

eQUEST OUTPUT ENERGY TYPES	eQUEST PROPOSED CONSUMPTION (MWh)	ACTUAL MEASURED CONSUMPTION (MWh)	Percent Extra Energy Consumption
Space Heat/Cool	96.6	192.1	99.8%
Vent. Fans	37.53	125.9	238.4%
Pumps & Aux.	10.05	27.6	156.7%
Ext Usage (lights)	27.02	21.3	-21.2%
Misc. Equipment	45.85	93.7	104.4%
Area lights	84.28	76.9	-8.8%
Totals	301.33	537.5	78.4%

Although it still singles out the fan and pump energies as the most critical to the building over consumption. A value has been place on each of these systems, which gives a better indication of how the building was performing. For example, from the analysis of splitting the building into just four subsets, the fan/pumping energy could have been the greatest variance while the pumping system could have been performing optimally resulting in the excess fan energy to dominate the analysis. As you continue to break down the model, information associated with smaller subsystems will provide more value and better energy metrics which reflect the building’s operation.

CHAPTER 4

M&V OPTION D – CALIBRATED ENERGY MODEL

4.1 IPMVP Option D Requirements

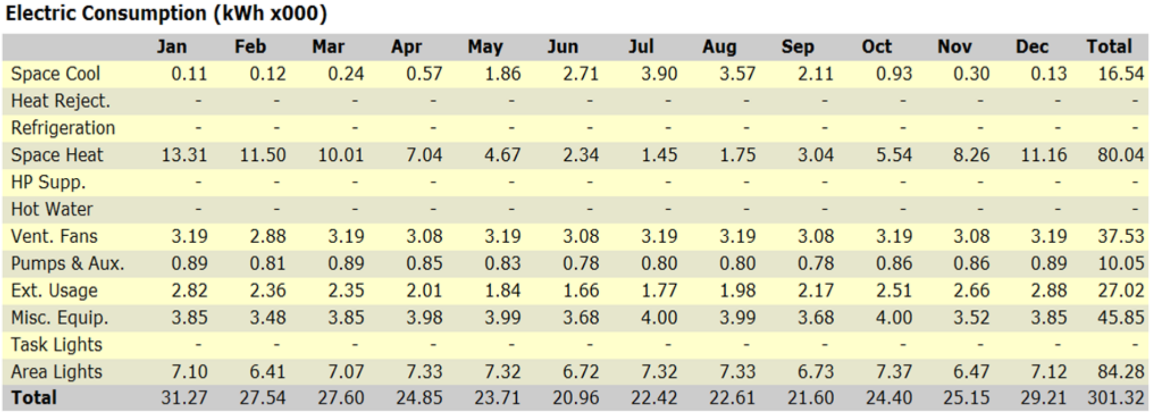
The International Performance Measurement and Verification Protocol (IPMVP) Option D, chosen for this facility, requires a computer simulation of the whole building energy use. The Post-Occupancy energy use is to be determined and validated through utility and/or electrical submetering. The process for this particular building involved calibration of the original proposed ESM with on-site measured results to demonstrate the authentic operation of the building. The IPMVP Option D M&V plan, chosen by the building's owner, was facilitated due to the extensive amount of electrical submetering along with the BAS trend data. The standard states that the use of electrical submetering and post-occupancy energy is invaluable to the calibration process, which is demonstrated at this site. This exercise is important to help understand what is required to bridge the gap between predicted verse actual energy consumption, and how to make ESM more reliable in the future[23].

Performing a bottom up analysis, the calibration of the ESM is straight forward and the steps will be discussed here in Section 4. A bottom up analysis of the building on a subsystem level provides detailed information on how to troubleshoot issues during the retro-commission process, while providing valuable data for the calibration of the ESM. The calibration will be performed by benchmarking specific actual end-use energy operations and determine how they relate to the ESM's energy performance. This process will also help to find faults or deviations quickly and effectively[27]. The overall process will translate into a building that is smarter, optimized, and consumes minimal energy.

Option D standard states that some energy consumption variances are more significant than others. It may not be practical to correct a number of deviations due to constraints in the ESM software being used. For this ESM those issues were realized in the modeling of the DOAS RTU ERV wheel. The ESM models a large RTU along with a make-up air unit (MAU) to simulate the ERV system. The model assumes there is a boiler providing “free energy” to mimic the effects of the ERV wheel on the incoming make-up air in the winter. Option D states that calibration investigations may uncover under-performance of as-built building equipment or systems which was the case here. These deficiencies will be included in the calibration model to account for actual operation. The standard also notes that some deviations between the as-built building and (baseline) proposed ESM (in terms of physical configuration, systems, and other key features) may dictate how many “as built” adjustments are applicable to the proposed ESM. In extreme cases where the model and actual building operations are completely dissimilar, the calibration may have little to no value beyond providing quality control check for the as-built model.

During the calibration of the ESM, an effort to reflect the as-built building’s post-occupancy energy consumption, concerns associated with modeling of the proposed ESM were uncovered. The issues stem from the modelers assumption that the buildings 40+ zones could be modeled with just 17 zones while capturing a majority of the building’s equipment and systems. Due to the extensive electrical submetering and independent measurements taken within the building, the calibrated ESM will depict the actual building operation.

Figure 4.1 shows the original proposed ESM predicted outputs handed down by the original modelers.



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.11	0.12	0.24	0.57	1.86	2.71	3.90	3.57	2.11	0.93	0.30	0.13	16.54
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	13.31	11.50	10.01	7.04	4.67	2.34	1.45	1.75	3.04	5.54	8.26	11.16	80.04
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	3.19	2.88	3.19	3.08	3.19	3.08	3.19	3.19	3.08	3.19	3.08	3.19	37.53
Pumps & Aux.	0.89	0.81	0.89	0.85	0.83	0.78	0.80	0.80	0.78	0.86	0.86	0.89	10.05
Ext. Usage	2.82	2.36	2.35	2.01	1.84	1.66	1.77	1.98	2.17	2.51	2.66	2.88	27.02
Misc. Equip.	3.85	3.48	3.85	3.98	3.99	3.68	4.00	3.99	3.68	4.00	3.52	3.85	45.85
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	7.10	6.41	7.07	7.33	7.32	6.72	7.32	7.33	6.73	7.37	6.47	7.12	84.28
Total	31.27	27.54	27.60	24.85	23.71	20.96	22.42	22.61	21.60	24.40	25.15	29.21	301.32

Figure 4.1: Original Proposed ESM

In order to avoid creating a new model (which is not required through the Option D standard), the building zones, construction materials, and system performance curves were not modified. This would require a more in depth study into the actual building construction and was out of the scope of this Thesis. The justification for not modifying the performance curves within the ESM was the model typically showed no turndown in system operations throughout the year. This indicates that the performance curves were not the initial source of error during the hourly simulations but may need to be investigated further at a later time.

4.2 Weather File Data

To perform the IPMVP Option D M&V protocol and calibrate the ESM, an actual measured weather data file for the building location is required. Performing the Option D M&V process was determined early in the building’s design process, therefore a weather station was installed at the facility. Data obtained from the weather station was fed directly into the BAS. The collected data at the weather station included outside dry-bulb air temperature, pressure, humidity, wind speed and direction, and the geographical solar irradiation. The ESM utilizes all of these data points when calculating the effects of weather on the annual energy performance.

The calibrated ESM requires the actual weather data collected from the building. The data has to be formatted in order for the eQUEST software to utilize it. In order to perform this task the DOE Weather Converter software tool was utilized along with the actual measured weather data collected. The weather data was recorded by the BAS in 15 minute intervals. The data was then placed in spreadsheet form to be converted to hourly average trends for capability with the DOE Weather Converter. Once in a spreadsheet, the data was run through a software program to create a tab comma delimited (CSV) file. This CSV file can then be read by the DOE Weather Converter which generates a weather bin file for the eQUEST's software. The eQUEST software was then programmed to use the weather file generated for that specific building locations actual measured weather. The first step to calibrating the ESMs actual energy consumption.

The weather calibration resulted in an ESM that consumed less energy than previously had been predicted. The reason being the variances in the actual weather forecasts for that year. The overall cooling energy increased due to some heat waves experienced during summer months, while an unseasonably warm winter reduced the overall heating energy consumption. These conditions can be observed in Figure 4.2 where the actual measured daily average outside dry bulb air temperature has been graphed for the entire year against that of the daily average TMY2 weather data. Note that the dry bulb temperature is not the only parameter that affects the ESM simulation, the wet bulb temperature is also a key factor in how HVAC systems perform and is not shown here.

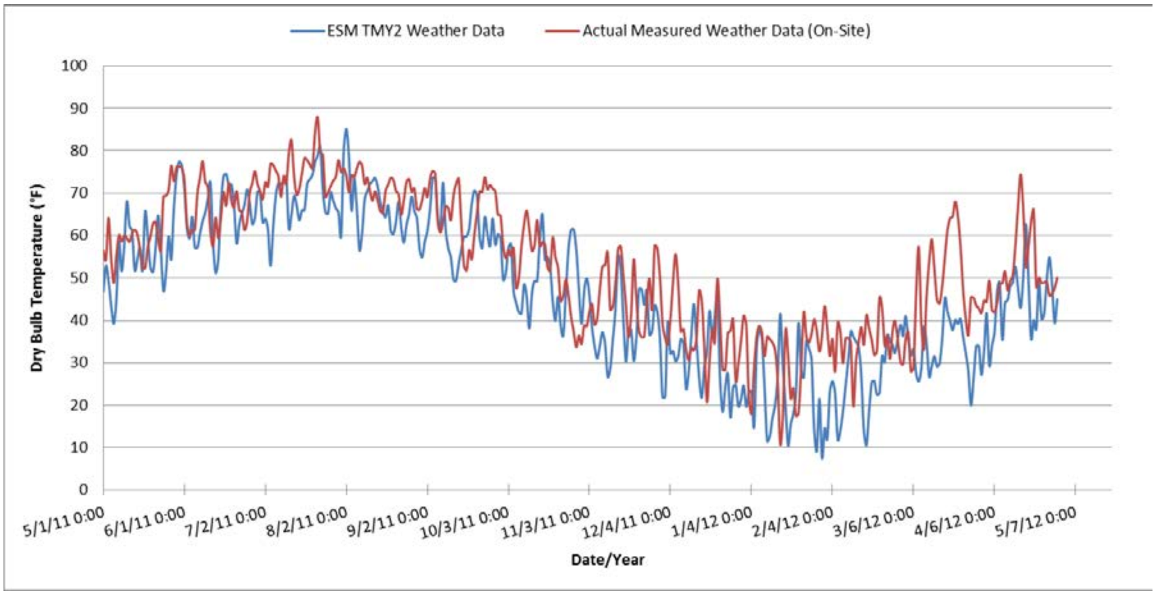
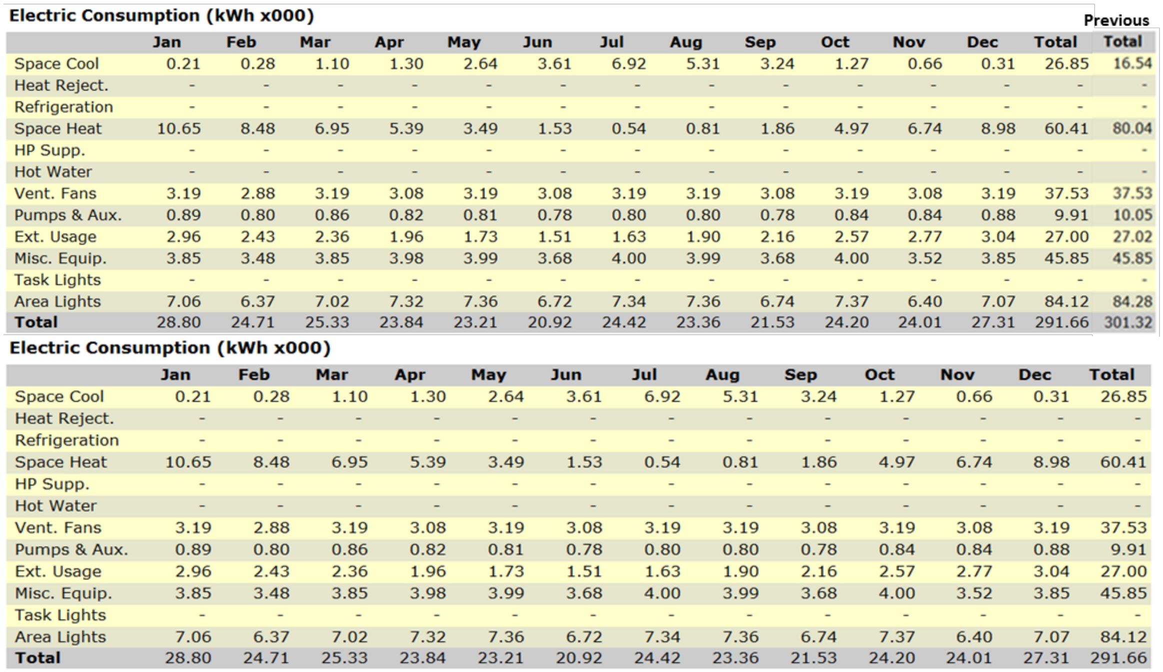


Figure 4.2: Comparison of Proposed ESM TYM2 Weather Data and Actual Measured Weather Data for Calibration Model

It can be observed that during the summer months (June – August) that the loads were comparable but during the winter months (November – February) the actual outside dry bulb temperature was warmer than the TMY average. Figure 4.3 shows the effects of the weather on the proposed ESM model, with the former being the proposed ESM predictions while the latter is the calibrated ESM corrected for weather.



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Previous Total
Space Cool	0.21	0.28	1.10	1.30	2.64	3.61	6.92	5.31	3.24	1.27	0.66	0.31	26.85	16.54
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	10.65	8.48	6.95	5.39	3.49	1.53	0.54	0.81	1.86	4.97	6.74	8.98	60.41	80.04
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	3.19	2.88	3.19	3.08	3.19	3.08	3.19	3.19	3.08	3.19	3.08	3.19	37.53	37.53
Pumps & Aux.	0.89	0.80	0.86	0.82	0.81	0.78	0.80	0.80	0.78	0.84	0.84	0.88	9.91	10.05
Ext. Usage	2.96	2.43	2.36	1.96	1.73	1.51	1.63	1.90	2.16	2.57	2.77	3.04	27.00	27.02
Misc. Equip.	3.85	3.48	3.85	3.98	3.99	3.68	4.00	3.99	3.68	4.00	3.52	3.85	45.85	45.85
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	7.06	6.37	7.02	7.32	7.36	6.72	7.34	7.36	6.74	7.37	6.40	7.07	84.12	84.28
Total	28.80	24.71	25.33	23.84	23.21	20.92	24.42	23.36	21.53	24.20	24.01	27.31	291.66	301.32

Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.21	0.28	1.10	1.30	2.64	3.61	6.92	5.31	3.24	1.27	0.66	0.31	26.85
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	10.65	8.48	6.95	5.39	3.49	1.53	0.54	0.81	1.86	4.97	6.74	8.98	60.41
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	3.19	2.88	3.19	3.08	3.19	3.08	3.19	3.19	3.08	3.19	3.08	3.19	37.53
Pumps & Aux.	0.89	0.80	0.86	0.82	0.81	0.78	0.80	0.80	0.78	0.84	0.84	0.88	9.91
Ext. Usage	2.96	2.43	2.36	1.96	1.73	1.51	1.63	1.90	2.16	2.57	2.77	3.04	27.00
Misc. Equip.	3.85	3.48	3.85	3.98	3.99	3.68	4.00	3.99	3.68	4.00	3.52	3.85	45.85
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	7.06	6.37	7.02	7.32	7.36	6.72	7.34	7.36	6.74	7.37	6.40	7.07	84.12
Total	28.80	24.71	25.33	23.84	23.21	20.92	24.42	23.36	21.53	24.20	24.01	27.31	291.66

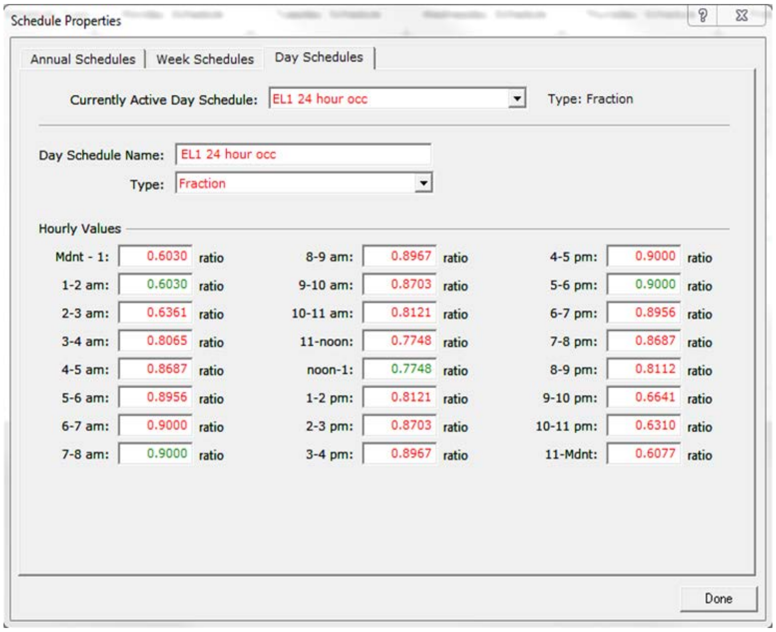
Figure 4.3: ESM Calibrated for Actual Weather Data

4.3 eQUEST Schedules (Occupancy and Equipment)

The ESM's predicted energy performance is driven by the modeler's assumptions about occupancy and equipment run time within the building. Occupancy within any building will typically call for more of the building's systems to run (lighting, HVAC, plug loads, etc.) and can have a great impact on the annual energy consumption. If a building runs all day, such as a hospital, the annual energy consumption can be assumed to be much greater than that of a partially occupied building such as a school. For this particular ESM model there are two different types of schedules to be considered, occupancy and equipment schedules.

Both the equipment and occupancy schedules utilize a percentage value to indicate expected occupancy or equipment load in order to calculate energy consumption on an hourly basis. The percentages with the overall installed loads are multiplied on hourly intervals to simulate and calculate energy consumption during turndowns. For instance if a zone is considered to have an equipment power rating of two (2) kW and the equipment schedule assumes a 0.5 percentage of occupancy, the ESM will calculate a (2 kW X 0. 5) one (1) kW power draw for that hour. This calculation is done over the year hour-by-hour for each of the ESM building zones for the HVAC, lighting, and equipment loads.

The occupancy schedules are utilized by the software to predict the assumed occupancy in each zone within the building on an hourly basis. Each zone can be designated an occupancy schedule of its own which will determine how the HVAC and other systems within the simulation operate. There are two day types considered for all the zones for this particular building's ESM, weekdays (WD) and weekend/holiday (WEH). These account for the building operation for work and non-work days. The occupancy schedules have been divided into three basic assumptions, a 24/7 operation which is seen in Figure 4.4.



Currently Active Day Schedule: EL1 24 hour occ

Type: Fraction

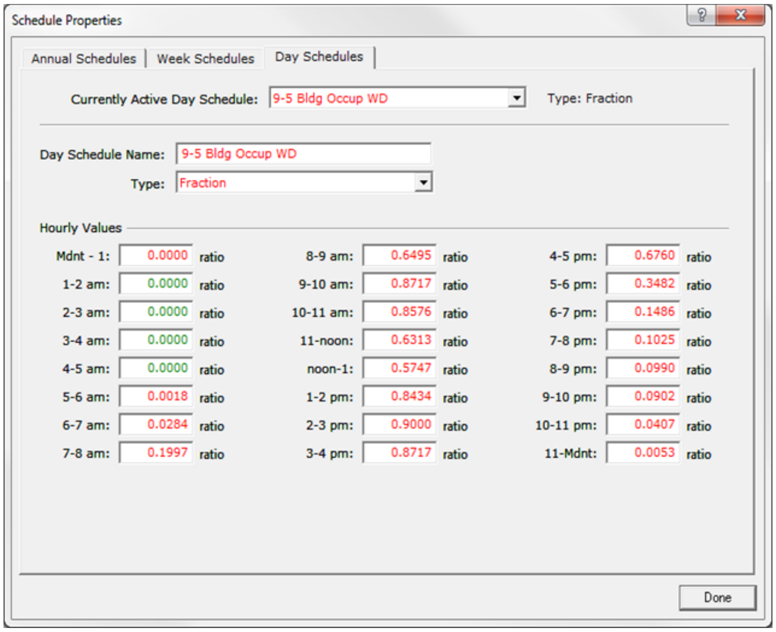
Day Schedule Name: EL1 24 hour occ

Type: Fraction

Mdnt - 1:	0.6030	ratio	8-9 am:	0.8967	ratio	4-5 pm:	0.9000	ratio
1-2 am:	0.6030	ratio	9-10 am:	0.8703	ratio	5-6 pm:	0.9000	ratio
2-3 am:	0.6361	ratio	10-11 am:	0.8121	ratio	6-7 pm:	0.8956	ratio
3-4 am:	0.8065	ratio	11-noon:	0.7748	ratio	7-8 pm:	0.8687	ratio
4-5 am:	0.8687	ratio	noon-1:	0.7748	ratio	8-9 pm:	0.8112	ratio
5-6 am:	0.8956	ratio	1-2 pm:	0.8121	ratio	9-10 pm:	0.6641	ratio
6-7 am:	0.9000	ratio	2-3 pm:	0.8703	ratio	10-11 pm:	0.6310	ratio
7-8 am:	0.9000	ratio	3-4 pm:	0.8967	ratio	11-Mdnt:	0.6077	ratio

Figure 4.4: ESM Occupancy Schedule for 24/7 Operations

A 9:00 A.M. to 5:00 P.M. schedule as can be seen in Figure 4.5.



Currently Active Day Schedule: 9-5 Bldg Occup WD Type: Fraction

Day Schedule Name: 9-5 Bldg Occup WD

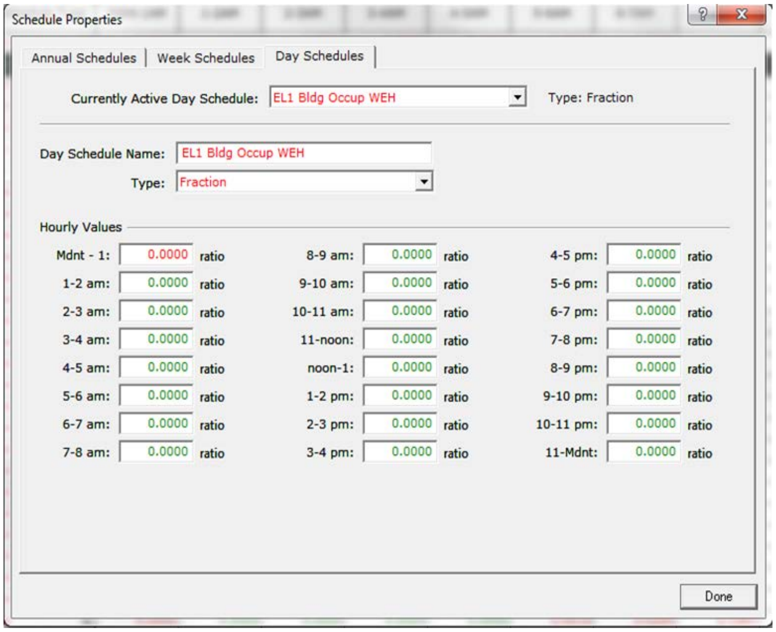
Type: Fraction

Hourly Values

Mdnt - 1:	0.0000	ratio	8-9 am:	0.6495	ratio	4-5 pm:	0.6760	ratio
1-2 am:	0.0000	ratio	9-10 am:	0.8717	ratio	5-6 pm:	0.3482	ratio
2-3 am:	0.0000	ratio	10-11 am:	0.8576	ratio	6-7 pm:	0.1486	ratio
3-4 am:	0.0000	ratio	11-noon:	0.6313	ratio	7-8 pm:	0.1025	ratio
4-5 am:	0.0000	ratio	noon-1:	0.5747	ratio	8-9 pm:	0.0990	ratio
5-6 am:	0.0018	ratio	1-2 pm:	0.8434	ratio	9-10 pm:	0.0902	ratio
6-7 am:	0.0284	ratio	2-3 pm:	0.9000	ratio	10-11 pm:	0.0407	ratio
7-8 am:	0.1997	ratio	3-4 pm:	0.8717	ratio	11-Mdnt:	0.0053	ratio

Figure 4.5: ESM Occupancy Schedule for 9-5 Operations

And a weekend/holiday (WEH) occupancy schedule as seen in Figure 4.6.



Currently Active Day Schedule: EL1 Bldg Occup WEH Type: Fraction

Day Schedule Name: EL1 Bldg Occup WEH

Type: Fraction

Hourly Values

Mdnt - 1:	0.0000	ratio	8-9 am:	0.0000	ratio	4-5 pm:	0.0000	ratio
1-2 am:	0.0000	ratio	9-10 am:	0.0000	ratio	5-6 pm:	0.0000	ratio
2-3 am:	0.0000	ratio	10-11 am:	0.0000	ratio	6-7 pm:	0.0000	ratio
3-4 am:	0.0000	ratio	11-noon:	0.0000	ratio	7-8 pm:	0.0000	ratio
4-5 am:	0.0000	ratio	noon-1:	0.0000	ratio	8-9 pm:	0.0000	ratio
5-6 am:	0.0000	ratio	1-2 pm:	0.0000	ratio	9-10 pm:	0.0000	ratio
6-7 am:	0.0000	ratio	2-3 pm:	0.0000	ratio	10-11 pm:	0.0000	ratio
7-8 am:	0.0000	ratio	3-4 pm:	0.0000	ratio	11-Mdnt:	0.0000	ratio

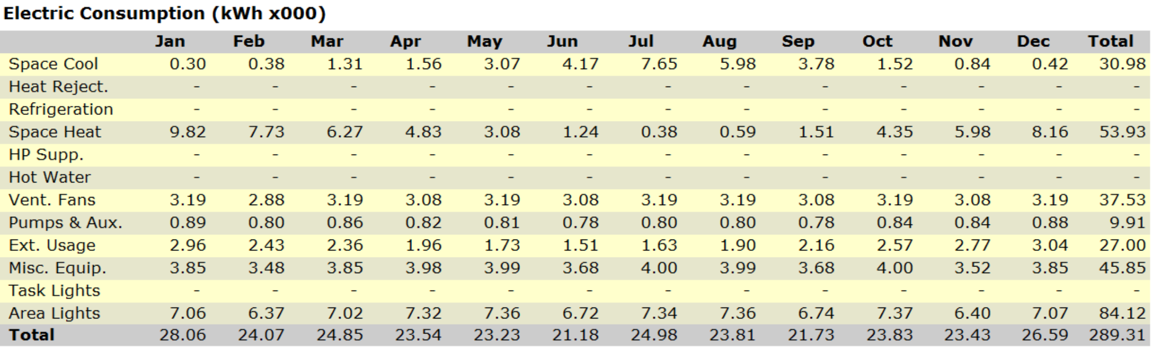
Figure 4.6: ESM Occupancy Schedule for Weekend/Holiday Operations

The EL1 designation in front of each schedule indicates what floor the schedule is for. For organization purposes the modeler can designate an occupancy schedule for each zone in order to account for possible occupancy variations in each space. For this particular ESM, the schedules did not change from zone to zone, all had the same fractional input ratios observed in the three schedules shown in Figures 4.4-6. These schedules were implemented for all of the buildings zones; therefore the occupancy was not assumed to change space to space by modelers.

Initial observations of the schedules suggested that there was a poor assumption for the weekend/holiday schedules. As the building is a police station, to assume that there are no operations on the weekends or holidays has no merit as there is no time throughout the year that the station can close down operation. Spot readings through the BAS also indicated that occupancy sensors and CO_2 sensors indicated occupancy in spaces within the building on weekends and during the night times. This justifies the requirement to address occupancy schedules in the ESM.

The ESM utilizes 17 zones to attempt to simulate the 40+ zones within the actual building, therefore lots of assumptions were made by modelers as to the operations of these zones. When compared to the actual post-construction blueprint, there were zones within the ESM that were shown to be occupied for longer periods through the BAS. This prompted a change to all schedules within the ESM to include a 24/7 occupancy schedule (Figure 4.4) for all of the building zones. This accounted for spaces that were occupied for longer times within the ESM zones. For instance a zone within the ESM model may have included 4 actual building zones where there was extended occupancy within the actual building’s zones. Therefore the entire zone occupancy was increased within the ESM to reflect these conditions.

The results of the increased occupancy schedules can be seen in Figure 4.7, where the ESM’s overall energy consumption over the year was mostly unchanged. The ESM showed an increase in cooling energy and similarly a decrease in heating energy. This is due to the model assuming more occupants occupying the zones and giving off more body heat than originally assumed. Therefore more cooling is required in the summer months while less heating is required during the winter.

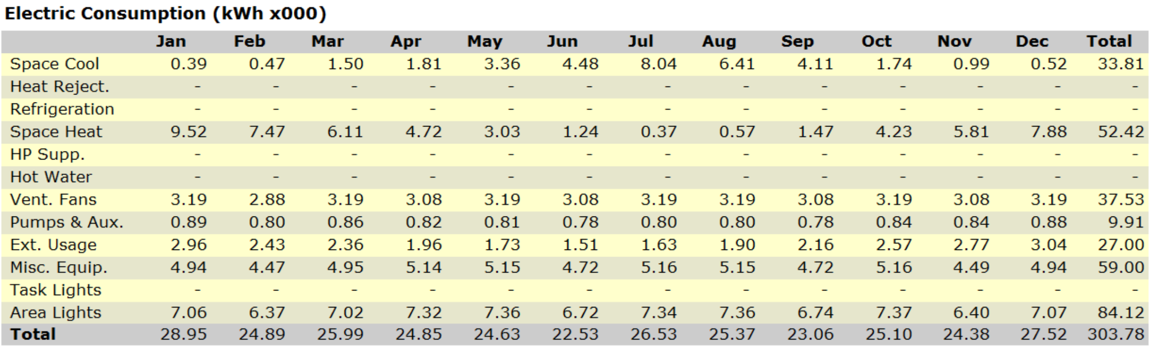


Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.30	0.38	1.31	1.56	3.07	4.17	7.65	5.98	3.78	1.52	0.84	0.42	30.98
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	9.82	7.73	6.27	4.83	3.08	1.24	0.38	0.59	1.51	4.35	5.98	8.16	53.93
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	3.19	2.88	3.19	3.08	3.19	3.08	3.19	3.19	3.08	3.19	3.08	3.19	37.53
Pumps & Aux.	0.89	0.80	0.86	0.82	0.81	0.78	0.80	0.80	0.78	0.84	0.84	0.88	9.91
Ext. Usage	2.96	2.43	2.36	1.96	1.73	1.51	1.63	1.90	2.16	2.57	2.77	3.04	27.00
Misc. Equip.	3.85	3.48	3.85	3.98	3.99	3.68	4.00	3.99	3.68	4.00	3.52	3.85	45.85
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	7.06	6.37	7.02	7.32	7.36	6.72	7.34	7.36	6.74	7.37	6.40	7.07	84.12
Total	28.06	24.07	24.85	23.54	23.23	21.18	24.98	23.81	21.73	23.83	23.43	26.59	289.31

Figure 4.7: ESM Calibrated for Actual Observed Occupancy

Next is to consider the equipment schedules. From the M&V process, it was measured that the building's actual plug load/miscellaneous equipment load was 104% higher than predicted by the modelers. This excess consumption is not considered the responsibility of the modelers. Due to the energy consumption of plug loads being directly related to the use of equipment by occupants within the building. An issue was found within the equipment schedules same as the assumed occupancy schedules; they have an aggressive assumption that on the weekends and holidays there is no activity in the building. Therefore corrections were made to the equipment schedules similar to the occupancy schedules, mainly to reflect the fact that when occupants are present, they will be consuming plug load energy. The results for implementing an equipment schedule to reflect the corrected occupancy schedule can be found in Figure 4.8. Again an increase in cooling energy and a decrease in heating energy are observed. This is due to the extra heat considered to be given off by the plug load equipment in use. Also observed is the increase in miscellaneous equipment (Misc. Equip.) as the plug loads are assumed to operate more often.



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.39	0.47	1.50	1.81	3.36	4.48	8.04	6.41	4.11	1.74	0.99	0.52	33.81
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	9.52	7.47	6.11	4.72	3.03	1.24	0.37	0.57	1.47	4.23	5.81	7.88	52.42
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	3.19	2.88	3.19	3.08	3.19	3.08	3.19	3.19	3.08	3.19	3.08	3.19	37.53
Pumps & Aux.	0.89	0.80	0.86	0.82	0.81	0.78	0.80	0.80	0.78	0.84	0.84	0.88	9.91
Ext. Usage	2.96	2.43	2.36	1.96	1.73	1.51	1.63	1.90	2.16	2.57	2.77	3.04	27.00
Misc. Equip.	4.94	4.47	4.95	5.14	5.15	4.72	5.16	5.15	4.72	5.16	4.49	4.94	59.00
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	7.06	6.37	7.02	7.32	7.36	6.72	7.34	7.36	6.74	7.37	6.40	7.07	84.12
Total	28.95	24.89	25.99	24.85	24.63	22.53	26.53	25.37	23.06	25.10	24.38	27.52	303.78

Figure 4.8: ESM Calibrated for Equipment Schedule Changes to Match Occupancy

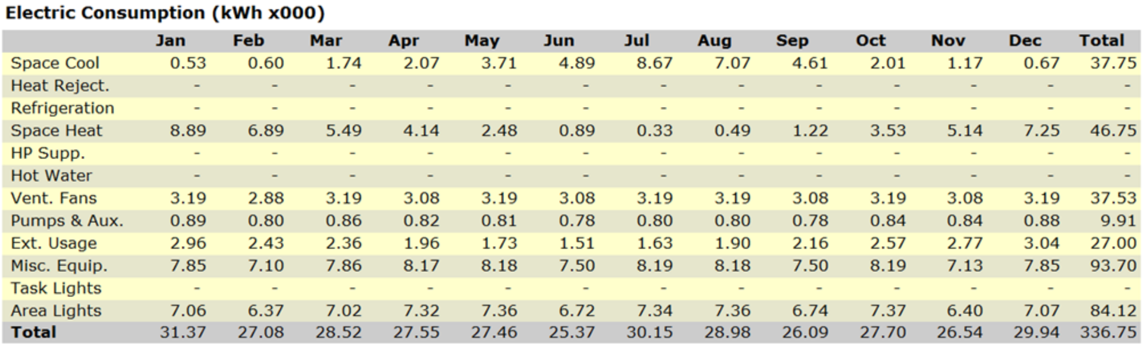
It can be observed that this did not increase the energy consumption to that of which was measured for the actual operation of the building. This will be addressed in the actual equipment power densities (W/ft^2).

4.4 eQUEST Power Density – Equipment, Fan, Pump, and Lighting

Calibrating the proposed ESM model involves more than just correcting the schedules. Each piece of equipment in each zone has its own power density which in the software is defined as a W/ft^2 (watt per square feet) metric for lighting and plug loads; or similarly a W/cfm (watt per cubic feet per minute) metric for HVAC loads. After analyzing the ESM it was observed that the floor by floor plug load consumption was not equivalent to the actual measured data from the submeters on a floor by floor basis. The electrical submeters responsible for monitoring the plug loads were configured floor-by-floor with a forth submeter designated for the third floor server room. When the ESM model was broken down into its zone by zone energy consumption it was noticed that the basement was not simulating the energy consumption per the actual measurements. It was also concluded that there seemed to be discrepancy with the server room energy consumption on the third floor. Therefore the ESM power densities in those areas were addressed to calibrate the model with as much precision as possible.

$$PD_{\text{Equipment}} = \frac{\text{Measured Consumption}_{\text{Submetered}}}{\text{Area}_{\text{ESM Zone}}} \tag{4.1}$$

Using the known area for each zone, the correct power density was determined in order to reflect what was recorded on the electrical submeters for that area, using equation 4.1. Therefore the power densities were relative to the ESM assumed zone floor square area along with measured values from the submeters. The results for this correction in plug load power densities was able to result in the exact consumption for the calibrated model as was measure on the building meters as seen in Figure 4.9.



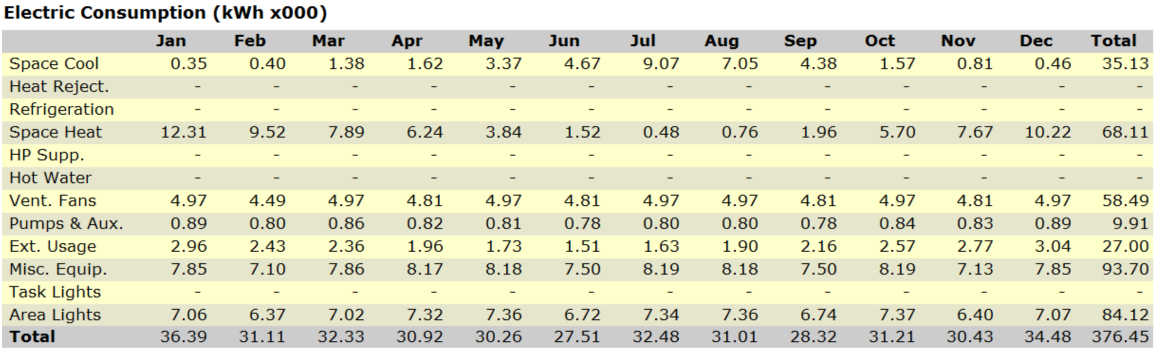
Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.53	0.60	1.74	2.07	3.71	4.89	8.67	7.07	4.61	2.01	1.17	0.67	37.75
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	8.89	6.89	5.49	4.14	2.48	0.89	0.33	0.49	1.22	3.53	5.14	7.25	46.75
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	3.19	2.88	3.19	3.08	3.19	3.08	3.19	3.19	3.08	3.19	3.08	3.19	37.53
Pumps & Aux.	0.89	0.80	0.86	0.82	0.81	0.78	0.80	0.80	0.78	0.84	0.84	0.88	9.91
Ext. Usage	2.96	2.43	2.36	1.96	1.73	1.51	1.63	1.90	2.16	2.57	2.77	3.04	27.00
Misc. Equip.	7.85	7.10	7.86	8.17	8.18	7.50	8.19	8.18	7.50	8.19	7.13	7.85	93.70
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	7.06	6.37	7.02	7.32	7.36	6.72	7.34	7.36	6.74	7.37	6.40	7.07	84.12
Total	31.37	27.08	28.52	27.55	27.46	25.37	30.15	28.98	26.09	27.70	26.54	29.94	336.75

Figure 4.9: ESM Calibrated for Actual Equipment Power Densities

Next was to address the energy consumption for the building's fans and pumps which was measured during the M&V process. Starting with fan energy consumption, adjustments are needed for the W/cfm metric within the ESM. The power consumption input related to the fans within the ESM directly correlates to the amount of air the program is assuming the building brings in. Data from the BAS determined an average of approximately 7,800 cfm of fresh outdoor air was being brought in regularly during the first year operation post-occupancy for the building.

Analyzing of the proposed ESM showed an assumed 4,900 cfm of fresh air being brought in by the DOAS RTU. Through further analyses the software showed that the total cfm of incoming air was directly related to all of the zones cfm air intake through the ESMs demand control ventilation (DCV) multiplier; a feature within the ESM that allows the modeler to simulate demand control ventilation. DCV is a scheme where fresh air is only sent to spaces that require fresh air through monitoring of zone CO_2 levels. Each zone is set to receive a fraction of the total incoming cfm per the DCV multiplier based on the room’s area and occupancy. The DCV multiplier upon further review was shown to be set at a 0.635 incoming air fraction. This fraction is a rating based off of the actual RTU full load specifications. As discussed in the previous M&V section, analysis of the BAS data on the RTU showed that there was no turndown of the equipment through the first year of operation. Therefore to calibrate the ESM to operate at the measured incoming airflow of 7,800 cfm, the maximum rated flow of the RTU, the DCV multiplier was set to one (1). By increasing the DCV multiplier to 1, the ESMs incoming fresh air was increased to 7,800 cfm resulting in higher fan consumption for the calibrated model as well as an increase in the required heating energy and decrease in the cooling energy as seen in Figure 4.10.



Electric Consumption (kWh x000)

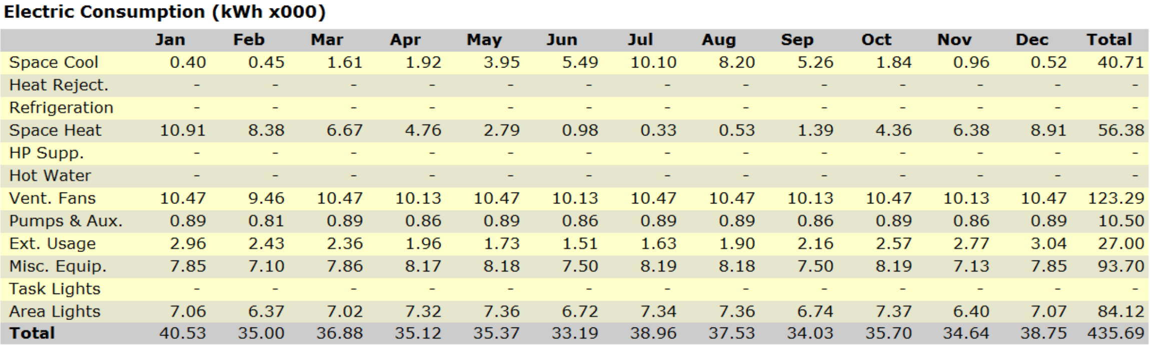
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.35	0.40	1.38	1.62	3.37	4.67	9.07	7.05	4.38	1.57	0.81	0.46	35.13
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	12.31	9.52	7.89	6.24	3.84	1.52	0.48	0.76	1.96	5.70	7.67	10.22	68.11
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	4.97	4.49	4.97	4.81	4.97	4.81	4.97	4.97	4.81	4.97	4.81	4.97	58.49
Pumps & Aux.	0.89	0.80	0.86	0.82	0.81	0.78	0.80	0.80	0.78	0.84	0.83	0.89	9.91
Ext. Usage	2.96	2.43	2.36	1.96	1.73	1.51	1.63	1.90	2.16	2.57	2.77	3.04	27.00
Misc. Equip.	7.85	7.10	7.86	8.17	8.18	7.50	8.19	8.18	7.50	8.19	7.13	7.85	93.70
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	7.06	6.37	7.02	7.32	7.36	6.72	7.34	7.36	6.74	7.37	6.40	7.07	84.12
Total	36.39	31.11	32.33	30.92	30.26	27.51	32.48	31.01	28.32	31.21	30.43	34.48	376.45

Figure 4.10: ESM Calibrated for Actual Measured Incoming Air Flow and DCV Multiplier Correction

The corrected airflow to the building is now accounted for within the calibrated ESM through the DCV multiplier, next will be to account for the corrected fan energy. This will be accomplished through a W/cfm metric within the ESM for the supply and exhaust fans. The systems in the ESM are designed to mimic the operations of the ERV wheel within the RTU. The model was analyzed to determine the predicted draw of the RTU supply and exhaust fans. Previously discussed was the fan energy of the 41 local HP fans and how there was no accounting for their operation within the proposed ESM. Due to the continuous operation of the HP fans their energy was not modelled through the HP's COPs due to the on/off operation not being able to capture all the energy. Instead the RTU fans average power draw of 9.9 kW and the summation of all the local HP fan power draw of 4.2 kW were included in the MAU Unit.

$$PD_{\text{Fans}} = \frac{\text{RTU Fans}_{\text{measured}} + \text{HP Fans}_{\text{Manufacturer}}}{\text{Total CFM}_{\text{ESM}}} \tag{4.2}$$

Dividing by the average air flow of 7,800 cfm, this resulted in a 0.001808 W/cfm metric. The results of the calibration for fan energy can be observed in Figure 4.11.



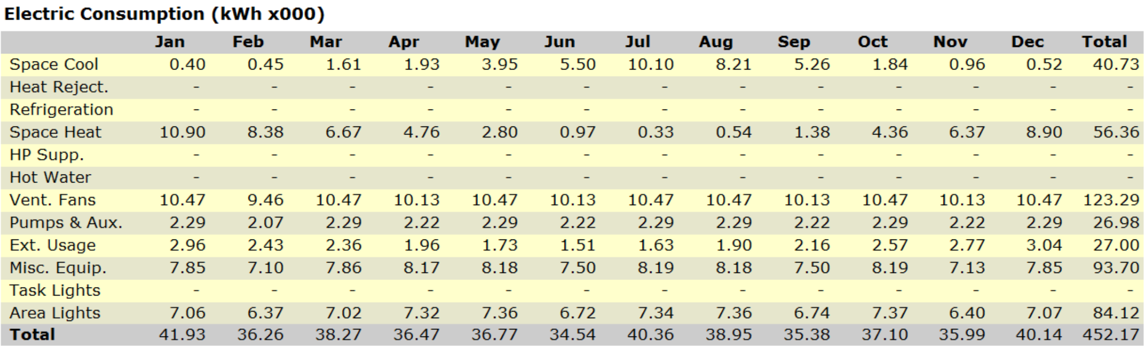
Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.40	0.45	1.61	1.92	3.95	5.49	10.10	8.20	5.26	1.84	0.96	0.52	40.71
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	10.91	8.38	6.67	4.76	2.79	0.98	0.33	0.53	1.39	4.36	6.38	8.91	56.38
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	10.47	9.46	10.47	10.13	10.47	10.13	10.47	10.47	10.13	10.47	10.13	10.47	123.29
Pumps & Aux.	0.89	0.81	0.89	0.86	0.89	0.86	0.89	0.89	0.86	0.89	0.86	0.89	10.50
Ext. Usage	2.96	2.43	2.36	1.96	1.73	1.51	1.63	1.90	2.16	2.57	2.77	3.04	27.00
Misc. Equip.	7.85	7.10	7.86	8.17	8.18	7.50	8.19	8.18	7.50	8.19	7.13	7.85	93.70
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	7.06	6.37	7.02	7.32	7.36	6.72	7.34	7.36	6.74	7.37	6.40	7.07	84.12
Total	40.53	35.00	36.88	35.12	35.37	33.19	38.96	37.53	34.03	35.70	34.64	38.75	435.69

Figure 4.11: ESM Calibrated for Actual Measured Total Fan Energy

The resulting ESM output indicated a 123.3 MWh fan energy consumption, within 2% of the actual measured consumption. This indicates that the calibrated ESM is modeling the fan energy as it currently operates. Also, observe the increased cooling energy and the decrease in heating energy due to the elevated fan horsepower. The ESM assumes the fan motors will generate heat warming air as it passes over the fan.

The calibrated ESM model will now be corrected for the pump power required for building operation. The model assumes that four pumps operate to serve the building HVAC systems, consuming a total of 2.08 kW. Actual measurements indicated four three (3) hp pumps run to provide GSHP loop fluid to the building. The model does assume that the pump runs on a VFD drive and the software has the ability to simulate the varying loads throughout the year. To calibrate the model to include all of the pumping energy required to run the actual building, the number of pumps that were found to be running continuously were input into the program. The secondary loop runs two 3 hp pumps continuously at 75% load while the primary loop runs one three (3) hp pump for about 80% of the time at close to 100% load. The sums of the three (3) hp pumps that operate were input into the calibrated ESM, which resulted in a 6.7 kW (9 hp X 0.746 kW/hp) pump rating for the entire system (it was assumed to let the program modulate the pumps flow through its installed VFD and pump performance curves which were observed to be turning down during the simulation). Figure 4.12 shows the results of the measured power input with the ESM varying its speeds as a function of the simulated hourly loads.



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.40	0.45	1.61	1.93	3.95	5.50	10.10	8.21	5.26	1.84	0.96	0.52	40.73
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	10.90	8.38	6.67	4.76	2.80	0.97	0.33	0.54	1.38	4.36	6.37	8.90	56.36
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	10.47	9.46	10.47	10.13	10.47	10.13	10.47	10.47	10.13	10.47	10.13	10.47	123.29
Pumps & Aux.	2.29	2.07	2.29	2.22	2.29	2.22	2.29	2.29	2.22	2.29	2.22	2.29	26.98
Ext. Usage	2.96	2.43	2.36	1.96	1.73	1.51	1.63	1.90	2.16	2.57	2.77	3.04	27.00
Misc. Equip.	7.85	7.10	7.86	8.17	8.18	7.50	8.19	8.18	7.50	8.19	7.13	7.85	93.70
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	7.06	6.37	7.02	7.32	7.36	6.72	7.34	7.36	6.74	7.37	6.40	7.07	84.12
Total	41.93	36.26	38.27	36.47	36.77	34.54	40.36	38.95	35.38	37.10	35.99	40.14	452.17

Figure 4.12: ESM Calibrated for Actual Measured Total Pump Energy

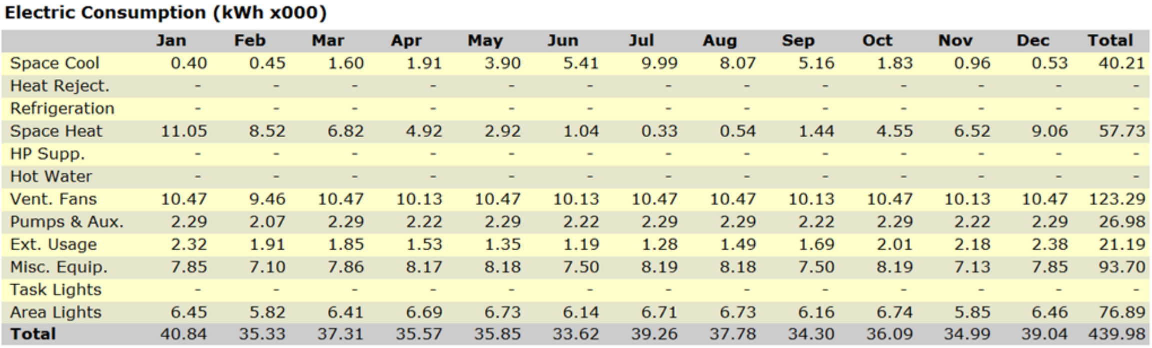
It is observed that the pumping energy simulated by the calibrated ESM assumed 26.98 MWh which is within 2% of the measured pumping energy of the actual building.

Last is to account for the reduction in interior and exterior lighting (Area Lights, Ext. Usage) measured for the facility. The exterior lighting was corrected simply through the outside lighting schedule within the ESM. The actual measured outside lighting (which was on its own electrical submeter) was divided by the proposed ESM simulated output energy.

$$\text{Fraction}_{\text{Outside Lighting}} = \frac{\text{Lighting Energy}_{\text{Submetered}}}{\text{Proposed Lighting Energy}_{\text{ESM}}}$$

This fraction was then used to as an input to the calibrated ESMs exterior lighting output density, which was currently set at one (1.0). This resulted in the calibrated ESM Ext. Usage output shown in Figure 4.13. The results from the ESM predicted outside lighting was simulated within 1% of the actual measured consumption.

The interior lights (Area Lights) were calibrated through the ESM lighting input density. Analysis of electrical submeter data showed the actual energy consumption within the basement varied from the proposed ESM. This was calibrated to match the actual measured energy consumptions obtained from the building's electrical submeters that measuring lighting (Equation 4.1). The results can be seen in Figure 4.13 where the calibrated ESM was able to model the energy within 1% of the actual measured energy.



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.40	0.45	1.60	1.91	3.90	5.41	9.99	8.07	5.16	1.83	0.96	0.53	40.21
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	11.05	8.52	6.82	4.92	2.92	1.04	0.33	0.54	1.44	4.55	6.52	9.06	57.73
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	10.47	9.46	10.47	10.13	10.47	10.13	10.47	10.47	10.13	10.47	10.13	10.47	123.29
Pumps & Aux.	2.29	2.07	2.29	2.22	2.29	2.22	2.29	2.29	2.22	2.29	2.22	2.29	26.98
Ext. Usage	2.32	1.91	1.85	1.53	1.35	1.19	1.28	1.49	1.69	2.01	2.18	2.38	21.19
Misc. Equip.	7.85	7.10	7.86	8.17	8.18	7.50	8.19	8.18	7.50	8.19	7.13	7.85	93.70
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	6.45	5.82	6.41	6.69	6.73	6.14	6.71	6.73	6.16	6.74	5.85	6.46	76.89
Total	40.84	35.33	37.31	35.57	35.85	33.62	39.26	37.78	34.30	36.09	34.99	39.04	439.98

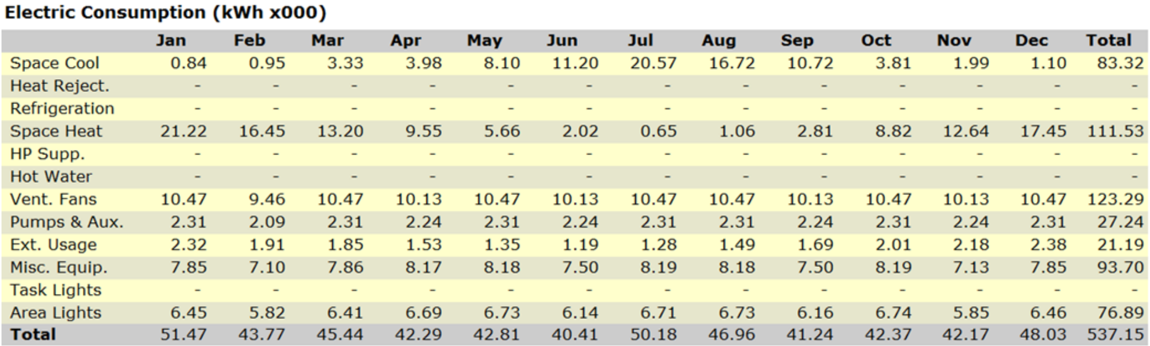
Figure 4.13: ESM Calibrated for Actual Measured Interior/Exterior Lighting Energy

4.5 Heating/Cooling Energy

As discussed earlier, the proposed ESM made some generalized assumptions as to how the building equipment would operate. The ESM zoned the entire building into only 17 zones when there were over 40 zones in the actual construction facility. A look at how the proposed ESM allocated its compressor energy showed that the proposed model assumed a make-up air unit (MAU) feeding a RTU which feeds the 17 zones within the building. The proposed ESMs MAU simulated the functions of the ERV wheel, using free fuel to pre-condition the incoming outside air to the air temperature and humidity conditions assumed through the performance of the actual ERV wheel within the buildings DOAS RTU. The proposed ESM then assumes that the RTU conditions the outside air fed from the MAU and serves all 17 zones within the building.

Actual operation involves the ERV wheel pre-conditioning the outside air, while the DOAS RTU compressors condition the incoming supply air again as it is sent down stream to the 40+ building zones. Each zone has dedicated heat pumps (HPs) that further condition the air depending on the incoming air and the zones set point requirements.

The proposed ESM only assumes that one RTU is run to supply all zones. Actual observation of the building’s HVAC equipment indicate “balanced” loads in the building where some of the spaces require cooling and others require heating. This indicates the proposed ESM has no ability to mimic this “balanced” operation. The inputs for the RTU heating and cooling coefficient of performance (COP) indicated it was specified by the manufacturer. Therefore the model needed to be corrected accordingly by adjusting the COP inputs of the RTU within the ESM. This will allow the ESM to reflect the actual energy required for the RTU to achieve actual measure conditions. The results indicated that the RTUs cooling COP and heating COP would need to be equivalent to 2.17 and 1.72, respectively, in order to match the actual measured compressor energy consumption. This is a significant deviation from the assumed COP of cooling (4.55) and heating (3.33) that was specified from the manufactures data. Results can be observed in Figure 4.14



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.84	0.95	3.33	3.98	8.10	11.20	20.57	16.72	10.72	3.81	1.99	1.10	83.32
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	21.22	16.45	13.20	9.55	5.66	2.02	0.65	1.06	2.81	8.82	12.64	17.45	111.53
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	10.47	9.46	10.47	10.13	10.47	10.13	10.47	10.47	10.13	10.47	10.13	10.47	123.29
Pumps & Aux.	2.31	2.09	2.31	2.24	2.31	2.24	2.31	2.31	2.24	2.31	2.24	2.31	27.24
Ext. Usage	2.32	1.91	1.85	1.53	1.35	1.19	1.28	1.49	1.69	2.01	2.18	2.38	21.19
Misc. Equip.	7.85	7.10	7.86	8.17	8.18	7.50	8.19	8.18	7.50	8.19	7.13	7.85	93.70
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	6.45	5.82	6.41	6.69	6.73	6.14	6.71	6.73	6.16	6.74	5.85	6.46	76.89
Total	51.47	43.77	45.44	42.29	42.81	40.41	50.18	46.96	41.24	42.37	42.17	48.03	537.15

Figure 4.14: ESM Calibrated for Compressor Coefficient of Performance (COP)

4.6 Calibrated Model Results

The process of calibrating the proposed ESM to match the actual building energy consumption obtained from the M&V findings was facilitated by extensive electrical submetering and independent measurements. The knowledge gained through the bottom up approach to building energy consumption, on a subsystem level, allowed for development of energy metrics linked to specific equipment operations. This type of diagnostics will help a building operator in the future benchmark and minimize a building’s energy consumption[25]. This will result in better performing buildings that are analyzed and benchmarked every year to assure sustainable operations.

Table 4.1: Results of Calibrating the Proposed ESM to Reflect M&V Findings

END USE ENERGY TYPES	ACTUAL MEASURED CONSUMPTION (MWh)	CALIBRATED ESM CONSUMPTION (MWh)	PERCENT DEVIATION FROM ACTUAL CONSUMPTION
Space Heat/Cool	192.1	194.9	1.4%
Vent. Fans	125.9	123.3	2.1%
Pumps & Aux.	27.6	27.2	1.2%
Ext Usage (lights)	21.3	21.2	0.5%
Misc. Equipment	93.7	93.7	0.0%
Area lights	76.9	76.9	0.0%
Totals	537.5	537.2	0.1%

The deviations observed from the proposed ESM and the building’s actual measured energy consumption were the outcome of the ESMs assumptions and energy targets, construction issues, and lack of operational control for some of the equipment. The model’s assumptions include the limited number of zones in the building, the power densities for each piece of equipment, and the operational schedules assumed for the building. There were no nighttime reductions, which are prescribed by the ESM, observed in the actual measured performance of the building. The RTU exhibited no turndown on the supply and exhaust fan speeds and was considered the result of leaky dampers not capable of closing off air to the spaces effectively. This resulted in an unachievable duct static pressure set point which left the RTU to run at full speed all times of the year.

Not all issues were the result of the modeler’s assumptions; leaky dampers, inadequate control techniques, etc. Therefore a retro-commissioning of the building systems will be done to see if the aggressive targets set forth by the modelers can be achieved. This will indicate if the model was unattainable. It also poses the question of, if this newly constructed “LEED” building is experiencing issues, how many other building are sitting in the same situation?

CHAPTER 5

RETRO-COMMISSIONING OF THE BUILDING'S SYSTEMS

5.1 Building Systems Pareto Analysis

After the first year post-occupancy was complete, opportunities were explored to minimize the building energy consumption. An attempt to match the actual building energy consumption to that of the proposed ESM was facilitated by the M&V data collected. This data could help indicate where and how to reduce the energy performance gap between the various building operations[26]. In order to successfully accomplish this, a system was devised in order to try and identify certain areas of deficiency that presented the best opportunity to minimize the building operator's time and resources. Energy efficiency measures (EEMs) were identified that were feasible and could be implemented in house through the resources that already existed within the building. To determine where EEMs exist and which ones provide the best benefit; the proposed ESM and M&V data was implemented. The objective is to assess what measures exist, and which will minimize energy consumption through the building with the least amount of resources. A simplified Pareto analysis was explored that will determine the most feasible way to minimize time and effort while maximize the EEMs impacts. Then EEMs could be implemented in a methodical fashion and energy savings can be verified through the same methods employed in Section 3 to measure building energy consumption. Figure 5.1 below shows how the proposed ESM, the M&V, and the BAS data can be used to find faults in the building's energy consumption and correct them.

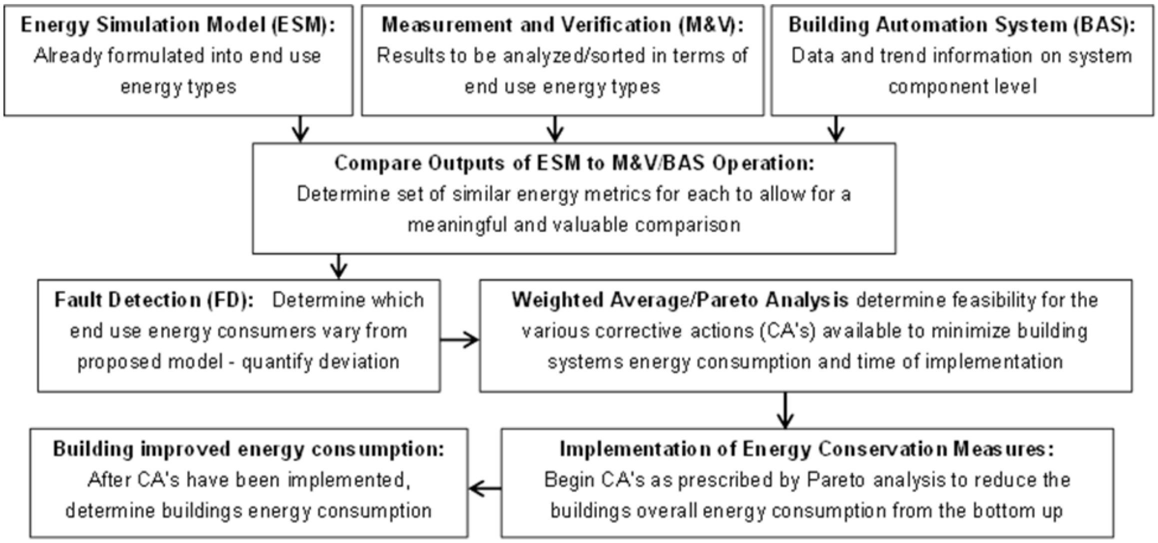


Figure 5.1: Logic Map for How to Use Buildings Systems to Help Alleviate Issues with Excess Energy Consumption

The weighted Pareto analysis would take the existing information known about each system within the building. Then help make a determination of the feasible EEMs to impact the overall energy consumption/reduction of the building. First the building's systems are broken down into the subcategories determined in Figure 3.2 (Section 3.1) (lighting, plug load, cooling/heating, and fans/pumps). By listing the equipment associated with each, a bottom up approach to the retro-commissioning process can be implemented on a subsystem level. Listing all possible equipment options for the possible EEMs, four categories will be considered to determine where to start allocating time and resources to help correct the building (note: more than or less than 4 categories could be constructed depending on the size and complexity of a building's systems). This analysis then prescribes weights (a number between 1 and 5) to each of the conditions and a summation of all of the conditions for each piece of equipment can be calculated, where the highest totals indicate the best opportunities. The categories consist of conditions that are deemed critical to the equipment's energy consumption. For this building the four weighted categories included the runtime of the equipment (the longer it runs the more energy it consumes), the size of the equipment (the larger the equipment's power draw, the more energy it consumes), the accessibility of the equipment (if there is no opportunity to physically access the equipment then it may not be feasible for the operator to perform EEMs), and the performance gap of the equipment (energy consumption deviation between the proposed ESM and the M&V data). Table 5.1 shows analysis for this particular building and how this method was employed to determine where to start the retro-commissioning activities to try and minimize the building energy consumption.

Table 5.1: Pareto Analysis Used to Determine Retro-Commissioning Opportunities for the Building

End Energy User Type	Description of System/Equipment (number of equipment)	BAS Data (available trends - hourly)	**Pareto Analysis (1-5)** (5 = highest priority)					
			Run Time	Size (hp/kW)	Accessibility	Performance Gap	Totals	Rank
Lighting	Outside/task/area lighting	on/off	3	3	3	1	10	5
Pumps	GSHP Primary Sesondary Loop (4)	pump status (on/off), pump speed (rpm)	5	1	5	3	14	3
	Hot Water/Baseboard Heater (2)	pump status (on/off)	3	1	3	5	12	4
Fans	RTU supply and exhaust (2)	fan status, fan speed	5	5	5	5	20	1
	Local Heat Pumps-one fan each (41)	fan status (on/off)	3	3	5	5	16	2
Heat/Cool	Dual capacity heat pumps (41)	compressor status (cool/heat)	3	3	3	3	12	4
	RTU compressors (2)	compressor status (cool/heat)	5	5	5	5	20	1
	ERV Wheel (1)	outside air flow (cfm),	5	1	5	1	12	4
	Baseboard Heating HP (2)	compressor status (on/off)	2	2	3	1	8	6
Plug Load	Anything plugged in	no data in BAS	-	-	-	-	-	-
	computers	***is excluded from ESM	-	-	-	-	-	-
	monitors		-	-	-	-	-	-

From the analysis it is clear that the RTU was a prime energy user for the facility and definitely deserved some attention to try and see if the proposed ESM predicted energy consumption targets are achievable.

5.2 RTU Fans and Compressor EEMs

The DOAS RTU supply and exhaust fans were analyzed first due to the fan systems having the largest performance gap from initial M&V measurements. Therefore their observation was explored and the fans were shown to be operating at close to 100% speed all year round. This was not the intent of designers who had originally expected the fans to modulate in accordance with occupancy within the building based on the Demand

Control Ventilation (DCV) scheme. The DCV system was installed to monitor the carbon dioxide (CO_2) levels in each room and supply fresh outside air when spaces reached their critical set points. This system was not performing correctly as the DOAS RTU fans ran consistently around 100% speed all year round. This was also observed during the M&V process as their power consumption remained constant and was over double of what had been assumed by the proposed ESM. Through the BAS, the RTU compressor operation was locked out leaving only the supply and exhaust fan to run. The RTU supply fan operates to maintain a specific static pressure set point within the buildings duct work. The exhaust fan modulates in accordance with the supply fan to make sure that the air entering the building can be exhausted (conservation of mass). Through the BAS, a static pressure set point reset was conducted in increments of 0.1 inch H_2O over the next 5 -10 minutes from its original 1.0 inch H_2O set point. At the same time, the power consumption of the unit was observed to see the effects of the RTU fans power draw in relation to the new static pressure set point. The RTU had been currently drawing an average of 9.9 kW during operation whereas the proposed ESM had predicted only 4.2 kW. Therefore the static pressure set point was reduced until the meter indicated a 4.2 kW power draw, which occurred at 0.3” of water static pressure, a significant turndown from the original 1.0”. Figure 5.2 shows the results of the data logger which was connected to the RTU unit prior to the test, showing the drop in power draw of the RTU from the static pressure reduction. The RTU fan power consumption was singled out by locking out the compressor operation during the test.

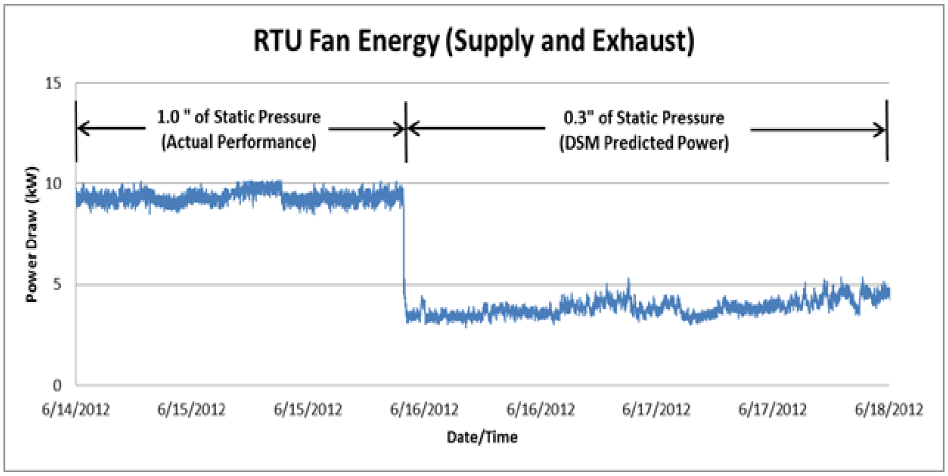


Figure 5.2: Results of the Duct Static Pressure Set Point Drop in Terms of RTU Fan Power Draw

This static pressure set point reset is assumed to save the building >49,000 kWh annually, which is consistent with calculations in Table 3.1 (Section 3.3). This measure was implemented by the building operator and will save upwards of $4,900 at a $0.10/kWh rate (typical for buildings in this region).

During the same exercise the RTU compressors were also addressed. From analysis of the proposed ESM, the total compressor energy within the model was allocated to just the simulated RTU, no HPs. Therefore there was no way to model the building’s balanced loads, when some HPs are in heating and others in cooling. The ESM assumed that the RTU just supplied the whole facility. The model also simulated a make-up air unit (MAU) with a free fuel source to mimic the operation of the ERV wheel for the DOAS RTU. Therefore the ESM only assumed one unit would condition all of the air supplied to all of the building zones, not 41 (all individual heat pumps). After some comparisons were done to determine the RTU’s COP compared to that of the local heat pumps, it was elected to lock out the RTU compressors altogether. Through the BAS sequences were observed where the RTU pre-cooled/heated the outside air before it was sent downstream where a heat pump would then have to heat/cool the air, respectively.

One of the necessary reasons for the RTUs to precondition air is in the severe summer conditions where the requirements for cooling the air involve a reheat to achieve a specific RH for the building spaces. Due to the mild nature of the weather at the time of this experiment it was decided to lock out the compressors of the RTU and allow the local HPs to condition their own spaces. This eliminates incoming outside air from potentially being conditioned twice. After the first week of this sequence there were no complaints from the building occupants in regards to desired room temperature set points not being satisfied so the RTU compressors were left off. It should be noted that the compressors were scheduled to cycle once a week to keep the compressors lubricated and prevent any damage from sitting too long.

It should be noted that there was an increase in energy for the buildings forty plus heat pumps after locking out the RTU compressors. This is due to the increased temperature differential resulting in an increased load on the local heat pumps. The net compressor energy however was reduced. This results in a more efficient use of energy to condition incoming air.

5.3 Heat Pump Fans

In terms of attempting to mitigate the losses from the heat pump (HP) fans, their operation was observed and analyzed over the year. As discussed earlier (Section 3.3) the HP fans were found through the BAS to be operating all year round. The proposed ESM showed no indication of HP compressor or fan energy within the simulation. Because the proposed ESMs HP compressors had not been considered the fan energy also was not accounted for, therefore the ESM had no way to account for the HP fan energy.

It appeared that the proposed ESM assumes that the RTU fan energy is all that is required to move air through the building and that assumed power draw was shown to be low from the analysis of the RTU supply and exhaust fan. In order to reduce the RTU's fan energy enough (through the static pressure set point) there would not be enough pressure in the duct to supply the zones. In fact one reason that the opportunity existed to reduce the static set point for the RTU so low was due to the ability of the local HP fans to pull air into their zones.

It was finally assumed that the modeler must have intended for the HP fan energy to be accounted for within the ESM's RTU. Though the COP for the proposed ESMs RTU was higher than the manufacturer's rating, which indicates the ESM didn't consider the fan energy either. It was considered to connect the HPs fans operation to the compressor status of the HP operation or the occupancy sensors with in each space. Either control strategy would mitigate any excess energy used by the building through the HP fans. Both control strategies can also be implemented directly through the BAS, which the building operator has complete control of. For this case the HP's fan operation was tied to the HP compressor status through the BAS. Savings are expected to be consistent with numbers shown in Table 3.3 in Section 3.3, reducing energy consumption by 32,000+ kWh or over $3,000 annually at $0.10/kWh.

5.4 GSHP Primary-Secondary Loop Pump Operation Optimization

For the primary-secondary GSHP operation of the building, the primary loop pump only utilized one pump to serve the secondary loop. The secondary loop delivers EWT to the building in which all of the building's HVAC equipment utilizes for either a heat sink or source for their refrigeration cycles. When the RTU or a HP unit is in heating mode, the EWT to the building acting as a heat source for the evaporator side for the refrigerant cycle where the incoming air to the zone will be brought up to temperature from the rejected heat on the condenser side. When the units are in cooling mode, a reverse valve is actuated reversing the refrigerant cycle which then uses the EWT as a heat sink for the condenser side of the refrigeration cycle where the incoming air will reject heat to the evaporator. The EWT operating range can supply both heating and cooling operations at the same time.

The secondary loop runs continuously all year long to supply the building's systems with EWT to enable zone conditioning and comfort for the occupants. It was observed during the M&V process (Section 3.4) that the two secondary pumps ran in parallel operation all year long. From the analysis of just those two pumps, they were shown to consume 17,864 kWh annually (for the first year post-occupancy) whereas the proposed ESM only allocated 10,050 kWh for the year for all of the buildings pumps. Although it is unlikely to get the buildings pumping energy to match that suggested by the proposed ESM due to the primary pumps and baseboard heater pumps, an attempt was made to try and reduce it as much as possible.

The Fluke 41b meter was implemented again to monitor the secondary GSHP loop performance. Operations for the one and two pumps were observed to determine if there was a need for two pumps to run simultaneously. When the secondary loop was allowed to operate with just one pump, the system ran as designed, the differential pressure (dP) set point was kept constant and no low pressure alarms were triggered in the RTU (the furthest piece of equipment within the loop, require most flow) which would have indicated the single pump could not supply enough flow or head pressure.

The Fluke 41b then captured the operating points for the pumps operating in parallel and for a single pump running alone. The power draw for a one pump operation was slightly higher than the power draw for a single pump in parallel but that is because the pumps in parallel operation share the load. For instance, one pump at 80% speed may have a power draw of 1.2 kW where one pump within the parallel operation may draw only 1.0 kW, but there are two pumps operating so the system actually draws 2 kW total power for the same operation. Figure 5.3 shows the relationship between the power draw of one pump on its own, one pump in parallel and the summation of the two pumps in parallel, along with the curve fits obtained for each set of data.

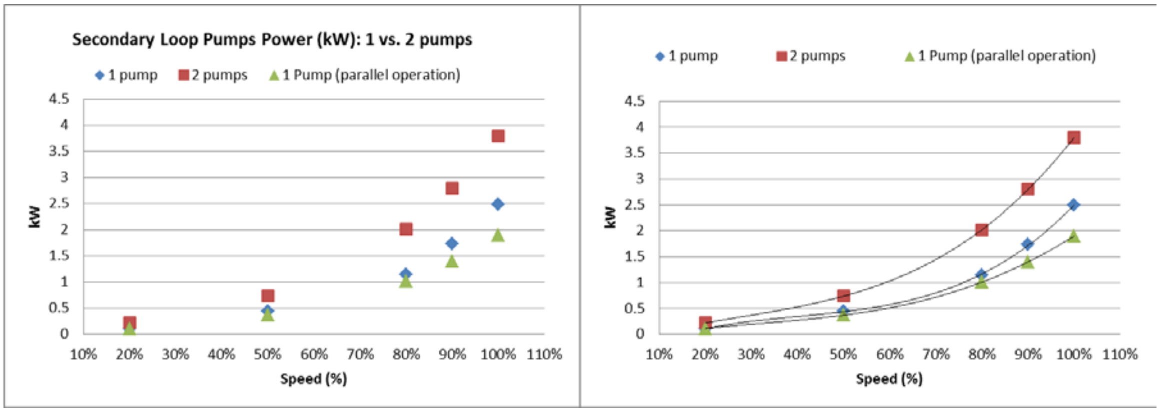


Figure 5.3: Results of the Secondary GSHP Loop Pump Operations Power Draw

Therefore the power savings associated with just operating one pump will not be equal to just half of the previously calculated secondary loop pump power. This is due to there being a greater load on just the one pump. The savings associated with running just one pump can be seen in Table 5.2. The pump speed did not vary in terms of percent operating speed over the year.

Table 5.2: Energy Savings Associated with Operating One Secondary Loop Pump

Percentage of Time Pumps Spend at Each Speed Interval For Parallel Pump and One Pump Operation				Power Calculations (kWh)	
% Speed	P-3	P-4	One Pump	2 Pumps	1 Pump
100%	1.1%	1.1%	1.1%	363	236.4
90-99%	6.8%	6.6%	6.7%	1,903	1,211.7
80-89%	40.2%	39.3%	39.7%	8,139	4,928.6
70-79%	51.4%	51.2%	51.3%	7,442	4,334.3
60-69%	0.2%	0.2%	0.2%	17	9.1
50-59%	-	-	-	0	0
40-49%	-	-	-	0	0
30-39%	-	-	-	0	0
20-29%	-	-	-	0	0
0%	0.4%	1.7%	1.1%	0	0
Totals	100.0%	100.0%	100.0%	17,864	10,720
			TOTAL ENERGY SAVINGS	**7,144 kWh Savings**	

To turn the secondary loops second pump off was again done through the BAS, where the building operator locked out one pump and put in a scheme to rotate the pumping operation. This will ensure that both pumps get enough run time during the week (while never running together) ensuring the seals within the pumps stay tight and lubricated for preventative maintenance purposes. Therefore by reducing the secondary loops pumping load to just the one pump, the energy savings associated with this measure are just above 7,000 kWh.

5.5 GSHP Secondary Loop EWT Control Optimization

After analyzing the trends of the building's HVAC systems through the BAS, a finding on how to determine the overall load within the building (heating/cooling load) was formulated. The building's overall loaded state for all HVAC equipment within the building could be determined simply from GSHP's secondary loops conditions. The secondary loops entering water temperature (EWT) and leaving water temperature (LWT) temperature differential (ΔT) indicated the net zone-conditioning load of the building. Figure 5.4 shows a diagram for this logic.

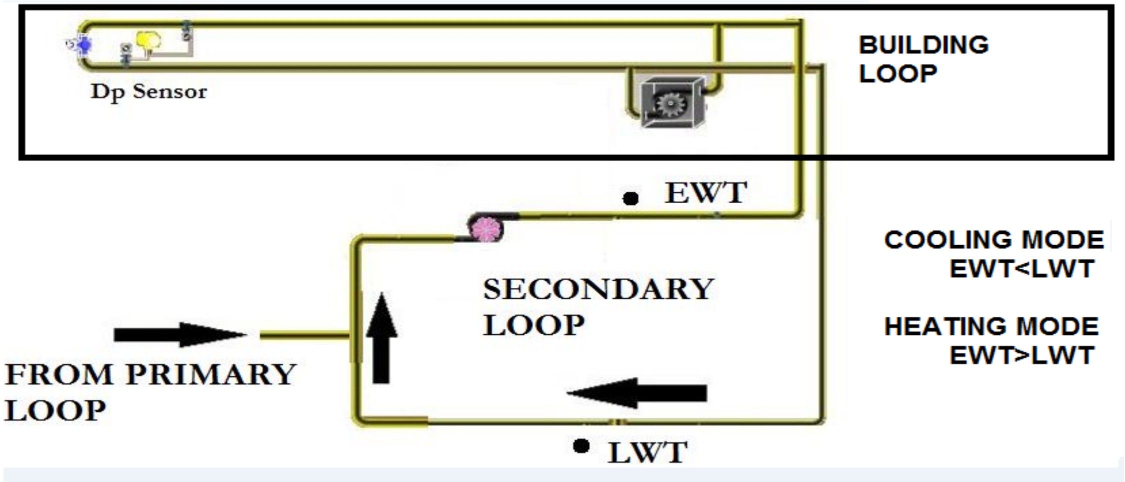


Figure 5.4: Relationship Between the Buildings EWT and LWT Condition

Algorithms using these sensors could serve as an input to some of the HVAC systems control sequences to ensure optimal performance and minimize over heating/cooling. For example, the RTU could at times pre-cool the outside air when a majority of spaces were actually calling for heat.

The BAS can provide the building operator complete control of all of the building's systems and equipment via a remote desktop. Figure 5.5 shows the building's primary-secondary GSHP loop as installed at the facility, this is also how it appears on the BAS. The diagram shows the four (4) vertical wells where flow through the wells is controlled via the primary loop pump. The secondary loop then circulates water throughout the facility via the secondary loop pump to provide water to the buildings HVAC equipment. The secondary loop system operation utilizes a differential pressure (dP) sensor , located strategically at the far legs of the system, to control the secondary loop pump's speed. When a zone calls for heating or cooling, solenoid valves open to allow the EWT flow to circulate through the operating HVAC equipment, and bypasses the equipment not running. The opening and closing of valves creates change in the systems pressure. The pressure variations control the secondary loop pump’s speed, the pump throttles accordingly through a feedback system to provide the proper dP through variable frequency drives (VFDs) resulting in a change in flow rate. A BAS collects data about the pumping systems speed, flow, EWT, LWT, and WWT of the primary-secondary loop through the sensor locations shown in Figure 5.5.

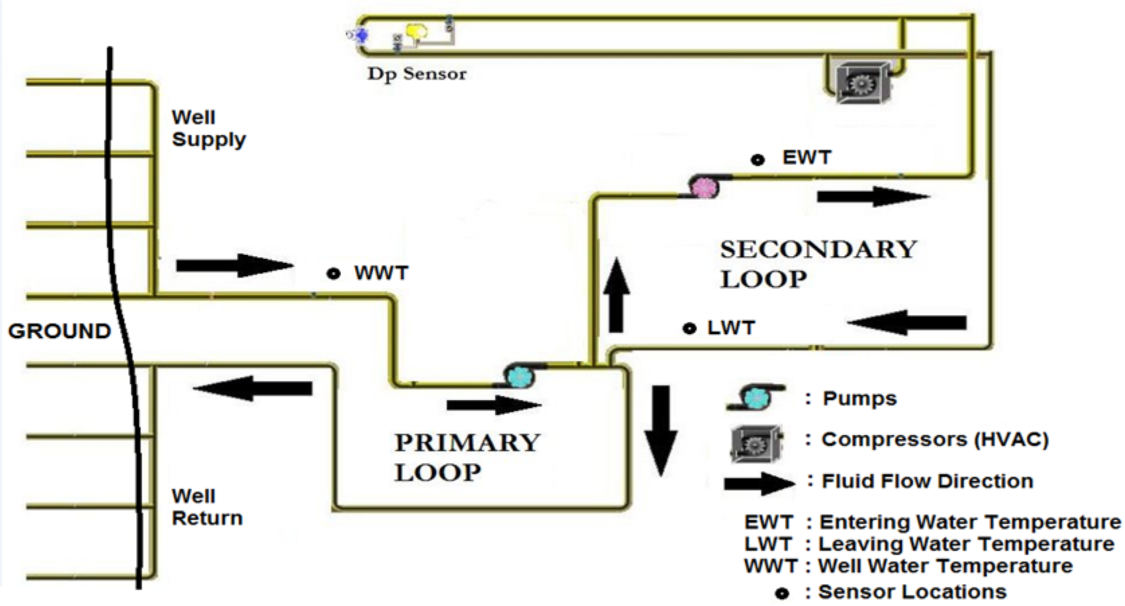


Figure 5.5: De-Coupled Primary-Secondary GSHP Loop Configuration

It should be noted that due to the nature of the decoupled system in Figure 5.5, to conserve pump energy the primary pumps should never provide more flow than the secondary loop requires, this leads to unnecessary recirculation. Another observation is the GSHP EWT and LWT conditions. The EWT and LWT of the secondary loop can provide insight to building’s current HVAC load. This ability to determine the building load is important to the sequence of operations of all the HVAC systems that work in series with the GSHP loop (which essentially is everything). Another observation while gathering data from the BAS showed an opportunity with the primary loop pumps control. Due to the majority of the HVAC systems within the building using heat pumps, their power consumption is directly related to the EWT received by the equipment. Data obtained through the BAS on the GSHP loop operation indicated that during times of both cooling and heating, there existed times where a more optimal well water temperature (WWT) existed. The more favorable WWT could be supplied by the primary pumps to the secondary loop to improve HVAC system energy performance. Figure 5.6 demonstrates the relationship for EWT and the coefficient of performance (COP) of the heat pump performance for one of the heat pumps[11]. All of the heat pumps within the building have the characteristic curve performance where the larger units typically will run more efficient.

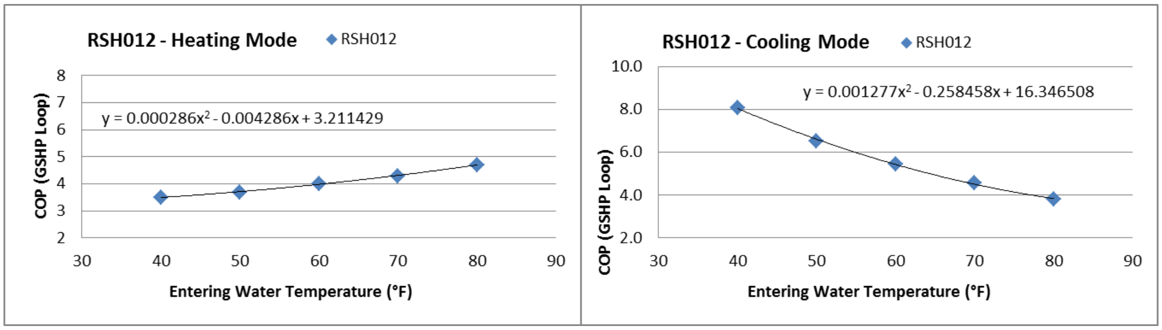


Figure 5.6: HP COP Performance Curves

The COP of the equipment is defined by equation 5.1.

$$\text{COP} = \frac{\text{Equipment Rated Power Output}}{\text{Equipment Power Input}} \tag{5.1}$$

Therefore when the heat pumps are in heating mode, the higher the temperature of the EWT, the less energy they will consume to provide the same heating load, and inversely for cooling operations. From Figure 5.7 we can see that there are many opportunities in which the primary pumps could have run to supply a more optimal EWT for the heat pumps and reduce the work required by the HPs to provide the same load.

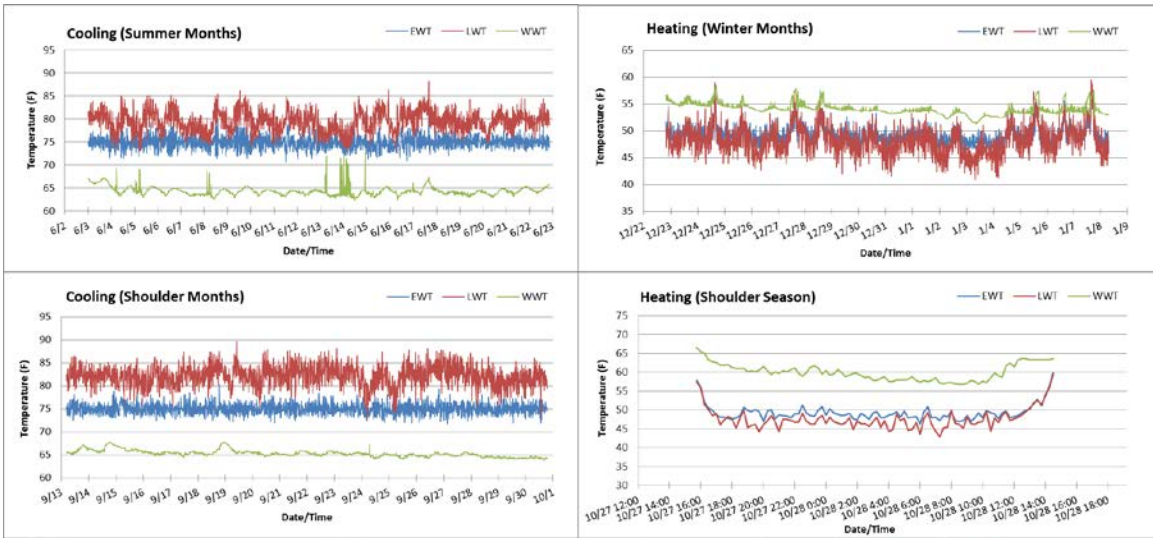


Figure 5.7: Example of Opportunities for Improving the Buildings EWT

From the figure it can be observed that in some cases there was opportunity to improve the building's EWT by 10 °F. This would lead to energy savings experience by those equipment's compressors in order to provide zone conditioning for occupants.

The primary well pump operates based on a fixed operating temperature set point range. This was determined not to be the most optimal control for the building's system in terms of the EWT condition and optimizing for the operating unit's COP. The current EWT band is set at 40-75°F. For example in the summer months when the temperature of the EWT exceeds the 75°F set point, the primary pump ramps up to lower the EWT to the highest temperature set point range, with the cooler WWT ground water. Due to the EWT control band, this sequence will often get the EWT, with an upper set point of 75°F down to 74-75°F before the primary pump shuts off. This is true even in cases where the WWT is lower and more favorable to the operating equipment's COP as seen in Figure 5.7. This operation then results in the primary pumps cycling on and off to maintain a 74°F EWT. Running the primary pump longer at reduced speeds would incur the same pump energy penalty[12] (while eliminating any over pumping) and the system could reduce the secondary loops EWT to match the WWT, which in some cases is at 10°F cooler. This would improve the cooling COP performance and reduce energy consumption of the HVAC compressors within the building. Same conditions can be found to hold true during the heating season.

The proposed operation would involve a control algorithm that will take into account all of the building systems, whether in cooling or heating, and determine the building's overall weighted COP and actual energy input. This will determine when to introduce the WWT into the secondary loop via the primary loop pump. The proposed algorithm can also determine actual energy consumption savings during the operation of the control, giving an indication as to how well the GSHP loop is performing.

To determine whether the primary pump should operate, the COP for the building in both heating and cooling modes will be determined. The HVAC equipment compressors input power based on the WWT will be calculated and compared to the existing COP. Calculations will be performed for the current EWT and for the WWT available. The proposed operation would involve the following sequence:

- Monitor the secondary GSHP loop's EWT vs. LWT and determine the dominant the building load; i.e., heating, cooling, or balanced (no temperature differential)
- When in heating or cooling load (defined by >1 °F differential); compare primary GSHP loop WWT with current EWT of the secondary loop
- For heating mode (WWT>EWT); and for cooling mode (EWT>WWT): run algorithm to determine if opportunity exists to reduce system power consumption by comparing building COP under existing and new operating conditions

The sequence will determine if the building compressors would require less power to run, and if the COP was improved by introducing the primary GSHP loop's water at WWT. If equation (5.2) is true, then the primary pump should operate to provide the WWT to the secondary loop.

$$\left(\text{Power}_{\text{input}}\right)\Big|_{\text{WWT}} < \left(\text{Power}_{\text{input}}\right)\Big|_{\text{EWT}} \tag{5.2}$$

This algorithm along with secondary loop EWT and WWT data collected from the BAS will determine the necessary power required to operate the buildings HVAC system. By determining which available water temperature best benefits the building system, a determination of whether to run the primary pump can be made. Savings will be realized from accessing the WWT to increase the buildings overall COP.

$$\text{Power}_{\text{input}} = \left(\text{Power}_{\text{cooling}} + \text{Power}_{\text{heating}}\right) \tag{5.3}$$

To determine the input power required for all working compressors, the units in heating and cooling mode will need to be identified through the BAS data. The summation of the rated power output from manufacturer’s data for all working compressors in each mode will then be calculated. The calculated rated output power for working compressors is then divided by the overall weighted COP for working compressors in both heating and in cooling mode, as seen in equation (5.4).

$$\text{Power}_{\text{input}} = \left[\left(\frac{\sum_{i=1}^{n}\left(\text{RP}_i\right)}{\left(\text{COP}_{\text{weighted}}\right)_{\text{cooling}}}\right)_{\text{cooling}} + \left(\frac{\sum_{i=1}^{n}\left(\text{RP}_i\right)}{\left(\text{COP}_{\text{weighted}}\right)_{\text{heating}}}\right)_{\text{heating}}\right]\Bigg|_{\text{EWT/WWT}} \tag{5.4}$$

$i \equiv$ all HVAC compressors within the building

$\text{RP}_i \equiv$ rated power of i^{th} compressor ($\text{RP}_i = 0$ if compressor is off)

To accurately determine the weighted COP (heating/cooling) for all compressors operating at any given time in cooling and in heating mode, equation (5.5) will be used. For this equation, compressor COPs will be calculated for each compressor type (based on the EWT). The COPs can then be normalized by multiplying their respective rated output power (not all equipment is the same size). The sum of all of the individual compressors' normalized COPs for heating and cooling is then to be divided by the sum of rated output power for all operating compressors, accounting for the various size equipment. This avoids situations where smaller more efficient units don't dominate the calculated COP of the system.

$$\mathrm{COP_{weighted}} = \left.\left(\frac{\sum_{i=1}^{n}\left(\mathrm{RP}_i \times \mathrm{COP}_{\mathrm{compressor}_i}\right)}{\sum_{i=1}^{n}\left(\mathrm{RP}_i\right)}\right)\right|_{\text{cooling/heating}} \tag{5.5}$$

To determine the COP for each piece of equipment operating in either heating or cooling mode, COP curve fit equations for each unit will be used. COP curves should be generated for each type of compressor for both the heating and cooling modes of operation and as a function of EWT (or possibly WWT) to the unit, which is denoted in equation (5.6) below.

$$\mathrm{COP}_{\mathrm{Compressor}_i} = \mathrm{COP}\left[f(\mathrm{EWT})\right]\Big|_{\text{EWT/WWT-curve fit equation as function of EWT}} \tag{5.6}$$

This algorithm with EWT and WWT data collected from the building BAS will determine the necessary power input to the building HVAC system. By determining which available water temperature best benefits the building system, a determination of whether to run the primary pump can be made. Savings will be realized from accessing the WWT to increase the buildings overall COP.

A sensitivity analysis was performed using the algorithm along with simplifications about the building's average characteristic loads for certain seasonal operations. Included is the heating and cooling season, along with the shoulder months cooling and heating operations. During the shoulder seasons is when the building encounters balanced loads where some equipment will be in heating while some in cooling. This could be the result of times when the building is heating but there are zones on the south facing walls that require cooling due to solar gains through the large windows. Table 5.3 shows the sensitivity analysis done to determine the weighted COP changes for the building equipment and opportunities for power savings for each condition.

Table 5.3: Sensitivity Analysis of WWT and Building COP

COOLING (Summer Months - Dominant Load)						**HEATING (Winter Months - Dominant Load)**					
Average EWT (BAS data)	Temperature Decrease	Overall Building COP	COP Improvement	(75%) Loaded System Power Savings	(50%) Loaded System Power Savings	Average EWT (BAS data)	Temperature Increase	Overall Building COP	COP Improvement	(75%) Loaded System Power Savings	(50%) Loaded System Power Savings
°F/°C	°F/°C	-	(%)	(kW)	(kW)	°F/°C	°F/°C	-	(%)	(kW)	(kW)
74.5/23.6	0/0	4.65	0%	0.0	0.0	46.5/8.1	0/0	3.80	0%	0.0	0.0
74.5/23.6	1/0.6	4.71	1%	0.6	0.5	46.5/8.1	1/0.6	3.84	1%	0.5	0.4
74.5/23.6	2/1.1	4.77	3%	1.2	0.9	46.5/8.1	2/1.2	3.88	3%	1.0	0.7
74.5/23.6	3/1.7	4.84	4%	1.7	1.3	46.5/8.1	3/1.7	3.93	4%	1.5	1.1
74.5/23.6	4/2.2	4.90	5%	2.3	1.7	46.5/8.1	4/2.3	3.97	5%	2.0	1.5
74.5/23.6	5/2.8	4.96	7%	2.8	2.1	46.5/8.1	5/2.8	4.01	6%	2.4	1.8
74.5/23.6	6/3.3	5.02	8%	3.3	2.5	46.5/8.1	6/3.4	4.06	7%	2.9	2.1
74.5/23.6	7/3.9	5.09	9%	3.9	2.9	46.5/8.1	7/4.0	4.10	8%	3.3	2.5
74.5/23.6	8/4.4	5.16	11%	4.4	3.3	46.5/8.1	8/4.5	4.14	9%	3.8	2.8
74.5/23.6	9/5	5.23	13%	5.0	3.8	46.5/8.1	9/5	4.18	10%	4.2	3.1
74.5/23.6	10/5.6	5.31	14%	5.6	4.2	46.5/8.1	10/5.6	4.22	11%	4.6	3.4

Cooling (Shoulder Seasons - Balanced Loads)						**Heating (Shoulder Seasons - Balanced Loads)**					
Average EWT (BAS data)	Temperature Decrease	Overall Building COP	COP Improvement	(50% cool to 10% heat) Loaded System Power Savings	(50% cool to 25% heat) Loaded System Power Savings	Average EWT (BAS data)	Temperature Increase	Overall Building COP	COP Improvement	(50% heat to 10% cool) Loaded System Power Savings	(50% heat to 25% cool) Loaded System Power Savings
°F/°C	°F/°C	-	(%)	(kW)	(kW)	°F/°C	°F/°C	-	(%)	(kW)	(kW)
74.5/23.6	0/0	4.66	0%	0.0	0.0	50/10	0/0	4.41	0%	0.0	0.0
74.5/23.6	1/0.6	4.72	1%	0.4	0.4	50/10	1/0.6	4.42	1%	0.3	0.2
74.5/23.6	2/1.1	4.77	3%	0.9	0.8	50/10	2/1.1	4.43	1%	0.5	0.3
74.5/23.6	3/1.7	4.83	4%	1.3	1.2	50/10	3/1.7	4.45	1%	0.8	0.5
74.5/23.6	4/2.2	4.88	5%	1.6	1.5	50/10	4/2.2	4.46	2%	1.0	0.6
74.5/23.6	5/2.8	4.94	6%	2.0	1.9	50/10	5/2.8	4.47	2%	1.3	0.7
74.5/23.6	6/3.3	5.00	8%	2.4	2.2	50/10	6/3.3	4.49	2%	1.5	0.8
74.5/23.6	7/3.9	5.06	9%	2.8	2.6	50/10	7/3.9	4.50	2%	1.7	0.9
74.5/23.6	8/4.4	5.12	10%	3.2	3.0	50/10	8/4.4	4.51	3%	1.9	0.9
74.5/23.6	9/5	5.19	12%	3.6	3.4	50/10	9/5	4.53	3%	2.1	1.0
74.5/23.6	10/5.6	5.27	13%	4.1	3.7	50/10	10/5.6	4.54	3%	2.2	1.0

A real time simulation was performed using the 15 minute BAS data. The EWT for each 15 minute time step was compared with the potential WWT available in the primary GSHP loop along with all the buildings compressors' status to implement the control algorithm. Figure 5.8 is a graph of the results over a year for the potential power savings achievable from implementing the control algorithm on the existing system. It is observed that the most savings occur during the shoulder months and the summer months.

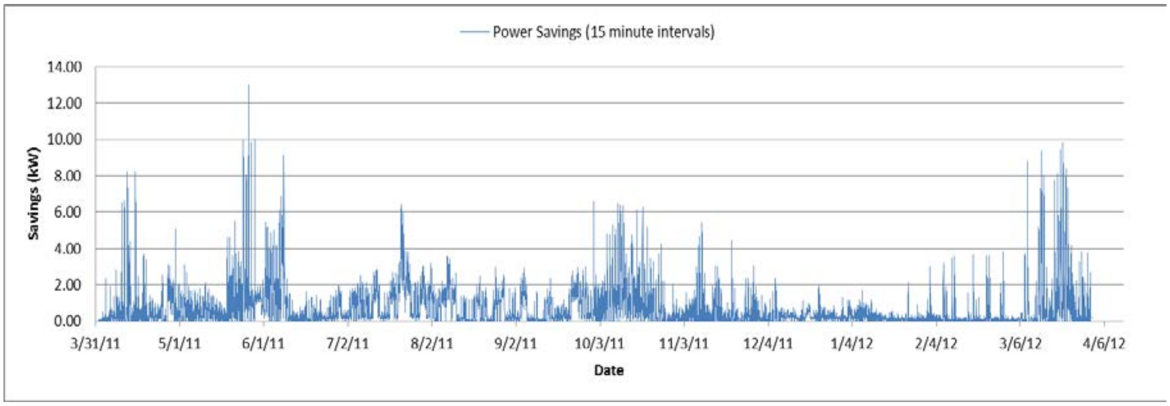


Figure 5.8: GSHP EWT Control Algorithm Expected Power Savings

During the summer months the opportunity exists to save energy because of the increased number of operating HVAC equipment. The temperature differential between the EWT and WWT during the summer is lower but there is still energy saving opportunities. For the summer scenario energy savings result due to a slight increase in COP for the cooling equipment. The slight increase in COP propagates as there are a higher number of HVAC equipment in operation, therefore the overall power reduction is experience over all of the operating compressors. There is little opportunity experienced for the winter months likely due to the mild weather during this time.

After the simulation was completed for each time step, all data, for the EWT and LWT for either cooling or heating mode of operation, was averaged on a monthly basis. The associated power savings from utilizing the WWT fluid to increase the HVAC systems COP was also averaged on a monthly basis for that year. Table 5.4 shows the results associated with the potential operation of the algorithm for this building over the first year post-occupancy.

Table 5.4: GSHP EWT Control Algorithm Monthly Data

		Current Secondary Loop Operation EWT						›roposed EWT (WWT		Temperature Change Results				Power/Energy Savings		
Year	Month	Actual Heating Mode Operation Opportunities			Actual Cooling Mode Operation Opportunities			Heating Mode WWT	Cooling Mode WWT	Increase Temperature Heating Mode		Decrease Temperture Cooling Mode		Heating Average Savings	Cooling Average Savings	Building Energy Savings
		°F	Hours	COP	°F	Hours	COP	°F	°F	°F	COP	°F	COP	(kW)	(kW)	(kWh)
2011	**April**	49.3	292.8	4.84	63.5	252.0	5.35	52.2	56.5	35.0	4.81	40.2	5.41	0.3	1.4	441.7
	May	52.7	19.8	4.82	66.2	674.5	5.05	57.2	60.6	36.5	4.76	37.9	5.19	0.3	0.9	633.9
	June	66.7	1.5	4.71	70.3	640.0	4.85	67.5	65.7	32.8	4.71	36.7	4.97	0.0	0.9	586.2
	July	-	0.0	-	73.7	744.0	4.72	-	71.0	-	-	34.7	4.84	-	1.1	837.7
	August	-	0.0	-	74.5	632.5	4.70	-	71.7	-	-	34.6	4.82	-	0.8	530.3
	Septembe	55.6	2.8	4.85	72.5	677.5	4.75	67.0	69.7	43.4	4.74	34.6	4.87	0.2	0.7	459.3
	October	48.3	50.0	4.92	74.8	534.8	4.69	54.3	66.0	38.1	4.80	40.7	4.93	0.3	1.3	694.4
	Novembe	49.4	157.0	4.89	73.1	314.8	4.72	56.4	61.1	39.0	4.77	42.2	4.89	0.3	0.8	305.1
	Decembe	47.1	573.8	4.73	72.3	47.3	4.67	49.4	61.1	34.3	4.70	42.2	4.91	0.3	0.7	182.1
2012	**January**	47.9	586.5	4.90	67.9	24.5	4.81	50.1	52.4	34.2	4.86	43.7	5.08	0.2	0.5	136.2
	February	48.1	205.3	5.11	68.1	141.5	4.88	50.7	54.8	34.6	5.03	44.5	5.20	0.1	1.0	154.0
	March	47.3	163.3	4.96	72.8	378.0	4.76	49.4	58.9	34.1	4.92	44.0	5.09	0.1	1.7	656.8
	TOTALS		2052.5			5061.3										5,618

The table also indicates that the COP during the heating opportunities was not significantly increased, if at all. This is believed to be a result of cooling equipment running at the same time and affecting the overall weighted COP, which is the COP that is reported within Table 5.4. The algorithm looks at the difference in energy required to operate the HVAC equipment with either the EWT or WWT. Although the COP did not increase, there were still savings experienced; although minimal when comparing heating verse cooling average kW savings in the table. It should be noted that the heating opportunities only account for 8% of the algorithms overall annual energy savings as opposed to the 92% from cooling.

There is opportunity for the use of this optimized EWT control for systems with a decoupled primary-secondary GSHP loop configuration. There were savings of approximately 3-4% of the overall compressor energy experienced during the entire annual simulation. It is also believed that there was missed opportunity during the winter due to the unseasonable weather experienced. Results also show that the greatest potential exists during shoulder and summer months to optimize a decoupled GSHP system to achieve additional performance improvement and energy savings.

Analysis for two different times of the summer was selected to demonstrate the proposed control algorithm. To help determine how the loading of the HVAC systems compressors for those days would affect the implemented algorithm performance and the building energy consumption. A five day period in June was analyzed where the outside temperature was mild along with a four day period in July during a heat wave. During the June time period, there was a greater temperature differential for the WWT verses the EWT, but due to the mild outside weather temperature, not as many compressors were operating. This resulted in a higher percent increase in the COP for a reduced compressor load which resulted in an average 2.04 kW power savings during that time. During the July heat wave, the temperature differential of the WWT verses the EWT had less potential, but more of the HVAC compressors were operating. This resulted in a lower percent increase in COP but for a higher compressor load which resulted in an average 1.45 kW power savings during that time. Results for both simulations can be viewed in Figure 5.9.

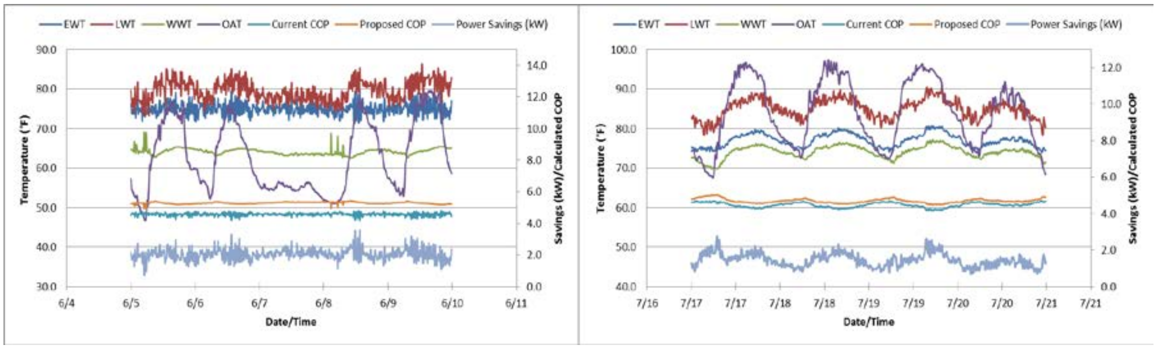


Figure 5.9: GSHP EWT Control Algorithm Summer Profile Result

This analysis shows that there is potential for the control algorithm when the HVAC loads within the building are small due to mild weather and when loads are high due to severe weather. There is more of an opportunity to increase the COP when a large temperature differential exists for the WWT verse the EWT, but due to less equipment in operation, there is only so much energy to be saved. During times of high loads, even a small change in temperature can affect the equipment’s COP resulting in power savings due to the increase power consumption of the buildings compressors.

The building energy consumption associated with compressor operations was estimated to be approximately 180,000 kWh, which agrees with various sub-meters installed within the facility. The proposed mode of operation indicates a 3-4% reduction in building compressor energy consumption without the need for any additional equipment.

5.6 Retro-Commissioning Results and Predictions

The retro-commissioning process was successful in reducing the energy consumption of the building. The identification and implementation of energy reduction measures was facilitated by the buildings network of electrical submeters and a BAS. For example reduction of the building’s fan operations were implemented solely through the BAS and resulted in considerable savings immediately. The installed technology within the building, not found in most new construction buildings, provided invaluable benefits to the retro-commissioning process. The on-site technologies, along with the proposed ESM, demonstrated a clear indication of what systems, in some cases what equipment, were to blame for the excess energy consumption. New construction buildings, if mandated to be installed with systems to monitor and help benchmark energy performance, would benefit in countless ways. If benchmarked performance metrics and a BAS are utilized, building operators and industry as a whole would acquire a better understanding of how their building operates and how it shouldn’t operate. This will enable operators to maintain control of their energy consumption for themselves and the nation.

The results for the retro-commissioning process can be realized through the measured, and expected savings from implementing the energy efficiency measures (EEMs). Figure 5.8 shows the progression of the building's proposed to the calibrated ESM. It then shows the building's actual measured energy consumption post-occupancy. Table 5.5 then shows the actual values for the buildings past and current energy consumption along with the projected savings from implementing the rest of the control algorithms discussed in previous sections.

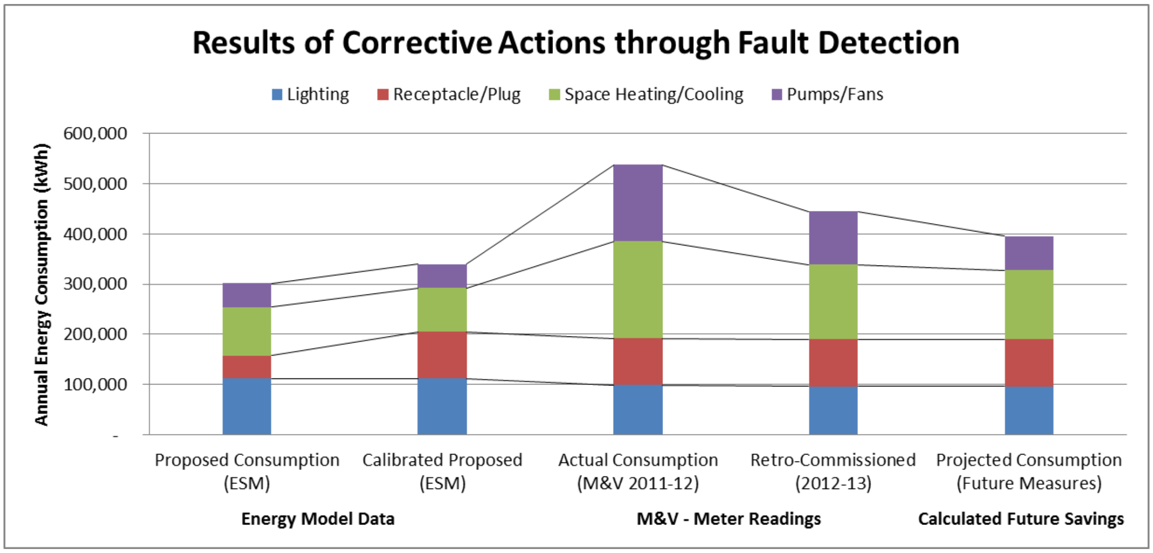


Figure 5.8: Progression of Buildings Energy Consumption

Table 5.5: Results of ESM, M&V Process along with Predicted Future Usage

ESM Results, M&V Results, Projected Results					
End User Category	**Proposed Consumption (ESM)**	**Corrected Consumption (ESM)**	**Actual Consumption (M&V 2011-12)**	**Retro-Commissioned (2012-13)**	**Projected Consumption (Future Measures)**
Lighting	111,305	111,305	98,200	95,943	95,943
Receptacle/Plug	45,848	93,700	93,700	93,811	93,811
Space Heating/Cooling	96,585	87,260	192,900	149,332	137,332
Pumps/Fans	47,605	47,440	152,800	105,334	68,334
TOTALS	**301,343**	**339,705**	**537,600**	**444,420**	**395,420**

From Figure 5.8 and Table 5.5 it is observed that even with the implementation of all the EEMs to the building, the proposed ESM targets will not be achieved. The main reason for this is the assumptions by the modelers for the building's HVAC system. By reducing the building's simulated zones down to just 17 (from an actual >40), the simulation couldn't account for the balanced loads. This was realized as the proposed ESM had not accounted for the energy consumption of the downstream HP operations. By modeling just one RTU to supply all of the buildings zones, the simulation could not properly demonstrate some of the issues experienced. For example heating of the incoming air by the RTU where a HP will cool it again downstream.

Assumptions made regarding the building's simulated fan energy was also not consistent with what was experienced within the building. The proposed ESM did drive the static pressure set point optimization but also failed in simulating the HP fan energy. By only assuming that a single RTU was to condition and supply all of the building's incoming air, was aggressive when the building's actual systems are considered. The actual building zones relied on the RTU and local HPs to provide conditioning, and as was the contributing factor to the large deviations experienced through analysis of the proposed ESM and M&V findings.

The modeler's aggressive assumptions on the buildings plug loads were corrected for in the calibrated ESM, but were not considered the fault of the modelers from the IPMVP Option D standard. Although no accounting for the building server room may be to blame for most of the measured deviation.

CHAPTER 6

CONCLUSION

To implement the overall process described in this Thesis, improvement is needed in the approach of new building construction regarding system operations/installations. In the future, the analysis of M&V data and ESM results to drive the retro-commissioning process of an underperforming building could become standard. Allowing efforts to focus on areas that require attention. Perhaps there will be a need to regulate and mandate the installation of electrical submeter configurations to ensure an easy and effective M&V and/or benchmarking process; maybe through new ASHRAE standards? When building owners and operators understand their building's energy consumption and overall function, they can properly manage their energy consumption and possibly collaborate to help other buildings through events and seminars.

This Thesis outlines an approach to utilizing BAS data and electrical submeters to generate energy metrics for a building's systems on a subsystem level. This approach develops benchmarks for the buildings various systems and utilizes existing data from an ESM to find faults and deviations in the current and future operation. Research indicates that buildings which benchmark energy performance show energy reductions for future years of operation[5,6]. Benchmarking allows building operators to identify and remedy issues associated with excess energy consumption before system deficiencies propagate resulting in lost capitol that could be allocated for better spending. Finding faults early on can lead to better equipment maintenance and overall building equipment life. The Department of Energy (DOE) has also implemented a Building Performance Database

(BPD) which would benefit from such energy benchmarks provided through this bottom up building systems approach.

Understanding how a building uses its energy through a reliable energy simulation model is important to the success of future buildings having the ability to monitor, detect, and perhaps troubleshoot building performance issues. Below Figure 6.1 depicts the possible capabilities for some existing BASs, if utilized. Figure 6.1 shows a static alarm set point used to monitor for potential over consumption. The graph is an example of how a top down analysis has faults in detecting issues. As seen, issues may not be realized for a period of time, and when they are, the actual problem is still not identified.

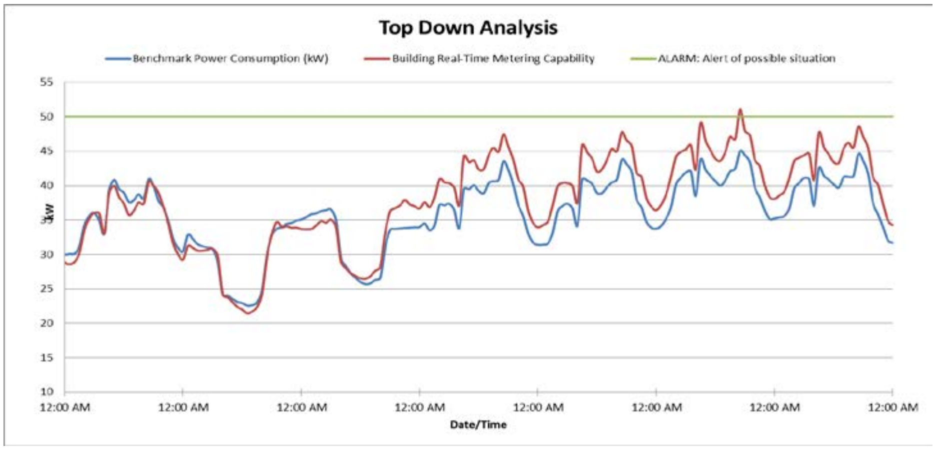


Figure 6.1: Top Down Approach Graphic

As technology evolves equipment such as wireless submeters will experience decreasing prices resulting in wider uses of the devices. In years past, the expertise and funds required to meter an entire facility for strictly energy applications was not cost effective or practical. With the wireless technology becoming cheaper, these types of analysis will become more practical, and necessary as utility prices will most likely continue to increase. Use of submetering will allow for the type of analysis shown in this Thesis for a larger set of customers. That will lead to a more specific monitoring of usage as seen in Figure 6.2 below. When a discrepancy in energy consumption is identified, it is associated with a specific system, narrowing the search for the culprit.

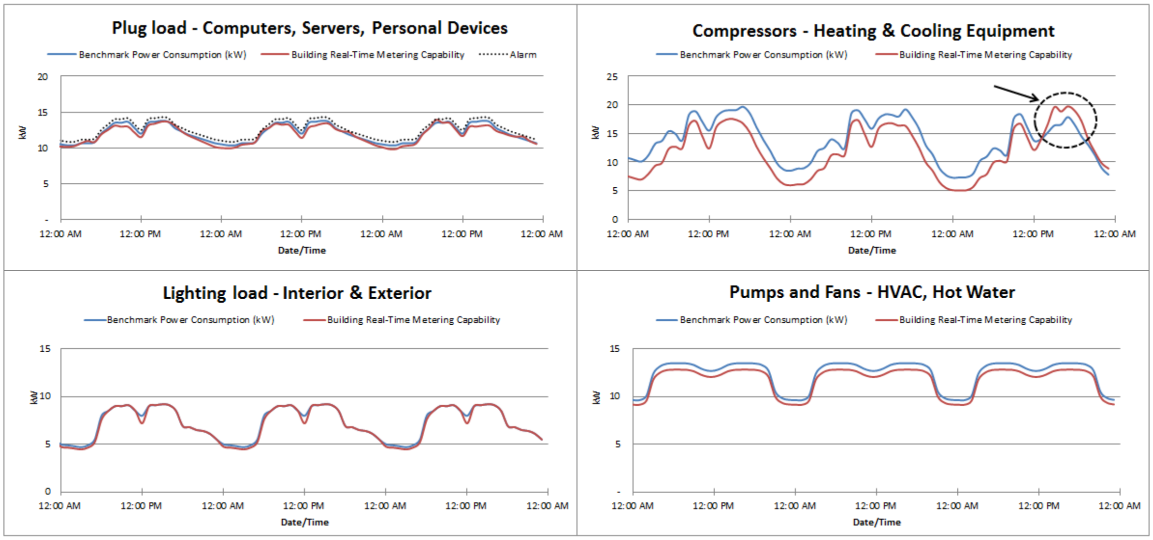


Figure 6.2: Bottom Up Approach Graphic

In the future, cheaper costs may lead to the capability of being able to monitor more of the building equipment allowing for knowledge and control over ones energy consumption.

The work done in this Thesis is unique as it provides the foundation for successfully benchmarking and monitoring new construction buildings for future years with currently available technology. As the technology becomes smaller, cheaper the access to such systems will become more available making the topic of this Thesis more relevant. To ensure industry moves forward in the right direction, proper logic is required to ensure systems operate as designed and continue to do so.

CHAPTER 7

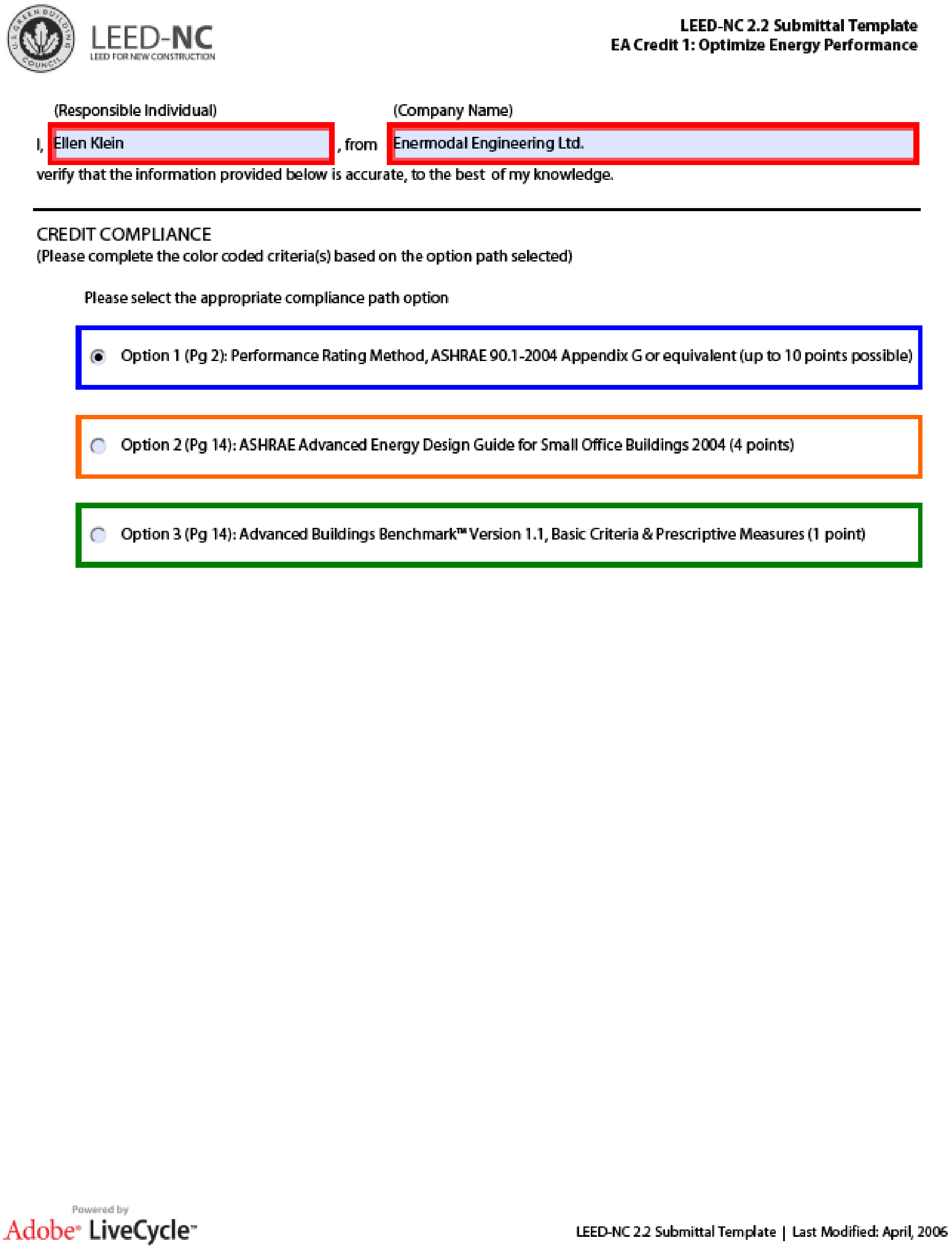
MOVING FORWARD

This Thesis depicts the opportunities that exist for future buildings. Work is still needed before building energy metering, building controls, and ESM become fully integrated. If the ESM engines becomes more reliable in the future (pre- or post-calibration); they can be programmed into the existing BAS along with submeter data resulting in one complete system. The BAS input data, obtained from various sensors located all over the facility, could be used with the ESM engine to perform real-time energy simulation analysis. This would allow for immediate benchmarking of the simulated consumption against actual measured building consumption. This type of real-time analysis would truly make buildings in the future smart, alerting building operators of issues early on.

Systems with sub metering capability within a facility are successful if monitoring of the data is performed routinely. Although monitoring of this type is typically not a top priority of any one person within the facility. Providing the building the ability to monitor itself through the ESM engine, submeter data, actual measured building conditions, and a centralized BAS can be a new concept that can benefit any building, existing or new. There is still a lot of work before all these various systems and data sets can talk together and benefit building energy consumption as described here. The future is bright when considering the possible technology advances on the horizon and the continued drive and focus on reducing the nation’s energy footprint.

APPENDIX

EQUEST ENERGY MODEL



LEED-NC
LEED FOR NEW CONSTRUCTION

LEED-NC 2.2 Submittal Template
EA Credit 1: Optimize Energy Performance

(Responsible Individual) (Company Name)

I, Ellen Klein, from Enermodal Engineering Ltd.
verify that the information provided below is accurate, to the best of my knowledge.

CREDIT COMPLIANCE
(Please complete the color coded criteria(s) based on the option path selected)

Please select the appropriate compliance path option

● Option 1 (Pg 2): Performance Rating Method, ASHRAE 90.1-2004 Appendix G or equivalent (up to 10 points possible)

○ Option 2 (Pg 14): ASHRAE Advanced Energy Design Guide for Small Office Buildings 2004 (4 points)

○ Option 3 (Pg 14): Advanced Buildings Benchmark™ Version 1.1, Basic Criteria & Prescriptive Measures (1 point)

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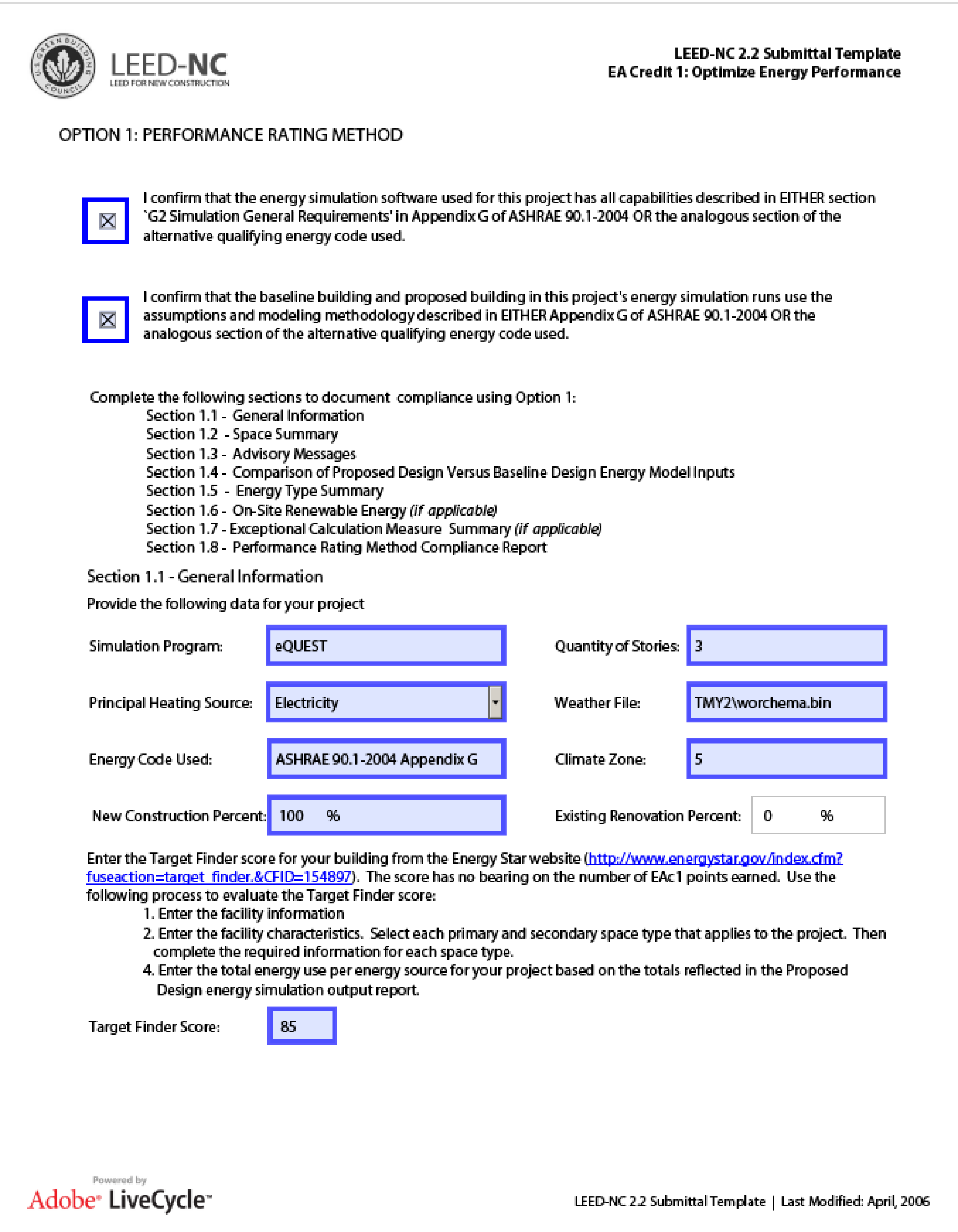
LEED-NC 2.2 Submittal Template | Last Modified: April, 2006



OPTION 1: PERFORMANCE RATING METHOD

☒ I confirm that the energy simulation software used for this project has all capabilities described in EITHER section `G2 Simulation General Requirements' in Appendix G of ASHRAE 90.1-2004 OR the analogous section of the alternative qualifying energy code used.

☒ I confirm that the baseline building and proposed building in this project's energy simulation runs use the assumptions and modeling methodology described in EITHER Appendix G of ASHRAE 90.1-2004 OR the analogous section of the alternative qualifying energy code used.

Complete the following sections to document compliance using Option 1:
- Section 1.1 - General Information
- Section 1.2 - Space Summary
- Section 1.3 - Advisory Messages
- Section 1.4 - Comparison of Proposed Design Versus Baseline Design Energy Model Inputs
- Section 1.5 - Energy Type Summary
- Section 1.6 - On-Site Renewable Energy *(if applicable)*
- Section 1.7 - Exceptional Calculation Measure Summary *(if applicable)*
- Section 1.8 - Performance Rating Method Compliance Report

Section 1.1 - General Information

Provide the following data for your project

Simulation Program:	eQUEST	Quantity of Stories:	3
Principal Heating Source:	Electricity	Weather File:	TMY2\worchema.bin
Energy Code Used:	ASHRAE 90.1-2004 Appendix G	Climate Zone:	5
New Construction Percent:	100 %	Existing Renovation Percent:	0 %

Enter the Target Finder score for your building from the Energy Star website (http://www.energystar.gov/index.cfm?fuseaction=target_finder.&CFID=154897). The score has no bearing on the number of EAc1 points earned. Use the following process to evaluate the Target Finder score:
1. Enter the facility information
2. Enter the facility characteristics. Select each primary and secondary space type that applies to the project. Then complete the required information for each space type.
4. Enter the total energy use per energy source for your project based on the totals reflected in the Proposed Design energy simulation output report.

Target Finder Score: 85

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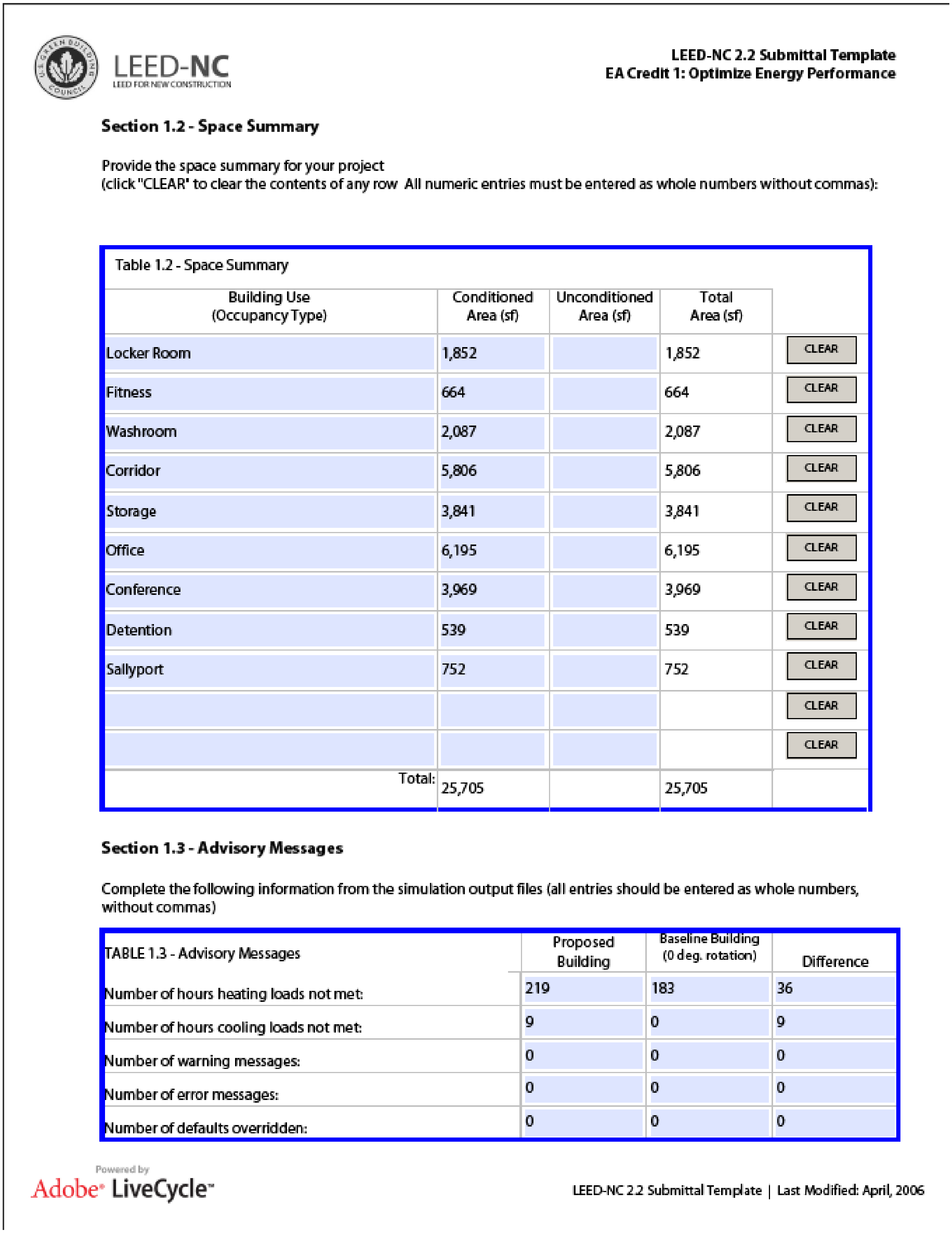

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LEED-NC 2.2 Submittal Template
EA Credit 1: Optimize Energy Performance

Section 1.2 - Space Summary

Provide the space summary for your project
(click "CLEAR" to clear the contents of any row All numeric entries must be entered as whole numbers without commas):

Table 1.2 - Space Summary

Building Use (Occupancy Type)	Conditioned Area (sf)	Unconditioned Area (sf)	Total Area (sf)	
Locker Room	1,852		1,852	CLEAR
Fitness	664		664	CLEAR
Washroom	2,087		2,087	CLEAR
Corridor	5,806		5,806	CLEAR
Storage	3,841		3,841	CLEAR
Office	6,195		6,195	CLEAR
Conference	3,969		3,969	CLEAR
Detention	539		539	CLEAR
Sallyport	752		752	CLEAR
				CLEAR
				CLEAR
Total:	25,705		25,705	

Section 1.3 - Advisory Messages

Complete the following information from the simulation output files (all entries should be entered as whole numbers, without commas)

TABLE 1.3 - Advisory Messages	Proposed Building	Baseline Building (0 deg. rotation)	Difference
Number of hours heating loads not met:	219	183	36
Number of hours cooling loads not met:	9	0	9
Number of warning messages:	0	0	0
Number of error messages:	0	0	0
Number of defaults overridden:	0	0	0

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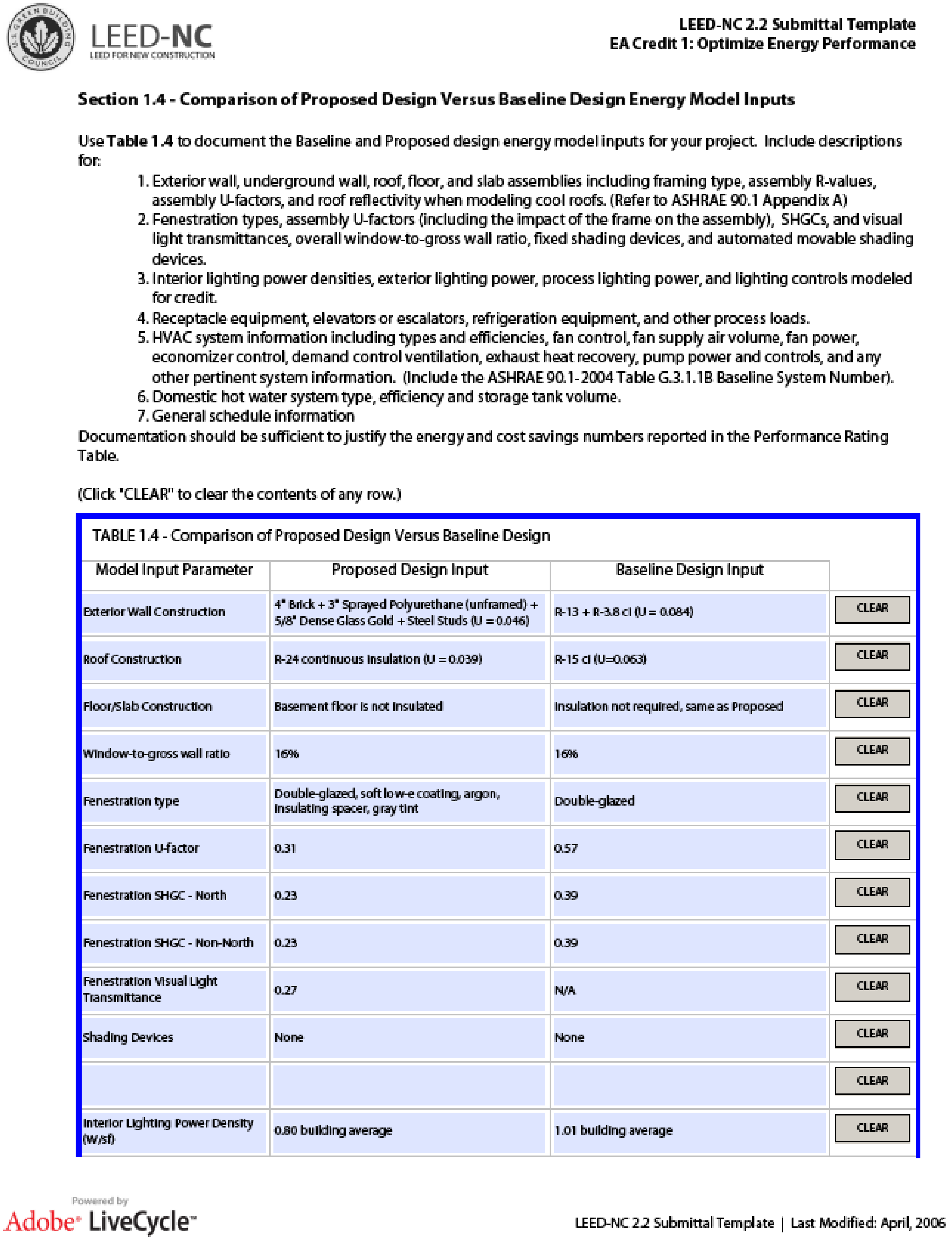

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Section 1.4 - Comparison of Proposed Design Versus Baseline Design Energy Model Inputs

Use **Table 1.4** to document the Baseline and Proposed design energy model inputs for your project. Include descriptions for:

1. Exterior wall, underground wall, roof, floor, and slab assemblies including framing type, assembly R-values, assembly U-factors, and roof reflectivity when modeling cool roofs. (Refer to ASHRAE 90.1 Appendix A)
2. Fenestration types, assembly U-factors (including the impact of the frame on the assembly), SHGCs, and visual light transmittances, overall window-to-gross wall ratio, fixed shading devices, and automated movable shading devices.
3. Interior lighting power densities, exterior lighting power, process lighting power, and lighting controls modeled for credit.
4. Receptacle equipment, elevators or escalators, refrigeration equipment, and other process loads.
5. HVAC system information including types and efficiencies, fan control, fan supply air volume, fan power, economizer control, demand control ventilation, exhaust heat recovery, pump power and controls, and any other pertinent system information. (Include the ASHRAE 90.1-2004 Table G.3.1.1B Baseline System Number).
6. Domestic hot water system type, efficiency and storage tank volume.
7. General schedule information

Documentation should be sufficient to justify the energy and cost savings numbers reported in the Performance Rating Table.

(Click "CLEAR" to clear the contents of any row.)

TABLE 1.4 - Comparison of Proposed Design Versus Baseline Design

Model Input Parameter	Proposed Design Input	Baseline Design Input	
Exterior Wall Construction	4" Brick + 3" Sprayed Polyurethane (unframed) + 5/8" Dense Glass Gold + Steel Studs (U = 0.046)	R-13 + R-3.8 ci (U = 0.084)	CLEAR
Roof Construction	R-24 continuous insulation (U = 0.039)	R-15 ci (U=0.063)	CLEAR
Floor/Slab Construction	Basement floor is not insulated	Insulation not required, same as Proposed	CLEAR
Window-to-gross wall ratio	16%	16%	CLEAR
Fenestration type	Double-glazed, soft low-e coating, argon, insulating spacer, gray tint	Double-glazed	CLEAR
Fenestration U-factor	0.31	0.57	CLEAR
Fenestration SHGC - North	0.23	0.39	CLEAR
Fenestration SHGC - Non-North	0.23	0.39	CLEAR
Fenestration Visual Light Transmittance	0.27	N/A	CLEAR
Shading Devices	None	None	CLEAR
			CLEAR
Interior Lighting Power Density (W/sf)	0.80 building average	1.01 building average	CLEAR

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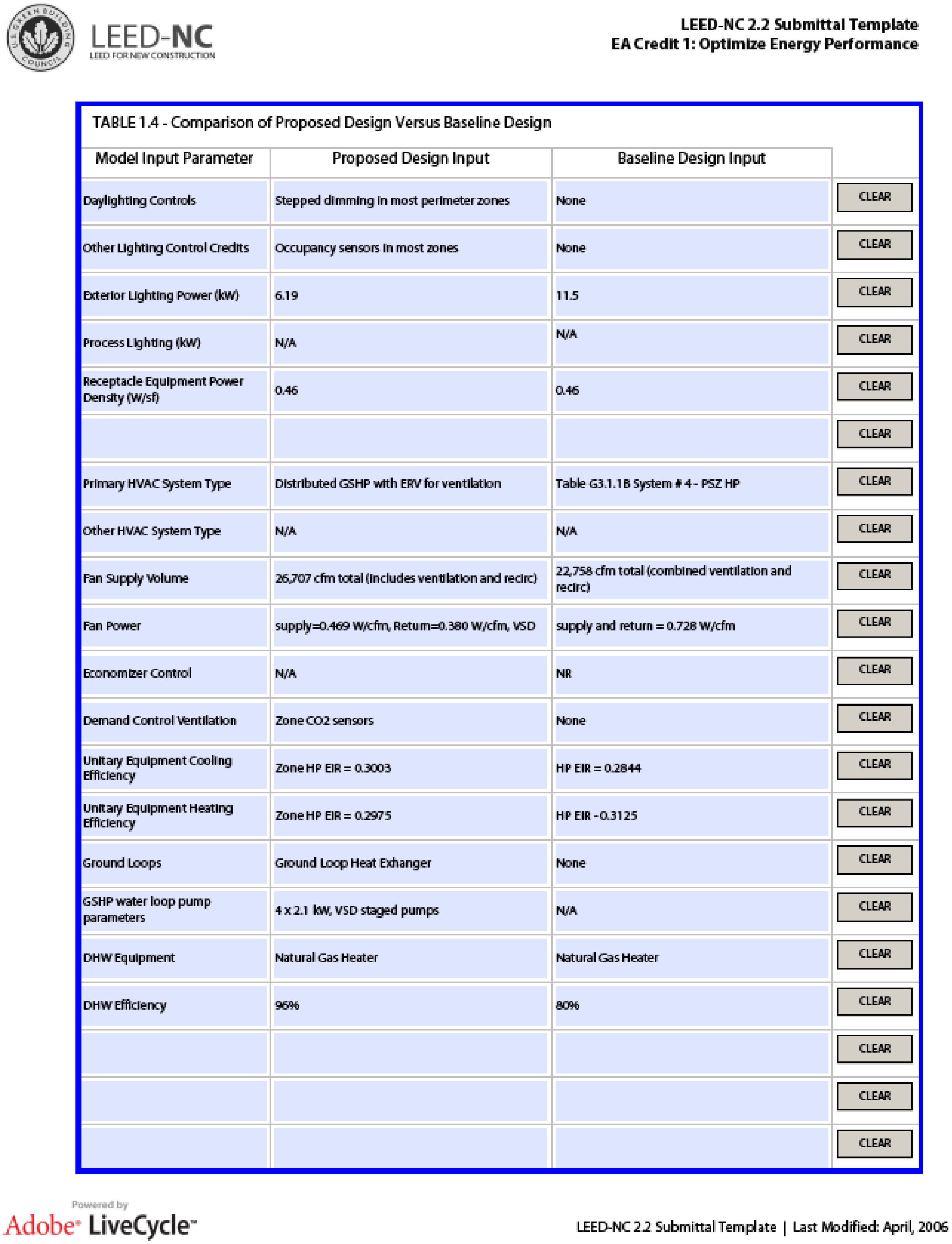

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TABLE 1.4 - Comparison of Proposed Design Versus Baseline Design

Model Input Parameter	Proposed Design Input	Baseline Design Input	
Daylighting Controls	Stepped dimming in most perimeter zones	None	CLEAR
Other Lighting Control Credits	Occupancy sensors in most zones	None	CLEAR
Exterior Lighting Power (kW)	6.19	11.5	CLEAR
Process Lighting (kW)	N/A	N/A	CLEAR
Receptacle Equipment Power Density (W/sf)	0.46	0.46	CLEAR
			CLEAR
Primary HVAC System Type	Distributed GSHP with ERV for ventilation	Table G3.1.1B System # 4 - PSZ HP	CLEAR
Other HVAC System Type	N/A	N/A	CLEAR
Fan Supply Volume	26,707 cfm total (includes ventilation and recirc)	22,758 cfm total (combined ventilation and recirc)	CLEAR
Fan Power	supply=0.469 W/cfm, Return=0.380 W/cfm, VSD	supply and return = 0.728 W/cfm	CLEAR
Economizer Control	N/A	NR	CLEAR
Demand Control Ventilation	Zone CO2 sensors	None	CLEAR
Unitary Equipment Cooling Efficiency	Zone HP EIR = 0.3003	HP EIR = 0.2844	CLEAR
Unitary Equipment Heating Efficiency	Zone HP EIR = 0.2975	HP EIR - 0.3125	CLEAR
Ground Loops	Ground Loop Heat Exhanger	None	CLEAR
GSHP water loop pump parameters	4 x 2.1 kW, VSD staged pumps	N/A	CLEAR
DHW Equipment	Natural Gas Heater	Natural Gas Heater	CLEAR
DHW Efficiency	96%	80%	CLEAR
			CLEAR
			CLEAR
			CLEAR

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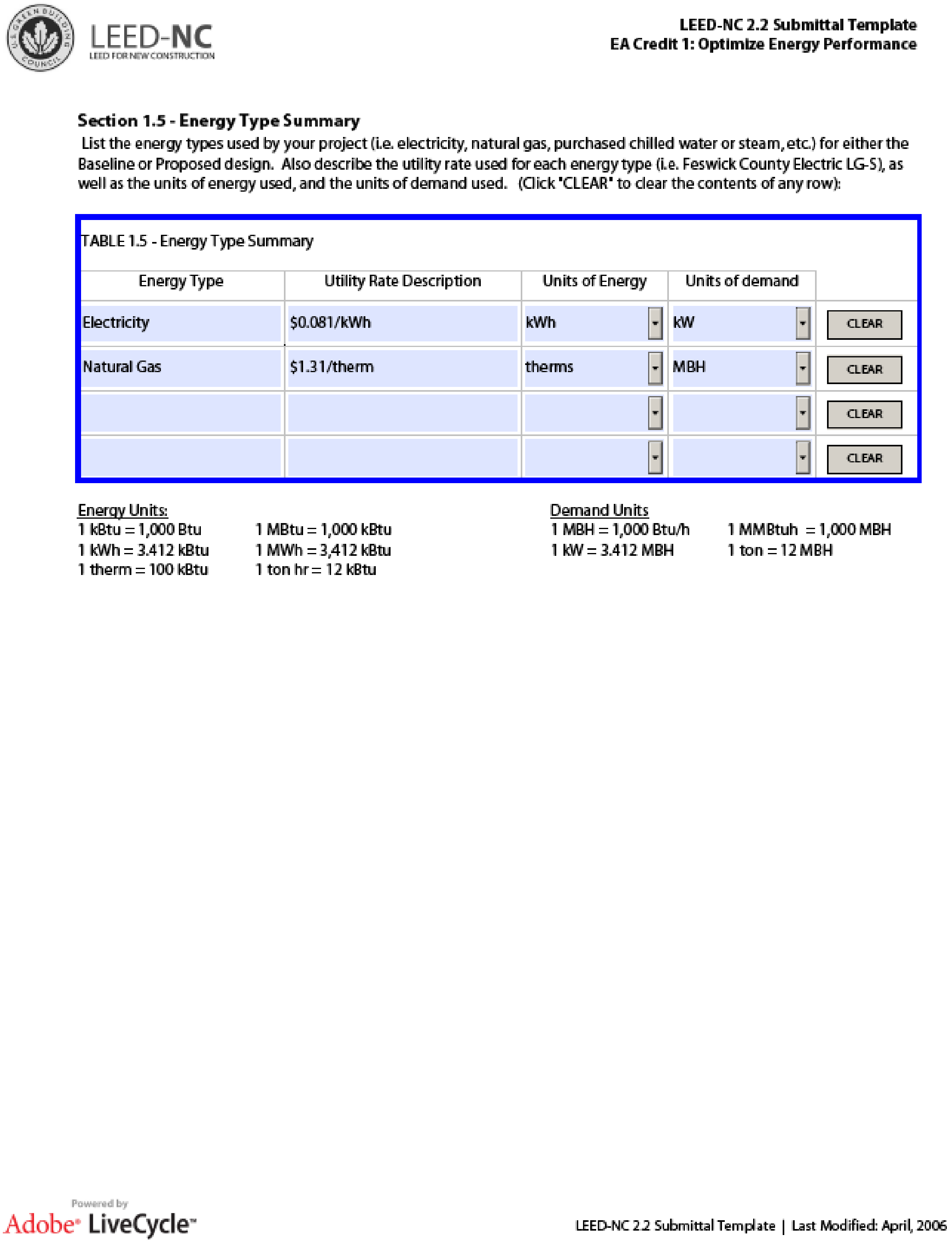


Section 1.5 - Energy Type Summary

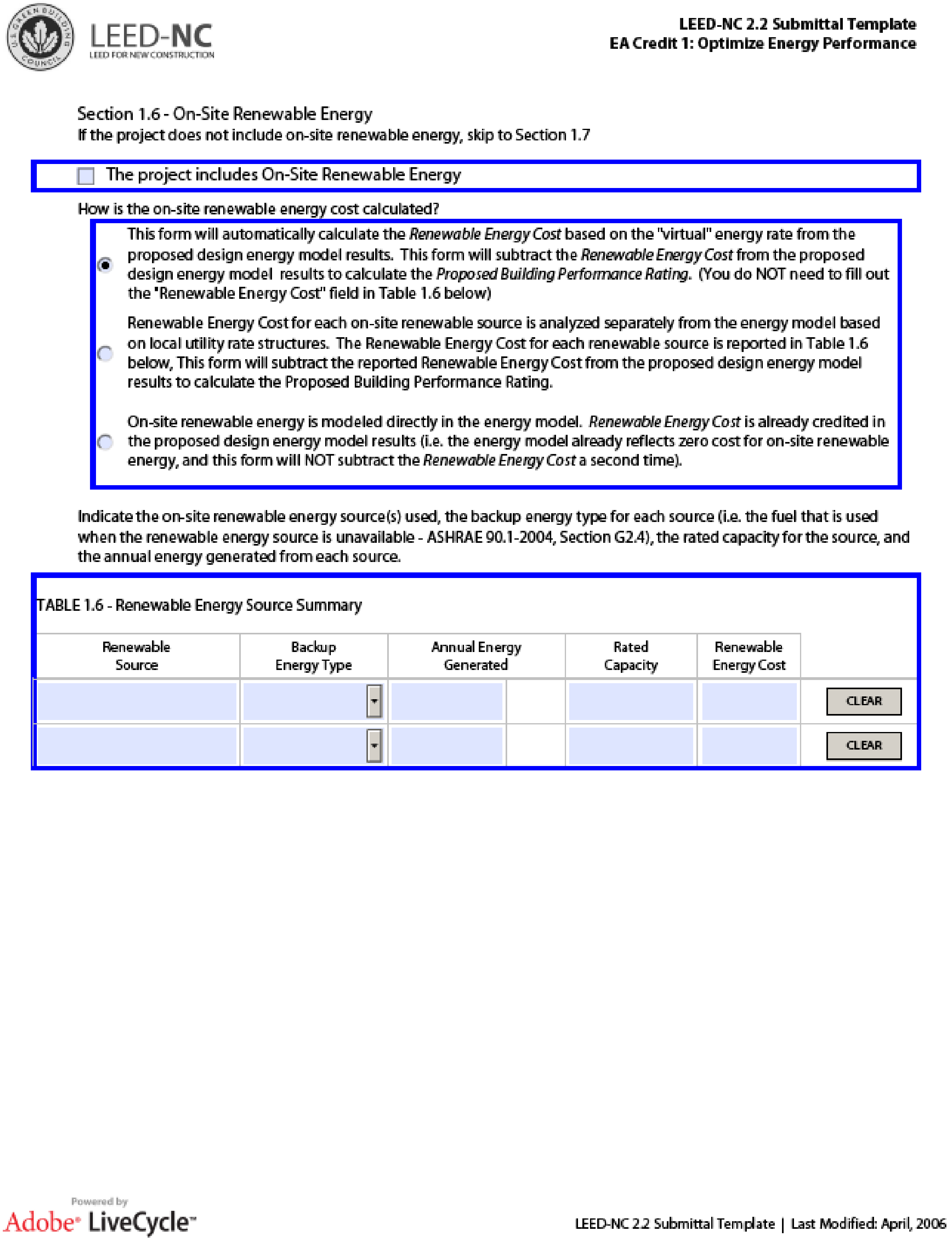
List the energy types used by your project (i.e. electricity, natural gas, purchased chilled water or steam, etc.) for either the Baseline or Proposed design. Also describe the utility rate used for each energy type (i.e. Feswick County Electric LG-S), as well as the units of energy used, and the units of demand used. (Click "CLEAR" to clear the contents of any row):

TABLE 1.5 - Energy Type Summary

Energy Type	Utility Rate Description	Units of Energy	Units of demand	
Electricity	$0.081/kWh	kWh	kW	CLEAR
Natural Gas	$1.31/therm	therms	MBH	CLEAR
				CLEAR
				CLEAR

Energy Units:
1 kBtu = 1,000 Btu
1 kWh = 3.412 kBtu
1 therm = 100 kBtu
1 MBtu = 1,000 kBtu
1 MWh = 3,412 kBtu
1 ton hr = 12 kBtu

Demand Units
1 MBH = 1,000 Btu/h
1 kW = 3.412 MBH
1 MMBtuh = 1,000 MBH
1 ton = 12 MBH



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Section 1.6 - On-Site Renewable Energy
If the project does not include on-site renewable energy, skip to Section 1.7

☐ The project includes On-Site Renewable Energy

How is the on-site renewable energy cost calculated?

● This form will automatically calculate the *Renewable Energy Cost* based on the "virtual" energy rate from the proposed design energy model results. This form will subtract the *Renewable Energy Cost* from the proposed design energy model results to calculate the *Proposed Building Performance Rating*. (You do NOT need to fill out the "Renewable Energy Cost" field in Table 1.6 below)

○ Renewable Energy Cost for each on-site renewable source is analyzed separately from the energy model based on local utility rate structures. The Renewable Energy Cost for each renewable source is reported in Table 1.6 below, This form will subtract the reported Renewable Energy Cost from the proposed design energy model results to calculate the Proposed Building Performance Rating.

○ On-site renewable energy is modeled directly in the energy model. *Renewable Energy Cost* is already credited in the proposed design energy model results (i.e. the energy model already reflects zero cost for on-site renewable energy, and this form will NOT subtract the *Renewable Energy Cost* a second time).

Indicate the on-site renewable energy source(s) used, the backup energy type for each source (i.e. the fuel that is used when the renewable energy source is unavailable - ASHRAE 90.1-2004, Section G2.4), the rated capacity for the source, and the annual energy generated from each source.

TABLE 1.6 - Renewable Energy Source Summary

Renewable Source	Backup Energy Type	Annual Energy Generated	Rated Capacity	Renewable Energy Cost	
					CLEAR
					CLEAR

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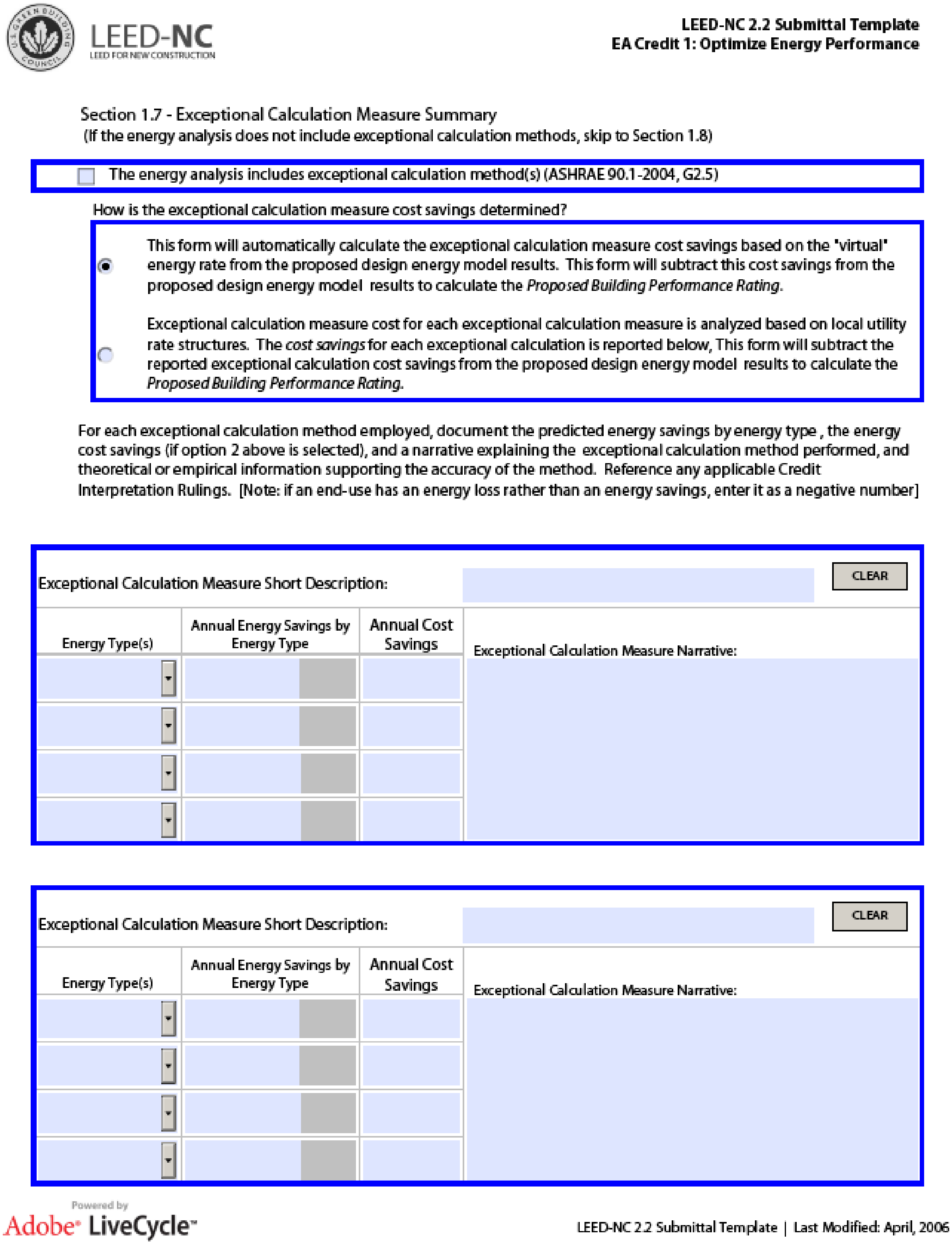

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Section 1.7 - Exceptional Calculation Measure Summary
(If the energy analysis does not include exceptional calculation methods, skip to Section 1.8)

☐ The energy analysis includes exceptional calculation method(s) (ASHRAE 90.1-2004, G2.5)

How is the exceptional calculation measure cost savings determined?

● This form will automatically calculate the exceptional calculation measure cost savings based on the "virtual" energy rate from the proposed design energy model results. This form will subtract this cost savings from the proposed design energy model results to calculate the *Proposed Building Performance Rating.*

○ Exceptional calculation measure cost for each exceptional calculation measure is analyzed based on local utility rate structures. The *cost savings* for each exceptional calculation is reported below, This form will subtract the reported exceptional calculation cost savings from the proposed design energy model results to calculate the *Proposed Building Performance Rating.*

For each exceptional calculation method employed, document the predicted energy savings by energy type , the energy cost savings (if option 2 above is selected), and a narrative explaining the exceptional calculation method performed, and theoretical or empirical information supporting the accuracy of the method. Reference any applicable Credit Interpretation Rulings. [Note: if an end-use has an energy loss rather than an energy savings, enter it as a negative number]

Exceptional Calculation Measure Short Description: CLEAR

Energy Type(s)	Annual Energy Savings by Energy Type	Annual Cost Savings	Exceptional Calculation Measure Narrative:
▾			
▾			
▾			
▾			

Exceptional Calculation Measure Short Description: CLEAR

Energy Type(s)	Annual Energy Savings by Energy Type	Annual Cost Savings	Exceptional Calculation Measure Narrative:
▾			
▾			
▾			
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Section 1.8 - Performance Rating Method Compliance Report *(Option 1 Compliance Only)*

In **Table 1.8.1**, list each energy end use for your project (including all end uses reflected in the baseline and proposed designs). Then check whether the end-use is a process load, select the energy type, and list the energy consumption and peak demand for each end-use for all four Baseline Design orientations. In **Table 1.8.1(b)** indicate the total baseline energy cost for each energy type for all four Baseline Design orientations. If either the baseline or proposed design uses more than one energy type for a single end use (i.e. electric resistance reheat, and central natural gas heating), enter each energy type as a separate end use (i.e. *Heating - Electric*, and *Heating, NG*).

Fill out the Proposed Design energy consumption and peak demand for each end use in **Table 1.8.2.** In **Table 1.8.2 (b)** indicate the total proposed energy cost for each energy type. [Note: Process loads for the proposed design must equal those listed in the Baseline design. Any process load energy savings for the project must be reported in Section 1.7.]

(Click "CLEAR" to clear the contents of any end use)

Table 1.8.1 - Baseline Performance - Performance Rating Method Compliance

End Use	Process?	Baseline Design Energy Type	Units of Annual Energy & Peak Demand	Baseline (0° rotation)	Baseline (90° rotation)	Baseline (180° rotation)	Baseline (270° rotation)	Baseline Design	
Interior Lighting	☐	Electricity	Energy Use (kWh)	108,993	108,993	108,993	108,993	108,993	CLEAR
			Demand (kW)	23.4	23.4	23.4	23.4	23.4	
Exterior Lighting	☐	Electricity	Energy Use (kWh)	50,201	50,201	50,201	50,201	50,201	CLEAR
			Demand (kW)	11.5	11.5	11.5	11.5	11.5	
Space Heating	☐	Electricity	Energy Use (kWh)	110,597	109,679	108,464	110,153	109,723.3	CLEAR
			Demand (kW)	171.6	173.3	172.9	172.5	172.6	
Space Cooling	☐	Electricity	Energy Use (kWh)	41,518	42,657	41,538	42,256	41,992.3	CLEAR
			Demand (kW)	56.8	58.2	57.4	58	57.6	
	☐		Energy Use						CLEAR
			Demand						
Pumps	☐		Energy Use	0	0	0	0	0	CLEAR
			Demand	0	0	0	0	0	
Fans - Interior	☐	Electricity	Energy Use (kWh)	195,483	196,366	193,958	195,312	195,279.8	CLEAR
			Demand (kW)	22.3	22.4	22.1	22.3	22.3	
	☐		Energy Use						CLEAR
			Demand						
Service Water Heating	☐	Natural Gas	Energy Use (therms)	1,742	1,742	1,742	1,742	1,742	CLEAR
			Demand (MBH)	0	0	0	0	0	
Receptacle Equipment	☒	Electricity	Energy Use (kWh)	45,848	45,848	45,848	45,848	45,848	CLEAR
			Demand (kW)	10.3	10.3	10.3	10.3	10.3	

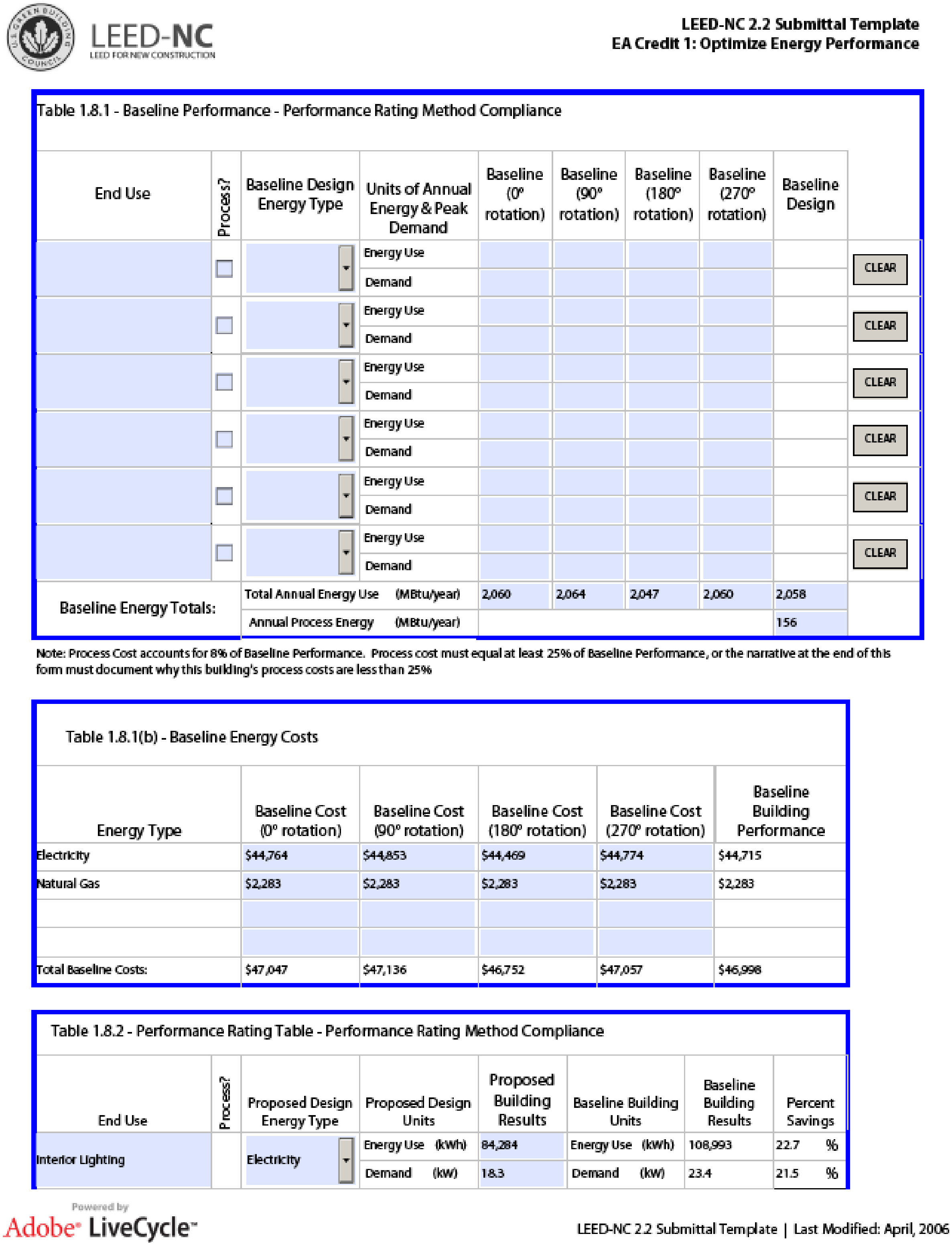

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Table 1.8.1 - Baseline Performance - Performance Rating Method Compliance

End Use	Process?	Baseline Design Energy Type	Units of Annual Energy & Peak Demand	Baseline (0° rotation)	Baseline (90° rotation)	Baseline (180° rotation)	Baseline (270° rotation)	Baseline Design	
	☐		Energy Use						CLEAR
			Demand						
	☐		Energy Use						CLEAR
			Demand						
	☐		Energy Use						CLEAR
			Demand						
	☐		Energy Use						CLEAR
			Demand						
	☐		Energy Use						CLEAR
			Demand						
	☐		Energy Use						CLEAR
			Demand						
Baseline Energy Totals:		Total Annual Energy Use (MBtu/year)		2,060	2,064	2,047	2,060	2,058	
		Annual Process Energy (MBtu/year)						156	

Note: Process Cost accounts for 8% of Baseline Performance. Process cost must equal at least 25% of Baseline Performance, or the narrative at the end of this form must document why this building's process costs are less than 25%

Table 1.8.1(b) - Baseline Energy Costs

Energy Type	Baseline Cost (0° rotation)	Baseline Cost (90° rotation)	Baseline Cost (180° rotation)	Baseline Cost (270° rotation)	Baseline Building Performance
Electricity	$44,764	$44,853	$44,469	$44,774	$44,715
Natural Gas	$2,283	$2,283	$2,283	$2,283	$2,283
Total Baseline Costs:	$47,047	$47,136	$46,752	$47,057	$46,998

Table 1.8.2 - Performance Rating Table - Performance Rating Method Compliance

End Use	Process?	Proposed Design Energy Type	Proposed Design Units	Proposed Building Results	Baseline Building Units	Baseline Building Results	Percent Savings
Interior Lighting		Electricity	Energy Use (kWh)	84,284	Energy Use (kWh)	108,993	22.7 %
			Demand (kW)	18.3	Demand (kW)	23.4	21.5 %

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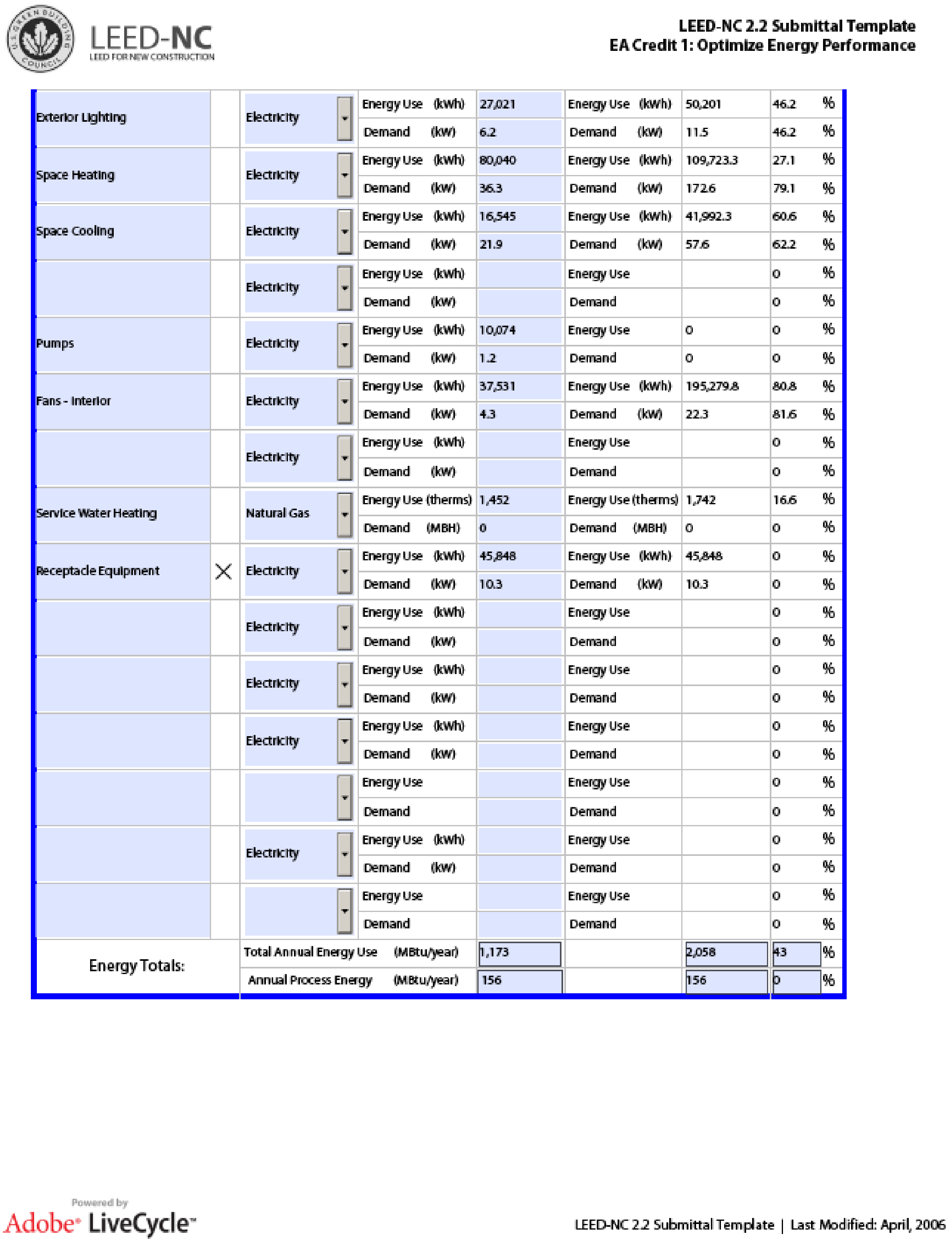

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Exterior Lighting		Electricity	Energy Use (kWh)	27,021	Energy Use (kWh)	50,201	46.2	%
			Demand (kW)	6.2	Demand (kW)	11.5	46.2	%
Space Heating		Electricity	Energy Use (kWh)	80,040	Energy Use (kWh)	109,723.3	27.1	%
			Demand (kW)	36.3	Demand (kW)	172.6	79.1	%
Space Cooling		Electricity	Energy Use (kWh)	16,545	Energy Use (kWh)	41,992.3	60.6	%
			Demand (kW)	21.9	Demand (kW)	57.6	62.2	%
		Electricity	Energy Use (kWh)		Energy Use		0	%
			Demand (kW)		Demand		0	%
Pumps		Electricity	Energy Use (kWh)	10,074	Energy Use	0	0	%
			Demand (kW)	1.2	Demand	0	0	%
Fans - Interior		Electricity	Energy Use (kWh)	37,531	Energy Use (kWh)	195,279.8	80.8	%
			Demand (kW)	4.3	Demand (kW)	22.3	81.6	%
		Electricity	Energy Use (kWh)		Energy Use		0	%
			Demand (kW)		Demand		0	%
Service Water Heating		Natural Gas	Energy Use (therms)	1,452	Energy Use (therms)	1,742	16.6	%
			Demand (MBH)	0	Demand (MBH)	0	0	%
Receptacle Equipment	☒	Electricity	Energy Use (kWh)	45,848	Energy Use (kWh)	45,848	0	%
			Demand (kW)	10.3	Demand (kW)	10.3	0	%
		Electricity	Energy Use (kWh)		Energy Use		0	%
			Demand (kW)		Demand		0	%
		Electricity	Energy Use (kWh)		Energy Use		0	%
			Demand (kW)		Demand		0	%
		Electricity	Energy Use (kWh)		Energy Use		0	%
			Demand (kW)		Demand		0	%
			Energy Use		Energy Use		0	%
			Demand		Demand		0	%
		Electricity	Energy Use (kWh)		Energy Use		0	%
			Demand (kW)		Demand		0	%
			Energy Use		Energy Use		0	%
			Demand		Demand		0	%
Energy Totals:		Total Annual Energy Use	(MBtu/year)	1,173		2,058	43	%
		Annual Process Energy	(MBtu/year)	156		156	0	%

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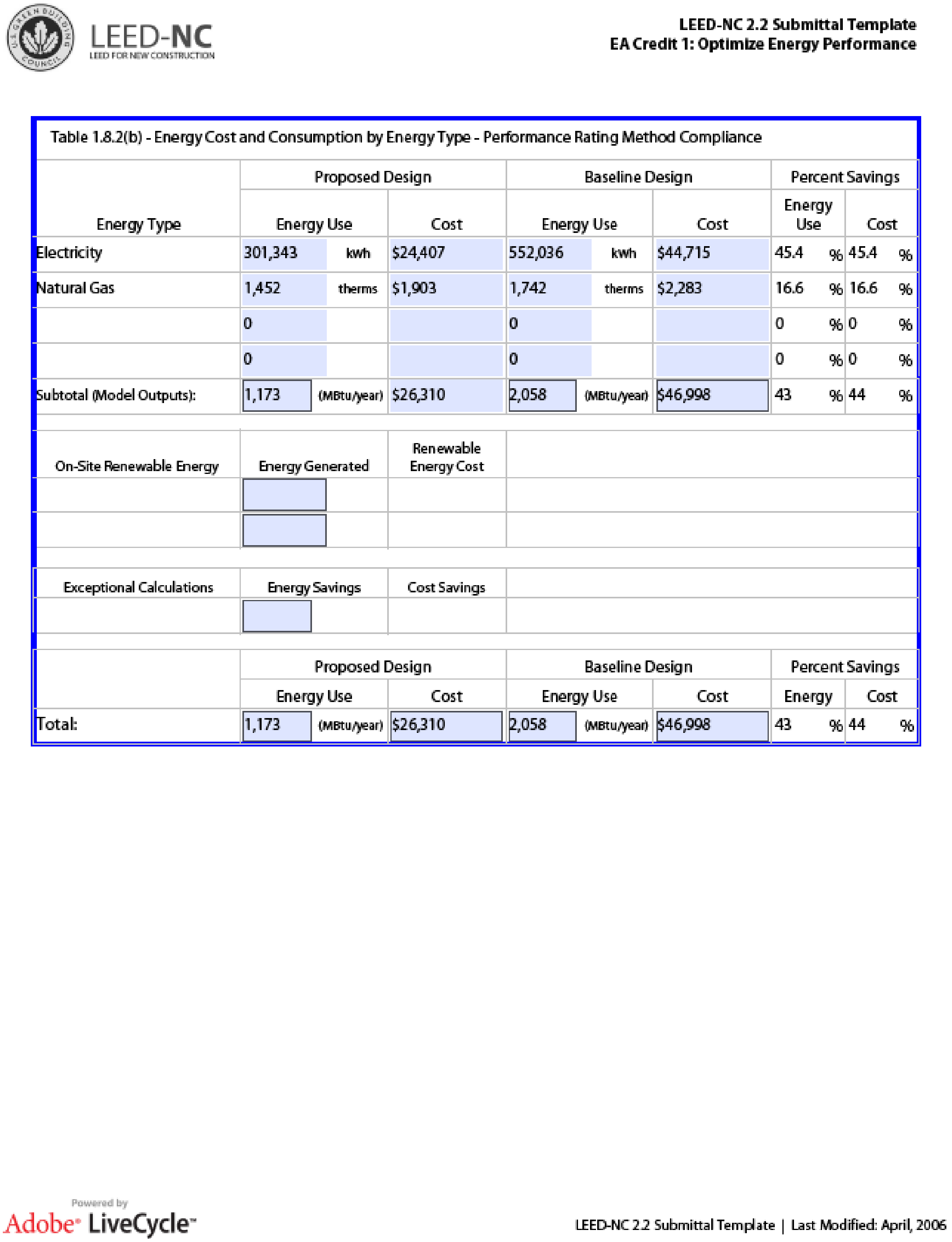

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Table 1.8.2(b) - Energy Cost and Consumption by Energy Type - Performance Rating Method Compliance

	Proposed Design			Baseline Design			Percent Savings	
Energy Type	Energy Use		Cost	Energy Use		Cost	Energy Use	Cost
Electricity	301,343	kwh	$24,407	552,036	kwh	$44,715	45.4 %	45.4 %
Natural Gas	1,452	therms	$1,903	1,742	therms	$2,283	16.6 %	16.6 %
	0			0			0 %	0 %
	0			0			0 %	0 %
Subtotal (Model Outputs):	1,173	(MBtu/year)	$26,310	2,058	(MBtu/year)	$46,998	43 %	44 %

On-Site Renewable Energy	Energy Generated	Renewable Energy Cost

Exceptional Calculations	Energy Savings	Cost Savings

	Proposed Design			Baseline Design			Percent Savings	
	Energy Use		Cost	Energy Use		Cost	Energy	Cost
Total:	1,173	(MBtu/year)	$26,310	2,058	(MBtu/year)	$46,998	43 %	44 %

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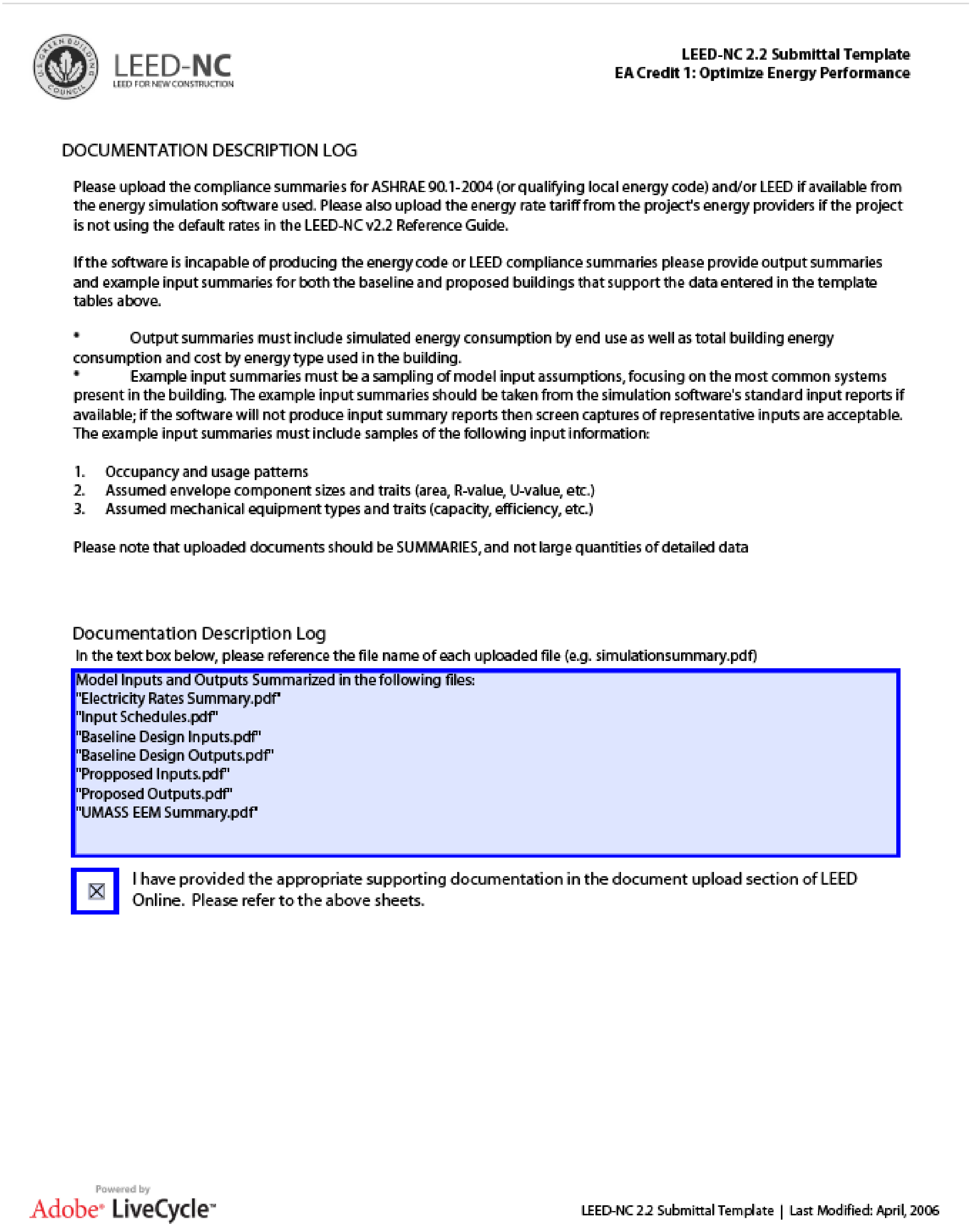

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EA Credit 1: Optimize Energy Performance

DOCUMENTATION DESCRIPTION LOG

Please upload the compliance summaries for ASHRAE 90.1-2004 (or qualifying local energy code) and/or LEED if available from the energy simulation software used. Please also upload the energy rate tariff from the project's energy providers if the project is not using the default rates in the LEED-NC v2.2 Reference Guide.

If the software is incapable of producing the energy code or LEED compliance summaries please provide output summaries and example input summaries for both the baseline and proposed buildings that support the data entered in the template tables above.

- Output summaries must include simulated energy consumption by end use as well as total building energy consumption and cost by energy type used in the building.
- Example input summaries must be a sampling of model input assumptions, focusing on the most common systems present in the building. The example input summaries should be taken from the simulation software's standard input reports if available; if the software will not produce input summary reports then screen captures of representative inputs are acceptable. The example input summaries must include samples of the following input information:

1. Occupancy and usage patterns
2. Assumed envelope component sizes and traits (area, R-value, U-value, etc.)
3. Assumed mechanical equipment types and traits (capacity, efficiency, etc.)

Please note that uploaded documents should be SUMMARIES, and not large quantities of detailed data

Documentation Description Log

In the text box below, please reference the file name of each uploaded file (e.g. simulationsummary.pdf)

Model Inputs and Outputs Summarized in the following files:
"Electricity Rates Summary.pdf"
"Input Schedules.pdf"
"Baseline Design Inputs.pdf"
"Baseline Design Outputs.pdf"
"Propposed Inputs.pdf"
"Proposed Outputs.pdf"
"UMASS EEM Summary.pdf"

☒ I have provided the appropriate supporting documentation in the document upload section of LEED Online. Please refer to the above sheets.

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OPTION 2: ASHRAE ADVANCED ENERGY DESIGN GUIDE FOR SMALL OFFICE BUILDINGS, 2004

The building complies with all the prescriptive measures of the ASHRAE Advanced Energy Design Guide for Small Office Buildings 2004. The following restrictions are applicable:

☐ The project is less than 20,000 square feet.

☐ The project is office occupancy.

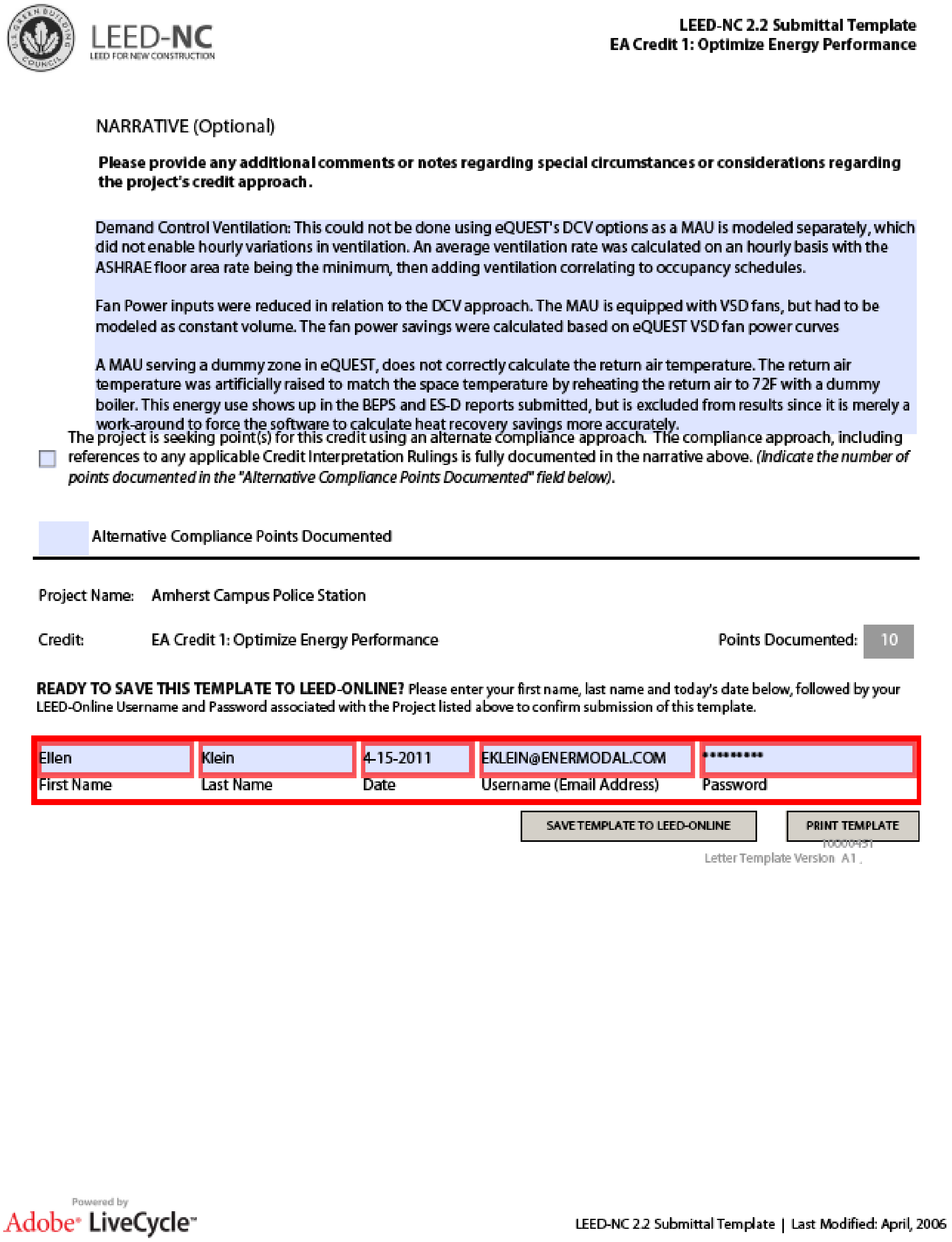
☐ The project has fully complied with all applicable criteria as established in the Advanced Energy Design Guide for the climate zone in which the building is located

Climate zone

OPTION 3: ADVANCED BUILDINGS BENCHMARK ™ VERSION 1.1

☐ The project fully complies with the Basic Criteria and Prescriptive Measures of the Advanced Buildings Benchmark™ Version 1.1 with the exception of the following sections: 1.7 Monitoring and Trend-logging, 1.11 Indoor Air Quality, and 1.14 Networked Computer Monitor Control.

Climate zone



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EA Credit 1: Optimize Energy Performance

NARRATIVE (Optional)

Please provide any additional comments or notes regarding special circumstances or considerations regarding the project's credit approach.

Demand Control Ventilation: This could not be done using eQUEST's DCV options as a MAU is modeled separately, which did not enable hourly variations in ventilation. An average ventilation rate was calculated on an hourly basis with the ASHRAE floor area rate being the minimum, then adding ventilation correlating to occupancy schedules.

Fan Power inputs were reduced in relation to the DCV approach. The MAU is equipped with VSD fans, but had to be modeled as constant volume. The fan power savings were calculated based on eQUEST VSD fan power curves

A MAU serving a dummy zone in eQUEST, does not correctly calculate the return air temperature. The return air temperature was artificially raised to match the space temperature by reheating the return air to 72F with a dummy boiler. This energy use shows up in the BEPS and ES-D reports submitted, but is excluded from results since it is merely a work-around to force the software to calculate heat recovery savings more accurately.

☐ The project is seeking point(s) for this credit using an alternate compliance approach. The compliance approach, including references to any applicable Credit Interpretation Rulings is fully documented in the narrative above. *(Indicate the number of points documented in the "Alternative Compliance Points Documented" field below).*

Alternative Compliance Points Documented

Project Name: Amherst Campus Police Station

Credit: EA Credit 1: Optimize Energy Performance

Points Documented: 10

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Ellen	Klein	4-15-2011	EKLEIN@ENERMODAL.COM	*********
First Name	Last Name	Date	Username (Email Address)	Password

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PRINT TEMPLATE

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REFERENCES

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