ABSTRACT

Title of Thesis:

ENABLING VOLTTRON: ENERGY MANAGEMENT OF COMMERCIAL BUILDINGS AT THE UNIVERSITY OF MARYLAND

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Buildings waste approximately 30% of energy they consume due to inefficient HVAC and lighting operation. Building Automation Systems (BAS) can aid in reducing such wasted energy, but 90% of U.S. commercial buildings lack a BAS due to their high capital costs. This thesis demonstrates how VOLTTRON, an open source operating system developed by Pacific Northwest National Laboratory, was used to disable the mechanical cooling of a rooftop unit (RTU) during unoccupied hours, on a building without a BAS. With cooling off, the RTU's electricity dropped from ~18 kW to ~7kW. These results indicate $450 to $550 can be saved on the monthly electric bill of the building during the summer, compared to when the RTU operated in cooling mode continuously. The installation cost of the equipment that enabled the

RTU to be controlled via VOLTTRON was $6,400, thus the project has a payback period of 13 months.

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by

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and for answering my various questions on building operation. Without the Facilities Management team, this thesis would not have been possible.

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List of Abbreviations

AHU: Air Handling Unit

ASHRAE: American Society of Heating, Refrigeration and Air Conditioning Engineers

BACnet: Building Automation and Control Network

BAS: Building Automation System

BEMOSS: Building Energy Management Open Source Software

CBECS: Commercial Building Energy Consumption Survey

DR: Demand Response

EUI: Energy Use Intensity

GHG: Greenhouse Gas

GUI: Graphical User Interface

HVAC: Heating, Ventilation, and Air Conditioning

IDE: Integrated Development Environment

RTU: Rooftop Unit

SOAP: Simple Object Access Protocol

TVB: Technology Ventures Building

UMD: University of Maryland, College Park

VAV: Variable Air Volume

Chapter 1: Introduction

1.1: Building Sector's Effect on the Environment

In the U.S., buildings are responsible for nearly 40% of human-made carbon dioxide emissions, one of the major greenhouse gas (GHG) affecting climate change [1]. Part of this GHG contribution is a result of the sources of energy used by buildings. For instance, buildings consume 70% of the electricity in the U.S., and 67% of electricity generated in the nation are from fossil fuels, such as coal and natural gas, with high concentration of carbon [2]. Additionally, U.S. buildings currently use about 8.05 quadrillion (10^{15}) BTUs of natural gas for space and water heating, 28% of the nation's total natural gas consumption [3]. Overall, buildings consume significant amounts of energy and waste an astonishing 30% of the energy they consume [4]. Hence even with advancements in the renewable and sustainable energy fields in addressing GHG emissions, improvements in the building sector are essential.

1.2: Thesis Motivation

1.2.1 Monitoring and Controlling Commercial Buildings

A major cause of wasted energy in buildings is inefficient building operation. This includes unnecessary lighting and mechanical cooling of spaces during unoccupied hours. Inefficient building operation is due to the lack of installed sensors and control systems to monitor and actuate building devices [5]. This is critical since establishing a building control system leads to potential energy savings between 13 to 66% [6].

However, the Commercial Building Energy Consumption Survey (CBECS) reports only about 10% of the buildings in the U.S. are equipped with a Building Automation System, (BAS), which enables remote control of the building equipment. The other 90% of buildings without such a system are mainly small and medium sized, under 100,000 square feet.

Understandably, the high capital cost of BASs prevents many of these building owners from considering BASs a viable energy efficiency measure. Given the average cost to deploy a BAS is \$2.50 - \$7.50 per square foot, the capital cost of a BAS can be over \$100,000 [7]. The primary reasons for costly BASs are the proprietary equipment and software of the systems. The lack of integration between devices using different communication protocols means a building owner may have to replace working, but incompatible devices, with the BAS company’s units. Additionally, the BAS software to monitor the building operation can be costly depending on the customization features the building owner or manager desires.

As such the motivation behind this thesis stems from the need for cost effective and customizable BAS in small and medium sized buildings. There have been research and technology developments to address energy management of small and medium sized buildings. Most focus on Internet based monitoring and control of Heating, Ventilation, and Air Conditioning (HVAC) systems as discussed in [8] [9] [10].

This thesis, which is partly funded by the Department of Energy *Building-Grid Integration Research and Development Innovations Program* (BIRD-IP), uses

VOLTTRON, an open source operating system recently developed by Pacific Northwest National Laboratory (PNNL), to address difficulties with energy management systems [11]. The Department of Energy BIRD-IP required participants to use VOLTTRON as a means to introduce researchers to VOLTTRON, demonstrate VOLTTRON's benefits and capabilities in relevant energy management applications, and receive feedback on the relatively new operating system. The following paragraphs briefly explain how VOLTTRON was used in this thesis. Further details on VOLTTRON will be provided in Chapter 2: Literature Review.

1.2.2 Addressing Inefficient HVAC Cooling of UMD Buildings with VOLTTRON

Cooling buildings can be costly and put a significant strain on the electric grid during the summer [12] [13]. Unnecessary cooling of spaces has contributed to these problems. Inefficient HVAC cooling typically arises from the lack of systems to monitor and control the HVAC equipment as previously discussed. As such, in this thesis, VOLTTRON was used to turn off the cooling of a packaged rooftop unit (RTU) on a building without an existing BAS, when cooling was not needed. Additionally, VOLTTRON was used to add custom monitoring of University of Maryland buildings controlled by a BAS to aid in diagnosing potential overcooled spaces.

1.3: Thesis Outline

The effect of buildings on the environment, the motivation of this thesis, and how VOLTTRON was used in this thesis have been discussed in the previous sections.

Chapter 2: *Literature Review* provides background information and related research about energy savings from setpoint temperature modulation, need for monitoring and control systems, rooftop units, VOLTTRON, and applications of VOLTTRON. Chapter 3: *Research Objective and Hypothesis* presents the objective and hypothesis of the thesis. Chapter 4: *Technology Ventures Building Case Study* presents why and how VOLTTRON was used to control one of the Technology Ventures Building's rooftop unit. Chapter 5: *Custom Monitoring of Buildings with a BAS* presents how VOLTTRON can be used in buildings with a BAS. This chapter also presents the key findings from a case study the author conducted on a building with a BAS. Chapter 6: *Conclusion* rehashes the key findings and research contribution of this thesis, and offers future research work.

Chapter 2: Literature Review

Numerous research studies concerning energy management of buildings focus on the effect a specific data point, such as the HVAC setpoint temperature, has on the building's energy use. Other studies delve into methods and technology to monitor and control the HVAC equipment to reduce wasted energy. Few studies have considered the use of VOLTTRON, a new operating system developed by Pacific Northwest National Laboratory, for managing HVAC operation. As such, this literature review focuses on the following groups of research studies: (a) energy savings from advanced HVAC setpoint temperature schedules, (b) the need for building monitor and control systems and (c) VOLTTRON, and (d) applications of VOLTTRON. Part of this literature review discusses the need to monitor rooftop units (RTUs), as RTUs are common HVAC units that typically operate inefficiently.

2.1: Energy Savings from Advanced HVAC Setpoint Temperature Schedules

HVAC devices are major energy consumers of commercial buildings. It is reported 43% of commercial buildings' energy use is from space heating, cooling, and ventilation [14]. Yet HVAC equipment are typically operated inefficiently. As such, researchers have investigated methods to reduce total energy and peak electricity consumption from HVAC operation, while maintaining occupant thermal comfort.

Several research study the effects of setpoint temperature modulation in reducing unnecessary HVAC cooling and heating to minimize HVAC energy use and associated costs. One study, which reviewed other research about commercial buildings' setpoint temperature, found the typical baseline setpoint temperature schedule in commercial buildings was for the occupied setpoint temperature to be at the lower boundary of the thermal comfort region, such as 72 °F, while the unoccupied setpoint temperature is significantly higher, such as 85 °F [15]. This baseline setpoint temperature schedule is widely implemented in buildings with HVAC scheduling capabilities because of its simplicity and adherence to thermal comfort range guidelines [15].

Research shows however that baseline setpoint temperature schedules are not effective in reducing unnecessary HVAC cooling and heating when compared to advanced setpoint temperature schedules [15] [16]. Study [15] reports advanced setpoint temperature schedules that incorporated peak electricity demand limits, and took advantage of the building's thermal mass via precooling, had peak demand reduction up to 42% when compared to the baseline setpoint schedule. For instance, the researchers of study [17] developed a setpoint temperature schedule that incorporated the building's thermal mass to reduce peak cooling demand of a building. They tested their advanced setpoint temperature schedule at a small bank in California for two weeks in October. Their advanced setpoint temperature schedule was to precool the building to 70°F in the morning from 6am to 12pm, then adjust the setpoint from 70°F to 78°F during peak hours of 12pm – 6pm using their demand limiting model. They also implemented an unoccupied setback temperature of 85°F from 6pm – 6am.

Compared to the baseline schedule of 72°F and 85°F during occupied hours (6am to 7pm), and unoccupied hours (7pm – 6am), respectively, the advanced setpoint schedule had an average peak air conditioner power reduction of 31.6%. Also, the average electricity peak savings was 9.1 kW [17].

Other studies incorporating advanced setpoint temperature schedules are listed in Table 2.1 and Table 2.2. Of note are the reported energy or peak demand reductions from the cited studies. Comparing the savings of the studies is difficult due to variability in the length of the research, what was calculated (i.e. peak savings, building energy use, HVAC energy use), and the number of buildings studied. For instance some studies lasted a few days while others lasted a year. Also note for study [18], though the average energy savings was 6.3%, some of the 22 buildings in the study actually had an increase in energy use.

With this in mind, the key finding from this section of the literature review is customized advanced setpoint temperature can lower peak demand, resulting in lower cost of operation and potentially lower energy consumption compared to the baseline setpoint temperature schedule. Details on the technology that can be deployed to implement these advanced schedules is needed though.

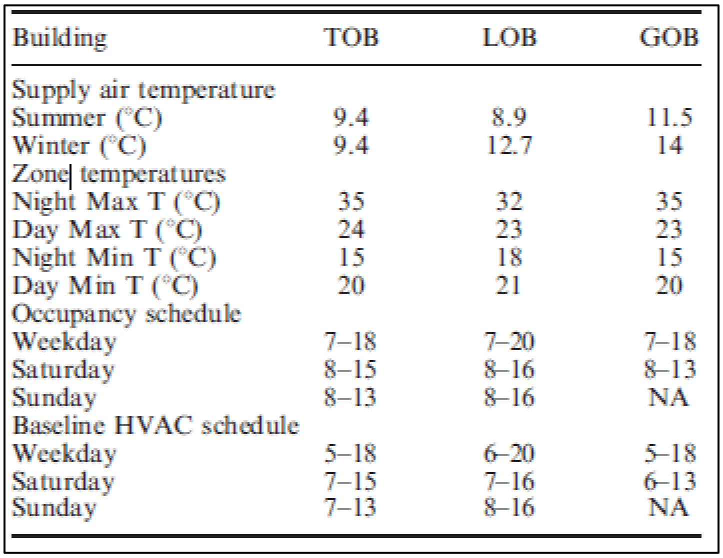
Table 2.1: Experimental studies of advanced setpoint temperature schedules

Ref.	Advanced Setpoint Temperature Schedule	Building(s) Location	Total Savings /Method	How Advanced Schedule was Implemented in Actual Building(s)
[19]	Schedule varies based on their Adaptive Comfort Temperature (ACT) model	55 offices in Hong Kong	**7% total energy savings** of the air handling unit cooling coil with adaptive comfort temperature model	Not mentioned
[18]	<u>Method 1</u> Temperatures increased 1°C higher than normal in the summer	22 buildings in Australia	**HVAC electricity reduction of 6%**	Used CSIRO intelligent HVAC supervisory control system
	<u>Method 2</u> Temperatures adjusted in direct response to variations in ambient. Supply air temperature also varied	5 buildings in Australia	**HVAC electricity reduction of 6.3%**	
[20]	Transition between two constant setpoint temperatures optimized	Environmental chamber	**8% peak reduction** compared to linear change in setpoint	Can be implemented with programmable thermostat

Table 2.2: Numerical studies of advanced setpoint temperature schedules

Ref.	Advanced Setpoint Temperature Schedule	Building Model Location	Results	Implementation in Actual Building
[21]	Thermal Energy Storage See Figure 2.1	3 offices in Chicago, IL	**Energy savings** up to **14%**	Not mentioned

[22]	Constant heating setpoint temperature of 70 °F Cooling setpoint temperature: 74°F to 80°F Baseline cooling setpoint 72°F	6 building types in Miami, Phoenix, Fresno, San Fransico, Baltimore, Chicago, Duluth	Average HVAC **energy savings** of **13%, 23%, 31%,** and **37%** when cooling setpoint 74°F, 76°F, 78°F, and 80°F respectively	Mentions thermostat retrofits
[14]	Daily setpoints: varies based on climate Baseline: Constant heating and cooling setpoint of 71°F and 74°F respectively	DOE commercial reference buildings	**Building total energy saving** up to **37.03%** based on climate	Not mentioned [*Authors mention difficulty to implement schedule*]



Building	TOB	LOB	GOB
Supply air temperature			
Summer (°C)	9.4	8.9	11.5
Winter (°C)	9.4	12.7	14
Zone temperatures			
Night Max T (°C)	35	32	35
Day Max T (°C)	24	23	23
Night Min T (°C)	15	18	15
Day Min T (°C)	20	21	20
Occupancy schedule			
Weekday	7–18	7–20	7–18
Saturday	8–15	8–16	8–13
Sunday	8–13	8–16	NA
Baseline HVAC schedule			
Weekday	5–18	6–20	5–18
Saturday	7–15	7–16	6–13
Sunday	7–13	8–16	NA

Figure 2.1: Model parameter for study [21]

2.2: Need for Monitoring and Control Systems in Buildings

2.2.1 Implementation of Advanced Setpoint Temperature Schedules

Section 2.1 of this literature review presented research studies about peak electricity reduction and energy savings from advanced setpoint temperature schedules. What was not fully discussed in the studies was implementation of the advanced setpoint temperature schedules. Study [17] does mention the bank was retrofitted with thermostats that allowed global temperature setpoints to be sent remotely. Study [18] mentions the use of an intelligent HVAC supervisory control system in their research, and study [20] mentions their method can be implemented with a programmable thermostat. Details of how the advanced setpoint temperature schedules were implemented are significant as HVAC equipment, controllers, and sensor setbacks can affect the potential energy savings, as discovered in this thesis. Additionally, as mentioned in Section 1.2.1 of this thesis, the capital cost of the technology needed to implement the advanced setpoint schedules, such as programmable thermostats, controllers, and a graphical user interface, can be a major barrier to building owners with limited budgets.

This thesis presents an example of how VOLTTRON can be used to implement custom control of an Internet enabled[1] RTU to reduce the RTU's energy consumption. The necessary equipment and cost of installation for the case study are reported in Chapter 4. Also, the RTU energy saving from the case study is presented.

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[1] Internet enabled here refers to the ability to view the HVAC controllers and sensor data via an IP address

2.2.2 Rooftop Units (RTUs)

RTUs are the typical HVAC equipment for commercial buildings, serving over 60% of U.S. commercial building floor space [23] [24]. As the name implies, these HVAC units are located on a building's roof, and can serve multiple spaces within the building. Though RTUs are widely used, they are known for their inefficient operation. Issues include lack of variable frequency drives to control the fan speeds, faulty sensors, refrigerant charge, and economizer control [23] [25] [26].

Indeed, the RTU on the case study building discussed in Chapter 4 of this thesis had several of these issues, making it difficult to implement some of the advanced control strategies that reduces the RTU's electricity consumption, while maintaining occupant thermal comfort. Still, use of VOLTTRON or a low cost system to monitor and control an RTU has the potential to reduce the RTU's electricity use when compared to the RTU's typical operation, as was the case in this thesis. Additionally, monitoring and control systems can aid in fault detection of the RTUs. Study [24] states due to the large number of RTUs, and the RTUs location on the roof rather than a more accessible room inside the building, service technicians are unable to spend a lot of time maintaining each RTU. Hence remote monitoring of the RTUs can lower labor cost in assessing and documenting issues with the RTUs.

Projects to improve the operation of RTUs include [27]- *Detection of Rooftop Cooling Unit Faults Based on Electrical Measurements.* The electricity consumption of the RTU in Chapter 4 of this thesis was monitored and correlated against the RTU operation, such as the number of compressors running. This aided in detection of issues with the RTU.

2.2.3 HVAC Automated Fault Detection and Diagnostics (AFDD)

Other benefits of monitoring and control systems include automated fault detection and diagnostics (AFDD) of the HVAC units. The purposes of AFDD systems are to assess issues with the equipment in real time, and relay the issues to the appropriate personnel (building owner, maintenance staff) [28]. Malfunctioning or ill-maintained HVAC systems can represent 1% to 2.5% of the total building's energy consumption according to report [28]. AFDD can help reduce inefficient energy consumption of HVAC units, and prevent major equipment failure by notifying equipment personnel of recurring issues. Research studies about AFDD include optimizing the algorithm to assess the issues with the HVAC equipment [29] [30], and creating a web enabled interface to report the AFDD [31]. In this thesis, enabling VOLTTRON allowed the author to view issues with an RTU and relay the information to the HVAC technician of the case study building.

2.3: VOLTTRON

Recently, PNNL addressed some of the difficulties of managing energy systems such as buildings, electric vehicles, renewable energy, and the electric grid via the development of VOLTTRON, an open source, multi-agent operating system that can be used for energy management [11]. As depicted in Figure 2.2, VOLTTRON is designed to enable data flow to and from Internet-enabled sensors, equipment, and databases for transactive based control strategies. This is done via applications, known as agents, within the VOLTTRON software.

Figure 2.2: Data transfer from and to devices via VOLTTRON. Note VOLTTRON does not have a GUIL. The depiction of the center tablet is for visualization purposes. Image from [32]

As shown in Figure 2.3, the VOLTTRON agents, depicted in green boxes, provide a communication path between the devices and the VOLTTRON message bus. Each agent is customizable, and via the message bus, each agent can exchange data with other agents. As such, one can create an agent to control a HVAC equipment based on the data collected from other agents (i.e. weather information, electricity price, occupant presence). VOLTTRON can also address interoperability issues seen in building operation, as equipment and devices using different protocols such as BACnet, Modbus, and LonWorks, can communicate and exchange data via the VOLTTRON agents. Other benefits of VOLTTRON include deployment on low cost CPU devices (i.e. Raspberry Pi), cybersecurity, and a Historian (data storage) framework [11].

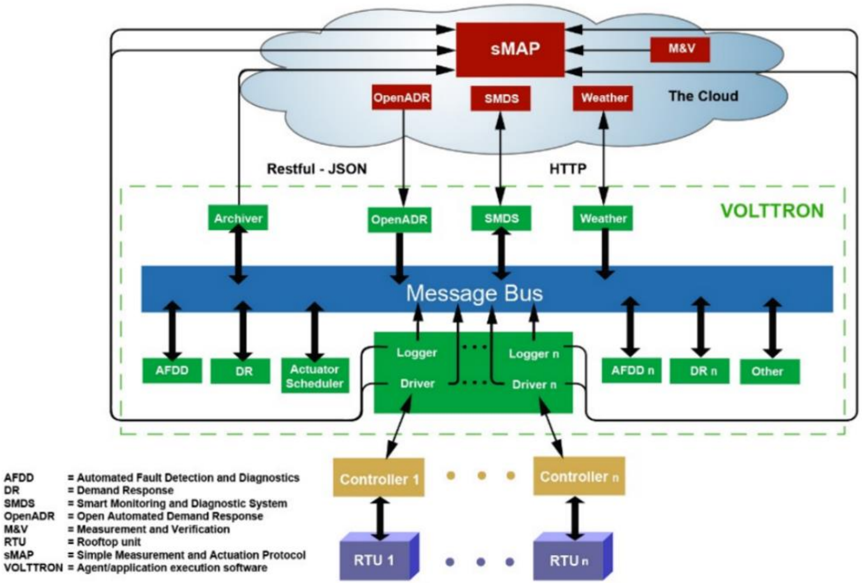

Figure 2.3: VOLTTRON layout. The agents are displayed in green. Image from [33]

It is critical to mention that VOLTTRON is not a BAS. In a BAS, the equipment controllers, Graphical User Interface (GUI), and control strategy for each enabled equipment is optimized for the building. VOLTTRON does not have a GUI, does not inherently contain the algorithm one may use to control an HVAC equipment, and does not inherently know if an equipment is not operating correctly. The user must write the code for the drivers that enable communication with the equipment, the control strategy for actuating the equipment, and the interpretation of the results in a computer terminal or an Integrated Development Environment (IDE). These codes are the agents.

As an open source operating system, the VOLTTRON developers provided drivers and example agents that individuals may use, alter for their own use, or use as references to create their own agents. Nevertheless, it is unlikely to use VOLTTRON in its current version (4.1) as the main automation system for buildings with several HVAC, plugload, and lighting equipment. VOLTTRON is a viable solution to enable supervisory control and monitoring of HVAC equipment, and to interface with an existing BAS to add custom control and monitoring.

2.4: Applications of VOLTTRON

Since its release in April 2014, there have been various usage of VOLTTRON. Notably, researchers and students at Virginia Tech incorporated VOLTTRON into their newly developed building operation system called BEMOSS (Building Energy Management Open Source Software). BEMOSS is created to optimize electricity usage and to implement demand response (DR) in small and medium sized buildings [34]. The desire for an open source building automation system to implement custom scripts and real time remote monitoring, while ensuring the proposed software is cost effective, interoperable with various smart building devices, and scalable, led to the conception and creation of BEMOSS. The four layers of BEMOSS are the user interface, application and data management, operating system and framework, and connectivity layers [34]. VOLTTRON is used as the operating system in BEMOSS, enabling devices with different data communication protocol to exchange information. Also, VOLTTRON enables custom applications called agents to be written. Some of the agents created in BEMOSS due to the availability of VOLTTRON are:

- *Discovery agent*: searches for new devices that can be used within BEMOSS
- *Control agents*: monitors and controls devices such as thermostats, lights, and plug loads
- *Database agent*: communicates and interfaces with the sMAP database to store metadata
- *OpenADR agent*: notifies certain agents of a demand response (DR) event. The OpenADR agent receives DR requests from utilities via the web
- *Demand response agent*: communicates with the control agents to reduce peak consumption

At Iowa State, researchers were aiming to optimize air handling units (AHU) and variable air volume (VAV) boxes systems supply air temperatures [35]. As noted in the conference paper, current air-side HVAC AHU-VAV systems are not optimized due to varying needs of each zones. Hence, the AHU supplies a fixed air temperature of approximately 55°F to the VAV boxes, where the VAV boxes then heats the air to the appropriate supply air temperature for the zone [35]. This causes wasted energy from cooling then reheating the air. Thus, the authors of [35] worked on creating an optimization agent within VOLTTRON that will calculate the optimal AHU supply air temperature needed based on weather information and zone information.

Companies such as Transformative Wave are incorporating VOLTTRON into their proprietary BASs due to VOLTTRON’s functionality and cost effectiveness [36].

Other applications of VOLTTRON include:

- A process that provides continuous automated condition based maintenance management (ACCBM) for building equipment [37].
- To control water heaters [38]
- A supervisory control strategy for limiting peak power demand for small and medium commercial buildings [39]

Of note is the majority of these projects were conducted in test lab and are presenting their methodology. This thesis demonstrates VOLTTRON’s capabilities as an energy management system platform in an actual occupied building, and presents the resulting energy and electric bill savings.

Chapter 3: Research Objective and Hypothesis

3.1: Research Objectives

The objective of this thesis is to enable novel energy management for small and medium size commercial buildings without impeding the productivity or thermal comfort of the occupants. The two specific tasks to accomplish the defined objective are:

1. Demonstrate a cost-effective method to monitor and control RTUs of small and medium sized building without an existing control or automation system, in order to reduce wasted energy from HVAC operation. In this task, the energy savings and payback period from implementing the custom control strategy are quantified.

2. Demonstrate the need for a custom monitoring system for a portfolio of commercial buildings. In this task, the key findings of a case study, and a method to potentially address the case study building's inefficient HVAC operation, is presented.

3.2: Research Hypothesis

The hypothesis of this thesis is implementing custom control via VOLTTRON will yield reduction in HVAC electricity use for the monitored buildings in this study.

Chapter 4: Technology Ventures Building Case Study

4.1: Introduction

The Technology Ventures Building, located in College Park, MD, is a medium sized, mixed use building without a BAS, programmable thermostats, and in some spaces, functioning manual thermostats. As such, implementing automatic setback temperatures to reduce mechanical cooling during unoccupied periods was not possible. The occupants in the spaces lacking a functioning thermostat were unable to modify the space temperature during occupied times, resulting in periods of overcooling.

Therefore, the goal of this case study was to use VOLTTRON to reduce the Technology Ventures Building's HVAC electricity consumption by reducing unnecessary cooling, while maintaining occupant thermal comfort. For this case study, the YORK RTU serving the CITY@UMD research office within the Technology Ventures Building was investigated. This 25 ton RTU only provides cooling [40], and was typically in mechanical cooling mode, meaning at least one of the four compressors was running throughout the day and night, even when cooling was not needed.

The following paragraphs provide the procedure for using VOLTTRON to monitor and control the RTU operation to lower the RTUs power consumption when feasible, problems that arose during the case study, and the results of the study.

4.2: Procedure

The Technology Ventures Building Case Study procedure is as followed:

(1) Deploy VOLTTRON

Deploy VOLLTRON to a Linux operating system. Refer to the updated VOLTTRON guide for instructions on downloading VOLTTRON, and running the necessary software libraries. After deployment, give time to learn how to use VOLTTRON. This may take a few months if the individual does not have experience writing Python scripts (VOLTTRON agents are written in Python). Even with a background in Python, time is needed to learn how to use and write VOLTTRON agents.

(2) Install BACnet MSTP to IP equipment

The YORK RTU in this study is controlled by its Simplicity Control Board [40], where input data and setpoints, such as the outdoor air temperature and the occupied cooling setpoint temperature, are used to determine how to operate the RTU (See Figure 4.1). Output data such as which compressor(s) are running are also monitored via the control board. The Simplicity Control Board uses the BACnet[2] MSTP RS485 protocol [42], thus the sensor input data, setpoints, and output status are specified as BACnet points (See Figure 4.2). With remote access to these BACnet points, one can monitor and control the RTU operation. Viewing the RTU BACnet points in VOLTTRON requires the points to be accessible via an IP address. The Simplicity Control Board for the RTU

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[2] BACnet is a communication protocol that stands for Building Automation and Control network. It was developed by the American Society for Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) [41]

operates on the BACnet MSTP RS485 network, and thus must be routed to a BACnet-IP router, and then to an Ethernet Jack as shown in Figure 4.3. The BASview in the center of Figure 4.3 is optional, and is not necessary to view the BACnet points in VOLTTRON. Table 4.1 lists the cost of the BACnet MST to IP installation. The installation cost, including the BASview, is about $6,400. Installation can take a couple of weeks to complete. In this study, the University of Maryland Facilities Management team completed the installation.

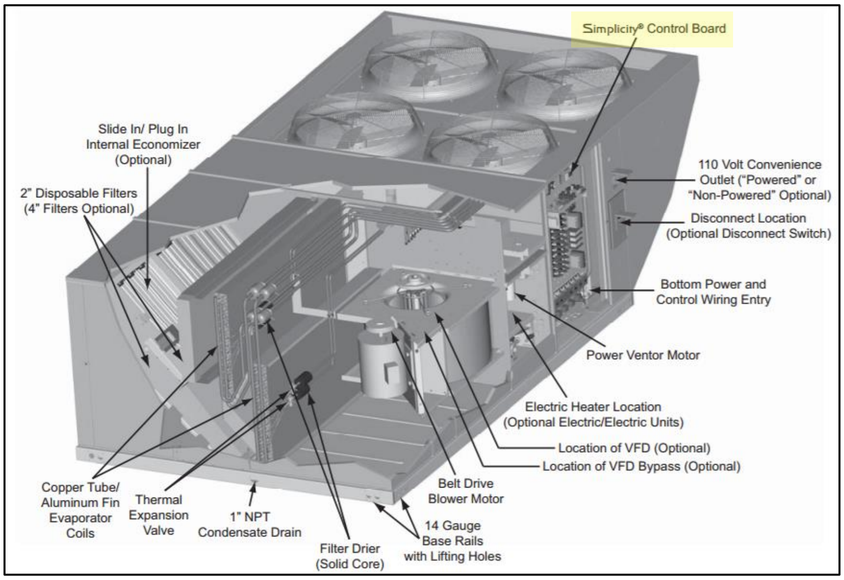


Figure 4.1: Schematic of the YORK rooftop unit (RTU). Note the control panel with the Simplicity Control Board. Image from the RTU manual [40]

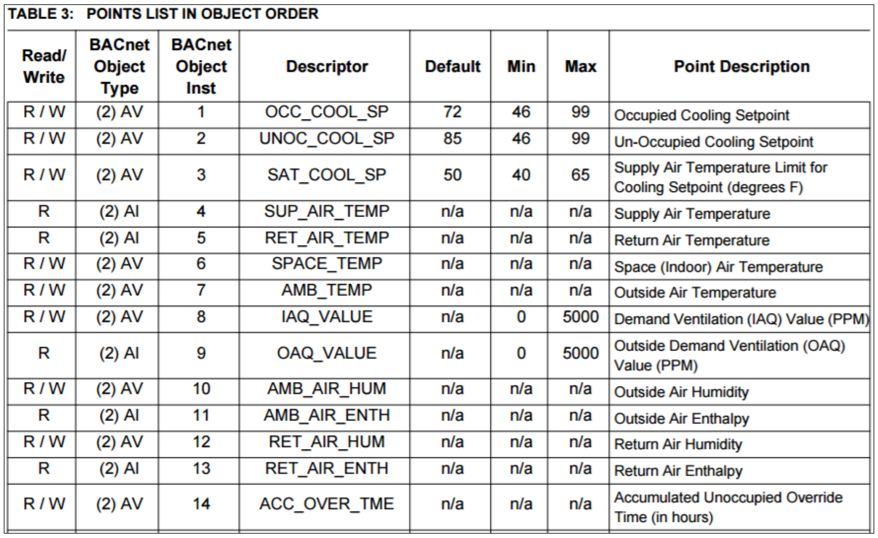


TABLE 3: POINTS LIST IN OBJECT ORDER

Read/ Write	BACnet Object Type	BACnet Object Inst	Descriptor	Default	Min	Max	Point Description
R / W	(2) AV	1	OCC_COOL_SP	72	46	99	Occupied Cooling Setpoint
R / W	(2) AV	2	UNOC_COOL_SP	85	46	99	Un-Occupied Cooling Setpoint
R / W	(2) AV	3	SAT_COOL_SP	50	40	65	Supply Air Temperature Limit for Cooling Setpoint (degrees F)
R	(2) AI	4	SUP_AIR_TEMP	n/a	n/a	n/a	Supply Air Temperature
R	(2) AI	5	RET_AIR_TEMP	n/a	n/a	n/a	Return Air Temperature
R / W	(2) AV	6	SPACE_TEMP	n/a	n/a	n/a	Space (Indoor) Air Temperature
R / W	(2) AV	7	AMB_TEMP	n/a	n/a	n/a	Outside Air Temperature
R / W	(2) AV	8	IAQ_VALUE	n/a	0	5000	Demand Ventilation (IAQ) Value (PPM)
R	(2) AI	9	OAQ_VALUE	n/a	0	5000	Outside Demand Ventilation (OAQ) Value (PPM)
R / W	(2) AV	10	AMB_AIR_HUM	n/a	n/a	n/a	Outside Air Humidity
R	(2) AI	11	AMB_AIR_ENTH	n/a	n/a	n/a	Outside Air Enthalpy
R / W	(2) AV	12	RET_AIR_HUM	n/a	n/a	n/a	Return Air Humidity
R	(2) AI	13	RET_AIR_ENTH	n/a	n/a	n/a	Return Air Enthalpy
R / W	(2) AV	14	ACC_OVER_TME	n/a	n/a	n/a	Accumulated Unoccupied Override Time (in hours)

Figure 4.2: Part of the Simplicity Linc Control Board BACnet point list. Image from the Simplicity Linc Control Board Manual [42]

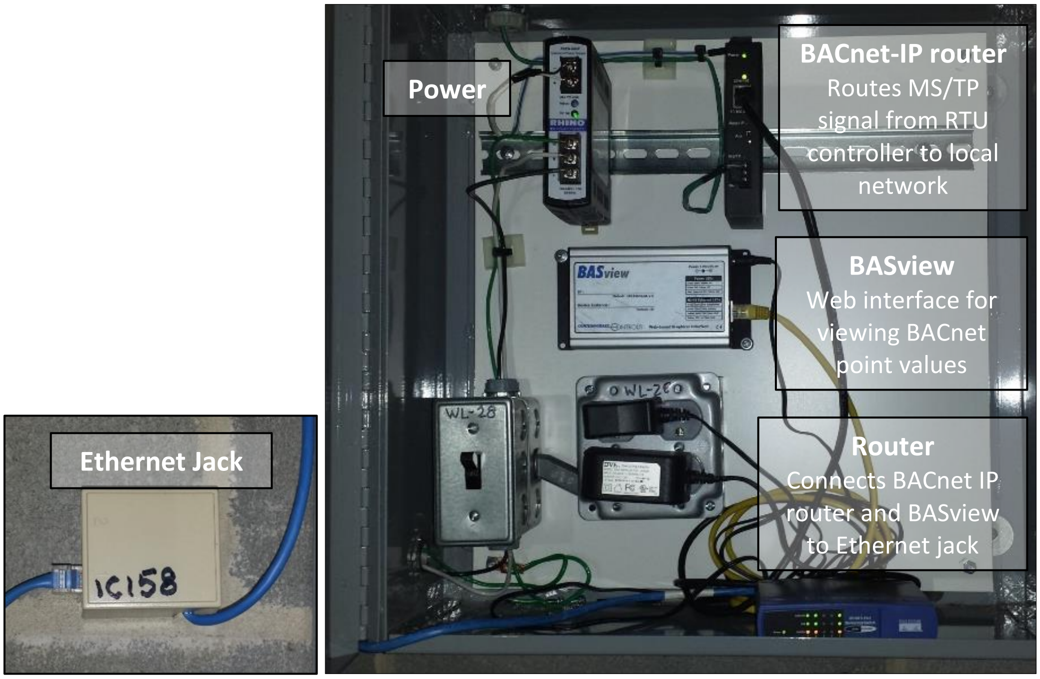


Figure 4.3: BACnet MSTP to IP installation

Table 4.1: Cost of the BACnet MSTP to IP installation

Contemporary Controls MODBUS to BACnet Gateway (*Not shown. Installed in the RTU control panel*)	$395
Contemporary Controls BACnet MSTP to IP router	$295
Communications Conduit & Cable Installation	$4,000
Campus Data Drop	$500
Labor	$1,207

(3) *Access RTU BACnet points in VOLTTRON*

Run the BACnet scan script within VOLTTRON to search for the RTU device address. Once the RTU device address is discovered, run the grab_bacnet_config script to save the BACnet configuration (name, type, read/write access, etc.) to a CSV file. Then configure the MasterDriver agent to retrieve the RTU BACnet point values. The MasterDriver agent is responsible for providing access from the equipment data to other agents, and vice versa.

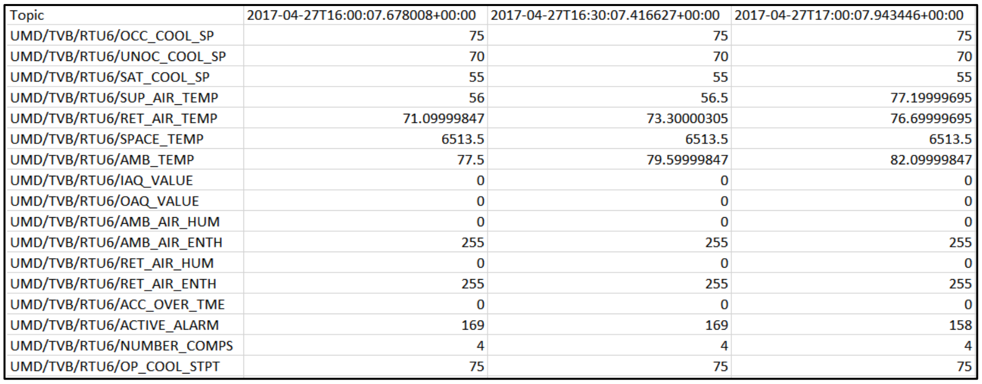
Given proper deployment of VOLTTRON and installation of the BACnet-IP equipment, this step should work relatively quickly. However, if unable to view the BACnet points, check the BACnet-IP network connection and refer to the updated VOLTTRON guide.

(4) *Store BACnet values to a CSV file*

Create an agent to store the RTU BACnet values to a CSV file. This aids in monitoring the RTU operation over time as the weather and BACnet point settings are changed. Time for this step varies based on the individual's experience and knowledge of libraries to create CSV files in Python. The author chose to use Pandas dataframes to store the BACnet values, and then saved the dataframe to a CSV file.

(5) Review BACnet values

Check for erroneous BACnet values, as this can indicate if the corresponding sensor is defective. Pay particularly attention to the SPACE_TEMP BACnet point. If the SPACE_TEMP BACnet point (i.e. the space temperature sensor) is defective, changing the occupied and unoccupied cooling setpoints (OCC_COOL_SP and UNOC_COOL_SP BACnet points respectively) will not affect the RTU operation, as was the case in this study. This step will take approximately three weeks to do a thorough review of the BACnet points to assess the RTU operation, and to verify faulty BACnet points. Figure 4.4 displays part of the CSV file with the BACnet point values for the RTU monitored in this case study. Note the value for the space temperature (SPACE_TEMP).



Topic	2017-04-27T16:00:07.678008+00:00	2017-04-27T16:30:07.416627+00:00	2017-04-27T17:00:07.943446+00:00
UMD/TVB/RTU6/OCC_COOL_SP	75	75	75
UMD/TVB/RTU6/UNOC_COOL_SP	70	70	70
UMD/TVB/RTU6/SAT_COOL_SP	55	55	55
UMD/TVB/RTU6/SUP_AIR_TEMP	56	56.5	77.19999695
UMD/TVB/RTU6/RET_AIR_TEMP	71.09999847	73.30000305	76.69999695
UMD/TVB/RTU6/SPACE_TEMP	6513.5	6513.5	6513.5
UMD/TVB/RTU6/AMB_TEMP	77.5	79.59999847	82.09999847
UMD/TVB/RTU6/IAQ_VALUE	0	0	0
UMD/TVB/RTU6/OAQ_VALUE	0	0	0
UMD/TVB/RTU6/AMB_AIR_HUM	0	0	0
UMD/TVB/RTU6/AMB_AIR_ENTH	255	255	255
UMD/TVB/RTU6/RET_AIR_HUM	0	0	0
UMD/TVB/RTU6/RET_AIR_ENTH	255	255	255
UMD/TVB/RTU6/ACC_OVER_TME	0	0	0
UMD/TVB/RTU6/ACTIVE_ALARM	169	169	158
UMD/TVB/RTU6/NUMBER_COMPS	4	4	4
UMD/TVB/RTU6/OP_COOL_STPT	75	75	75

Figure 4.4: BACnet point values for the RTU. Values are saved to a CSV file.

(6) Write space temperature agent

Due to the faulty SPACE_TEMP sensor, use a DHT22 temperature and humidity sensor to determine the temperature of the space being served by the RTU. Connect the DHT22 sensor to a low cost micro-computer, such as the Raspberry Pi 3, and write a Python script to collect the temperature reading, and send the temperature reading to a server. Then within VOLTTRON, write an agent to acquire the space temperature from the server. Refer to the Python POST/GET documentation for assistance. Time for this step will take to a couple of days, to a few weeks, based on the individual's background using a Raspberry Pi, Python POST/GET method, and writing a VOLTTRON agent.

(7) <u>Install Fluke Power Logger</u>

Install a Wi-Fi enabled power logger, such as the Fluke EUS 1736 model, to measure the electricity consumption of the RTU. This aids in measuring the typical electricity consumption of the RTU, and observing how changing certain BACnet points affect the RTU's electricity consumption. Estimated time to install the power logger is one to two weeks. In this study, the University of Maryland Facilities Management team installed the power logger.

(8) <u>Monitor RTU electricity use as BACnet settings are changed</u>

Establish a relationship between the BACnet points and RTU electricity consumption. Specifically, test if changing certain points, such as the RTU supply air setpoint temperature (SAT_COOL_SP) would affect the RTU power consumption. In this study, the RTU did not consistently meet the supply air temperature setpoint, thus changing supply air setpoint temperature was not a reliable method to control the cooling operation of the RTU. However, turning off the mechanical cooling, (changing COOL_ENA BACnet point to 0), consistently reduced the RTU power consumption to a baseline value. Additionally, monitor the space temperature via the space temperature agent, as changes are made to the RTU BACnet settings, to ensure the space does not become too hot during occupied hours. Do this for at least one week to verify how the BACnet points affect the electricity consumption of the RTU.

(9) Write RTU control agent

Create an agent to turn off the mechanical cooling during occupied and unoccupied periods based on the space temperature and local outdoor temperature values. Depending on the desired control strategy, time to test the agent, and time to revise the agent, the minimum time needed for this step is one week.

Summary of the Technology Ventures Building Case Study Procedure is

1. Deploy VOLTTRON
2. Install BACnet MSTP to IP equipment
3. Access RTU BACnet points in VOLTTRON
4. Store BACnet values to a CSV file
5. Review BACnet values
6. If needed, write space temperature agent
7. Install Fluke power logger
8. Monitor RTU electricity use as BACnet settings are changed
9. Write RTU control agent

4.3: Results and Discussion

4.3.1 Electricity Consumption of the RTU

Given setbacks with the RTU operation, particularly due to its defective space temperature sensor (SPACE_TEMP), large differences in the actual supply air temperature (SUP_AIR_TEMP) versus the supply air temperature setpoint (SAT_COOL_SP), and lack of control over the supply fan status (SFAN_VFD_OUT), the author created a VOLTTRON agent to automatically turn off the RTUs cooling (i.e. change COOLING_ENA from 1 to 0), at specified times, such as during unoccupied hours.

This strategy still resulted in electricity savings, as cooling was turned off during unoccupied periods, and during occupied periods when the outdoor temperature was cool or mild. Turning off the RTU cooling meant none of the RTU's four compressors operated. Conversely, when cooling was enabled, at least one of the RTU's four compressors operated.

Compressors are reported to be approximately 75% of a RTU's peak power and 55% of the RTU's total annual energy use [43] [44], hence opportunities to limit their operation can yield worthwhile energy savings.

In this case study, the electricity consumption of the RTU dropped from ~18 kW when two compressors were operating, to ~7 kW when none of the compressors were operating, as shown in Figure 4.5. The baseline of 7 kW is due to the supply fan, which operated continuously to provide ventilation to the office, even when cooling was off. The corresponding space temperature of the CITY@UMD office when the RTU cooling was turned on and off is displayed in Figure 4.6. As expected, when cooling was enabled, the office temperature was lower (73°F - 75°F) than when cooling was disabled (75°F - 78°F). Note cooling was turned off on Monday, May 29th, due to the U.S. Memorial Day Holiday.

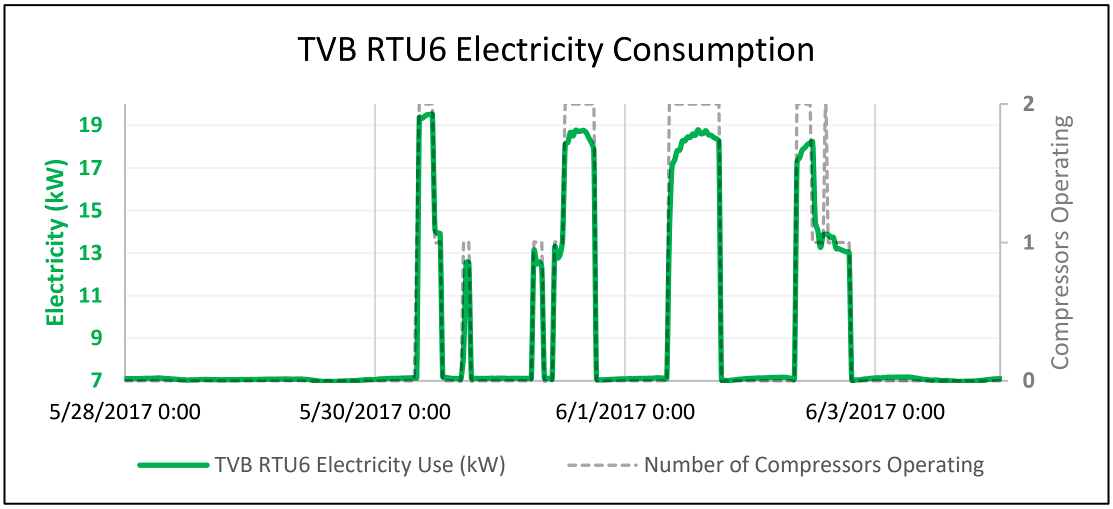


Figure 4.5: RTU6's electricity use and number of compressors on. Compressor status corresponds to cooling status of the RTU. (TVB: Technology Ventures Building)

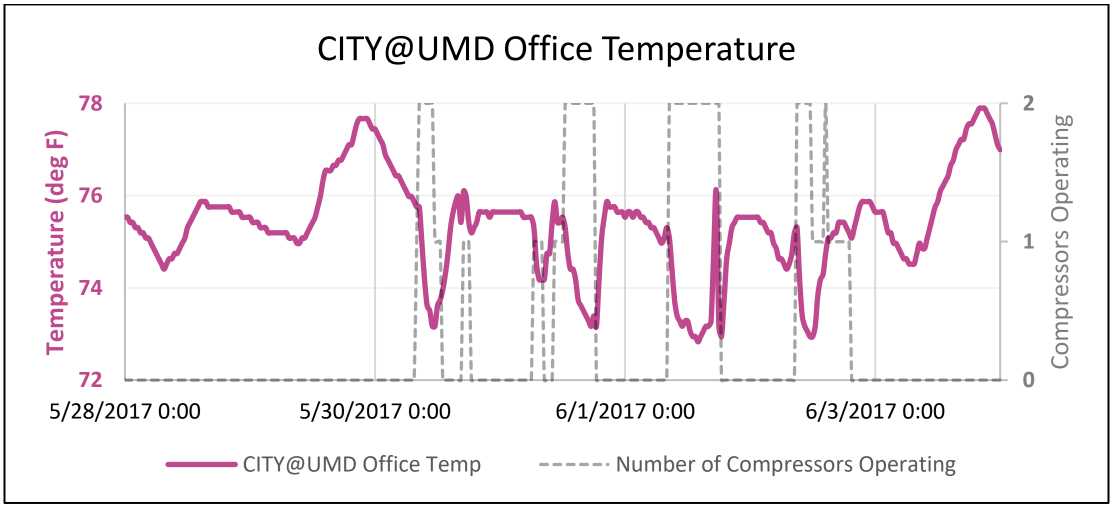


Figure 4.6: Temperature of the CITY@UMD office and number of RTU6's compressors on. Compressor status corresponds to cooling status of the RTU

4.3.2: RTU's Effect on the Technology Ventures Building's Electricity Bill

To assess the financial and energy benefits of turning off the RTU cooling, while maintaining occupant thermal comfort, the electricity consumption of the RTU was compared to the electricity bill of the Technology Ventures Building.

Recall prior to this thesis, a system to remotely monitor and control the RTU operation was unavailable, thus the RTU continuously operated in cooling mode, even when cooling was not needed. Hence, the RTU is estimated to have represented 10-12% of the Technology Ventures Building's electricity use, and electricity bill from June 2016 to September 2016. These calculations are just for the RTU investigated in this case study. Considering the Technology Ventures Building has six RTUs, none of which were remotely monitored or controlled, RTUs represent a sizable portion of the electricity consumed at the Technology Ventures Building.

The results of this case study indicate use of VOLTTRON to create an agent to control the RTU operation can yield valuable energy savings. With a modest schedule of turning off the RTU cooling for 12 hours Mondays through Fridays (example: 12am – 6am and 6pm – midnight), and keeping the cooling off on Saturdays and Sundays, compared to when the RTU cooling operated continuously, the total summer electricity use of the RTU could drop from ~ 53.6 MWh to ~32.4 MWh. This translates into a monthly savings of $450 to $550 on the summer electric bill (See Appendix for calculations).

Given the equipment and labor cost of the BACnet – IP installation was $6,400, implementing the modest cooling schedule during the summer yields a payback period of approximately 13 months.

Further savings and a shorter payback period can be achieved with supplemental control strategies, as was done in this case study. For instance, VOLTTRON was also used to turn off the RTU cooling during holidays, and to change the supply air temperature to decrease the number of compressors operating. Additionally, in the spring, VOLTTRON was used to turn off the RTU cooling during occupied hours when the outdoor temperature was mild. Use of the space temperature agent with the control agent prevented the space from becoming uncomfortably hot, as cooling was turned on if the space rose above a specified value. To prevent frequent cycling of the compressors turning on and off, if the control agent determined cooling was needed, cooling remained on for at least two hours.

4.3.3: Setbacks

Ideally, there would have been opportunities to reduce the RTUs electricity consumption during peak demand hours in the summer, as peak hours are the critical times that strain the electric grid, resulting in higher demand charges for building owners. However, occupant thermal comfort could not be neglected for energy savings. Turning cooling off meant none of the RTU's compressors operated, resulting in unconditioned outdoor air and recycled return air being sent to the space. During unoccupied hours at night time, the outdoor temperature is typically cooler, and the space temperature can be at higher temperatures that would be uncomfortable for occupants. However, during peak summer hours, which coincides with occupied time periods, turning off the RTU cooling would send hot, humid air to the space since the supply fan operated at full speed continuously.

To combat this, the author tested increasing the RTU's supply air setpoint temperature from the default setting. At times, the RTU successfully reached the supply air setpoint and decreased the number of compressors operating, while still providing cool air. Other times the actual supply air temperature was significantly higher than the setpoint, or the supply air temperature did not change regardless of the setpoint. Via review of the BACnet points, the author discovered two out of the four compressors that were originally in service were not in service anymore. This likely caused the difference between the setpoint and actual supply air temperature. This also made it difficult to implement a pre-cooling strategy, where the supply air temperature was lowered during off peak hours and then increased during peak hours.

Given the difficulties of controlling the supply air temperature, efforts to directly control the number of compressors operating were investigated. However, the RTU controller did not allow each compressor to be turned on and off at will.

Additionally, a few times the RTU completely stopped operating, due to a power outage. Figure 4.7 and Figure 4.8 display the RTU electricity use and the corresponding temperature in the CITY@UMD office in May and June respectively. As expected, the electricity consumption of the RTU during the power outage was ~0 kW, but the office temperature rose past 79 F during occupied hours in June. In May, due to the cooler outdoor temperature, space did not get as hot, but was still warmer than typical.

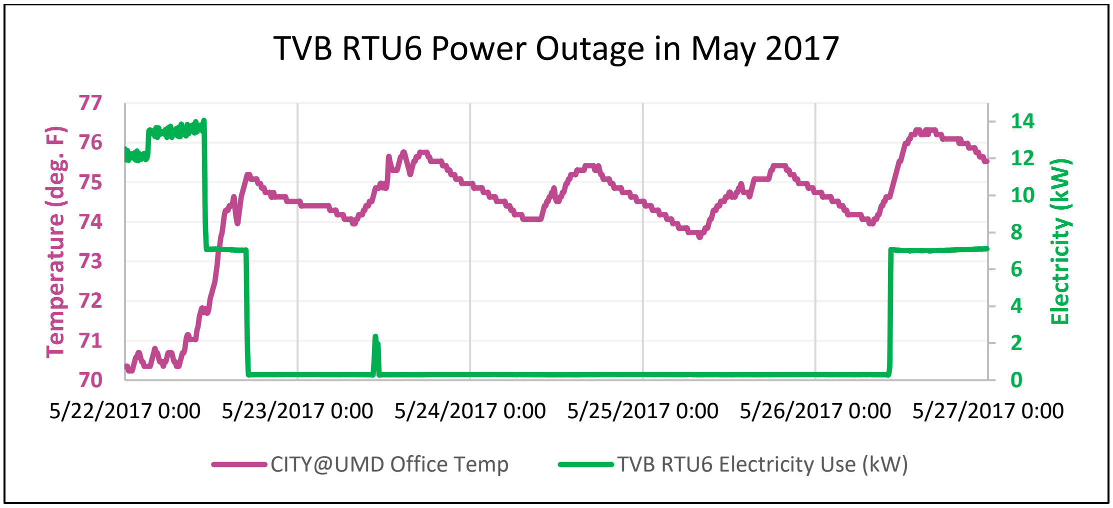


Figure 4.7: TVB RTU6 Electricity use and the CITY@UMD office temperature when the RTU experienced a power outage in May 2017. Outdoor temperatures were in the 60s, hence the office temperature remained below 78 deg. F

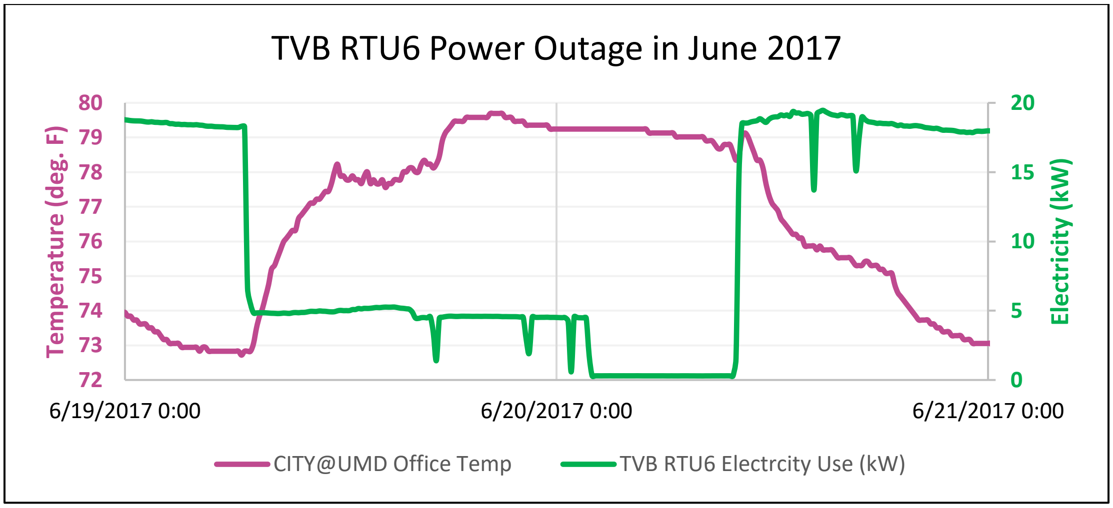


Figure 4.8: TVB RTU6 Electricity use and the CITY@UMD office temperature when the RTU experienced a power outage in June 2017. Outdoor temperatures were warmer, hence the office temperature rose above 79 deg. F

4.4: Case Study Summary

The key contribution of this case study is demonstrating how VOLTTRON was used to reduce unnecessary cooling from a RTU on a building without programmable thermostats or a BAS. Given the various setbacks with the RTU, the control strategy implemented via VOLTTRON was turning off the RTU's cooling during unoccupied hours, and during occupied hours when the local outdoor temperature was mild. With cooling off, the RTU's electricity dropped from ~18kW to ~7kW.

Chapter 5: Custom Monitoring of Buildings with a BAS

Chapter 4 detailed how VOLTTRON was used to reduce the electricity consumption of a RTU on a building without a BAS. This chapter briefly discusses how VOLTTRON can be used in buildings with a BAS, to aid in monitoring and controlling these buildings' HVAC units.

5.1: Introduction

The GUI of a BAS is an essential part of the BAS, as it enables building owners, operators, and researchers to view the status of a building's HVAC operation and energy use. Poor GUIs can cause frustration and wasted time searching for pertinent data [45]. This was apparent as the author used one of the BASs serving some of the University of Maryland's buildings. This BAS did have several positive features, such as vivid images of HVAC equipment operation, control schemes, and colored maps giving an overview of a buildings temperature distribution (see Figure 5.1). However, navigation through the BAS was difficult. For instance, an option to view the setpoint temperature of all of the zones monitored in the BAS was not available. Instead, each zone had to be selected one-by-one to view the zone's current temperature, airflow, setpoint temperatures and other zone-related data. Similarly, the historical data of each zone had to be selected one-by-one in a separate tab. A search bar to find a specific zone was also not available.

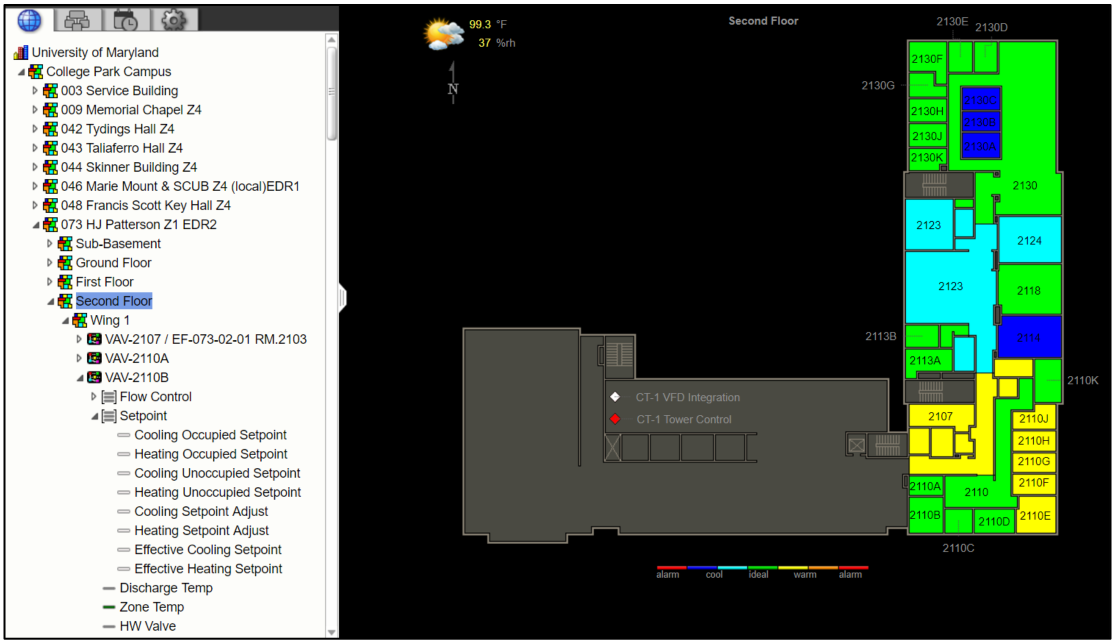
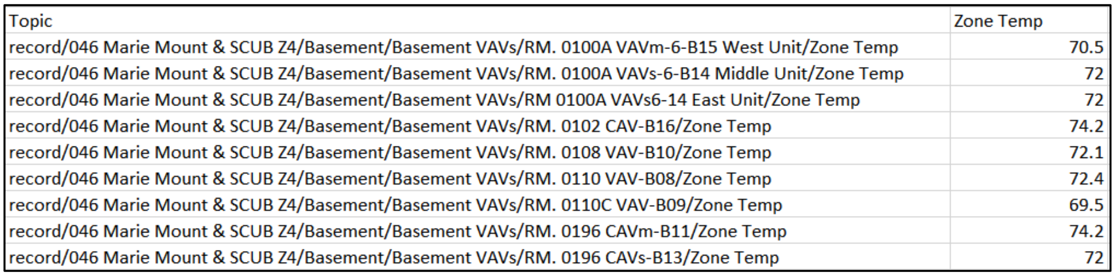


Figure 5.1: Color coded temperature map of a Univ. of Maryland building's floor in a Building Automation System. On the left-hand side is the navigation tabs to find a specific data point.

5.2: Building Monitor Agent

To aid in navigating through the BAS data, the University of Maryland Facilities Management team uses Microsoft Excel to interface with the BAS, via the SOAP communication protocol. With this, one can search and change BAS points in Excel. Information on the SOAP protocol can be found here [46] [47]. The author used the SOAP protocol in a python script, since the python script could then be modified to be a VOLTTRON agent. The resulting 'Building Monitor' agent written by the author allows one to view the current value for specific point(s), such as the temperature of zones on the first floor of Martin Hall. These data points could also be used by other agents within VOLTTRON.

Figure 5.2 displays the real-time zone temperature of some of the zones monitored in the BAS. The building monitor agent was used to retrieve the data from the BAS and save the data in a CSV file. Figure 5.3 displays a graph of the temperature of over 400 zones monitored in the BAS from eight buildings. One can quickly identify zones with extreme temperatures, and determine potential issues with a zone's thermostat reading. As noted by the green box in Figure 5.3, some zones had temperatures well below the ASHRAE thermal comfort range for summer [47]. The key findings from a case study on some of these subcooled zones is discussed in the following section.



Topic	Zone Temp
record/046 Marie Mount & SCUB Z4/Basement/Basement VAVs/RM. 0100A VAVm-6-B15 West Unit/Zone Temp	70.5
record/046 Marie Mount & SCUB Z4/Basement/Basement VAVs/RM. 0100A VAVs-6-B14 Middle Unit/Zone Temp	72
record/046 Marie Mount & SCUB Z4/Basement/Basement VAVs/RM 0100A VAVs6-14 East Unit/Zone Temp	72
record/046 Marie Mount & SCUB Z4/Basement/Basement VAVs/RM. 0102 CAV-B16/Zone Temp	74.2
record/046 Marie Mount & SCUB Z4/Basement/Basement VAVs/RM. 0108 VAV-B10/Zone Temp	72.1
record/046 Marie Mount & SCUB Z4/Basement/Basement VAVs/RM. 0110 VAV-B08/Zone Temp	72.4
record/046 Marie Mount & SCUB Z4/Basement/Basement VAVs/RM. 0110C VAV-B09/Zone Temp	69.5
record/046 Marie Mount & SCUB Z4/Basement/Basement VAVs/RM. 0196 CAVm-B11/Zone Temp	74.2
record/046 Marie Mount & SCUB Z4/Basement/Basement VAVs/RM. 0196 CAVs-B13/Zone Temp	72

Figure 5.2: Temperature of UMD zones in the BAS on July 26, 2016 at 5pm. Data was retrieved and saved to a CSV file using the author's 'Building Monitor' agent

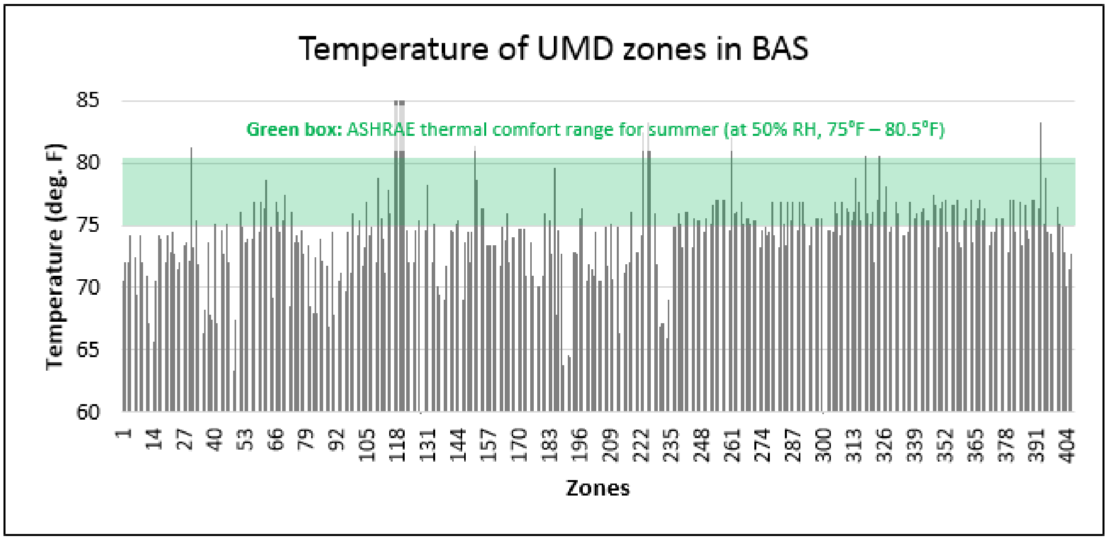


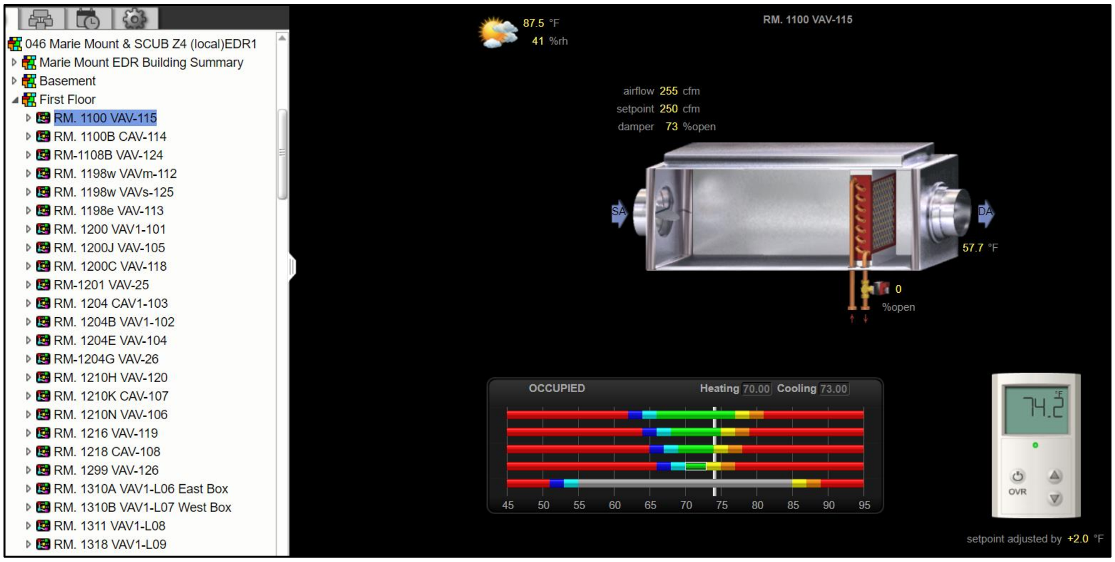
Figure 5.3: Graphical representation of UMD zones' temperature on July 26, 2016 at 5pm

5.3: Marie Mount Hall

Marie Mount Hall is one of the University of Maryland buildings that is monitored and controlled by the BAS discussed in this chapter. The results from the Building Monitor agent indicate Marie Mount Hall has several zones with relatively cold temperatures, some below 68°F. Thus a case study on Marie Mount Hall was conducted. The following sections present the actual zone temperature, setpoint temperature, and airflow rate of Marie Mount Hall in July of 2016. Numerical analysis on the potential energy savings from modifying the setpoint temperature and airflow rate is presented afterwards.

5.3.1 Introduction

Marie Mount Hall is a medium sized, mixed use building located in College Park, MD. It has four floors, including a basement. The basement has an art studio, the first floor has offices, conference rooms, and a lecture hall, the second floor has a mix of offices and labs, and the third floor has a majority of labs. The building has 137 thermal zones that are monitored and controlled in a BAS. Eight air handling units (AHUs) provide conditioned air to the zones via ductwork and zone level terminal units (i.e. variable air volume (VAV) boxes). Some of the terminal units have reheat, and each zone has a thermostat. Figure 5.4 displays the BAS graphic of a VAV box serving a zone in Marie Mount Hall. Section 5.3.2 briefly explains how VAV boxes operate, as most of the terminal units in Marie Mount Hall are VAV boxes.



87.5 °F
41 %rh

airflow 255 cfm
setpoint 250 cfm
damper 73 %open

57.7 °F

0 %open

Heating 70.00 Cooling 73.00

setpoint adjusted by +2.0 °F

Figure 5.4: BAS graphics of a zone's VAV box and temperature

5.3.2 VAV Systems

In a VAV system, the building's AHUs provide conditioned, ~55°F air to each VAV box. These VAV boxes modulate their damper position to vary the amount of air supplied to the building's zones, according to each zone's thermal and ventilation needs. When a zone's temperature reaches or exceeds its cooling setpoint temperature, the VAV box adjusts its current damper position to increase airflow to the zone. When the zone's temperature reaches or falls below the heating setpoint temperature, the heating coil within the VAV box is enabled, heating the ~55°F air entering the VAV box. The warmer air is supplied to the zone. When a zone's temperature is within the deadband[3] region, the VAV box supplies air at a rate that is at least equal to the required

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[3] Deadband region refers to temperatures between the heating and cooling setpoint temperatures

ventilation rate for the zone [48]. As such, a minimum amount of air is always supplied to the zones when the AHU and VAV boxes are operating.

5.4 Marie Mount Hall's Zones

5.4.1 Zone Temperature

Figure 5.5 displays the 34 zones on Marie Mount Hall's first floor that are investigated. The first floor is investigated because it is mainly composed of offices and conference rooms. Table 5.1 indicates the space type that makes up the majority or entirety of each zone. Figure 5.6 displays the zone temperature, cooling setpoint, and heating setpoint temperature for each zone on July 20, 2016 at 2pm. Key observations from Figure 5.6 are (1) each zone has a deadband of 7°F, with cooling setpoints ranging from 74°F to 78°F, and heating setpoints ranging from 67°F to 71°F, (2) some zones were considerably cold, with temperatures below 70°F, causing some of these zones to reach their heating setpoint temperature, and (3) the temperature of zones 15, 21, and 25 would have likely been lower than 70°F had their heating setpoint not been 71°F, 71°F, and 70°F respectively. No advanced temperature schedule, such as precooling the zones, were implemented.

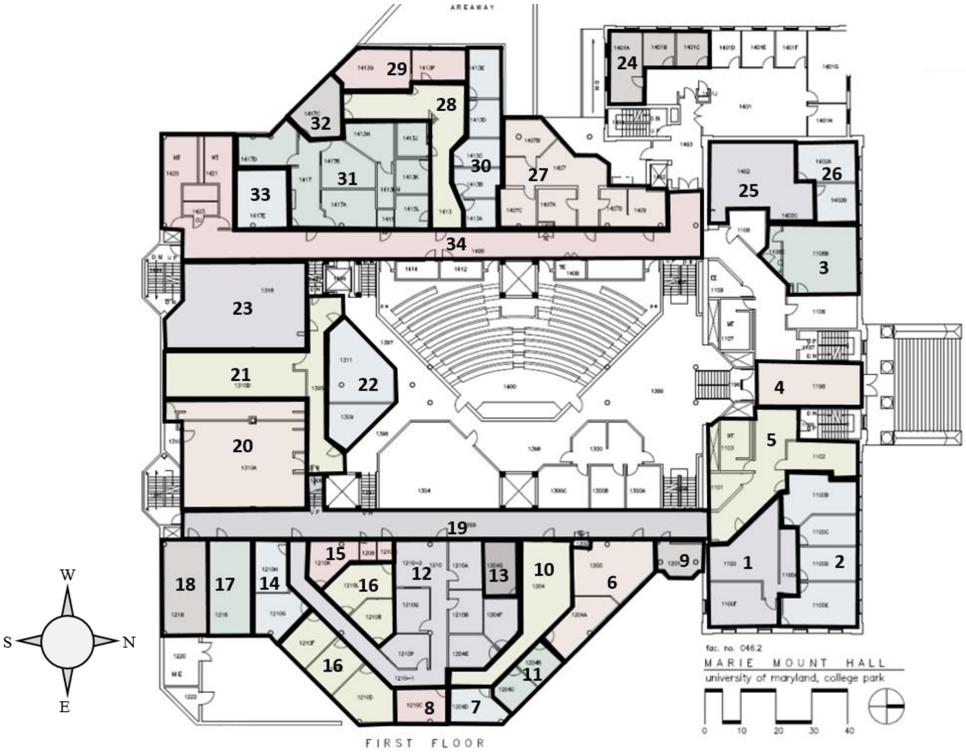

Figure 5.5: Marie Mount Hall's first floor, with thermal zones outlined. The colors in the figures are used to distinguish thermal zones, and do not represent zone temperature

Space Type	Office	Conference Room	Corridor	Research	Seminar Room
Zone	1, 2, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 24, 25, 26, 27, 29, 30, 31, 32, 33	6, 20, 21, 22, 23	4, 5, 19, 34	28, 31	3, 18

Table 5.1: Space type of the 34 zones. Zones with mixed use appear under multiple columns. Data retrieved from UMD Facilities room inventory [49]

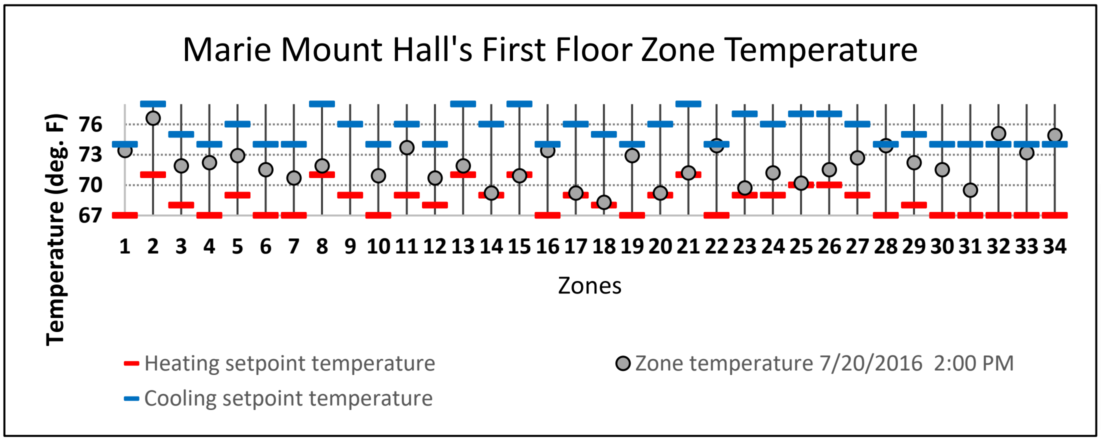

Figure 5.6: Zone temperatures on July 20, 2016 at 2pm, plotted with each zone's respective heating and cooling setpoint temperatures

Presented in Table 5.2 is the number of times each zone's temperature was within a temperature range, (ex. 71°F to 71.9°F) during the week of July 17, 2016. Only temperature values from Monday to Friday, 8:00 am to 8:00 pm, were analyzed because the goal was to assess how each zone's temperature varied during occupied-hours[4] when the VAV and AHU units operated. For a consistent sampling, temperature values on the hour (i.e. 8:00 am, 9:00 am, 10:00 am, etc.) were examined, for a total of 65 temperatures analyzed for each zone during the week of July 17, 2016. A key observation from this analysis was ten out of the 34 zones' temperature were below 70°F at least eight times. For instance, the temperature in zone 14 was below 70°F 61 out of the 65 hours examined.

ASHRAE recommends indoor temperatures of 75°F to 80.5°F with 50% relative humidity during the summer, thus temperatures less than 70°F are well below the thermal comfort range, even with humidity considered [47]. The low zone temperatures are also notable because they occur in the summer, indicating these zones are overcooled due to the VAV system, not cold outdoor temperatures. The author visited Marie Mount Hall's first floor in July of 2017, and noticed zones 17, 18, 20, 21, 22, 23, and 25 were unoccupied, thus the room lights were off, and the doors were locked. Some of the other zones appeared under-occupied given the empty chairs viewed from the interior windows. Given the low temperatures presented in Table 5.2, it is likely most of the zones were unoccupied or under-occupied in July of 2016, and possibly the entire summer semester. High air flowrates from VAV systems can cause zones to be overcooled [49], thus the airflow rates of Marie Mount Hall zones were examined.

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[4] Complete occupied schedule was 6:30am – 8pm, Mon. – Fri., and 8am – 2pm on Sat. and Sun.

Table 5.2: Temperature distribution of the 34 zones On Marie Mount Hall's first floor during the week of July 17, 2016, Mon. – Fri., 8am to 8pm. The red and blue bars represent the zones heating and cooling setpoint temperatures respectively. Some zones setpoint temperatures changed during the week, thus multiple red and blue bars may be shown per zone. An asterisk (*) indicates the zone has an outdoor window

		Zone Temperatures (deg. F)									
Zone	**Space use**	Less than 68	68 - 68.9	69 - 69.9	70 - 70.9	71 - 71.9	72 - 72.9	73 - 73.9	74 - 74.9	75 - 75.9	76+
1*	Office					6	18	36	3		2
2*	Office									14	51
3*	Seminar room					31	12	6	11		5
4	Corridor				4	20	28	9	1	1	2
5*	Office/Corridor						33	18	8	4	2
6*	Conf. rm. /Office				21	19	11	12		1	1
7*	Office			1	15	25	16	5	1		2
8	Office			3	28	28	2	2		1	1
9	Office										65
10	Office			3	17	22	17	4		1	1
11*	Office				2	4	4	7	15	25	8
12	Office			2	31	28	1	1			2
13	Office				15	20	16	7	3	2	2
14	Office	19	18	24	2			1			1
15	Office	3	2	14	21	22	1		1		1
16*	Office						12	35	11	5	2
17	Office	9	23	29	1	1		1			1
18	Seminar room	26	34	1	2		1				1
19	Corridor						2	25	28	5	5
20	Conf. rm.	27	24	12		1					1
21	Conf. rm.	12	10	4	7	30	1				1
22	Conf. rm.							47	14	2	2
23	Conf. rm.			8	31	16	7		1		2
24*	Office				14	19	22	1	1	5	3
25	Office	27	3	1	32		1				1
26*	Office	2	4	8	12	31	4	1	1		2
27*	Office						15	24	14	9	3
28	Research							14	24	15	12
29*	Lunch rm. /office			1	9	11	17	8	9	3	7
30	Office				5	10	7	30	5		8
31	Office/Research Lab			12	8	7	18	10	2		8
32*	Office						3	9	10	12	31
33	Office						9	46	3	1	6
34	Corridor								4	36	25

5.4.2 Zone Airflow

As discussed in Section 5.3.2, when a zone's temperature is within the deadband region, its VAV box supplies air at a rate that is at least equal to the zone's minimum required ventilation rate [48]. The ASHRAE Standard on *Ventilation for Acceptable Indoor Air Quality* lists the minimum ventilation rates for offices, conference rooms, and corridors as

$$0.06\ cfm/ft^2 + 5\ cfm/person$$

where ft^2 refers to the zones area. Table 5.3 presents the baseline airflow and area of each of the 34 zones. The calculated minimum airflow based on the estimated number of occupants for each zone is also presented in Table 5.3. The author estimated an occupancy density of three people per 120 sqft. for offices, and ten people per 120 sqft. for conference rooms.

As indicated by Table 5.3, practically all of the zones' baseline airflow rates were above the estimated minimum ventilation rate. This is expected, considering high baseline airflow rates may be needed to compensate for the other factors affecting a zone's temperature and air quality, such as internal loads (occupant activity, indoor lighting, plugloads), humidity, and outdoor conditions. However, airflow rates that are significantly above the needed ventilation rate can cause zones to be overcooled. This is especially the case when the zones are unoccupied. Sensors to track occupancy and plugload changes can be expensive and cumbersome to install, thus it is understandable why a constant baseline airflow rate is implemented for each zone. Low cost strategies are needed to address unnecessary ventilation and cooling of zones.

Table 5.3: Estimated minimum ventilation rate and actual baseline airflow rate. Shaded rows indicate zones that had low temperatures for the week of July 17, 2016 (see Table 5.2). An asterisk (*) indicates the zone has an outdoor window

Zone	Space use	Area (sqft)	Estimated occupants	Min. ventilation based on zone area and estimated occupants (cfm)	Actual Baseline Airflow rate (cfm)
1*	Office	642	17	124	255
2*	Office	780	20	147	158
3*	Seminar room	487	13	94	77
4	Corridor	1204	n/a	n/a	58
5*	Office/Corridor	797	n/a	n/a	148
6*	Conf. rm. /Office	512	32	191	163
7*	Office	143	4	29	124
8	Office	145	4	29	72
9	Office	111	3	22	90
10	Office	481	12	89	140
11*	Office	188	5	36	288
12	Office	1478	37	274	370
13	Office	158	4	29	163
14	Office	304	8	58	165
15	Office	199	5	37	138
16*	Office	785	20	147	404
17	Office	324	8	59	190
18	Seminar room	320	27	154	250
19	Corridor	1227	n/a	n/a	875
20	Conf. rm.	1078	90	515	753
21	Conf. rm.	773	65	371	816
22	Conf. rm.	501	42	240	324
23	Conf. rm.	897	75	429	751
24*	Office	382	10	73	249
25	Office	574	15	109	479
26*	Office	326	8	60	220
27*	Office	874	22	162	268
28	Research	543	n/a	n/a	512
29*	Lunch rm. /office	390	33	188	561
30	Office	517	13	96	386
31	Office/Research Lab	1192	n/a	n/a	788
32*	Office	180	5	36	250
33	Office	251	7	50	234
34	Corridor	2038	n/a	n/a	1093

5.4.3 Possible Strategy Using VOLTTRON

Accurate occupancy sensors or CO_2 monitors that could be used in the BAS to improve the HVAC operation can be expensive, and take time to install. Most of the overcooled zones were conference/seminar rooms, which are likely reserved by users via an online calendar. Thus, a possible remedy to these overcooled zones is to create a VOLTTRON agent that relays the reservation status of the rooms from the calendar to the BAS. With this the BAS can lower the airflow to the minimum ventilation rate if the zone is not reserved and the space temperature falls below 70°F. This agent can also be used for labs and offices, by using the online calendar to indicate when the labs and offices are occupied. The proposed agent would use the SOAP protocol to interface with the BAS, hence there would be no additional equipment cost.

5.5: Numerical Analysis: Potential Energy Savings

To assess the potential energy savings from modifying the baseline airflow, the author simulated Marie Mount Hall's energy consumption via energy modeling software. The modeling software used in this thesis use EnergyPlus as the energy analysis and thermal load simulation program [50]. EnergyPlus solves systems of equations to calculate the energy needed for heating and cooling the simulated building [50]. The heat balance equation used to determine the air needed from the HVAC system to address the building's thermal needs is displayed in Equation 1.

Equation 1: EnergyPlus heat balance equation used to determine air needed to address buildings thermal needs. Equation from EnergyPlus Engineering Reference [50]

$$C_z\frac{dT_z}{dt} = \sum_{i=1}^{N_{sl}} \dot{Q}_i + \sum_{i=1}^{N_{surfaces}} h_i A_i \left(T_{si} - T_z\right) + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p \left(T_{zi} - T_z\right) + \dot{m}_{\text{inf}} C_p \left(T_\infty - T_z\right) + \dot{Q}_{sys}$$

where:

$\sum_{i=1}^{N_{sl}} \dot{Q}_i$ = sum of the convective internal loads

$\sum_{i=1}^{N_{surfaces}} h_i A_i \left(T_{si} - T_z\right)$ = convective heat transfer from the zone surfaces

$\dot{m}_{\text{inf}} C_p \left(T_\infty - T_z\right)$ = heat transfer due to infiltration of outside air

$\sum_{i=1}^{N_{zones}} \dot{m}_i C_p \left(T_{zi} - T_z\right)$ = heat transfer due to interzone air mixing

$\dot{Q}_{sys}$ = air systems output

$C_z\frac{dT_z}{dt}$ =energy stored in zone air

$C_z = \rho_{air} C_p C_T$

ρ_{air} = zone air density

C_p = zone air specific heat

C_T = sensible heat capacity multiplier

5.5.1 Creation of Marie Mount Hall's Energy Model

VirtualPULSE was used to create the physical model (i.e. building shape, construction material), and select the space type and thermal zone set up. Additionally, the author used VirtualPULSE to select the HVAC system and designate typical load densities (i.e. plugloads and lighting loads) of Marie Mount Hall. VirtualPULSE is a low order simulation platform meant to ease and quicken simulating the energy use of buildings. Thus, the resulting model assumed each floor was a thermal zone, for a total of four thermal zones, though in actuality, there are multiple thermal zones per floor (See Figure 5.7 and Figure 5.8). For the HVAC system, the author chose district heating and cooling to represent Marie Mount Hall's chilled water and steam use. The model in VirtualPULSE was then exported to OpenStudio. In OpenStudio, the author modified the heating and cooling setpoint temperature, occupancy, lighting, and electrical equipment schedules. Additionally, the ventilation rate for each thermal zone was changed from the default of 20 cfm per person, to the total baseline airflow for the corresponding floor.

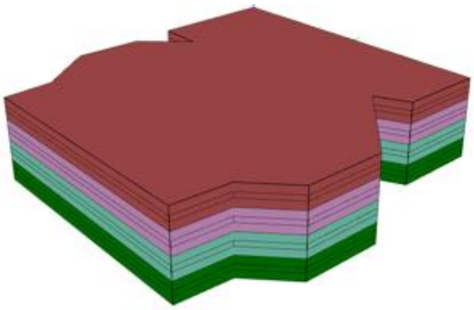


Figure 5.7: Marie Mount Hall model rendered by thermal zone

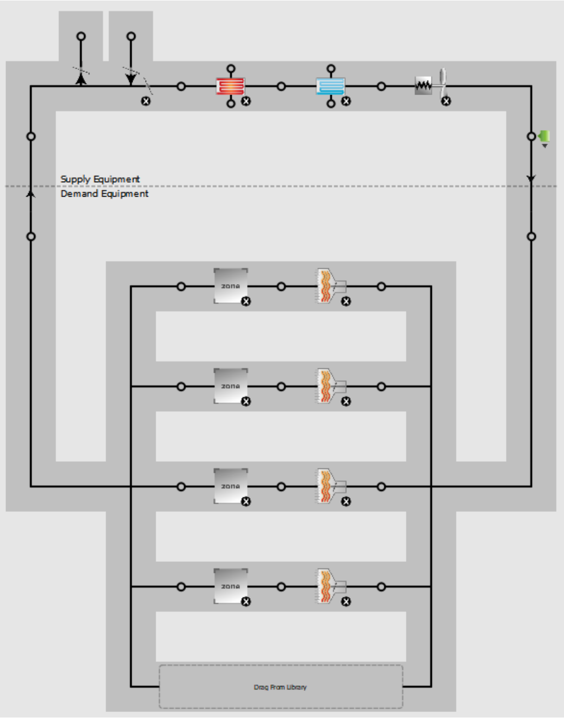
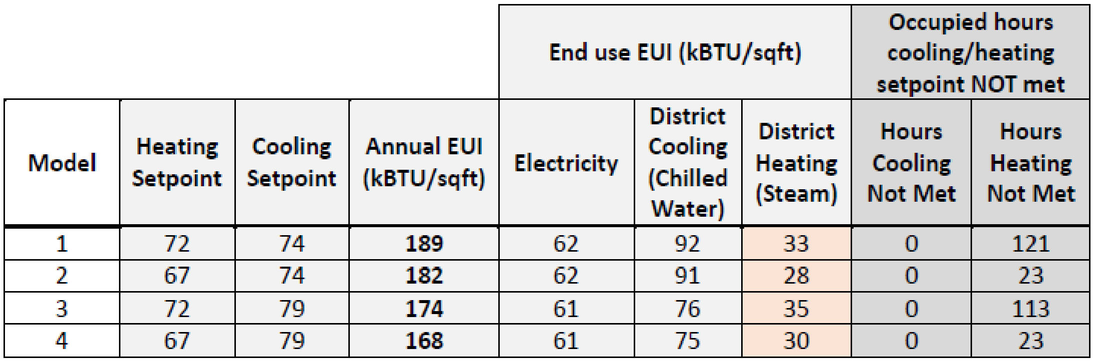


Figure 5.8: HVAC loop for Marie Mount Hall's model

5.5.2 Results: EUI with Baseline Airflow Rate

The simulated energy use intensity (EUI) of Marie Mount Hall given the baseline airflow, and various setpoint temperatures is presented in Table 5.4. Model 1, with the narrowest deadband of 2°F had the highest annual EUI of 189 kBTU/sqft. Model 4 with the widest deadband of 12°F had a lower EUI of 168 kBTU/sqft. The actual heating and cooling setpoint temperature of zones in Marie Mount Hall ranged from 67°F-72°F and 74°F-79°F respectively, with a deadband of 7°F. Model 2 and model 3, each with a deadband of 7°F, had an annual EUI of 182 kBTU/sqft and 174 kBTU/sqft respectively. Overall, increasing the cooling setpoint decreased the district cooling EUI, and decreasing the heating setpoint decreased the district heating EUI. Also, for all four models in Table 5.4, there were some hours where the zone temperature was below the heating setpoint temperature. This indicates the HVAC equipment was unable to satisfy all of the buildings heating needs, possibly due to the high ventilation rate.

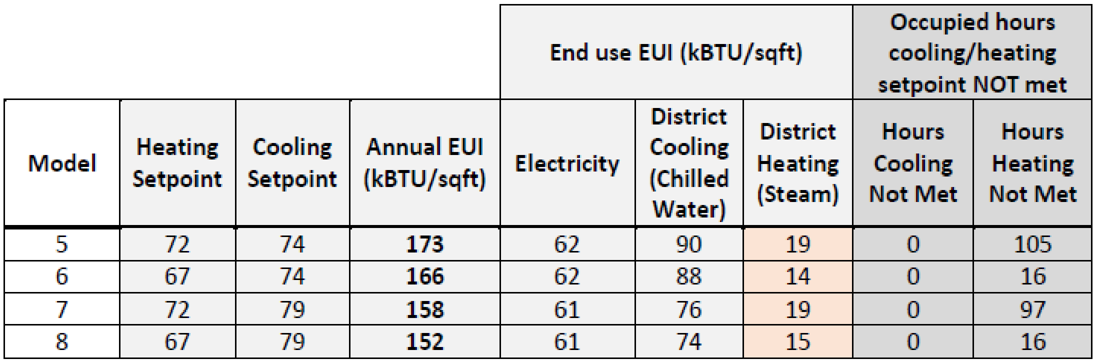


				End use EUI (kBTU/sqft)			Occupied hours cooling/heating setpoint NOT met	
Model	Heating Setpoint	Cooling Setpoint	Annual EUI (kBTU/sqft)	Electricity	District Cooling (Chilled Water)	District Heating (Steam)	Hours Cooling Not Met	Hours Heating Not Met
1	72	74	**189**	62	92	33	0	121
2	67	74	**182**	62	91	28	0	23
3	72	79	**174**	61	76	35	0	113
4	67	79	**168**	61	75	30	0	23

Table 5.4: Energy Use Intensity (EUI) and occupied hours cooling/heating setpoint not met for models 1-4. The total baseline airflow rates per floor, as indicated in the BAS, were used for the ventilation rate provided to each floor in the models

5.5.3 Results: EUI with Reduced Airflow Rate

For models 5-8, the author reduced the ventilation rate to 35% of the total maximum cooling airflow rate per floor, as indicated in the BAS. 35% was chosen since most VAV boxes are designed to supply at least 30% of its maximum flowrate when the AHU operates [50] [51]. The simulated EUI of Marie Mount Hall with the reduced zone airflow rate is presented in Table 5.5. Comparing models 5-8 to models 1-4, the annual EUI decreased when the ventilation rate decreased. The decrease in EUI was mainly due to the decrease in district heating. With the lower ventilation rate, the building's cooling needs are still met, but there are hours when heating is not meant. This is likely because lowering the ventilation to 35% of the maximum cooling airflow still significantly exceeded ASHRAE's recommended minimum ventilation rates. Overall though, reducing the baseline airflow rated decreased the EUI of models 1-4 by 16 kBTU/sqft. This translates into a potential 8% reduction in energy consumption if the baseline airflow rates are reduced.



				End use EUI (kBTU/sqft)			Occupied hours cooling/heating setpoint NOT met	
Model	**Heating Setpoint**	**Cooling Setpoint**	**Annual EUI (kBTU/sqft)**	**Electricity**	**District Cooling (Chilled Water)**	**District Heating (Steam)**	**Hours Cooling Not Met**	**Hours Heating Not Met**
5	72	74	**173**	62	90	19	0	105
6	67	74	**166**	62	88	14	0	16
7	72	79	**158**	61	76	19	0	97
8	67	79	**152**	61	74	15	0	16

Table 5.5: EUI and occupied hours cooling/heating setpoint not met for models 5-8.The reduced airflow rate were used for the ventilation rate provided to each floor in the models

Chapter 6: Conclusion

6.1: Thesis Contribution

VOLTTRON is a relatively new open source operating system developed by Pacific Northwest National Laboratory to address cost and interoperability issues with energy management systems. This thesis demonstrated use of VOLTTRON for energy management of commercial buildings with and without a BAS at the University of Maryland.

With any new software/operating system, individual training and guidance from the developers are needed to learn how to use the computer system. After months of learning Python programming, how VOLTTRON worked, and how VOLTTRON agents are written, the author was able to successfully write VOLTTRON agents to lower the energy use of a RTU from ~18kW to ~7kW, while maintaining appropriate indoor temperature in the CITY@UMD office. This experience gives the author the unique opportunity to teach other researchers about VOLTTRON, and how the operating system can be used to monitor and control HVAC units with Internet – enabled controllers. Indeed, the procedure and equipment needed to use VOLTTRON to control and monitor a RTU was presented Chapter 4 of this thesis, enabling researchers to replicate and expand upon this project on other buildings.

The author also discussed how VOLTTRON was used to interface with a BAS. The building monitor agent created aided in quickly identifying zones with extreme temperatures. A method to use VOLTTRON to address overcooled zones in a case study building was also mentioned in Chapter 5.

6.2: Future Research

Future research includes implementing VOLTTRON in other buildings without a BAS, addressing overcooled zones as mentioned in the Marie Mount Hall case study, and using VOLTTRON for demand response strategies.

Appendix 1: Technology Ventures Building Result Calculations

Presented is the calculations for the percentage of the Technology Ventures Building's electricity use and electricity bill from June 2016 to September 2016 estimated to be from RTU6's operation. (10 to 12% was stated in Section 4.3.2 of this thesis).

Table A1.1: Electricity use and electric bill for the Technology Ventures Building from 6/11/2016 to 10/12/2016

Billing Period	**6/11/2016 to 7/13/2016**	**7/14/2016 to 8/10/2016**	**8/11/2016 to 9/13/2016**	**9/14/2016 to 10/12/2016**	**Summer (6/11/2016 to 10/12/2016)**
TVB Total Electricity Use (kWh)	132,640 kWh	120,480 kWh	137,760 kWh	96,800 kWh	487,680 kWh
TVB Total Electric Bill ($)	$13,878	$12,872	$14,665	$10,667	$52,082

Table A1.1 displays the actual electricity use and electric bill of the Technology Ventures Building from 6/11/2016 to 10/12/2016. The total electricity use for the building in this time range was 487,680 kWh. The corresponding bill was $52,082. Data was retrieved from the PEPCO billing account.

It is assumed that RTU6 operated in cooling mode continuously from 6/11/2016 to 10/12/2016, with an average demand of 18 kW. This is a reasonable assumption, as the electricity use of the RTU oscillates around 18 kW when cooling is not turned off, as displayed in Figure A1.1.

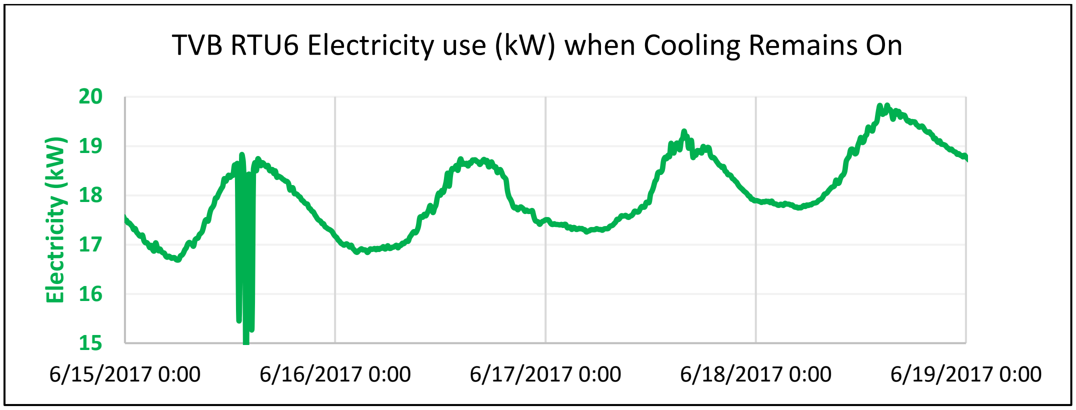


Figure A1.1: Electricity consumption of RTU6 on the Technology Ventures Building when cooling is on

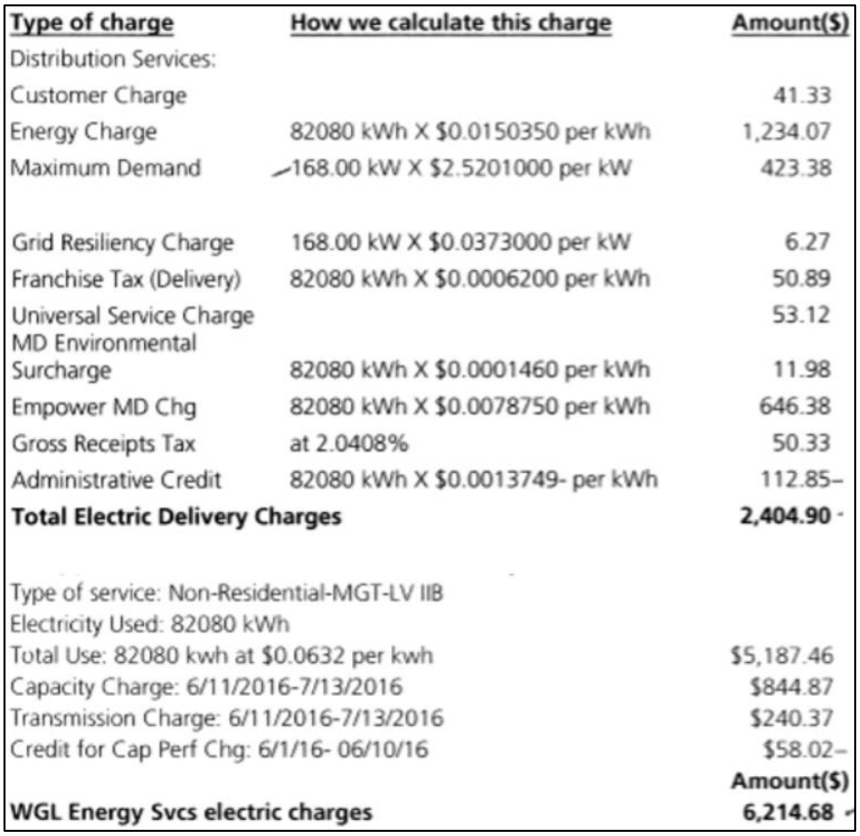
6/11/2016 to 10/12/2016 is 124 days. Therefore, the RTU electricity use during those 124 days is approximately 53,568 kWh as shown in Equation A1.1.

$$18\ kW \times 24\ \frac{hours}{day} \times 124\ days = 53{,}568\ kWh \qquad \textit{(Equation A1.1)}$$

The total electricity use of the Technology Ventures building from 6/11/2016 to 10/12/2016 was 487,680 kWh. As such, the RTU represented approximately 11% of the Technology Ventures Building electricity use during the summer of 2016, as shown in Equation A1.2.

$$\frac{53{,}568\ kWh}{487{,}680\ kWh} = 11\ \% \qquad \textit{(Equation A1.2)}$$

Figure A1.2 displays the actual billing charges for meter 1 of the Technology Ventures Building for the 6/11/2016 to 7/13/2016 bill. These charges were used to calculate the portion of the Technology Ventures Building electric bill that was from RTU6's operation.



Type of charge	How we calculate this charge	Amount($)
Distribution Services:		
Customer Charge		41.33
Energy Charge	82080 kWh X $0.0150350 per kWh	1,234.07
Maximum Demand	168.00 kW X $2.5201000 per kW	423.38
Grid Resiliency Charge	168.00 kW X $0.0373000 per kW	6.27
Franchise Tax (Delivery)	82080 kWh X $0.0006200 per kWh	50.89
Universal Service Charge		53.12
MD Environmental Surcharge	82080 kWh X $0.0001460 per kWh	11.98
Empower MD Chg	82080 kWh X $0.0078750 per kWh	646.38
Gross Receipts Tax	at 2.0408%	50.33
Administrative Credit	82080 kWh X $0.0013749- per kWh	112.85–
Total Electric Delivery Charges		**2,404.90**
Type of service: Non-Residential-MGT-LV IIB		
Electricity Used: 82080 kWh		
Total Use: 82080 kwh at $0.0632 per kwh		$5,187.46
Capacity Charge: 6/11/2016-7/13/2016		$844.87
Transmission Charge: 6/11/2016-7/13/2016		$240.37
Credit for Cap Perf Chg: 6/1/16- 06/10/16		$58.02–
		Amount($)
WGL Energy Svcs electric charges		**6,214.68**

Figure A1.2: Electric billing charges for the Technology Ventures Building (meter 1), 6/11/2016 to 7/13/2016 bill

As such, the Energy Charge for operating the RTU from 6/11/2016 to 7/13/2016 bill is approximately $214.34. Equations A1.3 and A1.4 display the calculations.

$$18\ kW \times 24\ \frac{hours}{days} \times 33\ days = 14{,}256\ kWh \qquad (Equation\ A1.3)$$

$$Energy\ Charge = 14{,}256\ kWh \times \$0.015035\ per\ kWh = \$214.34 \quad (Equation\ A1.4)$$

Table A1.2 lists the billing charges for the RTU. Customer Charge and Universal Service Charge are listed as zero as they are not dependent on the amount of electricity used or the peak demand.

Table A1.2: Billing Charges for RTU6

<table>
<tr><td colspan="4">RTU6 Total Electricity Use (kWh) from 6/11/2016 to 7/13/2016 is
14,256 kWh (see Equation A.3)</td></tr>
<tr><td colspan="4">Maximum on peak demand of RTU6 is
~18 kW</td></tr>
<tr><td colspan="4"></td></tr>
<tr><th>Type of Charge</th><th colspan="2">Rate</th><th>RTU6 portion of TVB bill</th></tr>
<tr><td>Customer Charge</td><td>-</td><td>Fixed</td><td>$0</td></tr>
<tr><td>Energy Charge</td><td>$0.015035</td><td>per kWh</td><td>$214.34</td></tr>
<tr><td>Maximum Demand</td><td>$2.5201</td><td>per kW</td><td>$45.36</td></tr>
<tr><td>Grid Resiliency Charge</td><td>$0.0373</td><td>per kW</td><td>$0.67</td></tr>
<tr><td>Franchise Tax (Delivery)</td><td>$0.00062</td><td>per kWh</td><td>$8.84</td></tr>
<tr><td>Universal Service Charge</td><td>-</td><td>Fixed</td><td>$0</td></tr>
<tr><td>MD Environmental Surcharge</td><td>$0.000146</td><td>per kWh</td><td>$2.08</td></tr>
<tr><td>Empower MD Charge</td><td>$0.007875</td><td>per kWh</td><td>$112.27</td></tr>
<tr><td>Gross Receipts Tax</td><td>$0.020408</td><td>-</td><td>$7.83</td></tr>
<tr><td>Administrative Credit</td><td>$0.0013749</td><td>per kWh</td><td>-$19.6</td></tr>
<tr><td>RTU6 Total Electric Charges</td><td colspan="2"></td><td>$371.79</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td>Total Use Charge</td><td>$0.0632</td><td>per kWh</td><td>$900.98</td></tr>
<tr><td>Capacity Charge</td><td colspan="2">~16% of Total Use Charge</td><td>$144.16</td></tr>
<tr><td>Transmission Charge</td><td colspan="2">~4.3% of Total Use Charge</td><td>$38.74</td></tr>
<tr><td>Credit for Cap Performance</td><td colspan="2">~1.1 of Total Use Charge</td><td>-$9.91</td></tr>
</table>

RTU6 WGL Energy Svcs electric charges		**$1073.97**
RTU6 Total Bill		**$1,445**

The total bill for the Technology Ventures Building from 6/11/2016 to 7/13/2016 was $13,878 as shown in Table A1.1. Thus, RTU6 was approximately 10.4% of the bill as shown in Equation A1.5. Similar calculations were done for the July, August, and September bills.

$$\frac{\$1,445}{\$13,878} = 10.4\% \qquad \textit{(Equation A1.5)}$$

In summary, the RTU consumed approximately 53.6 MWh of electricity during the summer of 2016, and accounted for approximately $5,441 of the total electric bill for the Technology Ventures Building. These values are based on the assumption that the RTU was continuously in cooling mode.

The following sections present the calculations for the RTU electricity consumption when implementing the modest cooling schedule as discussed in Section 4.3.2 of this thesis.

The modest cooling schedule is as followed:

- RTU cooling is on for 12 hours Mondays – Fridays
- RTU cooling is off for 12 hours Mondays – Fridays
- RTU cooling is off Saturdays and Sundays

When cooling is on, the RTU consumes approximately 18 kW of electricity. When cooling is off, the electricity use drops to 7 kW (see Figure 4.5).

Of the 124 days from 6/11/2016 to 10/12/2016, 36 days are weekends. This leaves 88 weekdays. As such the calculated electricity use of the RTU with the schedule is 32,448 kWh.

$$Occupied\ Weekday\ (RTU\ cooling\ on):$$

$$18\ kW\ \times\ 12\ \frac{hours}{day} \times\ 88\ days = 19{,}008\ kWh$$

$$Unoccupied\ Weekday\ (RTU\ cooling\ off):$$

$$7\ kW\ \times\ 12\ \frac{hours}{day} \times\ 88\ days = 7{,}392\ kWh$$

$$Weekends\ (RTU\ cooling\ off):$$

$$7\ kW\ \times\ 24\ \frac{hours}{day} \times\ 36\ days = 6{,}048\ kWh$$

The billing charges for RTU6 if the cooling schedule was implemented was also calculated. The maximum demand is still considered 18 kW, but the total electricity use of the RTU from 6/11/2016 to 7/11/2016 drops to 8,580 kWh compared to 14,256 kWh. Referring to Table A1.2, and substituting 14,256 kWh for 8,580 kWh, the RTU6 bill with the cooling schedule drops to $888. This is a $557 decrease from $1,445. Similar calculations were done for the July, August, and September bills.

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