MC-1 Energy Audit

Tiffany Price

Northwestern University

GEM Fellow

August 7, 2020

1 Introduction

1.1 Muon g-2 Experiment

The MC-1 building is a laboratory building located at Fermilab that is the home to the Muon g-2 experiment. The goal of the project is to measure the muon magnetic anomalous moment to a precision of 140 parts per billion (ppb). This is an unprecedented endeavor that will allow for a high precision comparison of the standard model's prediction and experimental value of the muon magnetic anomaly. If the difference is statistically significant this could mean there is undiscovered physics beyond the standard model.

A muon (μ) is an elementary particle and is part of the lepton classification in the standard model of physics. Muons are very similar to electrons in that they both have an electric charge of -1 and a spin of $\frac{1}{2}$. One major difference between electrons and muons is that muons are about 207 times heavier. The muon magnetic anomalous moment is defined as $a_\mu = \frac{g-2}{2}$ where g is the muon's gyromagnetic ratio or "g-factor". This number is essentially a measure of the muon's precession frequency when in the presence of a magnetic field. Physicist can measure the muon's g-factor to a very high precision and have found it to differ from 2 by about 0.1%. This difference is what the muon magnetic anomaly represents and is where the g-2 project gets its name.

To experimentally measure the muon magnetic anomaly, the g-2 experiment sends a group of polarized muons into the storage ring via the inflector. Once inside the ring these bunches of muons are accelerated and subjected to a magnetic field of about 1.45 T. To store the muon beam onto the central orbit for measurements to be taken, three electromagnetic kickers provide pulses of high voltages to the beam to "kick" it onto the desired orbit. Four quadrupoles provide vertical focusing of the beam to keep muons from spiraling out of the ring under the presence of the magnetic field. Calorimeters, trackers, and other detectors found along the ring measure the energy, momentum, and other properties of the muons and other decay particles. The major components of the storage ring can be found in Figure 1 [2].

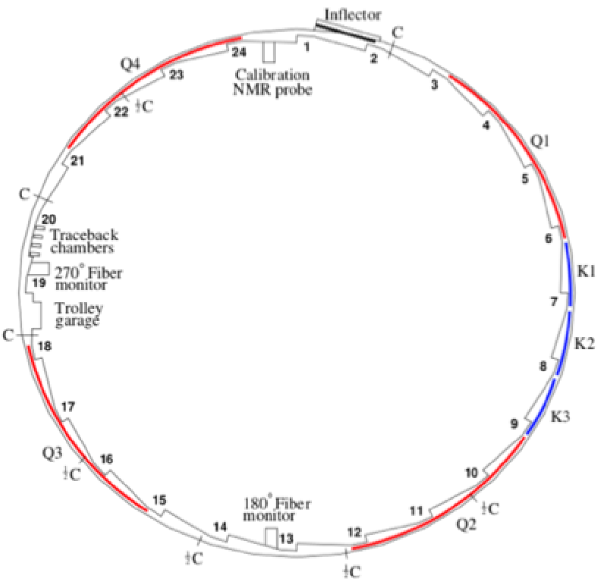

Figure 1: *Layout of the storage ring showing the location of the kickers (blue), quadrupoles (red), and calorimeters (labeled C)*

1.2 Energy Audit

An energy audit is an assessment of a building's energy consumption. These audits are performed to track a buildings energy usage to determine any ways to improve the energy efficiency of the building. They provide many benefits that include a reduction in energy costs and carbon footprint, an increase in equipment life as well as an improvement in comfort for building occupants. The typical steps in an energy audit are detailed below.

- Data Collection

This is the stage where you gather all historical energy consumption data as well as any information on equipment inventory.

- On-site Visit

Here is where you visit the building location and collect information on the building specifications like the square footage, construction material, and more. Unfortunately, because Covid-19 I was unable to visit the site and do an inspection, but I still collected as much information as I could for this step.

- Analyze Data

The next step is to analyze the data and determine a breakdown of the energy consumption by system.

- Propose Recommendations

After doing the analysis it is now time to propose a list of any recommendations on how to improve the energy efficiency of the building.

- Report Results

Once all the other steps are completed all the information from the audit is compiled into a report

2 Methods

To collect historical data on electricity consumption the Power Monitoring Expert or PME tool was used and access to this tool was provided by the FESS department. This tool allows FESS to monitor the electricity consumption of all Fermilab buildings, separately, on an hourly basis. This hourly data is only available for 24 hours and after that period historical electricity consumption can only be seen for daily usage. Figure 2 is a screenshot of the PME tool showing the daily electricity consumption of MC-1 for 2019 shown in light blue and the 2020 consumption shown in dark blue.

Natural gas consumption was obtained from the onsite gas meters that are manually read monthly. The FESS department provided those totals. The g-2 experiment's eLog was also used to determine the buildings daily operation conditions. This allowed the opportunity to see when the experiment was collecting data and all equipment was running and when the experiment was shut down and certain subsystems were off. The different running conditions could then be compared to determine what the energy consumption of each subsystem is. This step was vital for creating the energy consumption breakdown for the building.

Often times energy consumption of a building is compared to local weather data to gain a better understanding of the heating and cooling needs of an area during the analyzation period. To access this data, the National Oceanic and Atmospheric Administration's climate and weather search tool was used. The weather data was then used to determine degree days of a region which is what is used to compare against energy consumption. Degree days measure how hot or cold a location is by comparing the average outdoor temperature to a standard temperature of 65 °F. The more extreme the outside temperature is, the higher the number of degree days.

The two types of degree days are heating degree days (HDD) and cooling degree days (CDD). A heat-

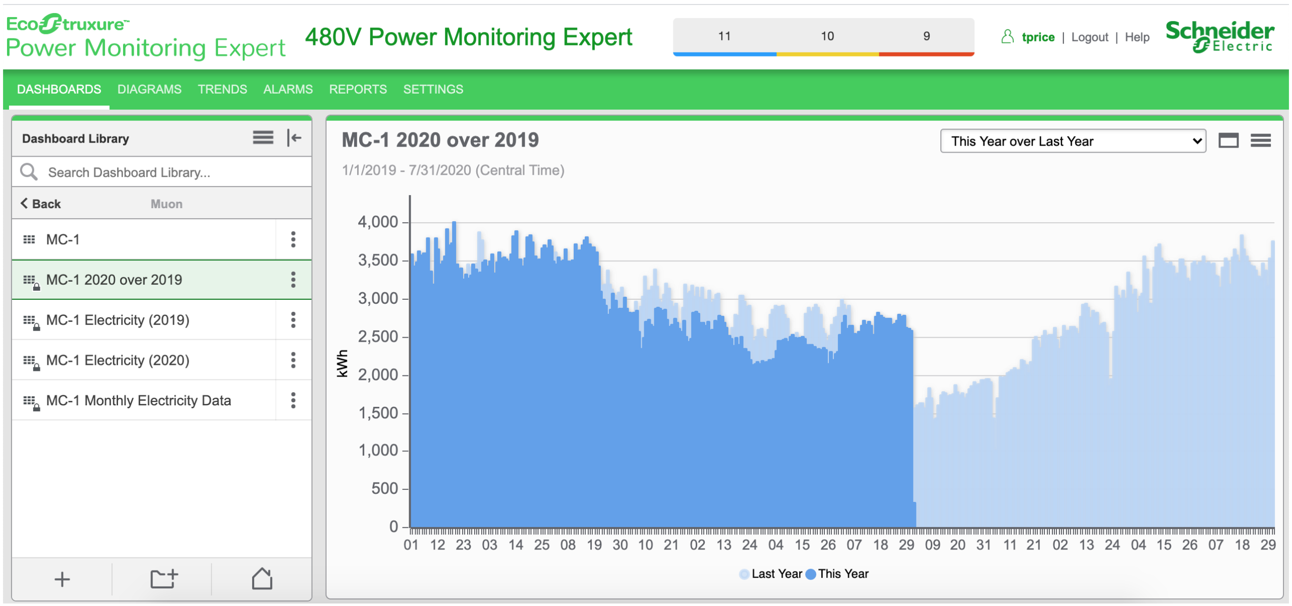

Figure 2: *PME tool*

ing degree day is calculated by subtracting the outside temperature from 65 °F. These days primarily occur during the winter when heating of a building is necessary. Cooling degree days are the opposite of heating degree days and are calculated by subtracting 65 °F from the outside temperature. These are days that primarily occur during the summer months when air conditioning is necessary. Generally speaking, a high number of degree days typically results in higher levels of energy use for heating and cooling.

$$HDD = 65°F - T_{outside}$$
$$CDD = T_{outside} - 65°F$$

3 Results

3.1 Building Description

The MC-1 building completed construction in 2014 and has an area of around 13,461 square feet. The building has two floors and a basement where the main ring is located. Figure 3 is a view from the first floor looking out into the basement without the ring there during construction. Figure 4 shows the basement with the ring in place. Figure 5 is a shot of the exterior of MC-1.

Figure 3: *View from the High Bay out into the basement*

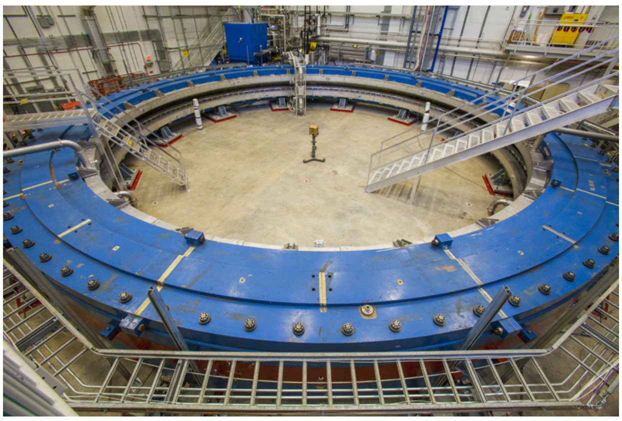

Figure 4: *Basement with ring in place*

Figure 5: *Exterior of MC-1*

3.2 Lighting Subsystem Description

Information on the lighting subsystem was obtained during the data collection portion of the audit. The lighting fixture schedule is shown in Figure 6 below. The majority of the lights used at MC-1 are basic fluorescent lights, compact fluorescent lights which are a more efficient version of normal fluorescent lights, and metal halides. In addition, there is one LED used at MC-1 and it's for an exit sign. LEDs are the most efficient bulb type while metal halides are the least. This information was very useful, and is what allowed for a more in-depth analysis of this system for the audit.

3.3 Energy Consumption Analysis

Monthly electricity consumption for MC-1 for 2019 versus cooling degree days and heating degree days was determined and the results are shown in Figure 7. The green bars represent the monthly electricity usage while the blue line shows the cooling degree days and the red line shows the heating degree days. Summer shutdown for the experiment happens from mid-July through September. The decrease in electricity consumption that occurs during these months is due to the shutdown where electricity demand drops off significantly since most of the equipment needed for data collection are turned off. This is not due to changing heating and cooling needs during the summer and therefore had no correlation with the decrease in heating degree days.

Monthly natural gas usage for MC-1 for 2019 also compared to cooling degree days and heating degree days is shown in Figure 8. Here it is seen that natural gas is only used during the fall and winter months from November to March. This graph does show a correlation between heating degree days and natural gas usage since it's during the same period that heating degree days rise, and natural gas usage also rises.

MC-1 used a total of 1,006,158 kWh of electricity and 145 therms of natural gas in 2019. To estimate the total utility costs spent in 2019 for MC-1, an overall site-wide average cost of \$0.0467/kWh for electricity and

LIGHTING FIXTURE SCHEDULE

TYPE	DESCRIPTION	LAMP	BALLAST	MANUFACTURER	CATALOG NUMBER	REMARKS
A	FLUORESCENT HIGH-BAY FIXTURE WITH (6) T5 HO FLUORESCENT LAMP WITH WIREGUARD	PHILIPS 54T5 HO	277V, SYLVANIA QUICKTRONIC UNIVERSAL BALLAST	ENERGY SOLUTIONS INTERNATIONAL, INC.	F24HG-EA-654-UNV-WG-CL	FOR HIGH BAY AREA, EXPERIMENTAL HALL
B	48" FLUORESCENT FIXTURE, 32W, 277V, 2 LAMPS, RAPID START, 10% UP LIGHT, OPEN TYPE	SYLVANIA F032/741	120V, MVOLT ELECTRONIC BALLAST	LITHONIA	LA232MVOLT-GEB10RS	FOR SERVICE AND TECH. AREA, ETC.
C	42W COMPACT FLUORESCENT WALL - MOUNT UTILITY VAPOR TIGHT LIGHT FIXTURE WITH GLASS GLOBE, WIRE GUARD AND JUNCTION BOX	42 WATT CFL	120V	LITHONIA	VW42L M6	FOR ELEVATOR SERVICE PIT AREA
D	EXIT SIGN WITH RED LETTERS, WHITE HOUSING, UNIVERSAL MOUNTING, WITH BATTERY, SINGLE OR DOUBLE FACE AS REQ'D.	L.E.D.	N/A	DUAL LITE	LX-U-R-W-E	EXIT SIGN. (TYP. MOUNTING HEIGHT 8' ABOVE FINISHED FLOOR)
E	48" SURFACE/PENDANT MOUNTED WRAPAROUND SQUARE-BASKET FLUORESCENT LIGHT FIXTURE	F32T8	120V, MVOLT ELECTRONIC BALLAST	LITHONIA	SB 2 32 MVOLT-GEB10RS	INDOOR
F	9" DEEP x 16" WIDE EXTERIOR WALL MOUNTED METAL HALIDE LIGHT FIXTURE	100MH	120V, MULTI - TAP (TB) PULSE START (SCWA)	LITHONIA	TWF1 100M TB SCWA SF PE	EXTERIOR, COLOR SELECTED BY FERMI LAB
G	6" DIAMETER CLASSIC ROUND PENDANT MOUNTED FLUORESCENT LIGHT FIXTURE UP/DOWN LENS AND UP/DOWN REFLECTOR, LIGHT DISTRIBUTION MOSTLY UP	F32T8	120V, MVOLT ELECTRONIC BALLAST	PEERLESS	LD6-321653-T8-4FT-R4-120-GEB-SCT-LP835-F3-C100	6" CLASSIC ROUND, (3) LAMPS, 2-UP & 1-DN, FOR BUILDING ENTRANCE
EM1	SURFACE MOUNTED, BATTERY PACK WITH TWO HEAD EMERGENCY LIIGHTING UNIT	HALOGEN	120/277V	LITHONIA	IND 1254 H1212 SEL	MOUNTING HEIGHT 8'-0" ABOVE FINISHED FLOOR UNLESS INDICATED OTHERWISE
H	6"x48" SURFACE/PENDANT MOUNTED FOR COLD TEMP. AND WET LOCATION FLUORESCENT LIGHT FIXTURE	F32T8	120V, MVOLT ELECTRONIC BALLAST	LITHONIA	XWL 2 32 MVOLT-GEB10RS	REFRIGERATION ROOM
I	9"Dx18"W EXTERIOR WALL MOUNTED METAL HALIDE LIGHT FIXTURE	150MH	120V, TB SCWA	LITHONIA	MRW 150M MD 120 SCWA SF QRS PE	EXTERIOR, COLOR SELECTED BY FERMI LAB
J	400W METAL HALIDE ROADWAY FIXTURE DOWN LIGHT, TENON - MOUNTED ON A 30-FOOT LONG, 6-INCH DIA. SQUARE ALUMINUM POLE (SEE REMARKS)	400MH	277V, HPF	QUALITY LIGHTING	125-23-3-MH-400-277-BKA-PCT-FD	PROVIDE FIXTURE WITH A 30 - FOOT SQUARE ALUMINUM POLE, QUALITY LIGHTING TYPE SQSA - 30 - 6 - DBA - BKA - D1 OR APPROVED EQUAL
K	24" x 48" FLUORESCENT FIXTURE, 32W, 2 LAMPS, RECESSED MOUNT, ACRYLIC LENS, HINGE DOOR, RAPID START	SYLVANIA FO32/41K	120V, MVOLT ELECTRONIC BALLAST	LITHONIA	2GT8-232A12MVOLT-GEB10RS	

Figure 6: *Lighting Fixture Schedule for MC-1*

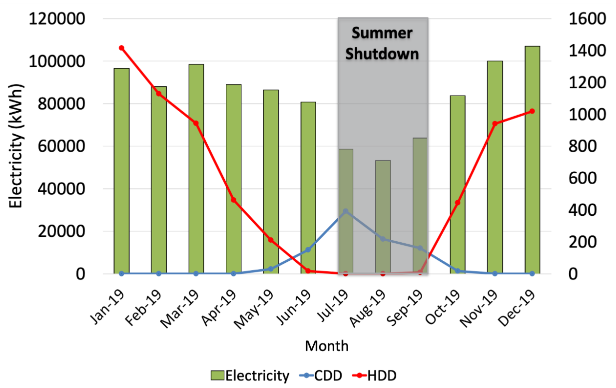

Figure 7: *Electricity consumption for MC-1 for 2019 vs. CDD and HDD*

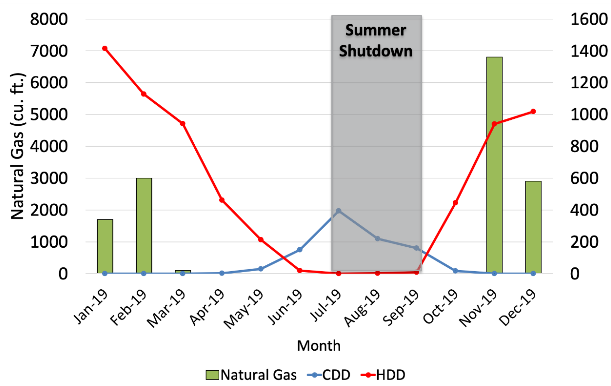

Figure 8: *Natural Gas consumption for MC-1 for 2019 vs. CDD and HDD*

$0.32/therm for natural gas were used. Using these values, the total utility cost came out to be $47,033.98. These totals are shown in Table 1.

Table 1: *MC-1 Energy Consumption Totals and Intensities*

MC-1 Energy Consumption		
Electricity (kWh)	Natural Gas (therms)	$ Energy
1,006,158.00	145	$47,033.98
kWh/sq.ft.	therms/sq.ft.	$/sq.ft
74.75	0.01	$3.49

While these raw totals can be helpful, it's best to look at these values in terms of their intensities. Using just the raw totals of energy consumption to compare buildings or to measure energy efficiency does not take into account building size and use. The use of energy intensity indicators provides the ability to equalize the way that energy use is compared between different types of buildings and to evaluate the means of reducing overall energy consumption. The bottom row of numbers in Table 1 gives energy intensity values for MC-1 by dividing the energy consumption and costs by the area of the building. Lower energy intensities are better because this means the building is using less energy per square foot.

It's useful in an energy audit to see how the building being audited compares to other buildings that have a similar purpose. To make this comparison, a tool called Target Finder provided by ENERGY STAR was used. The tool allows one to input building information of the audited site to see how it compares to other similarly classed buildings. Since MC-1 is considered a laboratory, it was compared with the national average of laboratories in the U.S. Figure 9 shows these results. On the left side of the graph we see MC-1's energy use intensity or EUI and estimated greenhouse gas (GHG) emissions. On the right are the same values but for the median laboratory in the U.S. It is seen that MC-1 has a lower energy intensity and emits about 33.7% less greenhouse gases than the median lab. This puts MC-1 in a great position.

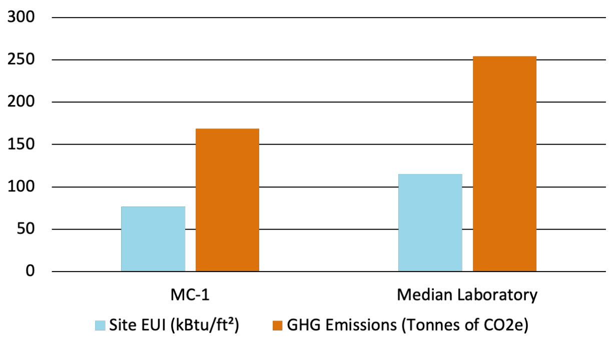

Figure 9: *MC-1 vs other U.S. Laboratories*

The pie chart shown in Figure 10 gives an estimate of the how the energy is used in MC-1. The energy used for process includes all the components necessary to power the ring and collect data. This makes up almost 39% of the energy used. The lighting subsystem accounts for almost 1% of the energy used. The category "HVAC and other" which includes subsystems like the DAQ make up around 60% of the consumption. This category includes all the subsystems that could not be teased using the eLog. To breakdown the energy consumption of MC-1 even further, more detailed information on equipment wattage ratings would be required.

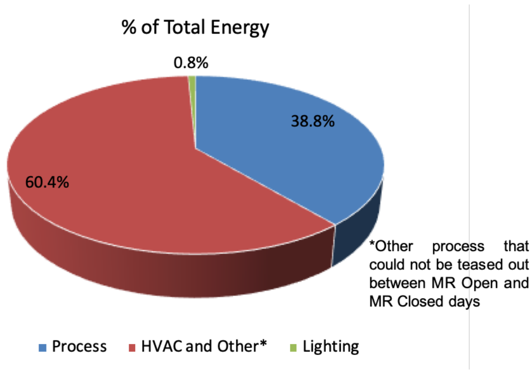

Figure 10: *Energy consumption breakdown by subsystem*

Heating, ventilation, and air conditioning (HVAC) as well as lighting provide opportunities for energy efficiency improvements, although these are limited, since these systems must still operate at levels that do not disturb the main purpose of the building which is running the g-2 experiment. But the equipment can still be improved to become more energy efficient which can provide savings.

3.4 Energy Reduction Proposal: LEDs

I recommend that MC-1 replace the existing lighting equipment with LEDs. LEDs are much more energy efficient than fluorescent and metal halide lamps and would reduce yearly energy costs if used. To determine these potential savings, estimates of how much money MC-1 currently spends on lighting each year were first determined. Next estimates of how much MC-1 would spend yearly if LED alternatives were used were determined. Some assumptions made to make these estimates were that all lights in the building are on for 16 hours a day, 365 days a year and the price of electricity remains constant. The LED alternatives used for this analysis could replace the current bulbs without having to change any of the current fixture equipment. This reduces the cost of implementing this proposal down to just changes in material costs for the LED bulbs. The results of this analysis are that MC-1 could reduce its current lighting consumption down from 7634.63 kWh and $356.54 to 2918.25 kWh and $136.28. This is a reduction of about 62%. Table 2 summarizes these results.

If MC-1 were to replace the current lighting with LEDs they could reduce their annual electricity consumption by 4716.38 kWh. The annual material costs would increase by $1.83 per year since the LED replacements are more expensive than the current bulbs, but they would reduce their energy costs by $220.26. In the end they would be spending $218.42 per year less on lighting. Further research into this proposal showed that normal LEDs do not perform well in high radiation areas. Radiation hardened LEDS would be needed for high rad areas in MC-1 which is the main ring area, but for common areas, regular LEDs should still be a suitable alternative. Rad hard LEDs are currently being researched and manufactured and a recent paper on this subject was published by CERN that looked into designing rad hard LEDs for accelerator tunnels [1].

4 Conclusion

The recommendation proposed to replace existing lighting equipment with LEDs would reduce MC-1's electricity consumption for lighting by 62%. It should be noted that radiation hardened LEDs would be necessary for high rad areas in MC-1. Further RD on this technology provides a new exploration into green designing that would allow more businesses and entities the opportunity to be more environmentally friendly.

While only one energy savings recommendation was evaluated and proposed, an in-depth analysis into the energy consumption of other subsystems at MC-1 could provide more opportunities to reduce the building's energy consumption and make it more energy efficient.

Table 2: *Current lighting system electricity consumption vs LED alternative electricity consumption*

		CURRENT EQUIPMENT				LED REPLACEMENT		
LIGHTING EQUIPMENT DESCRIPTION	NUMBER	LAMP TYPE	WATTS	kWh/yr	$/yr	WATTS	kWh/yr	$/yr
FLUORESCENT HIGH BAY FIXTURE WITH (6) H5 HO FLOURESCENT LAMP WITH WIRE GUARD	6	FLUORESCENT	54.1	1895.66	88.53	22	770.88	36.00
48" FLUORESCENT FIXTURE, 32W, 277V, 2 LAMPS, RAPIS START, 10% UP LIGHT, OPEN TYPE	2	FLUORESCENT	32	373.76	17.45	17	198.56	9.27
42W COMPACT FLOURESCENT WALL - MOUNT UTILITY VAPOR TIGHT LIGHT FIXTURE WITH GLASS GLOBE, WIRE GUARD AND JUNCTION BOX	1	CFL	42	245.28	11.45	16	93.44	4.36
EXIT SIGHT WITH RED LETTERS, WHITE HOUSING, UNIVERSAL MOUNTING, WITH BATTERY, SINGLE OR DOUBLE FACE REQ'D	1	LED	2.7	15.77	0.74	2.7	15.768	0.74
48" SURFACE/PENDANT MOUNTED FOR COLD TEMP. AND WET LOCATION FLUORESCENT LIGHT FIXTURE	1	FLUORESCENT	32	186.88	8.73	17	99.28	4.64
9" DEEP x 16" WIDE EXTERIOR WALL MOUNTED METAL HALIDE LIGHT FIXTURE	1	METAL HALIDE	100	584.00	27.27	22	128.48	6.00
6" DIAMETER CLASSIC ROUND PENDANT MOUNTED FLUORESCENT LIGHT FIXTURE UP/DOWN LENS AND UP/DOWN REFLECTOR. LIGHT DISTRIBUTION MOSTLY UP	1	FLUORESCENT	32	186.88	8.73	17	99.28	4.64
6" x 48" SURFACE/PENDANT MOUNTED FOR COLD TEMP. AND WET LOCATION FLUORESCENT LIGHT FIXTURE	3	FLUORESCENT	32	560.64	26.18	17	297.84	13.91
9"D x 18"W EXTERIOR WALL MOUNTED METAL HALIDE LIGHT FIXTURE	1	METAL HALIDE	150	876.00	40.91	54	315.36	14.73
400W METAL HALIDE ROADWAY FIXTURE DOWN LIGHT, TENON - MOUNTED ON A 30-FOOT LONG, 6-INCH DIA. SQUARE ALUMINUM POLE	1	METAL HALIDE	400	2336.00	109.09	120	700.8	32.73
24" x 48" FLUORESCENT FIXTURE, 32W, 2 LAMPS, RECESSED MOUNT, ACRYLIC LENS, HINGE DOOR, RAPID START	2	FLUORESCENT	32	373.76	17.45	17	198.56	9.27
			Total:	7634.63	$ 356.54		2918.25	$ 136.28

5 Acknowledgements

I would like to thank my advisor Dr. Jessica Esquivel for her guidance and help with completing my project and for giving me the opportunity to work with the g-2 collaboration.I would also like to thank Andrew Martens and Cedric Madison from FESS for providing access to the energy analysis and monitoring tools that were necessary to complete this project.

References

[1] James D. Devine and Alessandro Floriduz. Radiation hardening of led luminaires for accelerator tunnels. 2016.

[2] J. Grange et al. Muon (g-2) technical design report. 2015.

A Appendix

This section includes an image of the Excel workbook that was used to make all calculations and analyze the data for the energy audit.

	Timestamp	Series	Grouping	Value	Standardize
2	1/1/19 1:00	Muon.	1-Jan	3072.073	0.5201
3	1/2/19 1:00	Muon.	2-Jan	3077.98	0.5299
4	1/3/19 1:00	Muon.	3-Jan	3060.927	0.5017
5	1/4/19 1:00	Muon.	4-Jan	2803.949	0.0781
6	1/5/19 1:00	Muon.	5-Jan	2648.229	-0.1787
7	1/6/19 1:00	Muon.	6-Jan	2716.465	-0.0662
8	1/7/19 1:00	Muon.	7-Jan	2632.159	-0.2052
9	1/8/19 1:00	Muon.	8-Jan	2795.91	0.0648
10	1/9/19 1:00	Muon.	9-Jan	3110.557	0.5836
11	1/10/19 1:00	Muon.	10-Jan	3017.627	0.4304
12	1/11/19 1:00	Muon.	11-Jan	2932.39	0.2898
13	1/12/19 1:00	Muon.	12-Jan	2887.967	0.2166
14	1/13/19 1:00	Muon.	13-Jan	3042.595	0.4715
15	1/14/19 1:00	Muon.	14-Jan	3044.364	0.4744
16	1/15/19 1:00	Muon.	15-Jan	3002.794	0.4059
17	1/16/19 1:00	Muon.	16-Jan	2916.654	0.2639
18	1/17/19 1:00	Muon.	17-Jan	2830.53	0.1219
19	1/18/19 1:00	Muon.	18-Jan	2883.651	0.2095
20	1/19/19 1:00	Muon.	19-Jan	3132.323	0.6195
21	1/20/19 1:00	Muon.	20-Jan	3339.435	0.9609
22	1/21/19 1:00	Muon.	21-Jan	3319.273	0.9277
23	1/22/19 1:00	Muon.	22-Jan	3234.682	0.7882
24	1/23/19 1:00	Muon.	23-Jan	3160.337	0.6656
25	1/24/19 1:00	Muon.	24-Jan	3290.343	0.8800
26	1/25/19 1:00	Muon.	25-Jan	3448.846	1.1413
27	1/26/19 1:00	Muon.	26-Jan	3409.654	1.0767
28	1/27/19 1:00	Muon.	27-Jan	3398.616	1.0585
29	1/28/19 1:00	Muon.	28-Jan	3296.626	0.8903
30	1/29/19 1:00	Muon.	29-Jan	3462.109	1.1632
31	1/30/19 1:00	Muon.	30-Jan	3876.706	1.8467
32	1/31/19 1:00	Muon.	31-Jan	3770.254	1.6712
33	2/1/19 1:00	Muon.	1-Feb	3353.59	0.9843
34	2/2/19 1:00	Muon.	2-Feb	3255.59	0.8227

Month	MR Open Days	MR Closed Days	Differnce (kWh)	% Difference	# MR Open Days	# MR Closed Days
January	3703.02	3044.83	-658.20	-17.77%	3	27
February	3077.12	3265.58	188.46	6.12%	9	8
March	2952.10	3241.11	289.01	9.79%	4	20
April	2583.23	3060.80	477.57	18.49%	3	23
May	2459.01	2991.76	532.75	21.67%	10	18
June	2463.79	2799.85	336.06	13.64%	4	19
July	1588.36	2207.67	619.31	38.99%	13	15
August	1719.88	N/A	N/A	N/A	31	0
September	2128.78	N/A	N/A	N/A	27	0
October	2581.99	2908.78	326.79	12.66%	17	7
November	2979.79	3483.45	503.66	16.90%	6	18
December	N/A	3475.98	N/A	N/A	1	25
		Mean	290.60	13.39%		

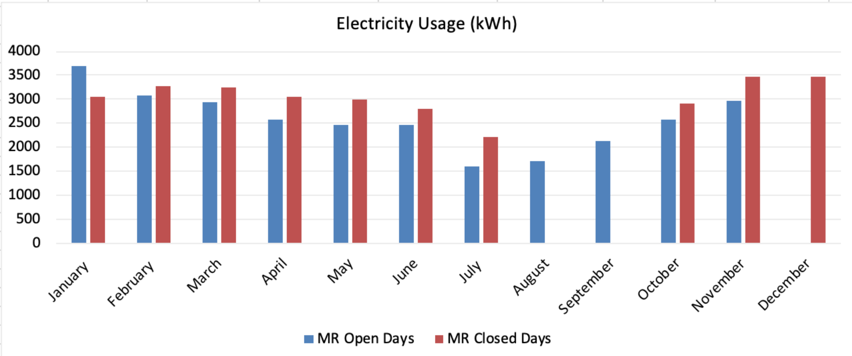

Figure 11: *Excel spreadsheet used to analyze the data*