ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA
I.C.A.I

PROYECTOS FIN DE GRADO
CURSO: 2018-2019

# DESIGN OF A COST-EFFECTIVE BUILDING MICROGRID: LOAD MODELING AND OPTIMIZATION OF THE ENERGY PERFORMANCE

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Madrid

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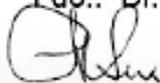Fdo.:  Jorge Goas Martín          Date: 20/06/2019

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PROJECT SUPERVISOR

Fdo.:  Dr. Pankaj Sen             Date: 20/06/2019

# DISEÑO DE MANERA ECONÓMICA DEL SISTEMA ÉLECTRICO DE UN EDIFICIO: MODELADO DE LAS CARGAS Y OPTIMIZACIÓN DEL RENDIMIENTO ENERGÉTICO

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Director: Sen, Pankaj
Entidades Colaboradoras:
- CSM – Colorado School of Mines
- ICAI – Universidad Pontificia Comillas

## RESUMEN DEL PROYECTO

INTRODUCCIÓN
El objetivo de este proyecto es realizar un estudio exhaustivo de un edificio recientemente construido en el campus de Colorado School of Mines, y equipado con tecnología de vanguardia, con el propósito de mejorar la eficiencia energética. Hay multitud de posibles enfoques para el cometido de reducir la demanda de energía del edificio. Después de contemplar varias posibilidades, y teniendo en cuenta la información disponible, el foco de atención se puso en la luminaria.

A pesar de que Coorstek Center es un edificio de última tecnología, se apreció que muchas de las luces del edificio eran fluorescentes. Normalmente las luces LED son una opción mas eficiente en comparación, sin embargo, el precio inicial es mas caro.

Por tanto, numerosas dudas asaltaron entorno a la intencionalidad de la empresa constructora a la hora de instalar luces fluorescentes. Para resolver esta pregunta, se diseñó un problema de optimización. Este problema consistía en una minimización de los costes de Coorstek Center a lo largo de un período de 25 años. En este problema de optimización, se consideraron dos variables: el número de luces LED o el número de luces fluorescentes a instalar. El problema de optimización consistía en tres partes principales, la factura eléctrica asociada a cada tipo de sistema de iluminación, y el coste capital y de mantenimiento de cada tipo de luces.

Con este problema de optimización, buscamos obtener como resultado que el uso de luces LED es la mejor solución a largo plazo, no sólo en términos de ahorros económicos, sino también en ahorro energético, y hacer el edificio más respetuoso con el medio ambiente.

Estado del arte
En lo que respecta a Colorado School of Mines, existe un interés creciente en esta universidad en el estudio de las instalaciones del campus y su sostenibilidad. Esta tarea de mejorar y hacer los edificios del campus y distintos espacios más rentables económicamente, ha sido dirigida principalmente por los departamentos mecánicos y eléctricos. Estos departamentos están encabezados respectivamente por Dr. Paulo Tablares (ME) y el Dr. Sen (EE), nuestro director de proyecto.

Muchos proyectos comparables han sido llevado a cabo en distintas instalaciones del campus. El proyecto más reciente en relación con estos temas es la tesis de master desarrollada por Brian Oldfield bajo la supervisión de Dr. Sen, y de título: *"PV AND*

*BESS DESIGN FOR THE COLORADO SCHOOL OF MINES: OPTIMAL DESIGN METHODOLOGY AND ECONOMIC FEASIBILITY".* En su tesis, existe un análisis exhaustivo acerca de la implementación de placas fotovoltaicas en el campus y como sacar el mayor rendimiento de ellas. Esto significa optimizar la orientación y ángulo de inclinación dependiendo de factores tales como las estaciones del año, la cantidad de radiación solar, la temperatura, la demanda en cada hora del campus y otros más.

Sin embargo, a pesar de que su tesis incluye la mayoría de los edificios del campus, este edificio nunca fue estudiado en estos proyectos, ya que Coorstek Center fue construido en 2018.

METODOLOGÍA Y RESULTADOS

Antes de centrarnos en mejorar el edificio, se hizo un estudio tanto del campus como del edificio en sí. Es importante conocer el contexto en el que se sitúa el edificio en cuestión antes de lanzarnos a optimizarlo. Se empezó haciendo un estudio un poco más superficial del campus. Con esto, podíamos conocer el diagrama unifilar del campus, los distintos niveles de tensión que alimentaban al campus en general y a los distintos edificios, y los transformadores utilizados para cada edificio.
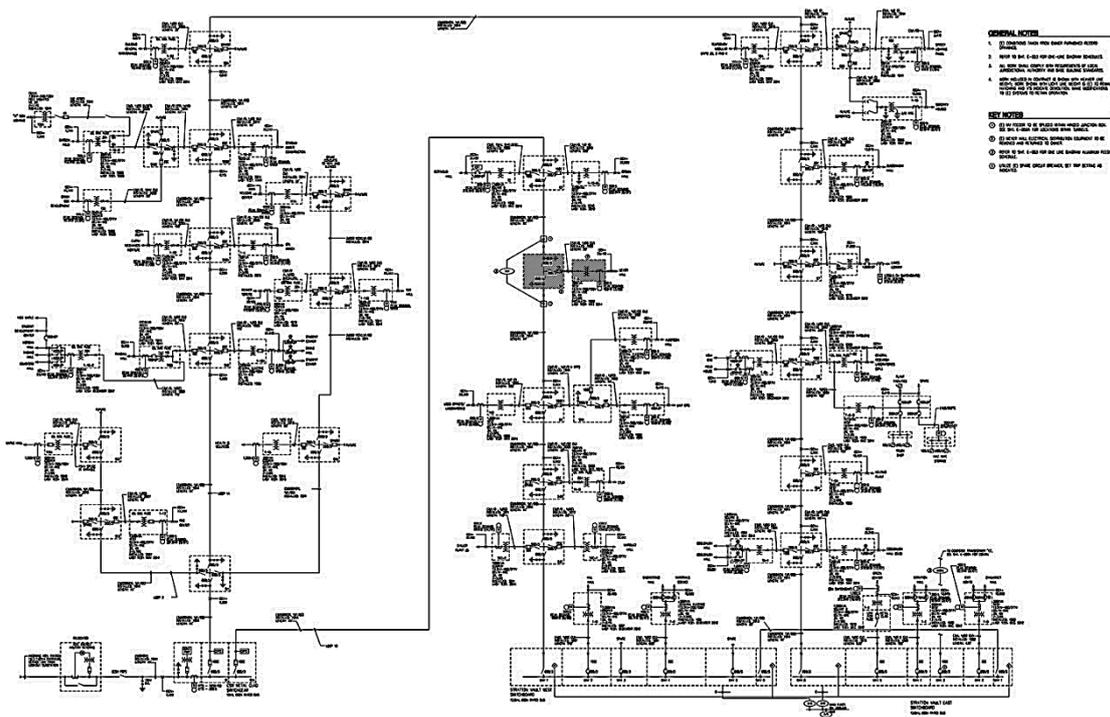


Tras tener un concepto general de cómo funcionaba el sistema eléctrico del campus, se pasó al estudio de el diagrama unifilar del edificio.

Electrical One-Line Diagram
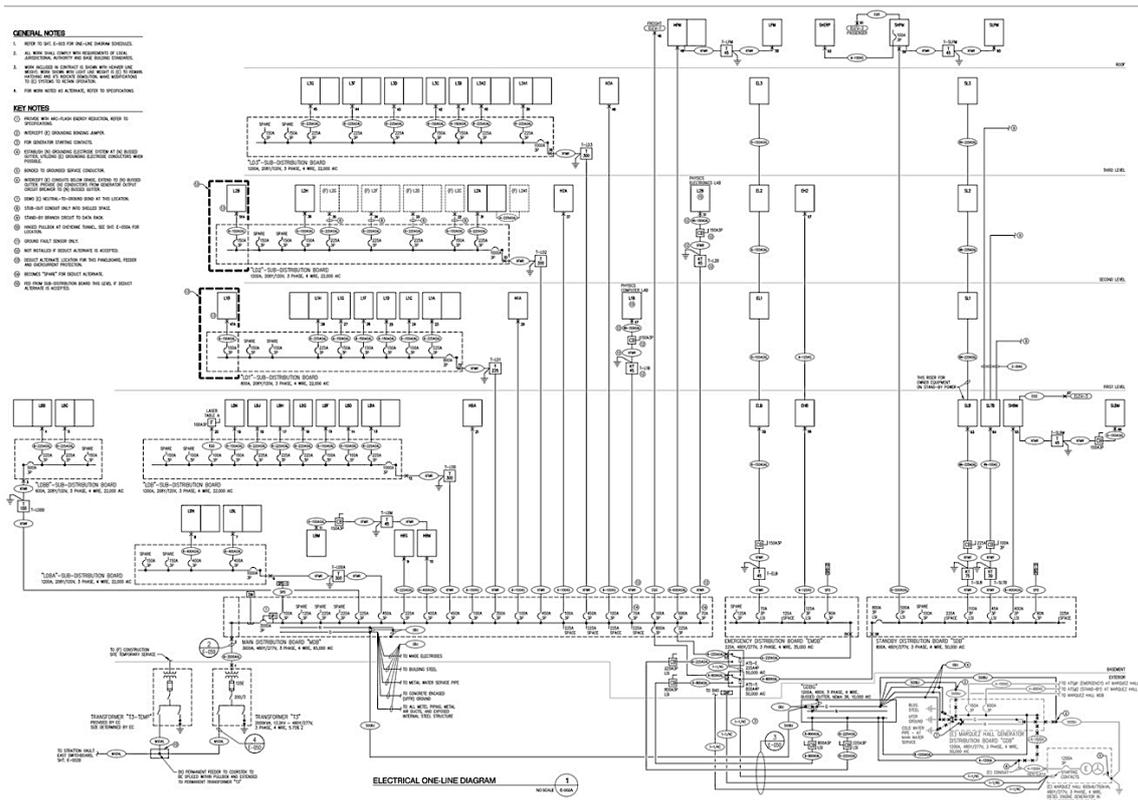
Este diagrama nos proporcionaba información muy útil, acerca del transformador que alimentaba el edificio, los tableros de distribución eléctrica, y los cuadros eléctricos. En los catálogos se podía encontrar mucha información de todas las cargas conectadas a cada cuadro eléctrico. Conociendo las cargas, se podía hacer los cálculos apropiados para calcular el tamaño de los cuadros, del cableado etc. Había que tener en cuenta ciertos aspectos a la hora de realizar los cálculos. El más obvio de ellos es la potencia de los aparatos, pero también el factor de demanda NEC. Este multiplicador determina la carga más probable que el cuadro va a tener que alimentar, de tal forma que dimensionado de éste sea más adecuado y realista. De esta forma se puede calcular el dimensionado adecuado para cada cuadro de distribución de acuerdo a la demanda total de cada uno.

| | L | First 10k R | Remaining R | Largest M | Remaining M(s) | E | H | K | Total Demand |
|---|---|---|---|---|---|---|---|---|---|
| **Load** | VA | VA | VA | VA | VA | VA | VA | VA | VA |
| **L1A** | | 10,000 | 8,180 | 2,020 | 1,280 | 7,240 | | 4,560 | |
| NEC Demand Factor | 1.25 | 1 | 0.5 | 1.25 | 1 | 1 | 1.25 | 0.8 | |
| NEC Demand Load | | 10000 | 4090 | 2525 | 1280 | 7240 | 0 | 3648 | **28783** |
| **L1C** | | 8,100 | | | | 1,300 | | | |
| NEC Demand Factor | 1.25 | 1 | 0.5 | 1.25 | 1 | 1 | 1.25 | 1 | |
| NEC Demand Load | 0 | 8100 | 0 | 0 | 0 | 1300 | 0 | 0 | **9400** |
| **L1D** | | 8,920 | | | | 3,220 | | | |
| NEC Demand Factor | 1.25 | 1 | 0.5 | 1.25 | 1 | 1 | 1.25 | 1 | |
| NEC Demand Load | 0 | 8920 | 0 | 0 | 0 | 3220 | 0 | 0 | **12140** |
| **L1F** | | 4,680 | | | | 3,560 | | | |
| NEC Demand Factor | 1.25 | 1 | 0.5 | 1.25 | 1 | 1 | 1.25 | 1 | |
| NEC Demand Load | 0 | 4680 | 0 | 0 | 0 | 3560 | 0 | 0 | **8240** |
| **L1G** | | 4,680 | | 2,490 | | 3,360 | | | |
| NEC Demand Factor | 1.25 | 1 | 0.5 | 1.25 | 1 | 1 | 1.25 | 1 | |
| NEC Demand Load | 0 | 4680 | 0 | 3112.5 | 0 | 3360 | 0 | 0 | **11152.5** |
| **L1H** | | 10,000 | 38,040 | | | 5,440 | | | |
| NEC Demand Factor | 1.25 | 1 | 0.5 | 1.25 | 1 | 1 | 1.25 | 1 | |
| NEC Demand Load | 0 | 10000 | 19020 | 0 | 0 | 5440 | 0 | 0 | **34460** |

Sin embargo, se observó que para un dimensionado óptimo del tablero de distribución, que alimenta al conjunto de cuadros, era mejor agrupar todos los cuadros eléctricos como si fueran uno sólo, de forma que se maximizaba la reducción producida por el factor de demanda NEC. Esto se puede observar en la siguiente tabla.

| | L | First 10k R | Remaining R | Largest M | Remaining M(s) | E | H | K | Total Demand |
|---|---|---|---|---|---|---|---|---|---|
| **Load** | VA | VA | VA | VA | VA | VA | VA | VA | VA |
| **L1A** | | 10,000 | 8,180 | 2,020 | 1,280 | 7,240 | | 4,560 | |
| **L1C** | | 8,100 | 0 | | | 1,300 | | | |
| **L1D** | | 8,920 | 0 | | | 3,220 | | | |
| **L1F** | | 4,680 | 0 | | | 3,560 | | | |
| **L1G** | | 4,680 | 0 | 2,490 | | 3,360 | | | |
| **L1H** | | 10,000 | 38,040 | | | 5,440 | | | |
| **Total** | | 10,000 | 82,600 | 2,490 | 3,300 | 24,120 | 0 | 4560 | |
| **NEC Demand Factor** | 1.25 | 1 | 0.5 | 1.25 | 1 | 1 | 1.25 | 1 | |
| **NEC Demand Load** | 0 | 10000 | 41300 | 3112.5 | 3300 | 24120 | 0 | 4560 | 86392.5 |

La demanda total calculada de esta forma es un 17,07% menor que si se sumaran las demandas individuales de cada cuadro eléctrico.

Se plantearon muchos caminos posibles para mejorar la eficiencia del edificio, pero la mayoría no eran viables, ya que requerían de información confidencial de la empresa constructora, o que aún no se había documentado correctamente. Analizando exhaustivamente el catálogo disponible del edificio, se observó que estaba equipado con una gran cantidad de luces fluorescentes. De esta manera se apostó por reducir la demanda de potencia del edificio, instalando luces LED. En el catálogo existían luces LED alternativas a las fluorescentes que serían instaladas, y se observaba que las LED tenían una potencia menor.

Se estudiaron las ventajas que podrían ofrecer las luces LED: mas durabilidad, mejor ratio lúmenes/vatios, menor transmisión de calor, menor producción de $CO_2$, no contenían mercurio, más silenciosas al no usar metales pesados, no tenían problemas de encendido por frío, iluminación instantánea. Además, en el catálogo se determinaba que eran necesarias menos lámparas LED por cada cierto número de lámparas fluorescentes.

De esta manera, el primer paso era estudiar que la luminosidad no se viera afectada al reducir el número de lámparas. Esto se hizo estudiando diagramas fotométricos aportados por la empresa fabricante.
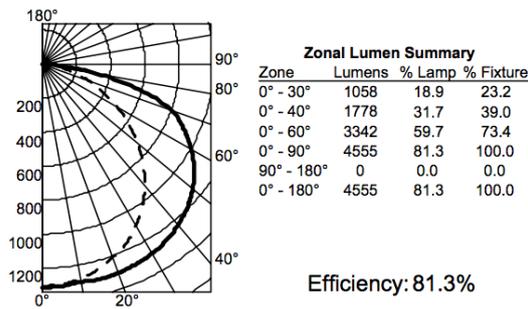


Además se hizo un estudio propio de luminosidad de una habitación estándar, con el programa AGI32 Illumination Engineering Software, que nos permitió comprobar que la iluminación de los espacios no se vería afectada.

Una vez comprobado esto, se analizó los ahorros de potencia demandada al instalar lámparas LED. Se puede observar en el siguiente di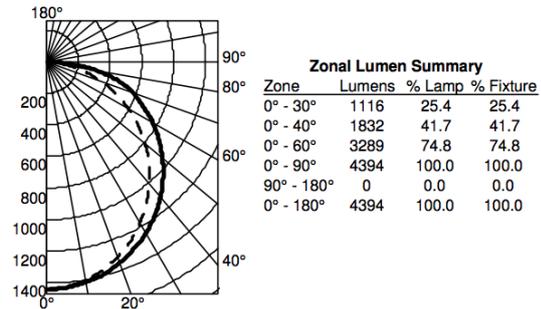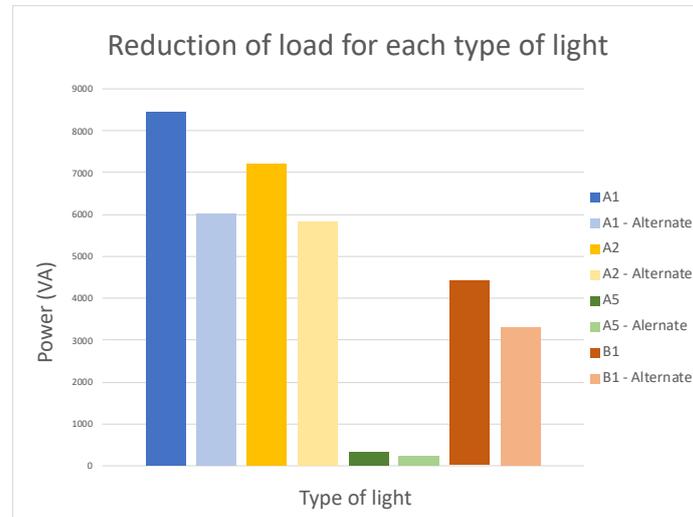agrama. Los nombres A1, A2, A5 y B1 son las designaciones de los distintos tipos de lámpara, y alternate hace referencia al sustituto LED.



Pero en este proyecto, se buscaba una reducción de la potencia, pero todo esto con la máxima rentabilidad. De esta forma, se planteó un problema de optimización que minimizara los costes del edificio en un plazo de 25 años. La función objetivo constaba de tres partes fundamentales: la factura eléctrica, el coste de la luminaria LED y el coste de la luminaria fluorescente. Las dos variables eran las lámparas LED o fluorescentes, para las cuales el programa tendría que decidir la opción óptima entre las parejas de posibilidades.

La factura eléctrica se basaba en los datos recogidos en el último año con las fluorescentes instaladas y en una previsión futura de esta, suponiendo un aumento de un 1% en la demanda del edificio para los años posteriores. En caso de instalar LEDs, esta factura disminuiría en relación a las tasas eléctricas acordadas en el Primary General Rates. Estas tasas incluían un cargo mensual fijo, otro que dependía de los picos máximos de potencia en cada mes, y otro de la energía a cada hora durante un mes.

En cuanto a los costes correspondientes a las lámparas LED y flourescentes, se tiene en cuenta el coste de comprar las lámparas y según la durabilidad, distinta para cada lámpara, el número de veces que habría que pagar dicho coste. Las lámparas LED son más caras pero necesitan menos recambios. Por otro lado, también se tiene en cuenta el coste de la mano de obra para cambiar cada lámpara.

La función objetivo es en resumen la siguiente:

$$minimizar \sum_{y=2019}^{2043} \left[ \sum_{m=1}^{12} \left( \sum_{d=1}^{31} \left( \sum_{h=0}^{23} rate_{m,h} * kWh_{y,m,d,h} - \sum_{i=1}^{3} rate_{m,16} * redenergy_i * L_i \right) \right. \right.$$

$$\left. + DR_m * \left( maxkW_{y,m} - \sum_{i=1}^{3} redpower_i * L_i \right) + fixed \right)$$

$$+ \sum_{i \, \varepsilon \, I} \left( lreplace_{y,i} * lprice_i * L_i + lreplcost_i * L_i + freplace_{y,i} * fprice_i * F_i \right.$$

$$\left. \left. + freplcost_i * F_i \right) \right]$$

CONCLUSIONES

Los resultados obtenidos fueron muy satisfactorios. El programa indicó que en el plazo de 25 años, la opción óptima era instalar todo lámparas tipo LED. Con esto se conseguía un ahorro en ese tiempo de 414.280$, un 11,14% de ahorro. De la misma manera, se conseguía una reducción de energía de 1,24%, correspondientes con los 505.901 kWh ahorrados.

En términos de impacto ambiental de esta mejora en el edificio, se consiguieron resultados destacables, evitando la emisión a la atmósfera de:
- 105,86 toneladas de $CO_2$
- 8,41 toneladas de dióxido de azufre
- 5,62 toneladas de óxidos de nitrógeno

Si esta mejora de 1,24% en la reducción de energía se extrapolara a escenarios más grandes, se obtendría los siguientes ahorros en emisiones.

| Area | Tipo de Emisión | Emisiones actuales en millones de toneladas métricas | Reducción de emisiones en millones de toneladas métricas |
|---|---|---|---|
| **Estados Unidos** | | | |
| | $CO_2$ | 1.763 | 21,8612 |
| | $SO_2$ | 1,9 | 0,02356 |
| | $NO_x$ | 1,8 | 0,02232 |
| **Mundo** | | | |
| | $CO_2$ | 30.027,81 | 372,34 |
| | $SO_2$ | 31,75 | 0,3937 |
| | $NO_x$ | 70 | 0,868 |

Por tanto, el objetivo de este proyecto se ha cumplido. Se ha demostrado que un pequeño ajuste en el edificio, cambiando solo unos cuantos tipos de lámpara, que corresponden apenas al 35% de la luminaria, se pueden lograr resultados asombrosos a escalas más grandes.

# PROJECT SUMMARY

## INTRODUCTION

The aim of this Project is to make an extensive study of a recently built building on Colorado School of Mines campus, equipped with the latest technologies, with the purpose of improving the energy efficiency. There are multiples ways to approach the task of reducing the energy demand of the building. After contemplating a few of them and bearing in mind the information available, the focus was placed on the luminaire.

Even though Coorstek Center is a state-of-the-art building, it was noted that the luminaire had several fluorescent fixtures. LED is usually a more efficient fixture in comparison, but the capital cost of buying LEDs is higher.

Hence, doubts about the intentionality with the installation of fluorescent fixtures by the constructor firm assailed. In order to solve that question, an optimization problem was developed. This problem consisted on a minimization of the total Coorstek Center costs incurred over a period of 25 years. In that optimization problem, two variables were considered: the number of LED fixtures or fluorescent fixtures to install. The optimization problem included three major parts, the electricity bill associated with each fixture, and the capital cost as well as the O&M cost from each type of fixture.

With this optimization, we seek to obtain as a result that the use of LED fixtures is the best solution for the long term, not only in terms of economic savings, but also regarding energy savings, and making the building more environmentally-friendly.

### State of the art

Concerning Colorado School of Mines, there is an increasing interest at Mines community in this study of the campus facilities and sustainability. This exercise of improving and economizing the campus buildings and some common areas is being conducted mainly by the electrical and mechanical departments, headed by our project director Dr. Sen (EE) and Dr. Paulo Tabares (ME) respectively.

Many comparable projects have been conducted in various other campus facilities. The most recent project regarding these aspects is a Master's thesis carried at Mines by Brian Oldfield under the supervision of Dr. Sen and the title of his work is: *"PV AND BESS DESIGN FOR THE COLORADO SCHOOL OF MINES: OPTIMAL DESIGN METHODOLOGY AND ECONOMIC FEASIBILITY"*. In his thesis, there is a thorough analysis of the implementation of PV on campus and how to make the best use out of them. This means optimizing the orientation and leaning angle depending on factors such as seasons of the year, the amount of sun, the temperature, campus' hourly energy demand and many other relevant factors.

However, even though the thesis includes most of the campus' buildings, this building was never part of these projects, since CoorsTek Center was finished on the year 2018.

## METHODOLOGY AND RESULTS

Before focusing on the enhancement of the building, a study was carried out both on campus and on the building. It is important to know the context in which the building is placed before optimizing it. It started by studying in a more superficial way the campus.

With this, we could understand the one-line diagram of the campus, the different voltage levels that feed the campus and the various buildings, and the transformers powering each building.
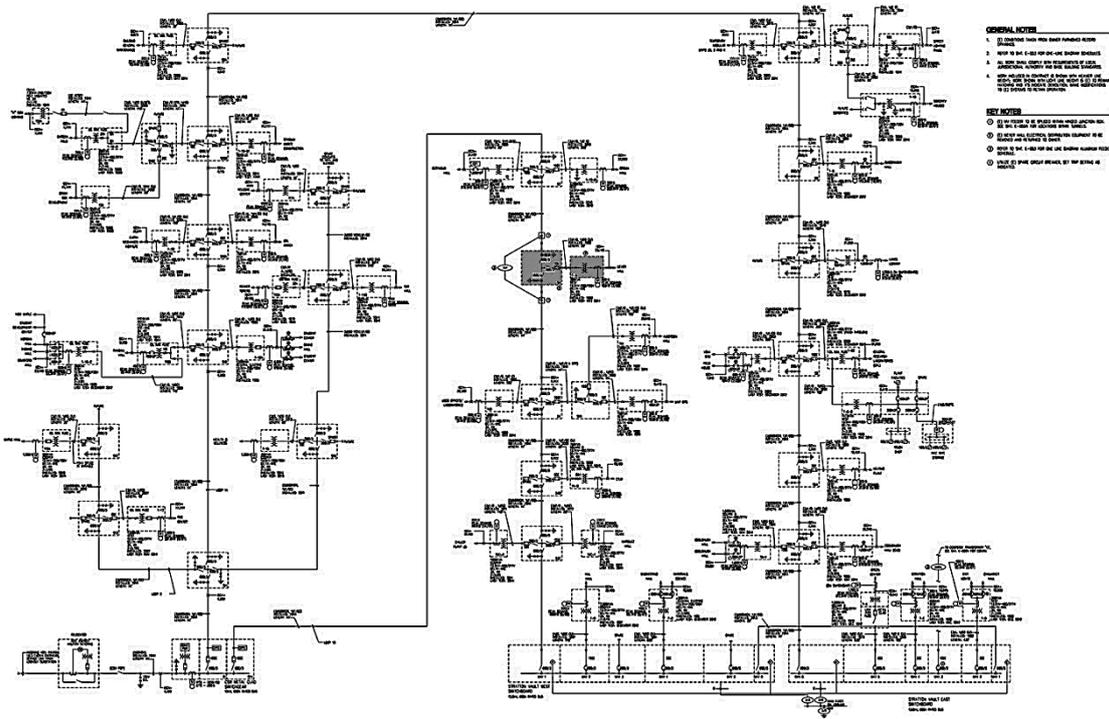


Once a general concept was obtained about how the electric system worked on campus, it followed a study of the one-line diagram of the building.
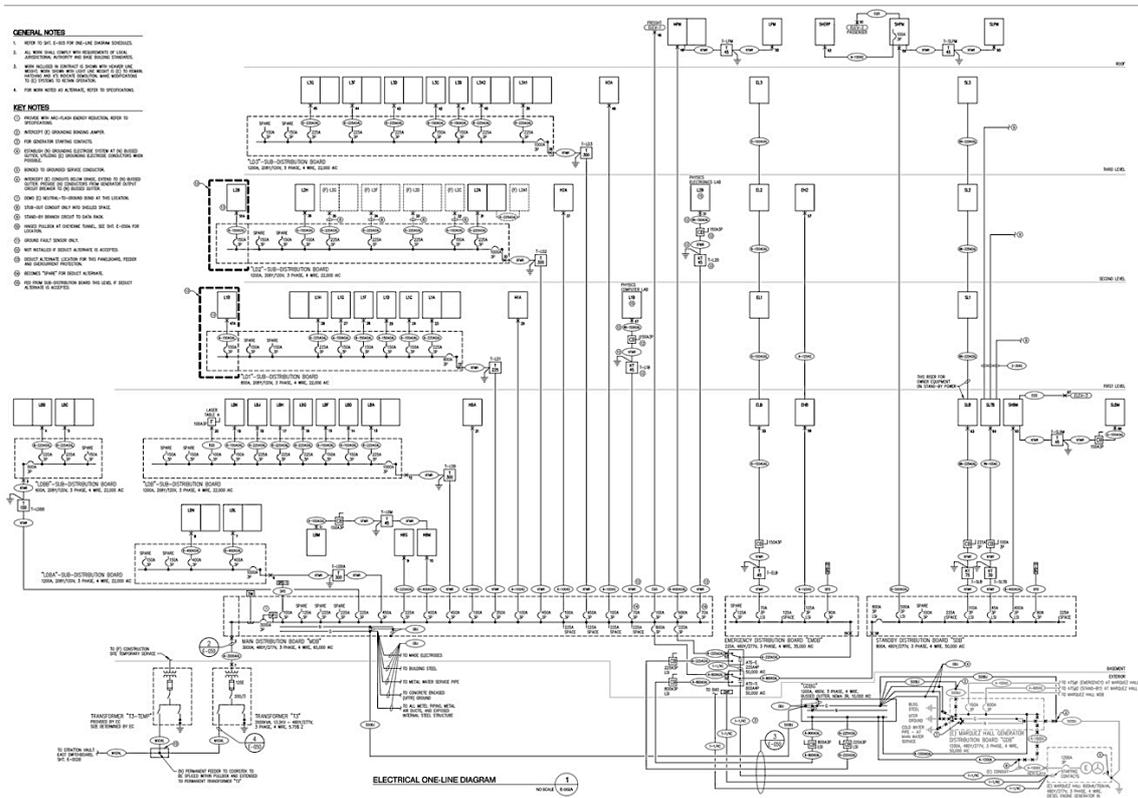
This diagram provides very useful information regarding the building's transformer, the distribution boards and panelboards. A lot of information could be found in the catalog about the building's loads connected to each panelboard. Knowing the loads, several calculations can be developed to size the panelboards, feeders… The NED demand factor needs to be taken into account. This multiplier determines the most probable load that the feeder is going to carry, so that the sizing is appropriate and realistic.

| | L | First 10k R | Remaining R | Largest M | Remaining M(s) | E | H | K | Total Demand |
|---|---|---|---|---|---|---|---|---|---|
| **Load** | VA | VA | VA | VA | VA | VA | VA | VA | VA |
| **L1A** | | 10,000 | 8,180 | 2,020 | 1,280 | 7,240 | | 4,560 | |
| NEC Demand Factor | 1.25 | 1 | 0.5 | 1.25 | 1 | 1 | 1.25 | 0.8 | |
| NEC Demand Load | | 10000 | 4090 | 2525 | 1280 | 7240 | 0 | 3648 | **28783** |
| **L1C** | | 8,100 | | | | 1,300 | | | |
| NEC Demand Factor | 1.25 | 1 | 0.5 | 1.25 | 1 | 1 | 1.25 | 1 | |
| NEC Demand Load | 0 | 8100 | 0 | 0 | 0 | 1300 | 0 | 0 | **9400** |
| **L1D** | | 8,920 | | | | 3,220 | | | |
| NEC Demand Factor | 1.25 | 1 | 0.5 | 1.25 | 1 | 1 | 1.25 | 1 | |
| NEC Demand Load | 0 | 8920 | 0 | 0 | 0 | 3220 | 0 | 0 | **12140** |
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| NEC Demand Load | 0 | 4680 | 0 | 0 | 0 | 3560 | 0 | 0 | **8240** |
| **L1G** | | 4,680 | | 2,490 | | 3,360 | | | |
| NEC Demand Factor | 1.25 | 1 | 0.5 | 1.25 | 1 | 1 | 1.25 | 1 | |
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| NEC Demand Factor | 1.25 | 1 | 0.5 | 1.25 | 1 | 1 | 1.25 | 1 | |
| NEC Demand Load | 0 | 10000 | 19020 | 0 | 0 | 5440 | 0 | 0 | **34460** |

However, it was observer that for a optimal sizing of the distribution board that feed the panelboards, it was better to consider all the panelboards as one. As a result, the redudction in the demand was maximized. This can be observed in the table.

| | L | First 10k R | Remaining R | Largest M | Remaining M(s) | E | H | K | Total Demand |
|---|---|---|---|---|---|---|---|---|---|
| Load | VA | VA | VA | VA | VA | VA | VA | VA | VA |
| L1A | | 10,000 | 8,180 | 2,020 | 1,280 | 7,240 | | 4,560 | |
| L1C | | 8,100 | 0 | | | 1,300 | | | |
| L1D | | 8,920 | 0 | | | 3,220 | | | |
| L1F | | 4,680 | 0 | | | 3,560 | | | |
| L1G | | 4,680 | 0 | 2,490 | | 3,360 | | | |
| L1H | | 10,000 | 38,040 | | | 5,440 | | | |
| Total | | 10,000 | 82,600 | 2,490 | 3,300 | 24,120 | 0 | 4560 | |
| NEC Demand Factor | 1.25 | 1 | 0.5 | 1.25 | 1 | 1 | 1.25 | 1 | |
| NEC Demand Load | 0 | 10000 | 41300 | 3112.5 | 3300 | 24120 | 0 | 4560 | 86392.5 |

The total demand calculated in this way was 17.07% smaller than if this calculations were done individually.

Many alternatives paths were discussed to improve the building's efficiency, but most of them were not feasible, since there was not enough information to continue. Thoughtfully analyzing the building's catalog, it was observed that the building was equipped with many fluorescent lights. We opted for reducing the power demand by installing LED lights. In the catalog there were alternative LED lights instead of the fluorescent that were installed. These LED lights' demand was slightly smaller.

More LED advantages were studied: longer lifespan, better lumen/watt ratio, less heat, lower $CO_2$ emission, mercury-free, more environmentally sound as they don't contain heavy metals, no cold starting issues, instantaneous lighting. Moreover, the catalagog stated that fewer LED lamps were needed for a certain number of fluorescent lamps.

The next step was to check that the luminosity was not affected by a reduction in the number of lamps. The photometrics shown by the manufacturer were studied
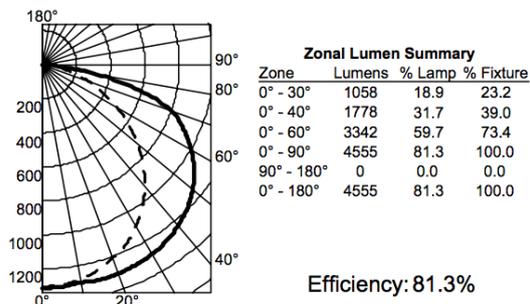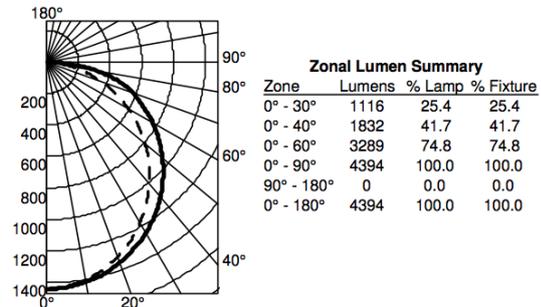


In addition, a personal analysis of the luminosity of a standard room was carried out, using the program AGI32 Illumination Engineering Software.

Office Fluorescent

| | | | | |
|---|---|---|---|---|
| 22.3 | 28.8 | 31.6 | 29.0 | 22.6 |
| 27.9 | 37.0 | 41.5 A1 | 37.3 | 28.3 |
| 32.1 | 43.5 | 49.2 | 43.9 | 32.5 |
| 34.7 | 46.7 | 52.5 | 46.9 | 34.9 |
| 35.3 | 47.4 | 53.0 A1 | 47.3 | 35.1 |
| 33.6 | 45.4 | 51.0 | 45.0 | 33.2 |
| 28.8 | 38.9 | 43.3 | 38.6 | 28.5 |

Office LED

| | | | | |
|---|---|---|---|---|
| 23.8 | 30.8 | 33.9 | 31.0 | 24.0 |
| 31.3 | 42.1 | 47.3 A1 (ALT) | 47.3 | 31.5 |
| 36.3 | 50.4 | 57.8 | 51.1 | 37.2 |
| 38.6 | 52.8 | 59.9 | 53.0 | 38.8 |
| 38.9 | 53.1 | 60.1 A1 (ALT) | 60.1 | 39.2 |
| 36.6 | 50.9 | 58.5 | 51.6 | 37.4 |
| 30.5 | 42.2 | 47.9 | 42.4 | 30.8 |

Once we checked that the luminosity was not affected, we calculated the demand savings by installing LED fixtures. It can be observed in the diagram below. The names A1, A2, A5 and B1 are designations for the different types of lamps and alternate refers to the LED substitute.
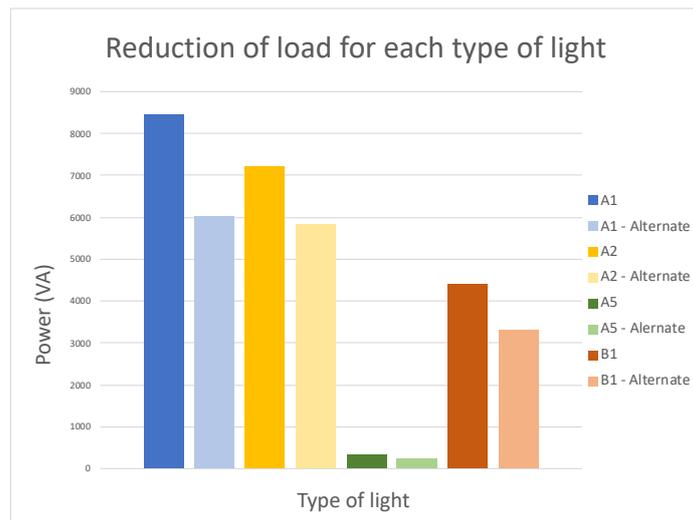


In this project, we seek for a reduction in the power demand but also a maximum economic profit. This way, we developed an optimization problem that minimized the total costs of the building in a period of 25 years. The objective function consisted in three fundamental parts: the electricity bill, the cost of LED fixtures and the cost of fluorescent fixture. The two variables were the LED and fluorescent lamps, for which the program had to choose the optimal option between the pairs of possibilities.

The electricity bill was based on data collected in the last year with the fluorescent lamps installed and in the foreseeable future, assuming an increase of 1% in the demand of the building for the coming years. In the case of installing LEDs, this bill would decrease in accordance with the electricity rates shown in the Primary General Rate. This rates include a monthly fixed charge, another charge depending on the maximum peak demand each month, and last a charge based on the hourly energy during a month.

Regarding the cost corresponding to LED and fluorescent fixtures, we consider the capital cost of buying the lamps and depending on the lifespan, variable for each type, the number of times that it had to be payed. LED lamps are more expensive, but need less replacements. In addition, it was also considered the cost of labor for replacing each fixture.

The objective function was the following:

$$
\begin{aligned}
minimize \sum_{y=2019}^{2043} & \left[ \sum_{m=1}^{12} \left( \sum_{d=1}^{31} \left( \sum_{h=0}^{23} rate_{m,h} * kWh_{y,m,d,h} - \sum_{i=1}^{3} rate_{m,16} * redenergy_i * L_i \right) + DR_m \right. \right. \\
& * \left( maxkW_{y,m} - \sum_{i=1}^{3} redpower_i * L_i \right) + fixed \Bigg) \\
& + \sum_{i \, \varepsilon I} \left( lreplace_{y,i} * lprice_i * L_i + lreplcost_i * L_i + freplace_{y,i} * fprice_i * F_i \right. \\
& \left. \left. + freplcost_i * F_i \right) \right]
\end{aligned}
$$

CONCLUSIONS

The results obtained were satisfactory. The program determined that in a period of 25 years, the optimal solution was to install LED fixtures. With this, we calculated 414,280$ savings in the cost, which corresponded to a 11.14% of the total costs. In addition, we obtained energy savings of 1.24%, which corresponded to 505,901 kWh.

In terms of environmental impact, this enhancement of the building achieved remarkable results, avoiding the emissions to the atmosphere of:
- 105.86 tons of $CO_2$
- 8.41 tons of sulfur dioxide
- 5.62 tons of nitrogen oxides

If this 1.24% improvement in energy efficiency was extrapolated to bigger scenarios, we could achieve the following savings in emissions.

| Area | Emission Type | Current Emission (Million metric tons) | Reduction in Emissions (Million metric tons) |
|---|---|---|---|
| United States | | | |
| | $CO_2$ | 1,763 | 21.8612 |
| | $SO_2$ | 1.9 | 0.02356 |
| | $NO_x$ | 1.8 | 0.02232 |
| World | | | |
| | $CO_2$ | 30,027.81 | 372.34 |
| | $SO_2$ | 31.75 | 0.3937 |
| | $NO_x$ | 70 | 0.868 |

Therefore, the objective of the goal was met. It was demonstrated that a minor adjustment in the building, changing less than 35% of the total luminaire, we can achieve incredible results in a bigger scale.

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# ACKNOWLEDGEMENTS

throught this project, and also the expert opinion from Emily Royal, which is her area of expertise.

In addition, I want to thank again Dr. PK Sen not only for his help, but also for all the people that he put in contact with us to make our lives easier. It is the case of Bob Slavik, who guided us through Coorstek Center of Applied Science and Engineering when we did the field observation. Dr. Sen also scheduled a presentation that we had to do, for which numerous master's students and ex-students that were currently working on the matter were present. The last person I want to mention is Brian Oldfield, who inspired out to carry out this project with his brilliant thesis work on Mines campus.

# 1. INTRODUCTION

I'm an exchange student from Universidad Pontificia Comillas, Madrid, Spain currently studying at Colorado School of Mines (Mines), Golden, Co, a prestigious engineering university located on the western side of Denver, Co. Mines has experienced a significant growth in the last decade, increasing the number of students with every passing year. This local expansion has also seen the effects of globalization and resulted in partnerships with other universities from all around the globe.

Similar to Universidad Pontificia Comillas, Colorado School of Mines shares the same passion for the innovative technologies and sustainability, as well as distinctive values like the concern for the environment and global warming. With this in mind, the end product for this design project focusses on making a contribution to minimize the environmental impact and reduce greenhouse gas emissions, everything done through an electrical energy perspective.



*Image 1: Colorado School of Mines*

The main objective of this design project is to do an extensive analysis of a small microgrid with the purpose of improving energy efficiency and grid reliability, as well as reduce operation and maintenance cost. CoorsTek Center for Applied Science and Engineering (1), a 95,000 square-foot building placed in the core of the campus that supports interdisciplinary academic and research activities, is used for the case of study. This building that cost $27 million, was finished in September 2017 and possess the latest technology and every detail of its design has been deeply analyzed, so trying to make any improvements will be a difficult but also exciting challenge. It is the home building for the Department of Physics and it is constantly full of activity and hosts hundreds of students in its three main floors. There are spacious common areas and flexible breakout rooms for study, conference rooms or small classes, lightened by Colorado's sunshine through its large windows. On the underground level, machines rooms and laboratories can be found. One of the objectives in the design is to make the space as flexible as possible. This is demonstrated by presentation spaces that can be easily combined to create a classroom with 100 seats in a matter of minutes.

*Image 2: Coorstek Center for Applied Science and Engineering*

In the task of minimizing the environmental impact corresponding to Mines emissions, CoorsTek Center includes some innovative energy-saving strategies, including controls to reduce daytime expenditures and a HVAC system that monitors wind speed and direction and adjusts exhaust fans accordingly. The building has received the distinction of achieving the LEED (2) Gold certificate, the most widely used green building rating system in the world. Another aim of this project is to try to improve the current score in the energy categories and, if possible, reach LEED Platinum certificate.

In order to develop the study and possibly implement future improvements, some data collection is required of the energy (electricity, gas and diesel fuel) from both the building and the entire campus as well, with the intention of obtaining a wider picture. The campus wide electricity use, and lighting must be analyzed so the grid can accommodate all of the loads while economizing the use of the resources available.

This project is executed by three students (one mechanical and two electrical) from I.C.A.I. There is a common data collection process, and from there, each one of the students analyzes three different aspects of solutions to possibly improve the building energy performance. I will be focusing primarily on optimizing the energy performance of the building in order to improve the current score in the LEED certificate. Moreover, the economical aspect is also taken into considerations, with a detail cost analysis and the minimization of capital expenses. Finally, the environmental impact is also included in the study.

## 2. STATE OF THE ART

The literature review is limited primarily to similar studies carried out as in Colorado School of Mines.

Concerning Colorado School of Mines, there is an increasing interest at Mines community in this study of the campus facilities and sustainability. The fact that all the new buildings at Mines require to meet the Leadership in Energy and Environmental Design (LEED) Gold Standard is but one illustration of the current situation. This exercise of improving and economizing the campus buildings and some common areas is being conducted mainly by the electrical and mechanical departments, headed by Dr. Sen (EE) and Dr. Paulo Tabares (ME) respectively. Dr. Sen is our project director and sponsor, providing us with more than 50 years of experience in areas like power plants and substations, system and feasibility studies, protection and relaying and power systems. Furthermore, it is not the first time he is involved in project like the one we are about to commence. He has supervised and/or mentored over 300 graduate students.

Many comparable projects have been conducted in various other campus facilities. These projects involved areas such as microgrid, implementation of Photovoltaics (PV) and Battery Energy Storage System (BESS) in buildings on campus, sustainability and cost of improvements. The most recent project regarding these aspects is a Master's thesis carried at Mines by Brian Oldfield under the supervision of Dr. Sen and the title of his work is: *"PV AND BESS DESIGN FOR THE COLORADO SCHOOL OF MINES: OPTIMAL DESIGN METHODOLOGY AND ECONOMIC FEASIBILITY"*. In his thesis, there is a thorough analysis of the implementation of PV on campus and how to make the best use out of them. This means optimizing the orientation and leaning angle depending on factors such as seasons of the year, the amount of sun, the solar path in each season, the temperature, campus' hourly energy demand and many other relevant factors.

However, even though the thesis includes most of the campus' buildings, this building was never part of these projects, since CoorsTek Center was finished on the year 2018. A complete study of the facility is yet to be conducted. Once the analysis of the building is finished, the goal is to optimize it as much as possible.

# 3. MOTIVATION

The reason that led me to choose this project has a strong relation with the values I have been taught at I.C.A.I and this year at Colorado School of Mines. It is also one of the reasons that helped me decide to study engineering: the possibility to make changes in my close surroundings or in a bigger scale. In this case, I wanted to make a contribution to the environmental cause.

Obviously, the study in which I am about to get involved is not going to solve the big real problem that we are facing, the climate change. The main purpose is to show that even latest technology can be improved towards being more environmentally friendly and make my small contribution. So, one of the goals of this project is giving a strong lead to others that changes can be achieved. It does not need to be said that the economic aspect will not be disregarded and will be thoroughly analyzed as well.

I decided to carry out the project at Colorado School of Mines because I believe it is a great opportunity to be able to work with my classmates from I.C.A.I in a completely different environment and culture, and to apply the knowledge obtained during the three years at I.C.A.I and now at Mines. Moreover, this project will also force us to undergo a process of self-learning, because there will be areas that we have never faced in our previous academic studies. As it was mentioned before, the building concerned has the latest technology in every aspect of its design. However, a thorough study on the energy efficiency of the structure has never been conducted by the university. That is the reason why our project director, Dr. Sen has motivated us to carry out this research.

Learning how the electric power system work in the United States, and the differences between my home country and what I can find here, is another aspect that I find really exciting and embarking in this new project. I will be able to appreciate the positive and negative sides of each system and gain a better perspective. The best way to achieve this is to get immerse in this vast world and have a first-hand experience.

Last, it is necessary to mention that the professors at Mines have been willing to help us since the first moment and provided us many ideas in the decision of choosing the project. We would like to show them our great appreciation by doing an excellent work with the hope it will be useful for future students.

# 4. DESCRIPTION OF THE CAMPUS

Colorado School of Mines campus is located in Golden, in a valley between Lookout Mountain and South Table Mountain and delimited by Clear Creek. It consists in an area of 373 acres and holds dozens of buildings that host 6,177 students. The campus is not only equipped with high tech buildings and laboratories, but also with incredible facilities that include soccer fields, baseball fields, basketball courts, indoor gymnasium and swimming pool… It has anything students need in their daily life to make them feel comfortable. Buildings welcome you to their interiors, as there are well illuminated, and the temperature is very nice all the time, no matter what the exterior conditions are or the number of people working inside the building.



*Image 3: Colorado School of Mines campus*

Just a quick walk around the campus is enough to see how much people are working on every facility and putting so much effort so that everything is in perfect condition. The interaction among students and the hundreds of workers makes the campus enjoy of a warm vitality. Moreover, there is an evident growth going on in the campus, as many buildings are being built at the same time, while others have just been finished. Mines is expecting to host around 8,000 students in the coming years, which is 129.5% of its current size.

## 4.1. DESCRIPTION OF THE CAMPUS ELECTRICAL ONE-LINE DIAGRAM

This project is based on a detailed study of the entire electrical distribution system of CoorsTek building. To achieve that goal, it is required to start by obtaining and understanding a big "picture" of the entire campus. Although the ultimate focus is placed on the building itself, these preliminary steps are crucial in order to obtain a proper understanding of the system that is feeding the building, and what other factors influence that system. Therefore, a data collection of the campus buildings is carried out. In addition, the campus medium voltage electrical one-line diagram, the backbone of the distribution system, is also examined.
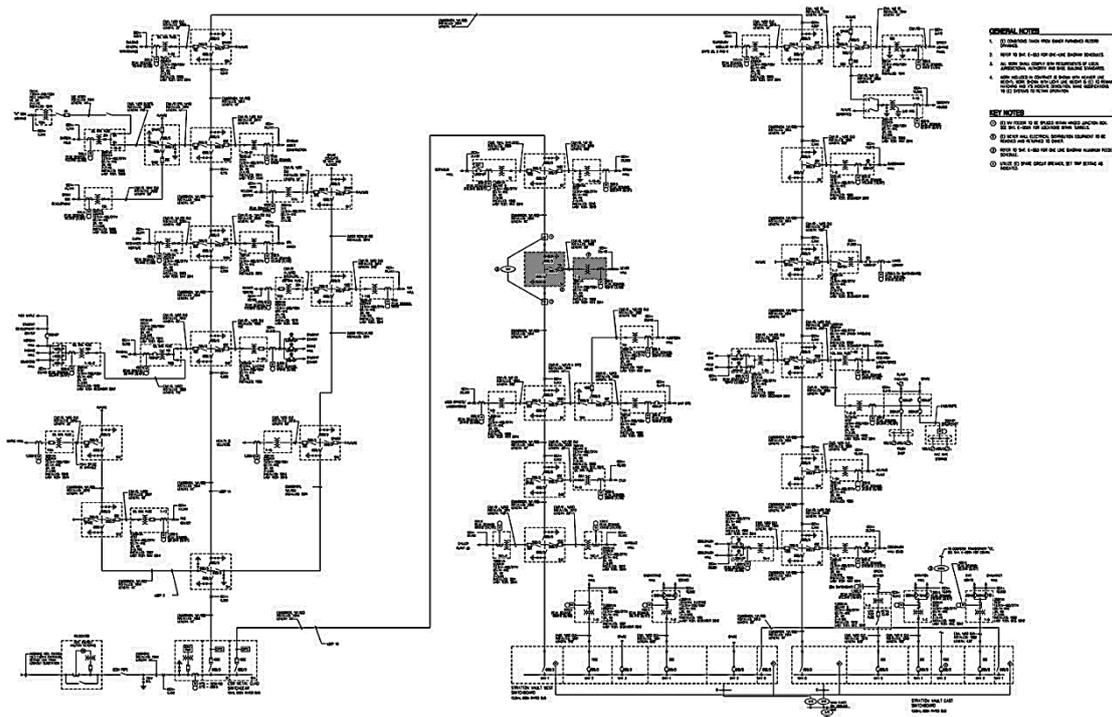
*Image 4: Campus medium voltage one-line diagram*

The above one-diagram represents the entire campus. Appendix A has a larger full-size drawing for more clarity. From the campus medium voltage one-line diagram, the following observations are made. There is an incoming Xcel Energy utility line feeding the campus at 13.2 kV and at a rated current of 600 A. This can be seen on the bottom left hand side corner of figure. The main distribution of the electrical system of the campus is designed in a loop shape, with all the buildings fed from the loop. While the incoming line is overhead, the campus is connected through underground cables. There are two loops, which are connected in the Stratton Vault switchgear. This switch combined with the mentioned loop distribution, allows the system to close one section of the loop so that the other section can pick the this one up. For this study, only the most common operating condition where all the switches are on is considered.

The following figure shows the simplified one-line diagram of the campus. The buildings or loads are classified in four different areas, depending on which part of the loop they are located.
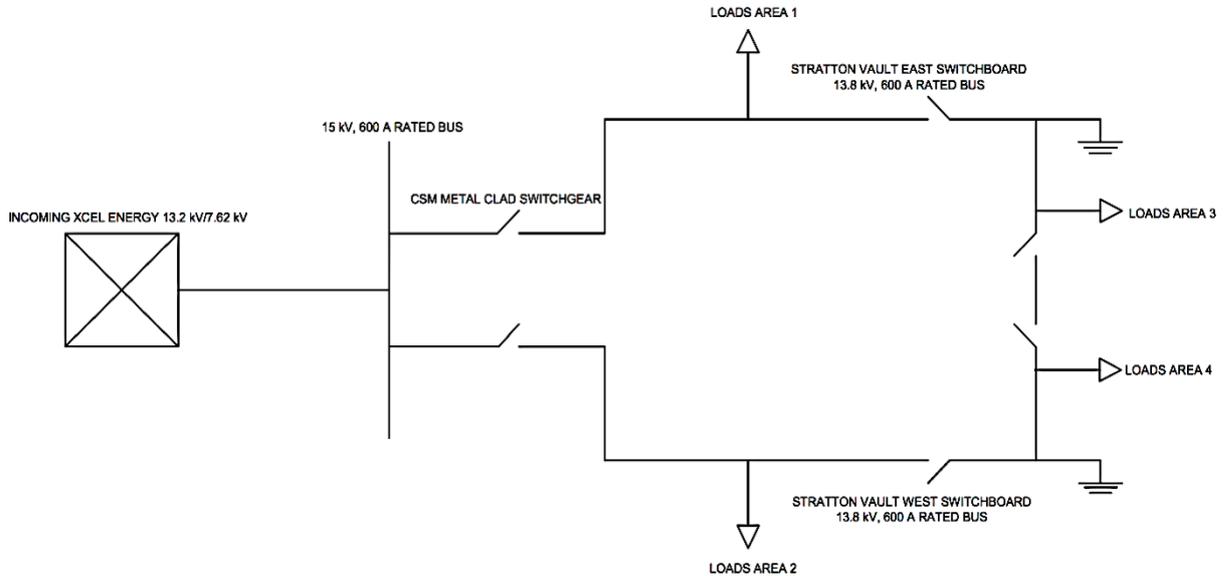


*Figure 1: Simplified campus one-line diagram*

In the above figure it can be seen that the entire loop can be closed with the CSM Metal Clad Switchgear. Once we have used the terms of switchgear and switchboard, it is time to explain the main difference between them.

- Switchgear: these devices are used to switch the electric power on and off for transformers, distribution lines, power networks, etc. They also provide major protection. They are used here in the medium voltage (13.2kV) system.
- Switchboard: the main goal of this device is to be able to divide the current in different circuits. They are used in the low voltage system feeding smaller loads.

## 4.2. DESCRIPTION OF THE CAMPUS LOADS

There are 42 different buildings and facilities on campus which is considered as load points and identified in the one-line diagram. We are not looking in further detail most of the loads connected to the campus loop. Only CoorsTek building is analyzed thoroughly, as it is the case of study. The following table shown in Appendix B provides all the important data concerning the electrical aspects of each transformer feeding every building. That is, the peak demands they are able to power, the phases and wires, the approximate impedance and the ratings, as well as the way the transformer is connected. As it was mentioned above, the buildings are organized in different areas.

In this first one-line diagram, Coorstek Center does not appear, as it was not constructed yet. It only mentions a future expansion for this building connected to a 'T3' transformer that we will see later in the description of the building. That fact is shown on the upper right hand side in the picture below, where a small section of the Stratton Vault East Switchboard is represented.
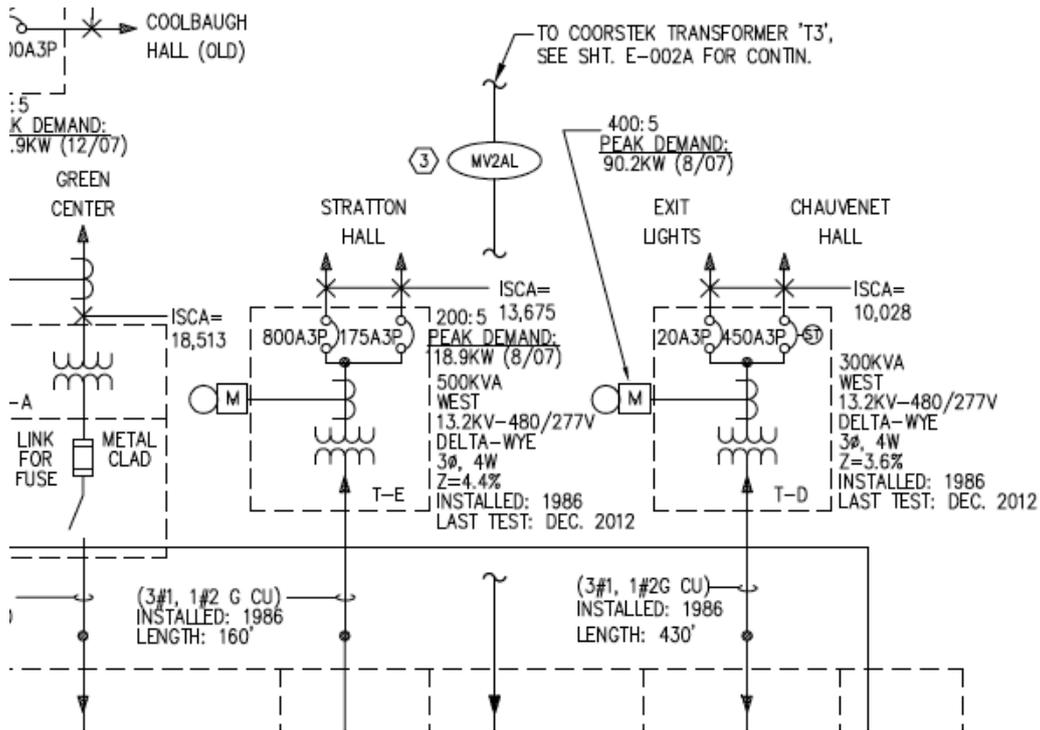
*Image 5: Closer look to Coorstek Center Transformer*

In addition, there is some information missing regarding the peak demand or the impedance of certain transformers. However, this issue is not a major concern, since we are just looking to obtain a general idea, and the exact numbers of all the transformer on the campus is not the goal of our project.

## 4.3. DESCRIPTION OF THE VOLTAGE LEVELS

As it can be seen on the figure above, the buildings are fed by the 13.2 kV line and that voltage is reduced by a specific transformer for each building. These transformers vary in output and % impedance values, but most of them have the same voltage ratio that reduces it from 13.2 kV to either 480 V or 208 V.
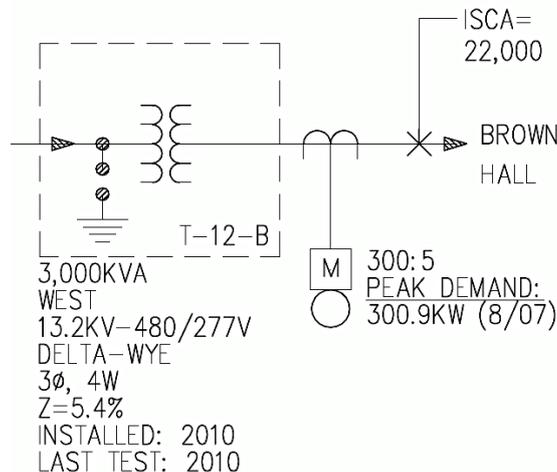


*Image 6: Example of common transformer on campus*

There are some buildings that are directly connected to the Stratton Vault and some lines which are not completed, and they have been left open for future campus expansion.

In the above figure we can see the different three phase voltage levels of the campus:
- Medium voltage (Distribution): 13.2 kV (LL) / 7.62 kV (LN)
- Low voltage (Utilization) 480 V (LL) / 277 (LN)
- Low voltage (Utilization): 208 V (LL) / 120 (LN)

LL stands for Line (Phase)-to-Line (Phase) voltages while LN means Line (Phase)-to-Neutral. In addition, there is a single phase low voltage level of 240 V connected with three wires, used to light the M sign located on the top of the mountain and also for street lighting panels. It is important to remark that there are two low voltage levels, but once we go deeper in the matter, these two utilization levels will be classified into high voltage and low voltage for 480 V and 208 V respectively.

# 5. DESCRIPTION OF THE BUILDING

Coorstek Center is a new building on campus located in the heart of the campus right next to Kafadar Commons garden and very close to Lakes Library. This is why on its surroundings and also in the interior, it is constantly full of students. In its three floors it can accommodate hundreds of students, professors and staff members that carry out their academic duties or research activities here. Many things have already been said in this project about this building, but in order to make an extensive analysis of the building, first it is necessary to have a proper understanding of its design and characteristics. The building electrical one-line diagram and the floor plans will provide us with enough information that is ultimately helpful to us to obtain a better idea.



*Image 7: Aerial view of Coorstek Center*

## 5.1. DESCRIPTION OF THE BUILDING ELECTRICAL ONE-LINE DIAGRAM

The entire building needs to be analyzed by first understanding how the electrical system is designed. Since this project involves the building in question, it is first analyzed and described in more depth. The electrical one-line diagram is of great help. This is shown in chart in the figure below. To see the figure in more detail, a full-size drawing is added in Appendix C.
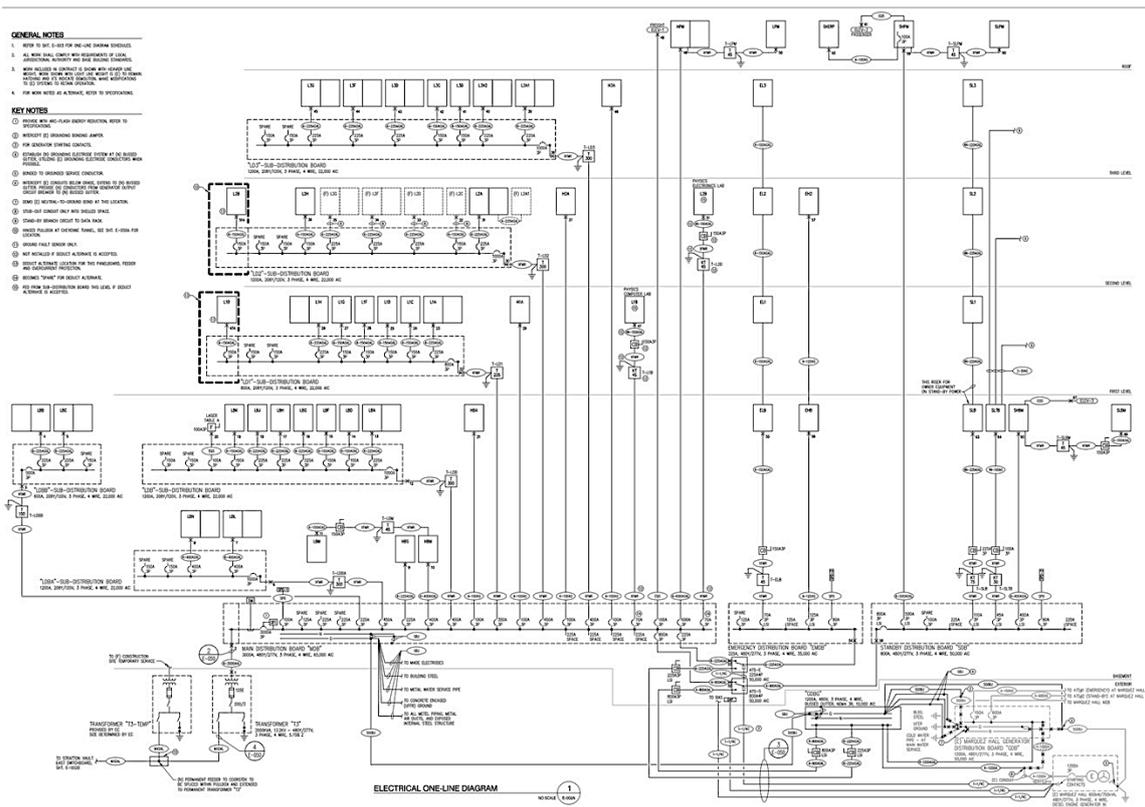
*Image 8: Building one-line diagram*

This drawing looks very complicated at first glance, but it can be simplified considerably once it is divided in three different sub-systems. One of these systems is the regular electrical system feeding the building loads while the other ones are an emergency backup system and a standby system. In all the buildings, there is a legally required emergency system that feeds loads such as fire alarms, elevators, ventilation and emergency lightning. These loads and the emergency system are connected to diesel generators equipped with automatic transfer switches (ATS). In a normal operating condition, the three systems will receive the power from the incoming Xcel Energy. In case there is a fault, it will result in no power to the regular circuit, while the ATS will switch the connection from the utility to the emergency generators, so that the emergency system never loses power. CoorsTek Center is not equipped with emergency diesel generators of its own. Instead, the emergency board is fed by Marquez Hall's generator. The standby system is also connected to the generators from Marquez. However, this system is not legally required as the emergency system. The standby system is designed in accordance to the requests of the owner, and therefore it can switch after the emergency system.

On the bottom left hand side corner of the figure, it can be seen that CoorsTek building is directly connected to the Stratton Vault East Switchboard and it is fed by the following transformer.

Transformer "T3":
- 2,000 kVA, ONAN
- 13.2 kV – 480 V; Delta – Solidly Grounded Wye
- 3 phase, 4 wire
- Impedance Z = 5.75 %

20

*Image 9: Coorstek Center Transformer 'T3'*

The transformer in the photo above is the one that powers Coorstek Center, and it is located right next to the building on the outside and very close to the master's room, which is the place that host most of the transformers and electrical control machines of the building.

That available power from the transformer secondary goes to the Main Distribution Board "MDB". This bus distributes that power to the different floors. The main characteristics of the "MDB" are the following.

Main Distribution Board:
- 3,000 A, Continuous Rating
- 480 Y/277 V
- 3 phase, 4 wire
- 65,000 AIC (Ampere Interrupting Capacity)



*Image 10: Main Distribution Board*

In the Main Distribution Board some spare breakers for future expansions can be found. The other lines coming out of this bus are going to other distribution boards located in the other floors. For each of the lines departing the bus, there are the adequate circuit breakers for currents in a range that vary from 70 – 600 A. The total current going through the bus is measured by a digital meter (DM) connected via a current transformer (CT). Supplementing this digital meter, there is a ground fault interrupter (GFI) in the bus connected to a breaker that trips over 3,000 A. Taking a closer look to each of the floors, the following buses are observed:

| Basement | | | | |
|---|---|---|---|---|
| "LDBA"-SUB-DISTRIBUTION LOAD | 1,200 A | 208 Y/120 V | 3φ,4w | 22,000 AIC |
| "LDB"-SUB-DISTRIBUTION LOAD | 1,200 A | 208 Y/120 V | 3φ,4w | 22,000 AIC |
| "LDBB"-SUB-DISTRIBUTION BOARD | 600 A | 208 Y/120 V | 3φ,4w | 22,000 AIC |

*Table 1: Basement Sub-Distribution Boards*



*Image 11: Closer look to Basement one-line diagram*

| Floor 1 | | | | |
|---|---|---|---|---|
| "LD1"-SUB-DISTRIBUTION LOAD | 800 A | 208 Y/120 V | 3φ,4w | 22,000 AIC |

*Table 2: Floor 1 Sub-Distribution Board*

| Floor 2 | | | | |
|---|---|---|---|---|
| "LD2"-SUB-DISTRIBUTION LOAD | 1,200 A | 208 Y/120 V | 3φ,4w | 22,000 AIC |

*Table 3: Floor 2 Sub-Distribution Board*

| Floor 3 | | | | |
|---|---|---|---|---|
| "LD3"-SUB-DISTRIBUTION LOAD | 800 A | 208 Y/120 V | 3φ,4w | 22,000 AIC |

*Table 4: Floor 3 Sub-Distribution Board*

*Image 12: Closer look to Floor 1, 2 and 3 one-line diagram*

The transformers used inside the building to feed the different loads and the buses described above are the following:

| Three Phase Dry-Type Transformers | | | | |
|---|---|---|---|---|
| Designation | kVA | Primary (V) | Secondary (V) | Impedance (%) |
| T45 | 45 | 480 Δ | 208 Y/120 V | 3.00 |
| T300 | 300 | 480 Δ | 208 Y/120 V | 4.00 |

*Table 5: Type of transformers*

## 5.2. DESCRIPTION OF BUILDING AREAS

Prior to performing the analysis of the different floors of the building, it is important to classify the areas according to the use of the space and the energy power needed in each room. The classification gathers various rooms in 10 categories: faculty offices, laboratories, computer laboratories, storage or cleaning rooms, active learning studios, conference rooms, lounges, electrical rooms, breakouts and common areas.

The *faculty offices*, which includes the graduate offices as well, are small rooms designed to be occupied for no more than 3 people (mostly one person per room) and equipped with one computer per person. In each faculty office there are around 5 outlets where small devices such as fans, computer or phones can be connected.

The *laboratories* in this building require larger amount of power, since they are equipped with big machine and powerful tools. In addition, in some of these laboratories there will be hazardous substances. This, combined with the previous mentioned machines, means that only very qualified people can enter this place, and therefore, the occupancy level of these laboratories is low. We will set an occupancy level to 5 people as an approximation.

The next category is *computer laboratories*. This categorization will group big rooms fully equipped with computers and with a high occupancy rate. For each computer, there is one computer case and two screens. With six tables and six computer per table, there are 36 computers and consequently 72 screens. In addition, these rooms are equipped with 8 televisions, some projectors and several lights. This classes are labelled for a maximum occupancy of 129 people, so the air conditioning must be taken into consideration as well. Knowing all this information, we can have a much better idea of the energy consumption of each one of the rooms composing this category.

Regarding the *storage and cleaning rooms*, it is clear that these spaces are most of the time empty and therefore, there is a very low energy consumption. The storage rooms will encompass the adjacent laboratory storage rooms too.

The *active learning studios* are spacious classes equipped with movable chairs and tables that make the areas more flexible. These classes are designed to be interactive and participatory. Thus, only a few projectors and a dozen of outlets are needed for these areas. Once again, a lot of people can enter these classes, so the human heat has to be counterbalanced with room-ventilation for people's comfort.

Similar spaces in comparison with the previous one is the *conference rooms*.

*Lounges* are confined spaces where people can gather and have a break. These rooms are equipped with a few devices such as microwaves, coffee machines… In these types of rooms, the average occupancy level is around 5 people.

*Electrical rooms* are spaces destined to accommodate electrical equipment such as transformers, distribution boards and panelboards. Moreover, numerous metering and control devices can be found in here.

Last but not the least, another important place, and even more in this building, are the *common areas*. This modern building is rich in these wide and lightened areas where students can gather to study or simply relax.

## 5.3. DESCRIPTION OF THE FLOOR PLANS

Starting from the bottom and moving upwards we can find: basement, first floor, second floor and third floor. The basement is where most of the big machine labs can be found. There are eleven laboratory rooms with their corresponding lab support rooms. In addition, this floor is equipped with storage rooms, chemical waste rooms, instrument rooms, bathrooms and more.

In the first floor which is the street level floor, there are spacious common areas where students can hang out or study. Moreover, there are three active learning studios. As in the basement, three labs can be found here, being two of them computer laboratories.

The second and third floor share a very similar arrangement for the rooms. One flank of the building host 25 faculty offices (2 of them breakouts). In the other flank there are three laboratories and one conference room. One of the laboratories occupies almost 40% of the floor space. Open terrace areas can also be found in this floor.

Finally, in the third floor there are faculty offices on both flanks of the building, summing a total of 43. Moreover, there are some laboratories and conference rooms. The distribution of this floor bears a resemblance to the second floor.

| | Office | Lab | Computer lab | Storage - Cleaning room | Active learning studio | Conference room | Lounge | Electrical room | Common areas |
|---|---|---|---|---|---|---|---|---|---|
| **Basement** | 1,021 | 6,840 | 0 | 5,308 | 0 | 0 | 0 | 1,152 | 10,679 |
| **1st Floor** | 0 | 1,733 | 3,617 | 693 | 2949 | 0 | 961 | 192 | 14,855 |
| **2nd Floor** | 10,286 | 9,349 | 0 | 165 | 0 | 729 | 0 | 192 | 1,279 |
| **3rd Floor** | 12,640 | 6,129 | 0 | 165 | 0 | 892 | 434 | 192 | 1,548 |
| **Total** | 23,947 | 24,051 | 3,617 | 6,331 | 2,949 | 1,621 | 1,395 | 1,728 | 28361 |

*Table 6: Distribution of the areas in the building*

**Distribution of building's areas**

Legend:
- Lab
- Computer Lab
- Storage-Cleaning Room
- Active learning Studio
- Conference Room
- Lounge
- Electrical Room
- Common Areas
- Office
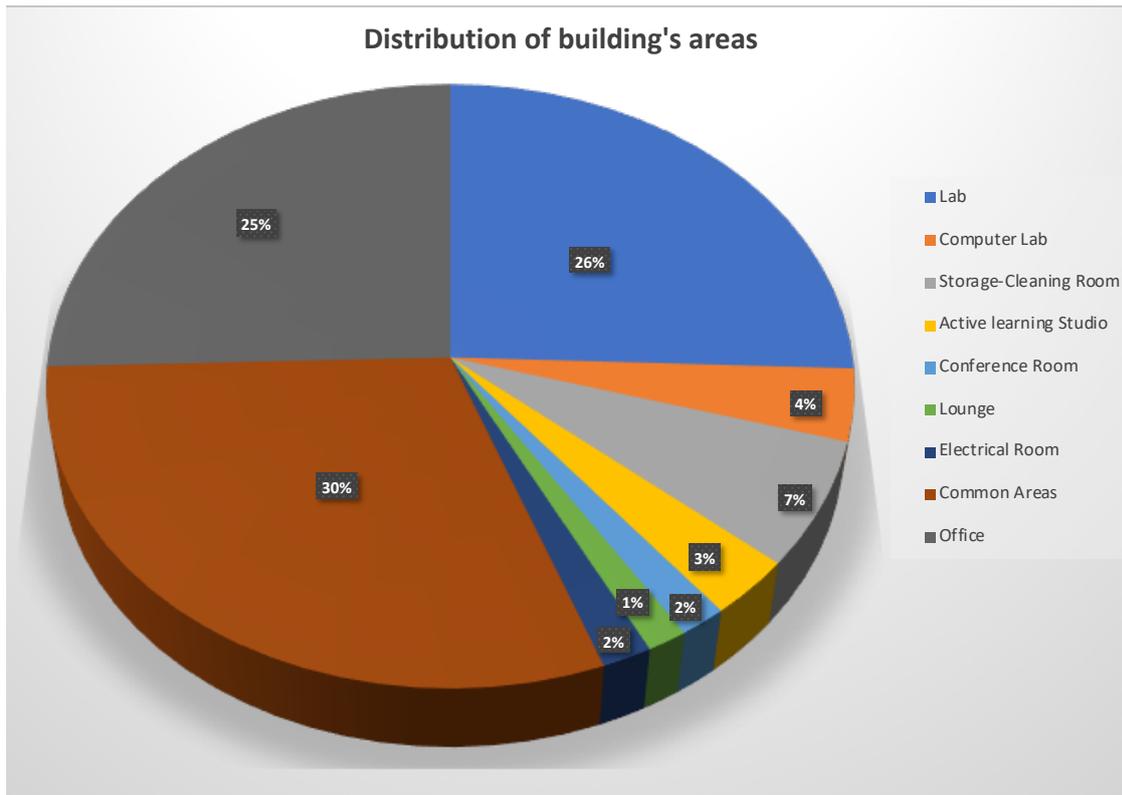
There are some important notes that need to be addressed to have a better understanding of the above table:

- Common areas include: bathrooms, janitor room, stairs, terraces…
- For the basement and floor 1 we approximated the area to be 25,000 square feet and for floors 2 and 3 the area estimated is 22,000 square feet. That gives a total area of 94,000 sq.ft. The building specification suggests it is 95,000 sq.ft, which is pretty close.

## 5.4. CALCULATION OF THE BUILDING LOADS

In order to calculate the approximate loads for each of the floors in the building, the information found on the distribution boards is used. For each of the distribution board there is a load summary containing the different panelboards. There is a more detailed description of all the connected load linked to the panelboards. That information is all what is needed to obtain the total demand of each floor. Combining all the floors, we would have the total maximum demand of the building.
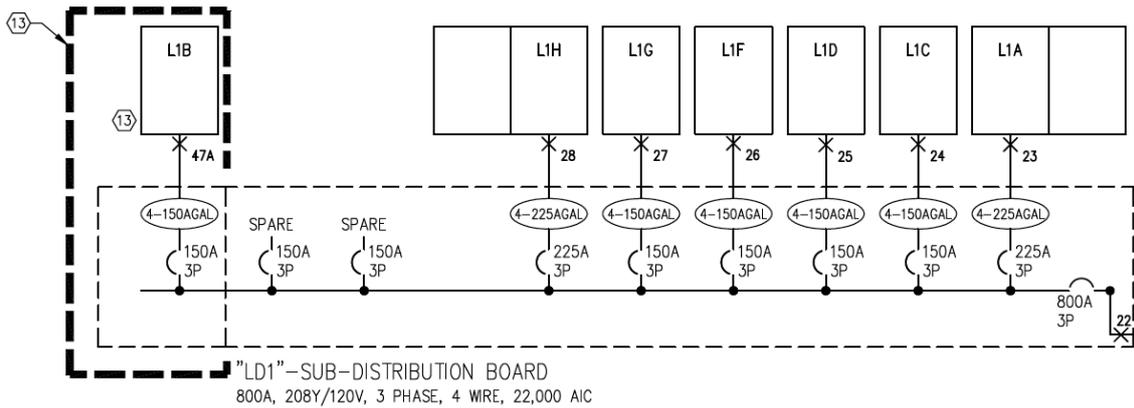
*Image 13: Panelboards connected to Sub-Distribution Board*

First, the panelboards are going to be analyzed. But before going deeper in the matter, there are some other factors that need to be addressed to understand the entire picture.

In the panelboards we can find the following loads:
- (R). *Receptacles*: The receptacles outlets, according to the NEC, should be calculated at not less than 180 VA for each single or for each multiple receptacle on one yoke.
- (E). *Equipment*: This category includes all the equipment that their specific characteristics are known.
- (K). *Kitchen*: In comparison with the previous category, it includes kitchen devices such as microwaves, coffee machines or toasters. However, the specific description of all these devices is not previously known.
- (M). *Motors*: It includes the different motors used in laboratories or for building comfort purposes.
- (L). *Lightning*: The luminaire of the building with all the different types of lamps conforms this point.
- (H). *Heating*: this category includes all the heating and cooling devices.

So, we will begin the calculations of the total demand of the 1st floor panelboards. Below is a sample example of what the panelboard loads look like.

Panelboard: L1A (BUS rating 225 A)

| TYP | VA | LOAD DESCRIPTION | P | CB | CCT | PH | CCT | CB | P | LOAD DESCRIPTION | VA | TYP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| R | 720 | GALLERY C-110, N WALL FLOOR RCPT | 1 | 20 | 1 | A | 2 | 20 | 1 | CORR C170/C180/C130, RCPT | 1080 | R |
| R | 1080 | CORR C-180,C-181,C-182,C-185, VEST C-110, RCPT | 1 | 20 | 3 | B | 4 | 20 | 1 | STUDY 159, RCPT | 720 | R |
| E | 300 | CORR C-180, VIDEO DISPLAY | 1 | 20 | 5 | C | 6 | 20 | 1 | STUDY 159, RCPT | 720 | R |
| R | 900 | MENS 178, WOMENS 179, JAN 180-A, RCPT | 1 | 20 | 7 | A | 8 | 20 | 1 | CLUB 149, GEN RCPT, NW POLE VIDEO DSPLY | 1080 | R |
| M | 480 | CORR C-185, EWC-1 | 1 | 20 | 9 | B | 10 | 20 | 1 | CLUB 149, NW POLE, SO. WALL WIREWAY RCPT | 540 | R |
| E | 1200 | VEND 180, VENDING MACHINE | 1 | 20 | 11 | C | 12 | 20 | 1 | CLUB 149, SO. WALL WIREWAY RCPT | 360 | R |
| E | 1200 | VEND 180, VENDING MACHINE | 1 | 20 | 13 | A | 14 | 20 | 1 | CLUB 149, NO. DISPLAY PLUGMOLD | 900 | R |
| R | 720 | SW EXTERIOR, RCPT | 1 | 20 | 15 | B | 16 | 20 | 1 | CLUB 149, NO. DISPLAY PLUGMOLD | 900 | R |
|  |  | SPARE | 1 | 20 | 17 | C | 18 | 20 | 1 | STAIRS-5 STEP RCPT | 720 | R |
| M | 200 | VEST C-100, AUTO DOORS | 1 | 20 | 19 | A | 20 | 20 | 1 | CORR C120 RCPT | 540 | R |
| R | 360 | CASE STOR 187, RCPT | 1 | 20 | 21 | B | 22 | 20 | 1 | STUDY 138, TABLE RCPT CCT | 1080 | R |
| R | 900 | PHYS STUDENT LOUNGE, RCPT | 1 | 20 | 23 | C | 24 | 20 | 1 | STUDY 138, TABLE RCPT CCT | 1080 | R |
| R | 720 | PHYS STUDENT LOUNGE, FLOOR RCPT | 1 | 20 | 25 | A | 26 | 20 | 1 | STUDIO PREP 139, WIREWAY RCPT | 360 | R |
| E | 480 | PHYS STUDENT LNGE, VIDEO PNL RCPT, SHADES | 1 | 20 | 27 | B | 28 | 20 | 1 | STUDIO PREP 139, WIREWAY RCPT | 180 | R |
| K | 1660 | PHYS STUDENT LOUNGE, GD-1 | 1 | 20 | 29 | C | 30 | 20 | 1 | STUDIO PREP 139, SE DED RCPT | 1200 | E |
| K | 1600 | PHYS STUDENT LOUNGE, AC RCPT (COFFEE) | 1 | 20 | 31 | A | 32 | 20 | 1 | NORTH EXTERIOR RCPT | 720 | R |
| K | 800 | PHYS STUDENT LOUNGE, MICROWAVE | 1 | 20 | 33 | B | 34 | 30 | 1 | ELEC 177, FCU-101 | 2020 | M |
| K | 500 | PHYS STUDENT LOUNGE, UC REFR | 1 | 20 | 35 | C | 36 | 20 | 1 | SPARE |  |  |
| R | 360 | EVENT 170, CTRL STAIR RCPT | 1 | 20 | 37 | A | 38 | 20 | 1 | SPARE |  |  |
|  |  | SPARE | 1 | 20 | 39 | B | 40 | 20 | 1 | CORR C-185, BF-1 | 600 | M |
| E | 360 | EVENT 170, PODIUM FLOOR RCPT | 1 | 20 | 41 | C | 42 | 20 | 1 | SPARE |  |  |

| TYP | VA | LOAD DESCRIPTION | P | CB | CCT | PH | CCT | CB | P | LOAD DESCRIPTION | VA | TYP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | SPARE | 1 | 20 | 43 | A | 44 | 20 | 1 | SPARE |  |  |
|  |  | SPARE | 1 | 20 | 45 | B | 46 | 20 | 1 | SPARE |  |  |
|  |  | SPARE | 1 | 20 | 47 | C | 48 | 20 | 1 | SPARE |  |  |
|  |  | SPARE | 1 | 20 | 49 | A | 50 | 20 | 1 | SPARE |  |  |
|  |  | SPARE | 1 | 20 | 51 | B | 52 | 20 | 1 | SPARE |  |  |
|  |  | SPARE | 1 | 20 | 53 | C | 54 | 20 | 1 | SPARE |  |  |
|  |  | SPARE | 1 | 20 | 55 | A | 56 | 20 | 1 | ELEC 177, SVC VEST C-105 RCPT | 360 | R |
|  |  | SPARE | 1 | 20 | 57 | B | 58 | 20 | 1 | DATA 176, GEN RCPT | 1080 | R |
|  |  | SPARE | 1 | 20 | 59 | C | 60 | 30 | 1 | DATA 176, RACK L5-30R RCPT | 2500 | E |
|  |  | SPACE |  |  | 61 | A | 62 |  |  | SPACE |  |  |
|  |  | SPACE |  |  | 63 | B | 64 |  |  | SPACE |  |  |
|  |  | SPACE |  |  | 65 | C | 66 |  |  | SPACE |  |  |
|  |  | SPACE |  |  | 67 | A | 68 |  |  | SPACE |  |  |
|  |  | SPACE |  |  | 69 | B | 70 |  |  | SPACE |  |  |
|  |  | SPACE |  |  | 71 | C | 72 |  |  | SPACE |  |  |
|  |  | SPACE |  |  | 73 | A | 74 |  |  | SPACE |  |  |
|  |  | SPACE |  |  | 75 | B | 76 |  |  | SPACE |  |  |
|  |  | SPACE |  |  | 77 | C | 78 |  |  | SPACE |  |  |
|  |  | SPACE |  |  | 79 | A | 80 |  |  | SPACE |  |  |
|  |  | SPACE |  |  | 81 | B | 82 |  |  | SPACE |  |  |
|  |  | SPACE |  |  | 83 | C | 84 |  |  | SPACE |  |  |

*Image 14: Load information from L1A panelboard*

With the information available from the above tables, it is possible to calculate the total maximum demand. However, there are some demand factors that adequate the total demand calculated to a more realistic value. These demand factors (3) are described in the National Electrical Code (NEC) (4).
We should not confuse demand factor with diversity factor.

- Diversity factor is the sum of every individual maximum peak load (non-coincident) of the electrical system or component of the system, divided by the maximum aggregated load of the electrical system or component of the system. What is the same, it is the average load divided by the peak load. It is usually more than one.
- Demand factor is the ratio of the maximum demand of a system or component of the system divided by the total connected load of the system or part of the system.

Therefore, the demand factor is a multiplier that determines the more probable load that the feeder is going to carry.

- (R): for receptacles, the demand factor is 1.0 for the first 10 kVA and 0.5 for the rest.

- (E): the equipment is thought to be used most of the time, so it has a demand factor of 1.0.
- (K): the demand factor for kitchen equipment vary according to the table below. It can be seen that the more equipment there is, the lower the demand factor is. It is a logical approximation, since not all the kitchen equipment is going to be used at the same time.

| Number of units of equipment | Demand factor |
|---|---|
| 1 | 1.0 |
| 2 | 1.0 |
| 3 | 0.9 |
| 4 | 0.8 |
| 5 | 0.7 |
| 6 and over | 0.65 |

*Table 7: Demand factors for equipments*

- (M): regarding the motors, there is a demand factor of 1.25 for the largest motor. That is because there exists an inrush when turning a motor on. For the rest of the motors, the DF is 1.0.
- (L): for the luminaire, as the standard from the NEC requires, the demand factor is 1.25. This standard state that this is the demand factor for continuous loads, those are loads where the maximum current is expected to continue for 3 hours or more.
- (H): in the same way as the lightning, the heating has a demand factor of 1.25.

Knowing all these demand factors, it is possible to calculate the total demand from all the panelboards as it is seen below.

| | L | First 10k R | Remaining R | Largest M | Remaining M(s) | E | H | K | Total Demand |
|---|---|---|---|---|---|---|---|---|---|
| **Load** | VA | VA | VA | VA | VA | VA | VA | VA | VA |
| **L1A** | | 10,000 | 8,180 | 2,020 | 1,280 | 7,240 | | 4,560 | |
| NEC Demand Factor | 1.25 | 1 | 0.5 | 1.25 | 1 | 1 | 1.25 | 0.8 | |
| NEC Demand Load | | 10000 | 4090 | 2525 | 1280 | 7240 | 0 | 3648 | **28783** |
| **L1C** | | 8,100 | | | | 1,300 | | | |
| NEC Demand Factor | 1.25 | 1 | 0.5 | 1.25 | 1 | 1 | 1.25 | 1 | |
| NEC Demand Load | 0 | 8100 | 0 | 0 | 0 | 1300 | 0 | 0 | **9400** |
| **L1D** | | 8,920 | | | | 3,220 | | | |
| NEC Demand Factor | 1.25 | 1 | 0.5 | 1.25 | 1 | 1 | 1.25 | 1 | |
| NEC Demand Load | 0 | 8920 | 0 | 0 | 0 | 3220 | 0 | 0 | **12140** |
| **L1F** | | 4,680 | | | | 3,560 | | | |
| NEC Demand Factor | 1.25 | 1 | 0.5 | 1.25 | 1 | 1 | 1.25 | 1 | |
| NEC Demand Load | 0 | 4680 | 0 | 0 | 0 | 3560 | 0 | 0 | **8240** |
| **L1G** | | 4,680 | | 2,490 | | 3,360 | | | |

| | L | First 10k R | Remaining R | Largest M | Remaining M(s) | E | H | K | Total |
|---|---|---|---|---|---|---|---|---|---|
| NEC Demand Factor | 1.25 | 1 | 0.5 | 1.25 | 1 | 1 | 1.25 | 1 | |
| NEC Demand Load | 0 | 4680 | 0 | 3112.5 | 0 | 3360 | 0 | 0 | **11152.5** |
| **L1H** | | 10,000 | 38,040 | | | 5,440 | | | |
| NEC Demand Factor | 1.25 | 1 | 0.5 | 1.25 | 1 | 1 | 1.25 | 1 | |
| NEC Demand Load | 0 | 10000 | 19020 | 0 | 0 | 5440 | 0 | 0 | **34460** |

*Table 8: L1A panelboard load demand calculation*

It is clear from the table we are not interested in summing up all the load demands from the different panelboards to obtain the total demand of the distribution load. The interest in doing this, is because if the NEC demand factor is applied to each panelboard, the feeders and breakers can be sized accordingly to minimize the costs. In other words, applying the factor to the panelboards maximizes the reduction of demand.

However, when the distribution board loads are calculated, the way of maximizing the reduction of demand is by applying the NEC demand factor once all the loads from the panelboards have been summed. The biggest reduction of the load demand can be found on the columns corresponding to receptacles and motors. This is achieved by performing some calculations. Only the receptacles calculations procedure will be explained, as it is the same process for the motors.

- The NEC Demand Factor is applied only to the largest load of the First 10k receptacles.
- For the remaining receptacles, we sum both columns (first 10k and remaining) and subtract the largest load of the First 10k. The Demand Factor is applied to the value obtained.

By doing that, we reduce the load that is going to be multiplied by the larger value of Demand Factor and multiply the remaining loads for a much smaller factor. This can be seen in the following table:

| | L | First 10k R | Remaining R | Largest M | Remaining M(s) | E | H | K | Total Demand |
|---|---|---|---|---|---|---|---|---|---|
| **Load** | VA | VA | VA | VA | VA | VA | VA | VA | VA |
| **L1A** | | 10,000 | 8,180 | 2,020 | 1,280 | 7,240 | | 4,560 | |
| **L1C** | | 8,100 | 0 | | | 1,300 | | | |
| **L1D** | | 8,920 | 0 | | | 3,220 | | | |
| **L1F** | | 4,680 | 0 | | | 3,560 | | | |
| **L1G** | | 4,680 | 0 | 2,490 | | 3,360 | | | |
| **L1H** | | 10,000 | 38,040 | | | 5,440 | | | |
| **Total** | | 10,000 | 82,600 | 2,490 | 3,300 | 24,120 | 0 | 4560 | |
| **NEC Demand Factor** | 1.25 | 1 | 0.5 | 1.25 | 1 | 1 | 1.25 | 1 | |
| **NEC Demand Load** | 0 | 10000 | 41300 | 3112.5 | 3300 | 24120 | 0 | 4560 | 86392.5 |

*Table 9: First floor Sub-Distribution Board load demand calculation*

The total demand after applying the NEC demand factor is 86,392.5 VA if we only count the first 10k receptacles and largest motors of all the panelboards, instead of counting them for each panelboard. If we had summed the sum of demands for each panelboard, the total demand is 104,175.5 VA.

In conclusion, in order to maximize the reduction of demand and therefore, size the distribution board accordingly, it is better to consider all the panelboards as one. This way, we can size the distribution board to be 17.07% smaller than doing this process with the other method.

# 6. ENERGY PERFORMANCE OPTIMIZATION

In this chapter, the focus is placed in improving the energy performance of the building. This is one of the sections of the LEED grading score in which we are going to place more emphasis. There are many ways to approach this issue. One way is to reduce the power factor, however, this task is very difficult in buildings, since the power factor is already really good. In this project, we will concentrate on the reduction of the current energy produced by the existing loads.

## 6.1. REDUCTION OF LOADS

In other to obtain a better energy performance and consequently, get more points in this section of the v3 – LEED 2009 BD+C: New Construction, a reduction of the loads is considered. For this, some alternate loads with lower power consumption will substitute the current loads.

Regarding the luminaire, there are numerous types of lights listed in the official catalog that could help us in reducing the power. In particular, these alternate lights are LED lights that would substitute the existing fluorescent lights.

LED technology is relatively modern, and a lot of advances have been carried out in the last 10 years. These lights provide great advantages compared to the widely used fluorescent lights. Some of these advantages (5) are:

- Longer lifespan. LED lights have an approximate lifespan of 60,000 hours compared to the 10,000 hours of the fluorescent lights. Interestingly, a LED bulb is considered to finish its rated life once its output drops 30 percent.
- Better Lumens/W ratio compared to the fluorescent lights. This allows to install a smaller number (or smaller wattage) of bulbs per lamp.
- Lower heat and $CO_2$ emission.
- In contrast to fluorescent lights, LED technology does not contain mercury. This fact is of great interest, since we would rather contaminate as little as possible.
- Are environmentally sound, since no Hg, Pb or heavy metals are used.
- They don't have cold starting issues related to the room temperature.
- Start instantly (nanoseconds).

The main disadvantage is that the cost of LED bulbs is higher compared to the fluorescent lights, and it would take some time to recover the initial expense. This negative aspect and its consequences are analyzed later in this study.

As it has been mentioned throughout this document, this building is designed to be highly versatile, and depending on the different areas, there are alternative ways of illuminating the spaces. Therefore, the building accommodates hundreds of different lightning loads. However, not all the fixtures have an alternative LED that can replace them, and only several types of lights have a corresponding replacement. The types of fluorescent lamps

that can be substituted for more efficient LED lights in order to improve the total power are the following:

| Designation | Description | Power per lamp W | Number of lamps | Voltage | Total VA |
|---|---|---|---|---|---|
| A1 | Fluorescent | 28 | 2 | 120/277 | 56 |
| A1 - **Alternate** | LED | 40 | 1 | 120/277 | 40 |
| A2 | Fluorescent | 28 | 3 | 120/277 | 84 |
| A2 - **Alternate** | LED | 68 | 1 | 120/277 | 68 |
| A5 | Fluorescent | 28 | 2 | 120/277 | 56 |
| A5 - **Alternate** | LED | 40 | 1 | 120/277 | 40 |
| B1 | Fluorescent | 28 | 2 | 120/277 | 56 |
| B1 - **Alternate** | LED | 42 | 1 | 120/277 | 42 |

*Table 10: Current and Alternative Fixtures*

The letters followed by the number is the categorization of each type of lamp as it appears in the catalog of the building by the construction firm. The above information regarding the power, number of lamps per fixture and voltages can be found in the catalog as well.

| Existing fixture | Alternative fixture | Reduction of Power (W) | Reduction of Power appliying NEC Demand Factor (W) |
|---|---|---|---|
| A1 | A1 - **Alternate** | 16 | 20 |
| A2 | A2 - **Alternate** | 16 | 20 |
| A5 | A5 - **Alternate** | 16 | 20 |
| B1 | B1 - **Alternate** | 14 | 17.5 |

*Table 11: Alternative Fixtures Power Reduction*

NOTE: the units W and VA are used interchangeably in this project since for new buildings the power factor is nearly 1.0. By searching in Niagara AX the actual power factor of CoorsTek Center, we find out that in fact, the power factor is 1.0. Having a power factor of 1.0 makes the calculations easier. The information collected on Niagara is shown below.

**BldgMeter**

| | | | |
|---|---|---|---|
| Delivered kWH | 250764 kW-hr | Phase A Volts THD | 5 V |
| Peak kW | 260 kW | Phase B Volts THD | 5 V |
| | | Phase C Volts THD | 6 V |
| Instantaneous kW | 182 kW | Phase A Amps THD | 60.0 A |
| Power Factor | 1 | Phase B Amps THD | 60.0 A |
| | | Phase C Amps THD | 11.0 A |
| Phase A Amps | 216 A | Neutral Amps THD | 1.0 A |
| Phase B Amps | 240 A | | |
| Phase C Amps | 240 A | kW Monthly Alarm | ALARM |

*Image 15: Niagara AX Power Quality Measurements*

Returning to the subject, from the table containing the types of lights, the interesting thing about the LED lights concerning our goal, is to install a lower number of lamps compared to the existing fluorescent, as it would demand less power. We mentioned before that the luminosity in terms of lumens per watts has a higher ratio for the LED lights. However, we have to make sure that if we install the number described in the table above, the luminosity of the rooms stays within an acceptable range compared with the fluorescent lights.

In order to calculate the luminosity of each of the lamps, it will be necessary to search for the features and specifications provided by the manufacturer Lithonia. The types of fluorescent lights used for A1, A2 and A5 are a VT Troffer impact-modified, single clear acrylic diffuser (5).

For lights of type A1 and A5, they can be gathered in a same table, since these two lights only differ in the type of mounting and not in the types of lamps used. These two lamps are going to be considered as one for the rest of the project. The types of LED fixtures are VTL Troffer impact-modified, single clear acrylic diffuser, 4800L 3500K (6).

| Catalog Series: VT | | | | | | |
|---|---|---|---|---|---|---|
| A1, A5 Ligths | Lumens per lamp (L) | Power per lamp W | Lumens/Watt | Number of lamps | Efficiency % | Total Lumens |
| Fluorescent VT – 28W T8 | 2,800 | 28 | 100 | 2 | 81.3 | 4,555 |
| LED: 2VTL4 48L ADP LP835 | 5,238 | 38.4 | 136.4 | 1 | 100 | 5,238 |

*Table 12: A1 and A5, and corresponding alternative fixtures luminosity*

It is seen that the luminosity using one single lamp of LED provides 683 lumens more compared to using 2 fluorescent lamps. For some lamps, the power does not fit with the rating shown in the catalog. In reality, sometimes numbers differ slightly, as it happens with the above LED fixture which is supposed to be 40W. In addition, there is another aspect that needs to be considered. Analyzing the photometrics charts for each of the lamps, we can compare the luminosity for any angle.

## 2VT  Volumetric Recessed Lighting 2'x4'

### PHOTOMETRICS

**2VT8 2 32 ADP**; 2800 lumens per lamp; s/m 1.2 (along), 1.4 (across); test no. LTL18809.



| CP Summary | 0° | 90 | pf pc pw | 80% 70%50%30% | 20% 70% 50%30%10% | 50% 50%30%10% | Zone | Lumens | % Lamp | % Fixture |
|---|---|---|---|---|---|---|---|---|---|---|
| 0° | 1313 | 1313 | 0 | 97 97 97 | 95 95 95 | 90 90 90 | 0° - 30° | 1058 | 18.9 | 23.2 |
| 5° | 1298 | 1310 | 1 | 88 83 80 | 81 78 75 | 78 75 72 | 0° - 40° | 1778 | 31.7 | 39.0 |
| 15° | 1252 | 1308 | 2 | 79 72 66 | 70 65 60 | 67 62 58 | 0° - 60° | 3342 | 59.7 | 73.4 |
| 25° | 1161 | 1298 | 3 | 71 62 55 | 61 54 49 | 58 53 48 | 0° - 90° | 4555 | 81.3 | 100.0 |
| 35° | 1019 | 1264 | 4 | 65 55 47 | 54 46 41 | 52 45 40 | 90° - 180° | 0 | 0.0 | 0.0 |
| 45° | 834 | 1196 | 5 | 60 49 41 | 48 40 35 | 46 39 35 | 0° - 180° | 4555 | 81.3 | 100.0 |
| 55° | 617 | 1081 | 6 | 55 44 36 | 43 35 30 | 41 35 30 | | | | |
| 65° | 391 | 915 | 7 | 51 39 32 | 39 32 26 | 37 31 26 | | | | |
| 75° | 190 | 586 | 8 | 47 36 29 | 35 28 23 | 34 28 23 | | | | |
| 85° | 40 | 110 | 9 | 44 33 26 | 32 26 21 | 31 25 21 | | | | |
| 90 | 2 | 0 | 10 | 41 30 23 | 30 23 19 | 29 23 19 | | | | |

Efficiency: 81.3%

*Image 16: A1 and A5 photometrics*

In the case of the fluorescent lights, as the above table shows, only 59.7% of the lumens in that lamp are between the range from 0 to 60 degrees. The fluorescent lights never reach 100% efficiency, since some of its lumens are illuminating in undesired directions, and 26,6% of the 81.3% lumens available, are lighting the room with an angle between 60-90 degrees.

## 2VTL  Volumetric Recessed Lighting 2'x4'

### PHOTOMETRICS

**2VTL4 40L ADP LP835,** 4393 delivered lumens, test no. LTL24782P105, tested in accordance to IESNA LM-79



| CP Summary | 0° | 90 | pf pc pw | 80% 70%50%30% | 20% 70% 50%30%10% | 50% 50%30%10% | Zone | Lumens | % Lamp | % Fixture |
|---|---|---|---|---|---|---|---|---|---|---|
| 0° | 1439 | 1439 | 0 | 119 119 119 | 116 116 116 | 111 111 111 | 0° - 30° | 1116 | 25.4 | 25.4 |
| 5° | 1428 | 1434 | 1 | 108 103 98 | 100 96 92 | 96 92 89 | 0° - 40° | 1832 | 41.7 | 41.7 |
| 15° | 1366 | 1392 | 2 | 97 89 81 | 87 80 74 | 83 78 73 | 0° - 60° | 3289 | 74.8 | 74.8 |
| 25° | 1251 | 1306 | 3 | 89 77 69 | 76 68 61 | 73 66 60 | 0° - 90° | 4394 | 100.0 | 100.0 |
| 35° | 1095 | 1188 | 4 | 81 68 59 | 67 58 52 | 64 57 51 | 90° - 180° | 0 | 0.0 | 0.0 |
| 45° | 911 | 1037 | 5 | 74 61 52 | 60 51 44 | 58 50 44 | 0° - 180° | 4394 | 100.0 | 100.0 |
| 55° | 706 | 865 | 6 | 69 55 46 | 54 45 39 | 52 44 38 | | | | |
| 65° | 484 | 677 | 7 | 63 50 41 | 49 40 34 | 47 39 34 | | | | |
| 75° | 254 | 466 | 8 | 59 45 36 | 44 36 30 | 43 36 30 | | | | |
| 85° | 55 | 153 | 9 | 55 41 33 | 41 33 27 | 40 32 27 | | | | |
| 90 | 4 | 10 | 10 | 52 38 30 | 38 30 25 | 37 30 25 | | | | |

*Image 17: A1 and A5 alternative photometrics*

The above picture shows the photometrics for a fixture with a different wattage, however the performance does not change in percentages. For that same range of 0 to 60 degrees, LED lamps provide 74.8% of the total lumens. Therefore, LED lights not only provide more luminosity with fewer lamps used, but they also illuminate the rooms in a more efficient way, because they light only in desired angles and this directionality means there is no wasted light. LED produce luminosity in a more uniform manner.

Moving on to the next alternate fixtures A2, there are two types corresponding to the Fluorescent and LED. For the LED lamp, the model used is a VTL Troffer impact-modified, single clear acrylic diffuser, 7200L 3500K, which can be found in the previous mentioned Lithonia Catalog.

| Catalog Series: VT | | | | | | |
|---|---|---|---|---|---|---|
| A2 Lights | Lumens per lamp (L) | Power per lamp W | Lumens/Watt | Number of lamps | Efficiency % | Total Lumens |
| Fluorescent: 28W T8 | 2,800 | 28 | 100 | 3 | 81.3 | 6,829 |
| LED: 2VTL4 85L ADP LP935 | 7,182 | 67,7 | 106.08 | 1 | 100 | 7,182 |

*Table 13: A2 and corresponding alternative luminosity*

Finally, the B1 lights belong to a different catalog series, the AL Series High-Performance Architectural Recessed. This time, we are comparing the fluorescent AL T8 Troffer impact-modified, single clear acrylic diffuser (7). For the alternate LED fixture, the ALL Troffer impact-modified, single clear acrylic diffuser 4000L 3500K (8) model is used.

| Catalog Series: AL | | | | | | |
|---|---|---|---|---|---|---|
| B1 Lights | Lumens per lamp (L) | Power per lamp W | Lumens/Watt | Number of lamps | Efficiency % | Total Lumens |
| Fluorescent VT – 28W T8 | 2,725 | 28 | 97.32 | 2 | 63.4 | 3,457 |
| LED: ALL4 40L EZ1 LP835 | 4,154.9 | 39 | 106.53 | 1 | 100 | 4,154.9 |

*Table 14: B1 and correspondent alternative luminosity*

**AL8 2 32**, 2725 lumens per lamp, test no. LTL22824



**CP Summary**

| | 0° | 90 |
|---|---|---|
| 0° | 1265 | 1265 |
| 5° | 1271 | 1238 |
| 15° | 1219 | 1190 |
| 25° | 1117 | 1096 |
| 35° | 975 | 969 |
| 45° | 803 | 810 |
| 55° | 606 | 625 |
| 65° | 401 | 424 |
| 75° | 205 | 216 |
| 85° | 42 | 46 |
| 90 | 2 | 1 |

**Coefficients of Utilization**

| pf | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| pc | 80% | | | 70% | | | 50% | | |
| pw | 70% | 50% | 30% | 50% | 30% | 10% | 50% | 30% | 10% |
| 0 | 76 | 76 | 76 | 74 | 74 | 74 | 70 | 70 | 70 |
| 1 | 69 | 66 | 63 | 65 | 62 | 60 | 62 | 60 | 58 |
| 2 | 63 | 58 | 53 | 56 | 53 | 49 | 54 | 51 | 48 |
| 3 | 57 | 51 | 46 | 50 | 45 | 41 | 48 | 44 | 40 |
| 4 | 53 | 45 | 39 | 44 | 39 | 35 | 43 | 38 | 34 |
| 5 | 48 | 40 | 34 | 39 | 34 | 30 | 38 | 33 | 30 |
| 6 | 45 | 36 | 31 | 36 | 30 | 26 | 34 | 30 | 26 |
| 7 | 41 | 33 | 27 | 32 | 27 | 23 | 31 | 27 | 23 |
| 8 | 39 | 30 | 25 | 30 | 24 | 21 | 29 | 24 | 21 |
| 9 | 36 | 28 | 22 | 27 | 22 | 19 | 26 | 22 | 19 |
| 10 | 34 | 25 | 20 | 25 | 20 | 17 | 24 | 20 | 17 |

20%

**Zonal Lumen Summary**

| Zone | Lumens | % Lamp | % Fixture |
|---|---|---|---|
| 0° - 30° | 971 | 17.8 | 28.1 |
| 0° - 40° | 1581 | 29.0 | 45.7 |
| 0° - 60° | 2759 | 50.6 | 79.8 |
| 0° - 90° | 3457 | 63.4 | 100.0 |
| 90° - 180° | 0 | 0.0 | 0.0 |
| 0° - 180° | 3457 | 63.4 | 100.0 |

*Image 18: B1 photometrics*

**ALL4 48L EZ1 LP835**, 4922.5 delivered lumens, test no. LTL26928P13, tested in accordance to IESNA LM-79.

| | | | | | | | Coefficients of Utilization | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | pf | | | | 20% | | | | | | | |
| | **CP Summary** | | | | pc | | 80% | | | 70% | | | 50% | **Zonal Lumen Summary** | | |
| | 0° | 90 | | | pw | 70% | 50% | 30% | 50% | 30% | 10% | 50% | 30% | 10% | Zone | Lumens | % Lamp | % Fixture |
| 0° | 1961 | 1961 | | | 0 | 119 | 119 | 119 | 116 | 116 | 116 | 111 | 111 | 111 | 0° - 30° | 1457 | 29.6 | 29.6 |
| 5° | 1941 | 1948 | | | 1 | 109 | 104 | 100 | 102 | 98 | 95 | 98 | 95 | 92 | 0° - 40° | 2332 | 47.4 | 47.4 |
| 15° | 1857 | 1826 | | | 2 | 99 | 91 | 85 | 89 | 83 | 78 | 86 | 81 | 76 | 0° - 60° | 3966 | 80.6 | 80.6 |
| 25° | 1685 | 1622 | | | 3 | 91 | 81 | 73 | 79 | 72 | 66 | 76 | 70 | 64 | 0° - 90° | 4922 | 100.0 | 100.0 |
| 35° | 1437 | 1387 | R C R | 4 | 83 | 72 | 63 | 70 | 62 | 56 | 68 | 61 | 55 | 90° - 120° | 0 | 0.0 | 0.0 |
| 45° | 1154 | 1135 | | | 5 | 77 | 64 | 55 | 63 | 55 | 48 | 61 | 54 | 48 | 90° - 130° | 0 | 0.0 | 0.0 |
| 55° | 852 | 867 | | | 6 | 71 | 58 | 49 | 57 | 49 | 43 | 55 | 48 | 42 | 90° - 150° | 0 | 0.0 | 0.0 |
| 65° | 554 | 589 | | | 7 | 66 | 53 | 44 | 52 | 44 | 38 | 50 | 43 | 37 | 90° - 180° | 0 | 0.0 | 0.0 |
| 75° | 291 | 300 | | | 8 | 61 | 48 | 40 | 47 | 39 | 34 | 46 | 39 | 34 | 0° - 180° | 4922 | 100.0 | 100.0 |
| 85° | 80 | 57 | | | 9 | 57 | 44 | 36 | 44 | 36 | 31 | 42 | 35 | 30 | | | | |
| 90 | 0 | 0 | | | 10 | 54 | 41 | 33 | 40 | 33 | 28 | 39 | 32 | 28 | | | | |

— — 0°    —— 90°

*Image 19: B1 alternative photometrics*

Finally, the A1 both existing and alternative fixtures are tested to ascertain the veracity of the above calculations. The program used for this verification is the AGI32 (9) Illumination Engineering Software. This simulation tool allows us to predict lighting results in a more realistic environment, and the interaction with various elements as it can be surfaces materials, reflectance, etc.

In order to compare the luminosity that each lamp provides, these two lamps are tested under the exact same conditions. Two lamps of each kind illuminate two different rooms. The rooms have the following properties:

- Reflectance: the factors used for this parameter are chosen considering the distance to the lamp.
    - Floor = 20%
    - Walls = 50%
    - Ceiling = 80%

Moreover, there is a Light Loss Factor (LLF) that contemplates how much light get loss due to inefficiency, dirtiness of the lamps, etc. The results obtained are shown below.

## Office Fluorescent

| 22.3 | 28.8 | 31.6 | 29.0 | 22.6 |
|------|------|------|------|------|
| 27.9 | 37.0 | A1 | 37.3 | 28.3 |
| 32.1 | 43.5 | 49.2 | 43.9 | 32.5 |
| 34.7 | 46.7 | 52.5 | 46.9 | 34.9 |
| 35.3 | 47.4 | A1 | 47.3 | 35.1 |
| 33.6 | 45.4 | 51.0 | 45.0 | 33.2 |
| 28.8 | 38.9 | 43.3 | 38.6 | 28.5 |

## Office LED

| 23.8 | 30.8 | 33.9 | 31.0 | 24.0 |
|------|------|------|------|------|
| 31.3 | 42.1 | A1 (ALT) | | 31.5 |
| 36.3 | 50.4 | 57.8 | 51.1 | 37.2 |
| 38.6 | 52.8 | 59.9 | 53.0 | 38.8 |
| 38.9 | 53.1 | A1 (ALT) | | 39.2 |
| 36.6 | 50.9 | 58.5 | 51.6 | 37.4 |
| 30.5 | 42.2 | 47.9 | 42.4 | 30.8 |
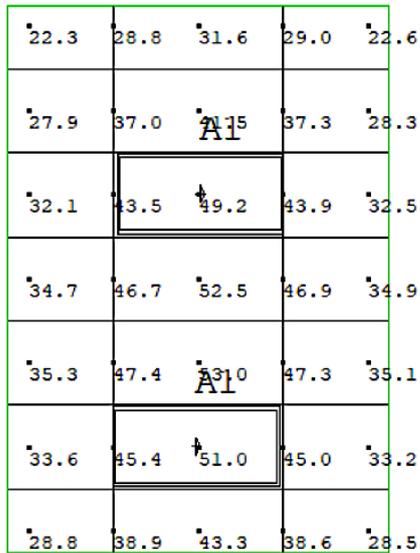
*Image 20: AGI32 Simulation Output*

The above figures are outputs from the top view of the rooms with the luminosity in foot candles (fc) in each of the square's subdivisions at a workplane height of 30 inches. Below, a table with the luminosity average, maximum and minimum in each room is provided. The table reaffirms that LED fixture provide a better luminosity over the entire space in comparison with the Fluorescent fixture.

| Luminaire Schedule | | | | | |
|---|---|---|---|---|---|
| Symbol | Qty | Label | Total Lamp Lumens | LLF | Description |
| | 2 | A1 | 5600 | 0.900 | 2VT8 2 32 ADP LPSM735 |
| | 2 | A1 (ALT) | N.A. | 0.900 | 2VTL4 48L ADPT EZ1 LP835 |

| Calculation Summary | | | | | | |
|---|---|---|---|---|---|---|
| Label | CalcType | Units | Avg | Max | Min |
| Office Fluorescent_Workplane | Illuminance | Fc | 37.93 | 53.0 | 22.3 |
| Office LED_Workplane | Illuminance | Fc | 42.50 | 60.1 | 23.8 |

*Image 21: AGI32 Simulations Outputs in Numbers*

Once it has been checked that the number of lights can be reduced without affecting the illuminance of the areas of matter, we can move on to calculate the number of lights that are going to be changed. So, with the help of the electrical lighting plan of each floor, and by identifying the loads named above, it is possible to calculate the number of lights that have to be changed for the LED equivalent. The table included in the Appendix D, contains the above-mentioned fluorescent lights that have been installed in the current building and also the panelboard that is feeding the luminaire. It is important to remind that this table includes the fluorescent lights which had alternative LED fixtures that can replace them. There are more existing fluorescent lights in the building that are not going to be modified.

While the above table include the existing lights, another table with the LED lights substitutes can be made. This table can be found in the Appendix E and contains all the relevant information regarding the alternate lamps.

With the table containing the alternate LED lights, it can be seen that there is an optimization not only in the total power but also in the number of lights used. It is time to analyze in more depth what the advantages of implementing the LED lights would be. Starting with the total power that each type of light consumes and comparing them with pairs of colors, we have:
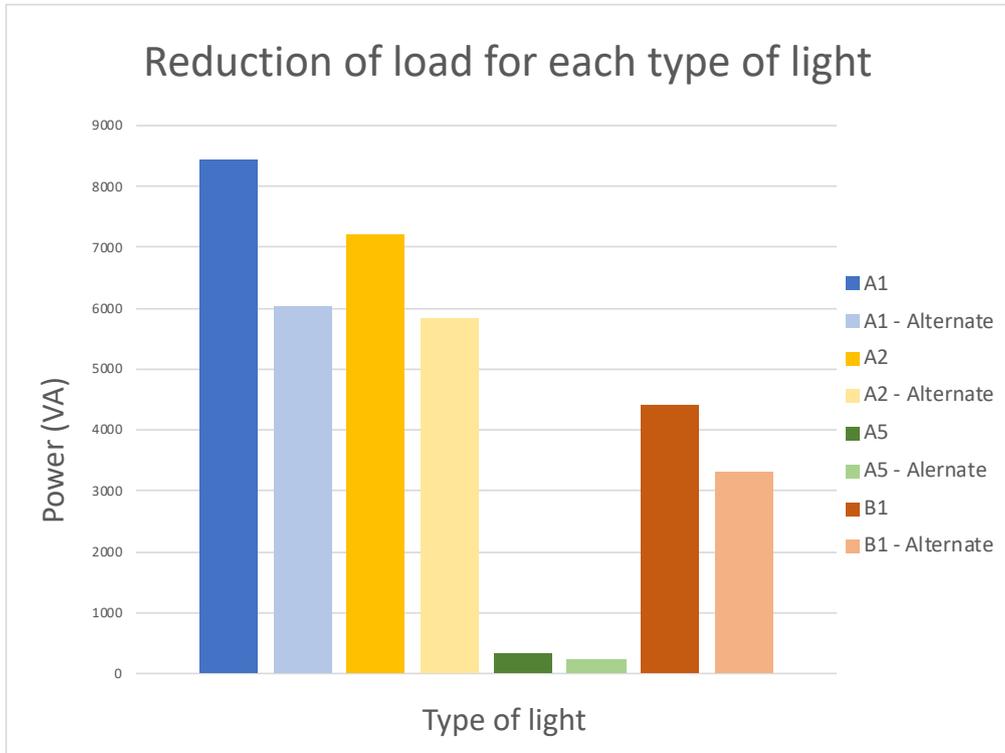


*Figure 2: Reduction of Load for each type of light*

In the above figure it can be observed the power corresponding to each type of existing light and the alternative solution. The reduction of power that each alternate type of light would bring can be seen by comparing the existing light to the alternate on the right. By summing separately, the power of the existing lights and the alternate lights, the total reduction of the load can be calculated.

| | |
|---|---|
| Existing fluorescent lights | 20,440 VA |
| Alternate LED lights | 15,446 VA |
| Reduction of load | 4,994 VA |

*Table 15: Total Reduction in power*

The total alternate luminaire load for the main distribution board can be divided into a smaller total power for each floor as it can be seen in the figure provided below.
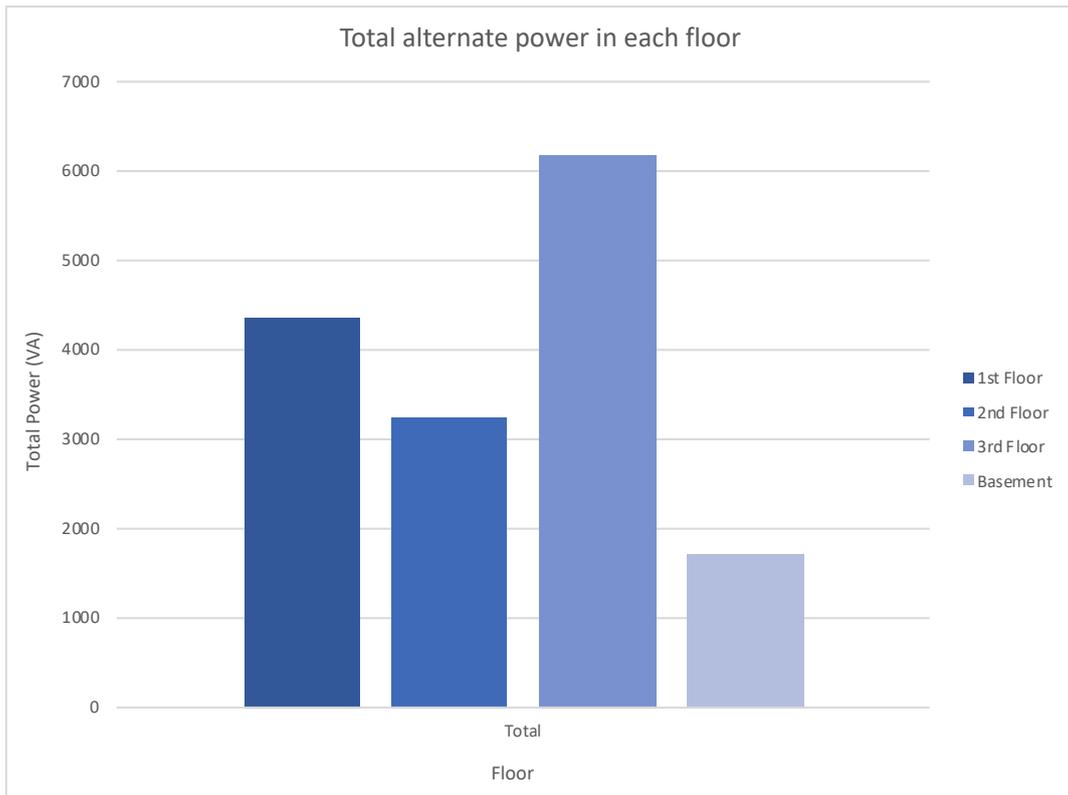
*Figure 3: Total Alternate power in each floor*

Comparing the above figure with the existing power for each floor in the figure below, it is easy to calculate the reduction of load for each floor.
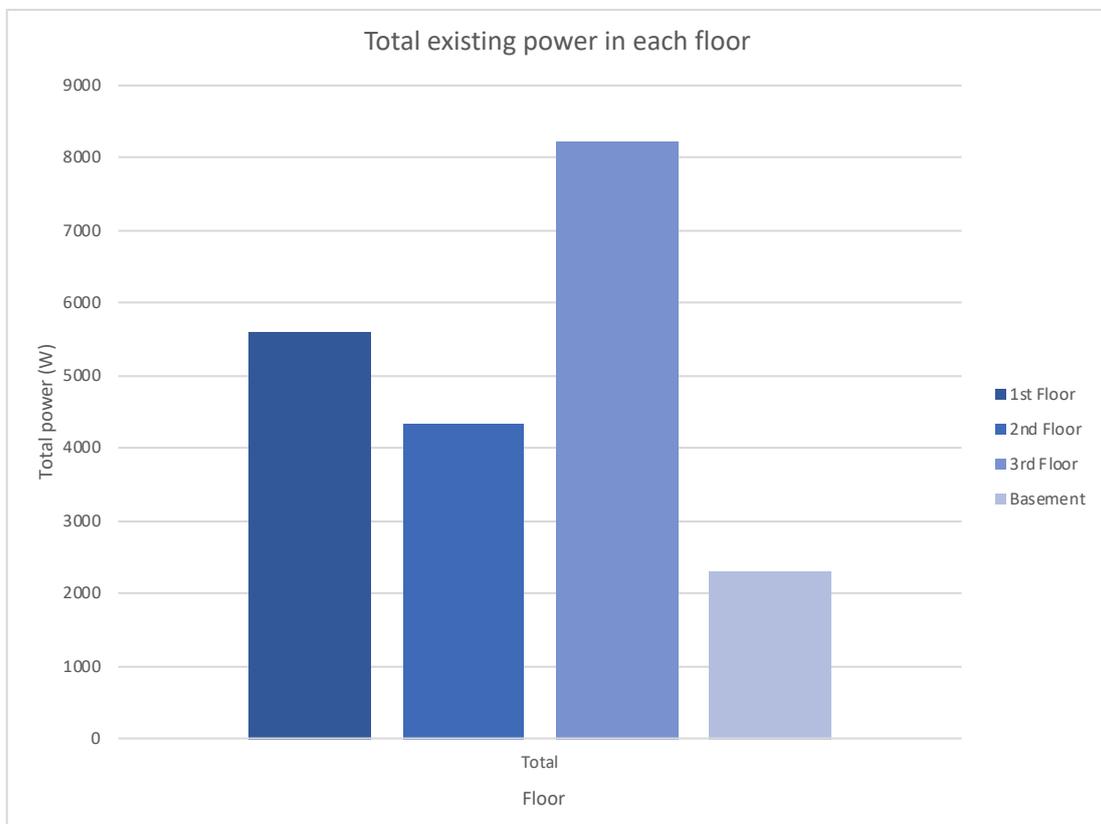


*Figure 4: Total Existing power in each floor*

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| Floor | Existing (VA) | Alternate (VA) | Reduction of load (VA) |
|---|---|---|---|
| **Basement** | 2,296 | 1,706 | 590 |
| **1st Floor** | 5,600 | 4,336 | 1,264 |
| **2nd Floor** | 4,340 | 3,236 | 1,104 |
| **3rd Floor** | 8,204 | 6,168 | 2,036 |

*Table 16: Comparative power in each floor depending on type of fixture*

Continuing the separation into smaller categories started above, the total power for the alternate design can also be divided considering the panelboard that is feeding the lights. All this information can be found in the figure below.
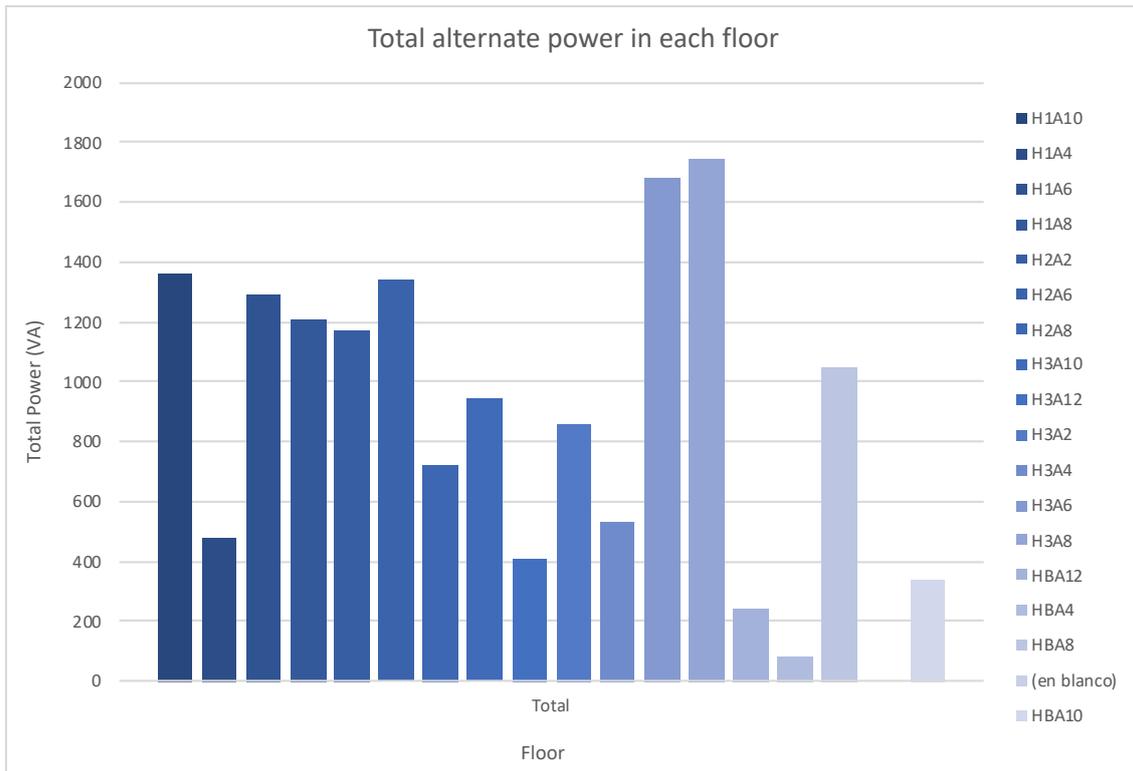


*Figure 5: Total alternate power in each panelboard*

Once the total load of replacing the luminaire has been calculated, it is time to translate those calculations to the actual panelboards applying the NEC Demand Factor. The panelboards feeding the luminaire are: HBA, H1, H2, H3. These panelboards collect all the lighting loads, including the ones we are going to replace. Following the same order, we can calculate the new tables:

- HBA:

| Lightning | Connected (VA) | NEC Demand Factor | Total Load (VA) |
|---|---|---|---|
| Existing | 14,369 | 1.25 | 17,961 |
| Improved | 13,779 | 1.25 | 17,224 |
| Reduction | 590 | 1.25 | 737.5 |

*Table 17: HBA panelboard reduction in power*

$$\%Reduction = \frac{737.5}{17{,}961} * 100 = 4.10\%$$

*Equation 1: %Reduction of load for panelboard HBA*

Applying the NEC Demand Factor, there is a greater reduction of the total load connected to the panelboard. That reduction goes from 590 VA to 737 (=1.25*590) VA. That allows the panelboard to be sized smaller, and consequently the feeders and wires. In this case, we can size the feeders to be 4.10% smaller. The same procedures are applied for the rest of panelboards.

- H1A:

| Lightning | Connected (VA) | NEC Demand Factor | Total Load (VA) |
|---|---|---|---|
| Existing | 12,620 | 1.25 | 15,775 |
| Improved | 11,356 | 1.25 | 14,195 |
| Reduction | 1264 | 1.25 | 1,580 |

*Table 18: H1A panelboard reduction in power*

$$\%Reduction = \frac{1{,}580}{15{,}775} * 100 = 10.01\%$$

*Equation 2: %Reduction of load for panelboard H1A*

- H2A:

| Lightning | Connected (VA) | NEC Demand Factor | Total Load (VA) |
|---|---|---|---|
| Existing | 9,715 | 1.25 | 12,144 |
| Improved | 8,611 | 1.25 | 10,763 |
| Reduction | 1104 | 1.25 | 1,380 |

*Table 19: H2A panelboard reduction in power*

$$\%Reduction = \frac{1{,}380}{12{,}144} * 100 = 11.36\%$$

*Equation 3: %Reduction of load for panelboard H2A*

- H3A:

| Lightning | Connected (VA) | NEC Demand Factor | Total Load (VA) |
|---|---|---|---|
| Existing | 15,119 | 1.25 | 18,899 |
| Improved | 13,083 | 1.25 | 16,353 |
| Reduction | 2036 | 1.25 | 2,545 |

*Table 20: H3A panelboard reduction in power*

$$\%Reduction = \frac{2{,}545}{18{,}899} * 100 = 13.47\%$$

*Equation 4: %Reduction of load for panelboard H3A*

$$Total\ Lighting\ Reduction = (590 + 1{,}264 + 1{,}104 + 2{,}036) * 1.25 = 6{,}242.5\ VA$$

$$\%Lighting\ Reduction = \frac{6{,}242.5}{(14{,}369 + 12{,}620 + 9{,}715 + 15{,}119) * 1.25} * 100$$
$$= 9.64\%$$

*Equation 5: Luminaire load reduction*

We also know the total demand of the building (lighting, receptacles, motors…) once the NEC Demand Factor has been applied. Summing the reduction of each panelboard and applying the NEC Demand Factor to the total sum, in order to see the reduction for the Main Distribution Board, we have:

$$Total\ Building\ Demand$$
$$= 83{,}530 + 10{,}000 + 268{,}106 + 72{,}750 + 820{,}400 + 595{,}076$$
$$+ 158{,}353 + 16{,}601 = 2{,}024{,}816\ VA$$

$$\%Main\ Distribution\ Board\ Reduction = \frac{6{,}242.5}{2{,}024{,}816} * 100 = 0.31\%$$

*Equation 6: Main Distribution Board load reduction*

In conclusion, simply by replacing the fluorescent fixtures by LED alternatives, we can reduce the number of lights and total power significantly and leave a greater margin when sizing the breakers and panelboards. However, these substitutions have almost no impact in the Main Distribution Board, as the weight of all the remaining loads, such as the motors, are still much higher.

## 6.2. OPTIMIZATION OF THE LOADS

In the task of optimizing the energy performance, we will also consider a second optimization problem, which is designing the most cost-effective luminaire.

The existing luminaire has a finite lifespan. Every few years, the lamps need to be replaced in order to avoid malfunctions. The total cost of replacing the luminaire and running it will try to be minimized. For this optimization problem, the task is to reduce the total cost of electricity from the entire building in the long-term, by just adjusting the luminaire. Therefore, a 25 years period is set. Since this facility is brand new, and only energy data for the last year and a half has been collected, it is necessary to make assumptions for the expected data in the coming years. The estimation is based on the growth that the building is going to experience. There are many spaces inside the building that are still under construction, so a slight increase in the energy demand in the coming years is estimated. A prediction of an increment in the demand of 1% is assumed, starting in 2020. Also, no leap years are considered.

The objective function is explained below, and each of the terms conforming the formula will be developed thereafter.

## 6.2.1 OBJECTIVE FUNCTION

The objective function in this study consists in two independent variables. One of them corresponds to the existing fluorescent fixtures while the second one refers to the LED alternative fixtures. As the building is already equipped with fluorescent luminaire, this first variable only adds cost when replacing it and buying spare fixtures. The second variable also implies operation and maintenance cost, but they can also reduce the current electricity cost. Once the problem is solved, the objective function provides the dependent value that we seek to minimize, which in this case is the cost. The objective function consists on the following differentiated parts:

$$Costs = Electricity\ Cost + LED\ Cost + Fluorescent\ Cost$$
*Equation 7: Simplified Objective Function*

There are some economic aspects that need to be included to make this optimization more realistic.

First, the discount rate is a valuable factor for determining the present cost of a future project. There are two main factors involved in the discount rate: the time value of money (inflation) and the risk of uncertainty. A high discount rate implies great uncertainty and low present value of our future cash flow. The weighted average cost of capital is a good method to calculate the discount rate that should be used. For this project, it is going to be used a discount rate of 3%, which is provided by the DOE and used in the NIST (10) for energy conservation projects.

In the NIST, there are some life-cycle cost analysis tables. The way to calculate the Single Present Value factor for non-fuel costs is the following:

$$P = C_y * \frac{1}{(1 + Discount\ Rate)^y} = C_y * (1 + Discount\ Rate)^{-y}$$
*Equation 8: Discount Rate*

That discount rate formula is applied for many of the next calculations and will be of great help. The first term of the objective function is the electricity cost. For that, the current Xcel electricity rates are needed.

In a similar manner, there is the rate escalation. This is the rate at which the electric market prices rise every year. Therefore, the charges are constantly adjusting themselves to follow the trends in money value. For this rate, we are going to use a 3% escalation as well, which is a good approximation in energy projects.

## 6.2.2 ELECTRICITY RATES

With the purpose of calculating the total costs, we use the information found on Xcel Energy website. The electricity rates summary is provided in the Appendix F (11) and the Appendix G (12). Each table corresponds to a different calendar rate. Appendix F refers

to winter season while Appendix G concerns the summer months. Colorado School of Mines is registered in the Primary General rate structure. This structure is summarized in the following tables:

| Charge in Winter Season October 1-May 31 | Description | Calculation | Total Monthly Rate |
|---|---|---|---|
| Service and Facility per Month | Fixed Charge per month | | $322.00 |
| Winter Demand | Charge per kW for 15-minute peak demand during the billing month between: October 1-May 31 | Demand Charge (3.86) + Generation and transmission demand (9.55) + PCCA (1.29) + DSMCA (0.59) + TCA(0.47) + CAJCA (0.90) + RESA (0.32183) – GRSA (4.19%) | $16.41 |
| On-peak Energy per kWh | Charge per kWh consumed in hours: 9:00-21:00 on weekdays, non-holidays | On-peak energy (0.00458) + ECA (0.04248) + RESA (0.00094) | $0.04781 |
| Off-peak Energy per kWh | Charge per kWh consumed in hours: 21:00-23:00 and 0:00-9:00 | Off-peak energy (0.00458) + ECA (0.02970) + RESA (0.00068) | $0.03477 |

Table 21: Winter Season Rates

| Charge Summer Season June 1-September 30 | Description | Calculation | Total Montlhly Rate |
|---|---|---|---|
| Service and Facility per Month | Fixed Charge per month | | $322.00 |
| Summer Demand | Charge per kW for 15-minute peak demand during the billing month between: June 1-September 30 | Demand Charge (3.86) + Generation and transmission demand (14.26) + PCCA (1.29) + DSMCA (0.54) + TCA(0.47) + CAJCA (0.90) + RESA (0.41165) – GRSA (4.19%) | $21.00 |
| On-peak Energy per kWh | Charge per kWh consumed in hours: 9:00-21:00 on weekdays, non-holidays | On-peak energy (0.00458) + ECA (0.00354) + RESA (0.00080) | $0.04059 |

| Off-peak Energy per kWh | Charge per kWh consumed in hours: 21:00-23:00 and 0:00-9:00 | Off-peak energy (0.00458) + ECA (0.02426) + RESA (0.00058) | $0.02973 |

*Table 22: Summer Season Rates*

## 6.2.4 ELECTRICITY BILL

In order to implement the electricity bills in our LP, we use the information found on Niagara AX with the electricity demands for the building in the last year and a half. As it was mentioned before, with that data, and by predicting a future increase in the building load, an approximation of the demand over the next years is made. This current electricity demand corresponds to the building with fluorescent fixtures. In the case of adding LED lamps, the electricity bill is calculated by a slight modification that includes their impact in the formulas below. If no LED fixtures are added at the end of the optimization problem, the impact on the electricity bills will be zero.

$$Electricity\ Cost = \sum_{y=1}^{n} (Annual\ Electricity\ Bill * (1 + Discount\ Rate)^{-y})$$

*Equation 9: Coorstek Center Electricity Cost*

$$Annual\ Electricity\ Bill = \sum_{m=1}^{12} (Monthly\ Energy\ Charge + Monthly\ Demand\ Charge + Monthly\ Fixed\ Charge)$$

*Equation 10: Coorstek Center Annual Electricity Bill*

The first term of the above formula, the Monthly Energy Charge, may seem clear for all the people. It is the total energy use in a month measured in kWh multiplied by the energy rate. For the reduction that adding LED fixtures to the ceiling would produce, we introduce a parameter of energy that each lamp reduces per day, hence, this parameter stays out of the hour summation. This reduction is assumed to be with the LED lamps operating on peak hours. Therefore, we fix the set hour to remain at hour 16, which corresponds to the range of on-peak.

$$Monthly\ Energy\ Charge = \sum_{d=1}^{31} \left[ \sum_{h=1}^{24} (Energy\ Rate_{m,h} * Hourly\ Xcel\ kWh) \right] - \sum_{i=1}^{3} LED\ Lamp\ Type_i * Reduction\ Energy\ LED\ Lamp\ Type_i * Energy\ Rate_{m,16}$$

*Equation 11: Coorstek Center Monthly Energy Charge*

$$Energy\ Rate_{mh} = \begin{cases} Summer \begin{cases} On-peak\ = \dfrac{\$0.04059}{kWh} * (1 + Rate\ escalation)^y \\[4mm] Off-peak\ = \dfrac{\$0.02973}{kWh} * (1 + Rate\ escalation)^y \end{cases} \\[10mm] Winter \begin{cases} On-peak\ = \dfrac{\$0.04781}{kWh} * (1 + Rate\ escalation)^y \\[4mm] Off-peak\ = \dfrac{\$0.03477}{kWh} * (1 + Rate\ escalation)^y \end{cases} \end{cases}$$

<center><em>Equation 12: Energy Rates of tables simplified</em></center>

The second term of the annual electricity bill may bring some troubles. Monthly Demand Charge refers to the highest amount of power required during a period of time. The meter will measure the greatest peak of demand during the month in kW and multiply that by the demand rate. In most of the cases, the peak demand is not an instantaneous power demand. Instead, it is an average peak demand for intervals of 15 minutes. Since making an optimization problem over a 25 years period in intervals of 15 minutes would require a tremendous running-time, instead, the peak demands are measured with the mean demand on each hour. Obviously, this mean is lower than the actual peak, and a multiplying factor would be required to correct this deviation. However, the program itself is able to measure the peak over that hour measured.

In order to introduce the influence of the LED fixtures in reducing this power peak demand, we subtract the sum of all the LED lights instantaneous power.

$$\begin{aligned} Monthly\ Demand\ Charge \\ = Demand\ Rate_m * [\max(Hourly\ Xcel\ kW) \\ - \sum_{i=1}^{3} Power\ Reduction\ LED_i * LED\ Lamp\ Type_i] \end{aligned}$$

<center><em>Equation 13: Coorstek Center Monthly Demand Charge</em></center>

$$Demand\ Rate = \begin{cases} Summer = \dfrac{\$21.00}{kW} * (1 + Rate\ escalation)^y \\[4mm] Winter = \dfrac{\$16.41}{kW} * (1 + Rate\ escalation)^y \end{cases}$$

<center><em>Equation 14: Demand Rates from tables simplified</em></center>

The Monthly Fixed Charge needs to be payed regardless of how much energy the building consumes. This is a mandatory bill that every customer has to pay before the meter starts counting, only for the possibility to have access to that power. Therefore, reducing the energy consumption of the building won't have any effect on this bill. The monthly fixed charge for summer and winter does not change.

$$Monthly\ Fixed\ Charge = \$322 * (1 + Rate\ escalation)^y$$

<center><em>Equation 15: Coorstek Center Monthly Fixed Charge</em></center>

For the reduction of demand that each alternate LED lamp produces, we can calculate by using the Table from chapter 6. The NEC Demand Factors are not applied, since they are only used when sizing the breakers and panelboards. If we also consider the number of hours that we are going to run each light, then we can make a new table with the energy per day and instantaneous power that we use on the monthly energy charge and monthly demand charge formulas respectively. The assumptions on the hours that each lamp is lighting per day can be found on the next section 6.2.5.

| Alternative fixture | Reduction of Power (kW) | Number of hours used | Reduction in energy per day (kWh) |
|---|---|---|---|
| A1 - **Alternate** | 0.016 | 12 | 0.192 |
| A2 - **Alternate** | 0.016 | 12 | 0.192 |
| A5 - **Alternate** | 0.016 | 12 | 0.192 |
| B1 - **Alternate** | 0.014 | 7 | 0.098 |

*Table 23: Reduction in power and energy per fixture*

## 6.2.5 LED COSTS

The second term of the objective function allude to the cost that involve the implementation of LED fixtures in the building. This cost can be subdivided in two components. The first one is the LED Capital Cost, which consist on the money needed to buy the calculated number of lamps. This cost is different depending on the type of lamp. The second component is the LED Operation & Maintenance Cost, which includes the expenditure that comes with the replacement of the luminaire and the labor cost of the hired personal.

$$LED\ Cost\ NPV = LED\ Capital\ Cost\ NPV + LED\ O\&M\ Cost\ NPV$$
*Equation 16: LED Cost NPV*

$$LED\ Capital\ Cost\ NPV$$
$$= \sum_{y=1}^{n} \sum_{i\ \varepsilon I} LED\ replacement_{y,i} * LED\ Lamp\ Type_i$$
$$* LED\ Capital\ Cost_i * (1 + Discount\ rate)^{-year\ installed}$$
*Equation 17: LED Capital Cost NPV*

For the LED Capital Cost depending on the type of lamp, the following table which include the price of each fixture is provided

| i | Designation | LED Lamp Type i | LED Capital Cost ($/unit) |
|---|---|---|---|
| 1 | A1, A5 - Alternates | 2VTL4 - 48L ADP LP835 | $230 |
| 2 | A2 - Alternate | 2VTL4 - 85L ADP LP935 | $310 |
| 3 | B1 - Alternate | ALL4 - 40L EZ1 LP835 | $250 |

*Table 24: Capital Cost for each LED fixture*

There is a term contained in the capital cost formula, that has not been explained yet. That is the replacement depending on sets year and type of lamp. Every lamp has a finite lifespan, and they have to be changed once this is over. Therefore, this parameter is zero when the lamp does not need to be replaced, and one when its life period is finished.

The LED operation and maintenance (O&M) cost every time the life cycle of the light is complex to determine. LED lighting replacement and labor cost is much lower compared to the fluorescent lights, since they don't need to be replaced as frequently. Therefore, we have to make some assumptions based on many different sources (13) and expert opinion from Emily Royal.

- LED light cycle = 60,000 hours
- Lamps operating time = 12 hours (on-peak hours) · 350 days/year = 4,200 hours/year.
- Average time to change a lamp = 15 minutes
- Labor rate = 30$/hour

$$Annual\ replacement\ of\ a\ lamp = \frac{4,200\ hours/year}{60,000\ hours} = 0.07\ lamp/year$$

$$Labor\ cost\ to\ change\ a\ lamp = 15\ min * \frac{30\ \$}{60\ min} = 7.5\ \$/lamp$$

$$Annual\ cost\ of\ replacing\ a\ lamp\ (O\&M\ Cost) = \frac{7.5\ \$}{lamp} * \frac{0.07\ lamp}{year}$$

$$= 0.525\frac{\$}{year \cdot lamp}$$

To make approximations more realistic, for B1 LED fixtures we use a different time when it comes to the number of hours these lights are operating. Since 41 from a total of 79 B1 lamps are used to light lab support rooms and storage rooms which are not as frequented, we are going to assume the following:

- B1 lamps operating time = 7 hours (on-peak hours) · 350 days/year = 2,450 hours/year.

$$Annual\ replacement\ of\ a\ B1\ Alternate\ lamp = \frac{2,450\ hours/year}{60,000\ hours}$$
$$= 0.041\ B1\ ALT\ lamp/year$$

$$Annual\ cost\ of\ replacing\ a\ B1\ Alternate\ lamp\ (O\&M\ Cost)$$
$$= \frac{7.5\ \$}{lamp} * \frac{0.041\ lamp}{year} = 0.3075\ \$/year$$

$$LED\ O\&M\ Cost\ NPV$$
$$= \sum_{i\ \varepsilon I} \sum_{y=1}^{n} LED\ Lamp\ Type_i * LED\ O\&M\ Cost_i$$
$$* (1 + Discount\ rate)^{-y}$$

*Equation 18: LED O&M Cost NPV*

The salvage value of a fixture is the initial expense minus the depreciation over the years.

| LED type i | Lifetime in hours | Operating hours/day | Lifetime in years |
|------------|-------------------|---------------------|-------------------|
| 1 | 60,000 | 12 hours | 13.69 |
| 2 | 60,000 | 12 hours | 13.69 |
| 3 | 60,000 | 7 hours | 23.48 |

*Table 25: LED lifetime in years per fixture*

## 6.2.6 FLUORESCENT COST

$$Fluorescent\ Cost\ NPV$$
$$= Fluorescent\ Capital\ Cost\ NPV + Fluorescent\ O\&M\ Cost\ NPV$$

*Equation 19: Fluorescent Cost NPV*

$$Fluorescent\ Capital\ Cost\ NPV$$
$$= \sum_{i\ \varepsilon I} Fluorescent\ replacement_{y,i} * Fluorescent\ Lamp\ Type_i$$
$$* Fluorescent\ Capital\ Cost_i * (1 + Discount\ rate)^{-year\ installed}$$

*Equation 20: Fluorescent Capital Cost NPV*

| i | Designation | Fluorescent Lamp Type i | Fluorescent Capital Cost ($/unit) |
|---|-------------|-------------------------|-----------------------------------|
| 1 | A1, A5 | 2VTL8 − 2 32 ADP | 172.5 |
| 2 | A2 | 2VTL8 − 2 32 ADP | 232.5 |
| 3 | B1 | AL8 − 2 32 | 187.5 |

*Table 26: Capital Cost per Fluorescent fixture*

The prices for the above light fixtures are not easy to find, since the company supplier policy is not to provide that confidential information. However, with the help of my supervisor and Accredited Professional in LEED, Emily Royal, we choose to set fluorescent prices 25% lower in comparison with their correspondent LED alternative.

As done for the LED lights, we follow the same procedure in order to calculate the operation and maintenance cost of fluorescent fixtures. The assumptions are very similar to the ones for the LED lamps, with the only difference being the lifespan of each fixture:

- T8 Fluorescent light cycle = 30,000 hours (13)
- Lamps operating time = 11 hours (from 8am-20pm) · 350 days/year = 3,850 hours/year.
- Average time to change a lamp = 15 minutes
- Labor rate = 60$/hour

$$Annual\ replacement\ of\ a\ lamp = \frac{4,200\ hours/year}{30,000\ hours} = 0.14\ lamp/year$$

$$Labor\ cost\ to\ change\ a\ lamp = 15\ min * \frac{60\ \$}{60\ min} = 15\ \$/lamp$$

$$Annual\ cost\ of\ replacing\ a\ lamp\ (O\&M\ Cost) = \frac{7.5\ \$}{lamp} * \frac{0.14\ lamp}{year}$$
$$= 1.05\ \$/year$$

This time, for the fluorescent B1 we follow the same procedure done with the LED fixtures, and we assume an operation time of 7 hours.

- B1 lamps operating time = 7 hours (off-peak hours) · 350 days/year = 2,450 hours/year.

$$Annual\ replacement\ of\ a\ B1\ lamp = \frac{2,450\ hours/year}{30,000\ hours} = 0.082\ B1\ lamp/year$$

$$Annual\ cost\ of\ replacing\ a\ B1\ lamp\ (O\&M\ Cost) = \frac{7.5\ \$}{lamp} * \frac{0.081\ lamp}{year}$$
$$= 0.6075\ \$/year$$

$$Fluorescent\ O\&M\ Cost\ NPV$$
$$= \sum_{i\,\varepsilon\,I}\sum_{y=1}^{n} Fluorescent\ Lamp\ Type_i * Fluorescent\ O\&M\ Cost_i$$
$$* (1 + Discount\ rate)^{-y}$$

*Equation 21: Fluorescent O&M Cost NPV*

| Fluorescent type i | Lifetime in hours | Operating hours/day | Lifetime in years |
|---|---|---|---|
| 1 | 30,000 | 12 hours | 6.85 |
| 2 | 30,000 | 12 hours | 6.85 |
| 3 | 30,000 | 7 hours | 11.74 |

*Table 27: Fluorescent Lifetime in years per fixture*


## 6.2.7 CONSTRAINTS

Constraints are a fundamental part in an optimization problem. The constraint set establish the limits for both the dependent and independent variables. Defining some boundaries reduces the area of the  feasible region and consequently makes the running time of the program faster. Finally, constrains are also decisive in order to make the problem reasonable and realistic.

Maximum number of units per lamp

| Type of light | Number of units |
|---|---|
| A1 - Alternate | 151 |
| A2 - Alternate | 86 |
| A5 - Alernate | 6 |
| B1 - Alternate | 79 |
| **Total** | **322** |

*Table 28: Maximum number of units per type of LED fixture*

| Type of light | Number of units |
|---|---|
| A1 | 302 |
| A2 | 258 |
| A5 | 12 |
| B1 | 158 |
| **Total** | **730** |

*Table 29: Maximum number of units per type of Fluorescent fixture*

Assembling the subdivisions in the entire objective function, with the complete set of constrains, the independent variables and initial sets, we have the following simplified optimization problem in the standard form of a LP:

Sets:
$i \, \varepsilon \, I$      / I = 1, 2, 3          # Fixture type i
$h \, \varepsilon \, H$    / H = 0, 2, …, 23   # Hours in a day
$d \, \varepsilon \, D$    / D = 1, 2, …, 31   # Days in a month
$m \, \varepsilon \, M$   / M = 1, 2, …, 12   # Months in a year
$y \, \varepsilon \, Y$    / Y = 1, 2, …, 25   # Years to be optimized

Parameters:
$lprice_i$ = price of buying a LED light fixture i                                       [\$/unit]
$fprice_i$ = price of buying a Fluorescent light fixture i                            [\$/unit]
fixed = monthly fixed charge                                                                  [\$]
$rate_{m,h}$ = energy rate on month m and hour h                                    [\$]
$DR_m$ = demand rate on month m                                                          [\$]
$redpower_i$ = reduction of instantaneous power per LED light fixture i      [kW/unit]
$redenergy_i$ = reduction of energy per LED light fixture i in a day      [kWh/unit·day]
$lreplcost_i$ = annual cost of replacing a LED light fixture i               [\$/unit·year]
$freplcost_i$ = annual cost of replacing a Fluorescent light fixture i        [\$/unit·year]
$lreplace_{y,i}$ = need of a replacement for LED lamp yes (1) or no (0)          [#]
$freplace_{y,i}$ = need of a replacement for fluorescent lamp yes (1) or no (0)      [#]
$maxkW_{y,m}$ = maximum peak of power consumption each month            [kW]
$kWh_{y,m,d,h}$ = energy consumption for each hour, day, month and year       [kWh]

Variables:
$L_i$ = number of LED light fixture i
$F_i$ = number of Fluorescent light fixture i

## Objective Function:

The objective function can be simplified once all the different parts are gathered. The discount rates are neutralized with the rate escalations for the electricity bill, and we do not include them in the rest of the optimization to make the program compute faster.

$$minimize \sum_{y=2019}^{2043} \left[ \sum_{m=1}^{12} \left( \sum_{d=1}^{31} \left( \sum_{h=0}^{23} rate_{m,h} * kWh_{y,m,d,h} \right. \right. \right.$$
$$- \sum_{i=1}^{3} rate_{m,16} * redenergy_i * L_i \left. \right) + DR_m$$
$$* \left( maxkW_{y,m} - \sum_{i=1}^{3} redpower_i * L_i \right) + fixed \right)$$
$$+ \sum_{i \, \varepsilon I} \left( lreplace_{y,i} * lprice_i * L_i + lreplcost_i * L_i + freplace_{y,i} \right.$$
$$\left. \left. * fprice_i * F_i + freplcost_i * F_i \right) \right]$$

*Equation 22: Extended Objective Function*

This is how the objective function is written in the program.

```
minimize Cost: sum{y in Yi} (sum{m in M} (sum{d in D} (sum{h in
H} rate[m,h]*kWh[y,m,d,h]
        - sum{i in I} rate[m,16]*redenergy[i]*L[i])
             +          DR[m]*(maxkW[y,m]-sum{i        in
I}redpower[i]*L[i]) + fixed)
             +          sum{i          in          I}
((lreplace[y,i]*lprice[i]+lreplcost[i])*L[i]
        + (freplace[y,i]*fprice[i]+freplcost[i])*F[i]) )
        + sum{y in Yf} (sum{m in M} (sum{d in D} (sum{h in H}
rate[m,h]*kWhn[m,d,h]
        - sum{i in I} rate[m,16]*redenergy[i]*L[i])
             + DR[m]*(maxkWn[m]-sum{i in I}redpower[i]*L[i])
+ fixed)
             +          sum{i          in          I}
((lreplace[y,i]*lprice[i]+lreplcost[i])*L[i]
        + (freplace[y,i]*fprice[i]+freplcost[i])*F[i]) );;

s.t. C1: L[1]+F[1]/2 = 157;
s.t. C2: L[2]+F[2]/3 = 86;
s.t. C3: L[3]+F[3]/2 = 79;
```

Constraints:
$C1$: $L[1] + F[1]/2 = 157$
$C2$: $L[2] + F[2]/3 = 86$
$C3$: $L[3] + F[3]/2 = 79$

The mod file of AMPL containing the variables, the objective function and constraints is shown in Appendix H.

The AMPL dat file containing the values of the parameters corresponding to each set (year, month, type of lamp…) is shown in Appendix I. Some parameters are so extensive that are called from different dat files. This is the case of the electricity rates (Appendix J) and the kWh (Appendix K) and maximum kW (Appendix L). For the energy and power, two more dat files have been developed for the following years, as their values are going to remain unchanged. These two files are shown on Appendix M and Appendix N respectively.

Finally, AMPL run file is shown in Appendix O.

# 7. RESULTS

Once the entire optimization problem is set up and programmed, we can run it and obtain different results depending on the results we are seeking to analyze. This can be achieved by sectioning the objective function in the different parts that conform it. In this project place the attention only in these three aspects: economic results, energy savings and environmental impact.

## 7.1 ECONOMIC RESULTS

Our optimization model's target is to reduce as much as possible the electricity bill costs. For that, there were a variety of six different types of fixtures divided in three pairs, and the program has to choose the most cost-efficient lamp for each pair of fixtures in the long term. After running the program, we obtain the following results at the end of year 2043.

```
CPLEX 12.9.0.0: optimal solution; objective 3303643.666
0 dual simplex iterations (0 in phase I)
Objective = Cost
L [*] :=
1   157
2    86
3    79
;

F [*] :=
1   0
2   0
3   0
;

Cost = 3303640
```

*Figure 6: Results for 25 years period*

For a period of time of 25 years, the program indicates that the optimal solution is an entire implementation of LED lights for the three types of fixtures and no fluorescent lamps. The number of lamps for each type of LED fixture is shown above. The total cost of the electricity bill and also including the cost of buying and replacing that number of lamps is 3,303,640$. This cost is significantly high, but some aspects need to be considered to understand this magnitude and why it is a reasonable result.

First, it is a prolonged period of time and thus, it covers 300 energy bills. Therefore, the next question is if it is reasonable that each monthly bill is 11,012$. To answer this, we use the help of some numbers and easy calculations shown below.

Colorado's monthly energy payment is enclosed in a range between 100$ and 180$, with the average being at 130$. There is no information on the size of a typical home in Colorado. However, in the United States, the average size for a family home is 2,467 sq ft (14). Nonetheless, most of the houses possess gardens that make the magnitude of those spaces deceiving in order to scale our values. If we discount the gardens, where there are

no appliances and do not need to be illuminated, we can say that the average inside size of American houses is around 1,800 sq ft.

| | Coorstek Center | Average House |
|---|---|---|
| Monthly Payment | 11,012 $ | 130$ |
| Area | 95,000 sq ft | 1,800 sq ft |

*Table 30: Comparison between Coorstek and a standard U.S home*

The area of Coorstek Center is 52.8 times the average area of a house in the United States. In addition, Coorstek pays an average monthly bill 84.7 times more than a typical house. So, in perspective, if a home was to be the size of Coorstek Center, it would pay 1.6 times less than the campus building. This number is reasonable because of the the volume of work inside it. It is one of the largest buildings on campus and it is operating from dusk till dawn. Moreover, there are tools and machinery in the building's laboratories that demand a lot of power. On the other hand, houses are normally empty for some periods during the day, when members of families leave it to go to work, schools, universities or other duties. For all these reasons we can determine that results are logical and satisfactory.

It is interesting to also analyze the same problem but for a different term and see how the results change. This analysis is not crucial in our study, but it complements it and demonstrates that the program is working correctly. This time, we set a shorter period of time, for instance 7 years, ending in the year 2025. The LP performance does not change, and neither does the objective function and constraints. The only difference is that shorter data is considered. After performing the program, we obtain the following results:

```
CPLEX 12.9.0.0: optimal solution; objective 936926.228
0 dual simplex iterations (0 in phase I)
L [*] :=
1  157
2   86
3    0
;

F [*] :=
1    0
2    0
3  158
;

Cost = 936926
```

*Figure 7: Results for 7 years period*

Obviously, the total costs have been reduced since fewer years are considered. However, it can be observed that the optimal solution for this case is to install fluorescent fixtures for B1. This fact is easily explained if we take into account the longevity of the lamps. For the years considered, the longer lifespan of LED lights is not an advantage compared to the fluorescent, since until this year B1 fluorescent don't need to be replaced. In contrast, fluorescent fixtures have a head start in relation with LED when it comes to the initial capital cost. This edge proves to be a determining factor when the period analyzed is short.

Returning to the issue of the project, we can calculate how much money the use of LED lamps saves in a period of 25 years. To do this, first we need to calculate the total cost at the end of the period if had never installed LED lights. We can obtain this value by computing the same LP program and forcing it to select only fluorescent fixtures. This can be achieved adding three more constraints that state that the number of each type of LED fixture has to be zero. The results obtained are these:

```
Solution determined by presolve.
L [*] :=
1  0
2  0
3  0
;

F [*] :=
1  314
2  258
3  158
;

Cost = 3717920
```

*Figure 8: Results using only fluorescent for 25 years period*

Using only fluorescent lamps, the total projected cost in 25 years is 3,717,920$. With this information, the money savings incurred all those years due to the use of the LED lights are easily obtained.

$$LED\ Cost\ Savings = 3,717,920 - 3,303,640 = 414,280\$$$

And consequently, we know the percentage of savings.

$$\%\ LED\ Cost\ Savings = \frac{414,280}{3,717,920} * 100 = 11.14\%$$

*Equation 23: %Cost Savings in Coorstek Center because of LEDs*

In conclusion, in 25 years LED lights are able to reduce the total expenses by slightly more than 10 percent. The amount of money that can be saved using LED fixtures instead of fluorescent fixtures for only three types of lights in the entire building should not be disregarded. This percentage is only going to increase with the passing of the years, as the capital cost and operation and maintenance cost would lose weight in comparison with the electricity bill.

From the total costs calculated, we can make subdivision in order to have a better understanding on where money is being spent. These subdivisions correspond to the three main terms that play a role in the objective function: LED Capital Cost, LED O&M Cost and the Electricity bill.

$$LED\ Capital\ Cost = \sum_{y=2019}^{2043} \sum_{i=1}^{3} \left(lreplace_{y,i} * lprice_i * L_i\right) = 165,040\ \$$$

*Equation 24: LED Capital Cost*

$$LED\ O\&M\ Cost = \sum_{y=2019}^{2043} \sum_{i=1}^{3} (lreplcost_i * L_i) = 3,796.69\ \$$$

*Equation 25: LED O&M Cost*

$$Electricity\ Bill\ Cost = 3,303,640 - 165,040 - 3,796.69 = 3,134,803.31\ \$$$

The chart below shows the previously calculated terms and the percentage of weight that every subdivision has on the total costs. As we can see, the Operation and Maintenance costs are almost insignificant in the long-term compared to the other ones. As it has been mentioned earlier, the weight of the electricity bill compared to the other two components is only expected to increase if we analyze more years
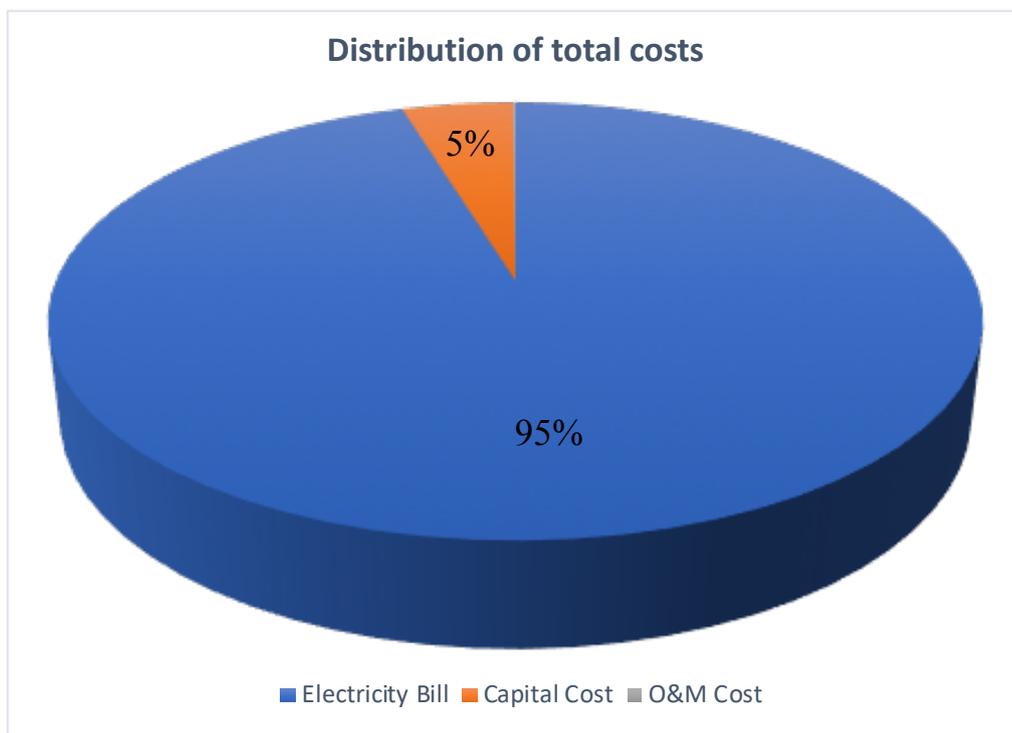


*Figure 9: Distribution of total costs*

On section 6.2.4, we split the electricity bill in three parts: monthly energy charge, monthly demand charge and fixed charge. So, for the 95% of the total cots corresponding to the electricity bill, we want to know how much of that cost derive from each charge. The results are shown below.

```
MonthlyEnergyCharge = 1,598,380 $
MonthlyDemandCharge = 1,439,830 $
Fixed = 96,600 $
```
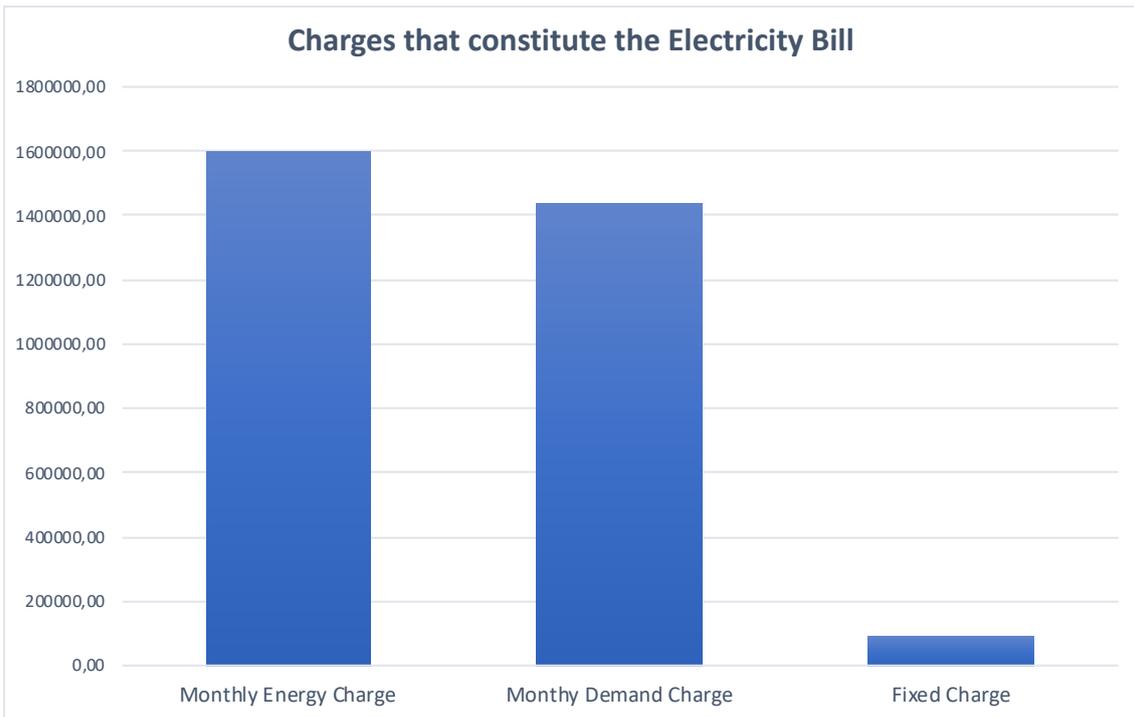
*Figure 10: Column chart with charges that constitute the electricity bill*
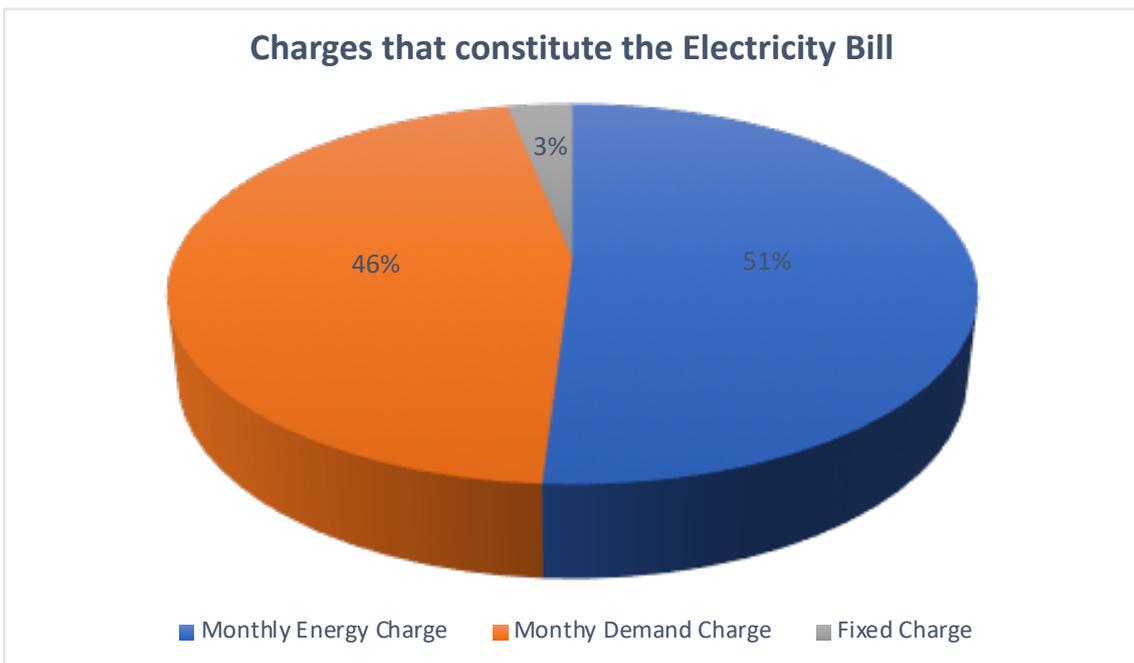


*Figure 11: Cheesecake chart of the different bill charges*

LED SALVAGE VALUE

The salvage value is the money that could be recovered if we decided to sell the existing fixtures. This value determined with the formula below. No assistance of computer programs is needed to solve this problem, since it can be solved by hand. At the end of the period of 25 years, two types of lamps have been replaced once and the spare fixtures have one year of life remaining while the third one still has 21 years of lifetime.

$$\sum_{i=1}^{3} \frac{Fluorescent\ Cost\ NPV_i}{n\ (Lifetime\ of\ Fluorescent\ Type_i\ in\ years)} * (n-y)$$

$$= 157 * \frac{230}{13} * (13-12) + 86 * \frac{310}{13} * (13-12) + 79 * \frac{250}{23}$$
$$* (23-2) = 22{,}861.07\$$$

*Equation 26: LED Salvage Value at the end of year 25*

The result show that if the material is suddenly sold in 2044, Mines would get back 22,861.07$.

A more extensive analysis could be carried out if we involve heat transfer, as fluorescent bulbs releases heat to the room, while LED fixture thermal paths are accomplished by conduction. Therefore, LED fixtures also save money in ventilation of the rooms.

## 7.2 ENERGY SAVINGS

Similar analysis can be carried out focusing on the energy demand until the year 2043. With the information obtained from the optimization problem, we can determine how much energy the installation of LED fixtures have saved and make comparisons with the total energy that the building demands. It is important to remark that results are not 100% accurate, since we are assuming there are no leap years.

$$Energy\ savings = \sum_{y=2019}^{2043} \sum_{m=1}^{12} \sum_{d=1}^{31} \sum_{i=1}^{3} redenergy_i * L_i = 505{,}901\ kWh$$

*Equation 27: Coorstek Center Energy Savings in 25 years*

The total energy without subtracting the energy that the implementation of LED fixtures implies is:

$$Total\ Energy\ (With\ current\ fluorescent\ fixtures)$$
$$= \sum_{y=2019}^{2043} \sum_{m=1}^{12} \sum_{d=1}^{31} \sum_{h=0}^{23} kWh_{y,m,d,h} = 40{,}596{,}100 kWh$$

*Equation 28: Coorstek Center total energy if current luminaire is maintained*

$$\%\ LED\ Energy\ Savings = \frac{505{,}901}{40{,}596{,}100} * 100 = 1.24\%$$

*Equation 29: %Energy Savings because of LEDs*

$$Total\ Energy\ after\ improvement = 40{,}596{,}100 - 505{,}901 = 40{,}090{,}199\ kWh$$

With the calculated total costs in section 7.1 and the total energy after installing LED lamps, it is possible to calculate the cost of electricity for Coorstek Center in $/kWh.

$$Cost\ of\ electricity = \frac{3,303,640}{40,090,199} = 0.082\$/kWh$$

*Equation 30: Coorstek Center Cost of electricity*

It is a reasonable number compared to the average electricity generation costs in Colorado (15) shown below for the year 2017.
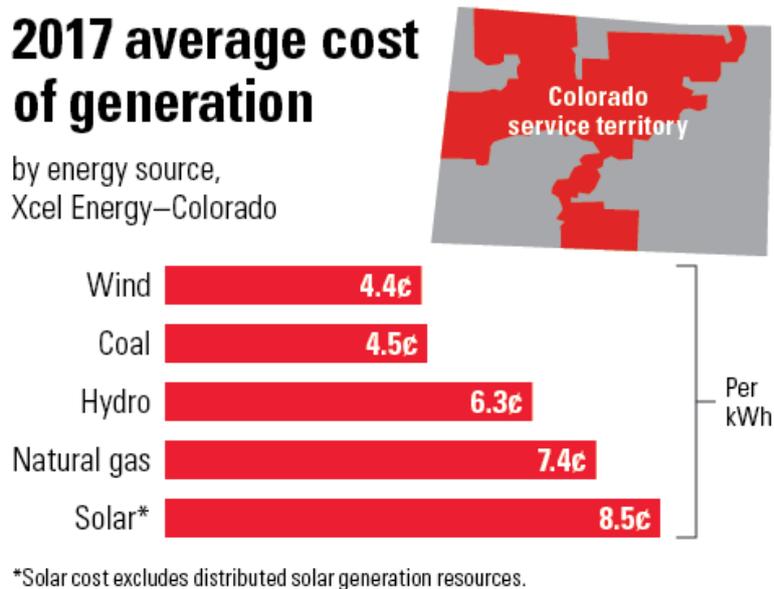


*Image 22: Average Xcel cost of Generation in Colorado*

## 7.3 ENVIRONMENTAL IMPACT

Finally, the third aspect that is examined is the effect that the energy improvement on the building has in terms of reducing the carbon footprint.

As it has been previously mentioned in this project, Mines is enrolled in a contract with Xcel Energy. This company has made great advances when it comes to cutting down the greenhouse gases emitted, not only in Colorado but in many other states. These actions that this corporation is undertaking are in accordance with a plan started a few years ago that sets a goal of zero emissions by 2050. This plan is called Clean Air-Clean Jobs Act (16).

Information on Excel`s carbon footprint produced during generation in Colorado is not easy to find, and complementary information needs to be gathered to have the big picture.

*Image 23: C02 Emission Rates in Colorado [lbs/MWh]*

With the chart above, we can know the initial situation in Colorado regarding carbon emissions (17). However, there is no data as of 2013, and that is precisely what we desire to know. We have to resort to another chart found in Excel page, that displays the evolution in the past years and also the plan in the coming years, of the reduction in the emissions of carbon (18). Therefore, if we have the initial value in 2005 and the percentage of reduction, we can determine the amount of emissions per MWh each year.
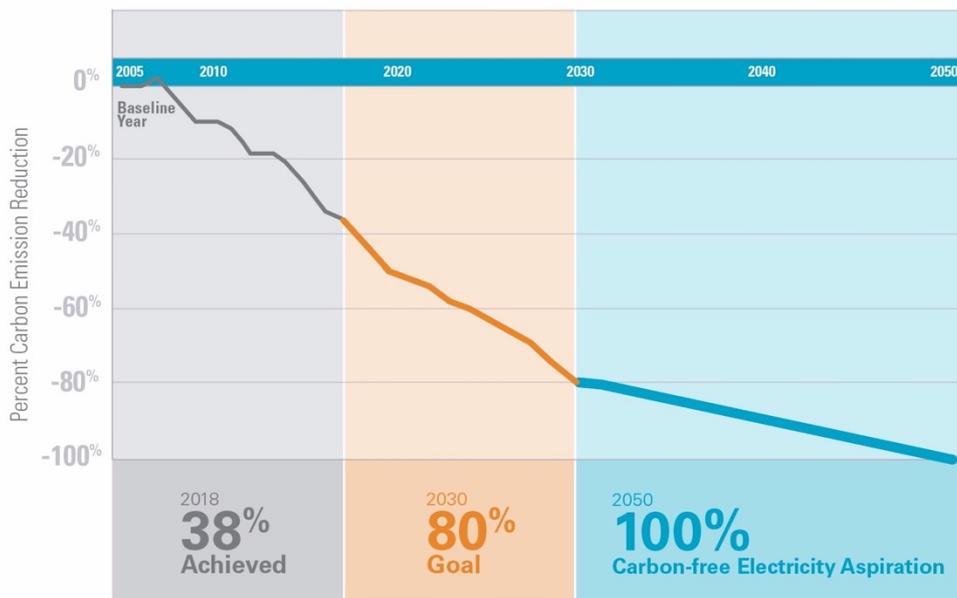


*Image 24: C02 Emission Rates trend in Colorado*

It was not possible to find the exact numbers, so we depict approximate values of the percentage of reduction in the following table and the correspondent amount of emissions each year.

| Year | Reduction % | Lbs/MWh | Year | Reduction % | Lbs/MWh |
|------|-------------|---------|------|-------------|---------|
| 2019 | 41 | 1,090 | 2032 | 82 | 333 |
| 2020 | 50 | 924 | 2033 | 83 | 314 |
| 2021 | 52 | 887 | 2034 | 84 | 296 |
| 2022 | 53 | 869 | 2035 | 85 | 277 |

| | | | | | |
|---|---|---|---|---|---|
| 2023 | 56 | 813 | 2036 | 86 | 259 |
| 2024 | 59 | 758 | 2037 | 87 | 240 |
| 2025 | 63 | 684 | 2038 | 88 | 222 |
| 2026 | 67 | 610 | 2039 | 89 | 203 |
| 2027 | 71 | 536 | 2040 | 90 | 185 |
| 2028 | 75 | 462 | 2041 | 91 | 166 |
| 2029 | 78 | 406 | 2042 | 92 | 148 |
| 2030 | 80 | 369 | 2043 | 93 | 129 |
| 2031 | 81 | 351 | --- | --- | --- |

*Table 31: Approximate CO2 Emission Rates the coming years*

$$Total\ Energy\ (With\ current\ fluorescent\ fixtures)$$
$$= \sum_{y=2019}^{2043} \sum_{m=1}^{12} \sum_{d=1}^{31} \sum_{h=0}^{23} kWh_{y,m,d,h} = 40{,}596{,}100 kWh$$

If we take the total energy that the building demands in 25 years we can make a similar table with the emissions that this demand would produce. Supposing that the energy demand is distributed equally all those years (40,596,100 kWh / 25 = 1,623.8 MWh)

| Year | Lbs/Mwh | MWh | Lbs | Year | Lbs/Mwh | MWh | Lbs |
|---|---|---|---|---|---|---|---|
| 2019 | 1090.00 | 1623.800 | 1769942 | 2032 | 333.00 | 1623.800 | 540725.4 |
| 2020 | 924.00 | 1623.800 | 1500391.2 | 2033 | 314.00 | 1623.800 | 509873.2 |
| 2021 | 887.00 | 1623.800 | 1440310.6 | 2034 | 296.00 | 1623.800 | 480644.8 |
| 2022 | 869.00 | 1623.800 | 1411082.2 | 2035 | 277.00 | 1623.800 | 449792.6 |
| 2023 | 813.00 | 1623.800 | 1320149.4 | 2036 | 259.00 | 1623.800 | 420564.2 |
| 2024 | 758.00 | 1623.800 | 1230840.4 | 2037 | 240.00 | 1623.800 | 389712 |
| 2025 | 684.00 | 1623.800 | 1110679.2 | 2038 | 222.00 | 1623.800 | 360483.6 |
| 2026 | 610.00 | 1623.800 | 990518 | 2039 | 203.00 | 1623.800 | 329631.4 |
| 2027 | 536.00 | 1623.800 | 870356.8 | 2040 | 185.00 | 1623.800 | 300403 |
| 2028 | 462.00 | 1623.800 | 750195.6 | 2041 | 166.00 | 1623.800 | 269550.8 |
| 2029 | 406.00 | 1623.800 | 659262.8 | 2042 | 148.00 | 1623.800 | 240322.4 |
| 2030 | 369.00 | 1623.800 | 599182.2 | 2043 | 129.00 | 1623.800 | 209470.2 |
| 2031 | 351.00 | 1623.800 | 569953.8 | 2044 | | | 0 |
| Total | 18724037.8 | | | | | | |

*Table 32: CO2 emissions from Coorstek Demand with current fixtures*

If nothing is changed in this 25 years, Coorstek Center demand of energy implies the emission of 18,724,037.8 lbs of $CO_2$, or equivalently, 8,493.08 tons of $CO_2$

To put this numbers in perspective, we want to determine how much we have reduced emissions of pollutant gases with the optimization of the building. We had previously calculated the energy savings with the formula below.

$$Energy\ savings = \sum_{y=2019}^{2043} \sum_{m=1}^{12} \sum_{d=1}^{31} \sum_{i=1}^{3} redenergy_i * L_i = 505{,}901\ kWh$$

This energy divided in 25 years give us a reduction in energy of 20.24 MWh per year. Repeating the same procedure, and again, using the table with the approximate percentage of reductions we obtain the following table.

| Year | Lbs/Mwh | MWh | Lbs | Year | Lbs/Mwh | MWh | Lbs |
|---|---|---|---|---|---|---|---|
| 2019 | 1090.00 | 20.240 | 22061.6 | 2032 | 333.00 | 20.240 | 6739.92 |
| 2020 | 924.00 | 20.240 | 18701.76 | 2033 | 314.00 | 20.240 | 6355.36 |
| 2021 | 887.00 | 20.240 | 17952.88 | 2034 | 296.00 | 20.240 | 5991.04 |
| 2022 | 869.00 | 20.240 | 17588.56 | 2035 | 277.00 | 20.240 | 5606.48 |
| 2023 | 813.00 | 20.240 | 16455.12 | 2036 | 259.00 | 20.240 | 5242.16 |
| 2024 | 758.00 | 20.240 | 15341.92 | 2037 | 240.00 | 20.240 | 4857.6 |
| 2025 | 684.00 | 20.240 | 13844.16 | 2038 | 222.00 | 20.240 | 4493.28 |
| 2026 | 610.00 | 20.240 | 12346.4 | 2039 | 203.00 | 20.240 | 4108.72 |
| 2027 | 536.00 | 20.240 | 10848.64 | 2040 | 185.00 | 20.240 | 3744.4 |
| 2028 | 462.00 | 20.240 | 9350.88 | 2041 | 166.00 | 20.240 | 3359.84 |
| 2029 | 406.00 | 20.240 | 8217.44 | 2042 | 148.00 | 20.240 | 2995.52 |
| 2030 | 369.00 | 20.240 | 7468.56 | 2043 | 129.00 | 20.240 | 2610.96 |
| 2031 | 351.00 | 20.240 | 7104.24 | 2044 | | | 0 |
| Total | 233387.44 | | | | | | |

*Table 33: CO2 savings from Coorstek demand with LED fixtures*

So in 25 years, the building's improvement in the efficiency has stopped 233,387.44 lbs or 105.86 tons of $CO_2$ from going into the atmosphere.

$$\% \; Emissions \; reduced = \frac{105.86}{8,493.08} * 100 = 1.24\%$$

*Equation 31: Coorstek Center %Reduction in CO2 emissions*

$$Total \; Emissions \; of \; CO_2 \; after \; improvement = 8,493.08 - 105.86$$
$$= 8,387.22 \; tons \; of \; CO_2$$

Xcel Energy provides information on other pollutant substances emitted during generation in Colorado. This information can be found in their website (19) and is shown in the charts below.

In the first chart we find the emissions of sulfur dioxide and nitrogen oxides in lbs/MWh from 2005 and the projection in the incoming years.

Air Emissions
(from owned and purchased generation)

By 2030, we expect to reduce SO$_2$ **80%** and NO$_x$ nearly **90%** from 2005 levels
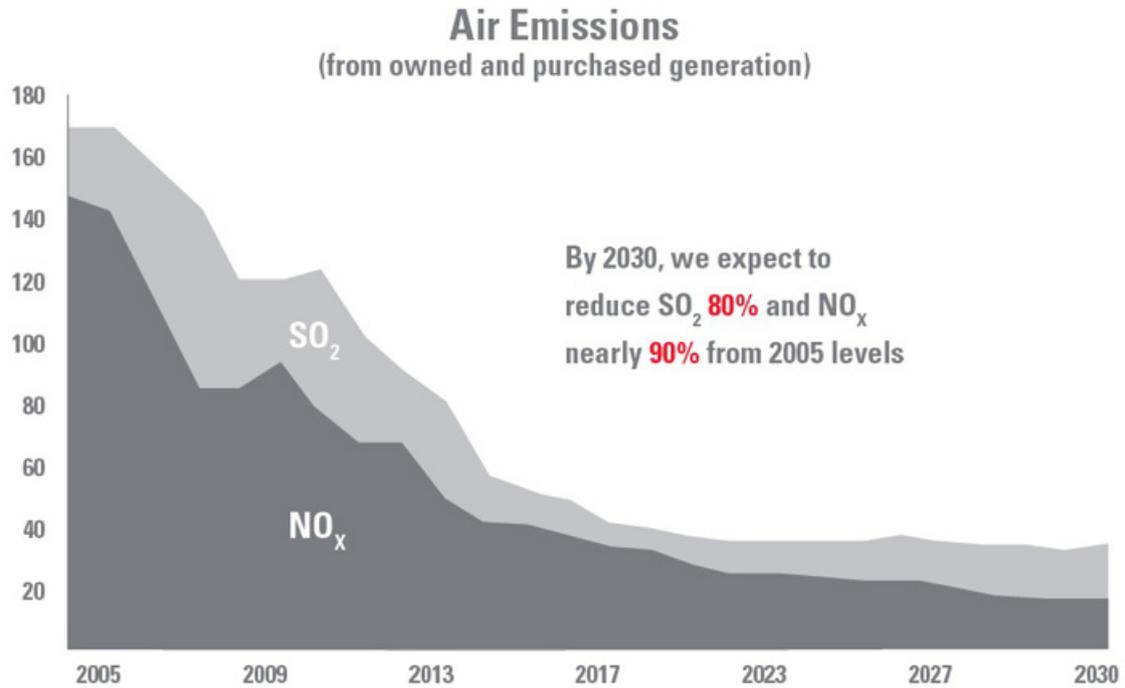
*Image 25: Xcel Colorado trend in emissions*

The two next charts show the same emissions with the difference that these charts involve only owned generation. That explains why the numbers are slightly inferior compared to the owned and purchased generation chart.



| 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 148,706 Tons | 137,384 Tons | 124,698 Tons | 114,700 Tons | 95,443 Tons | 97,773 Tons | 83,749 Tons | 74,335 Tons | 69,466 Tons | 59,102 Tons | 48,838 Tons | 45,591 Tons |
| 3.7 Lbs/MWh | 3.4 Lbs/MWh | 3.2 Lbs/MWh | 3.0 Lbs/MWh | 2.7 Lbs/MWh | 2.5 Lbs/MWh | 2.2 Lbs/MWh | 2.0 Lbs/MWh | 2.0 Lbs/MWh | 1.6 Lbs/MWh | 1.3 Lbs/MWh | 1.2 Lbs/MWh |

**Sulfur Dioxide Emissions (owned generation)**
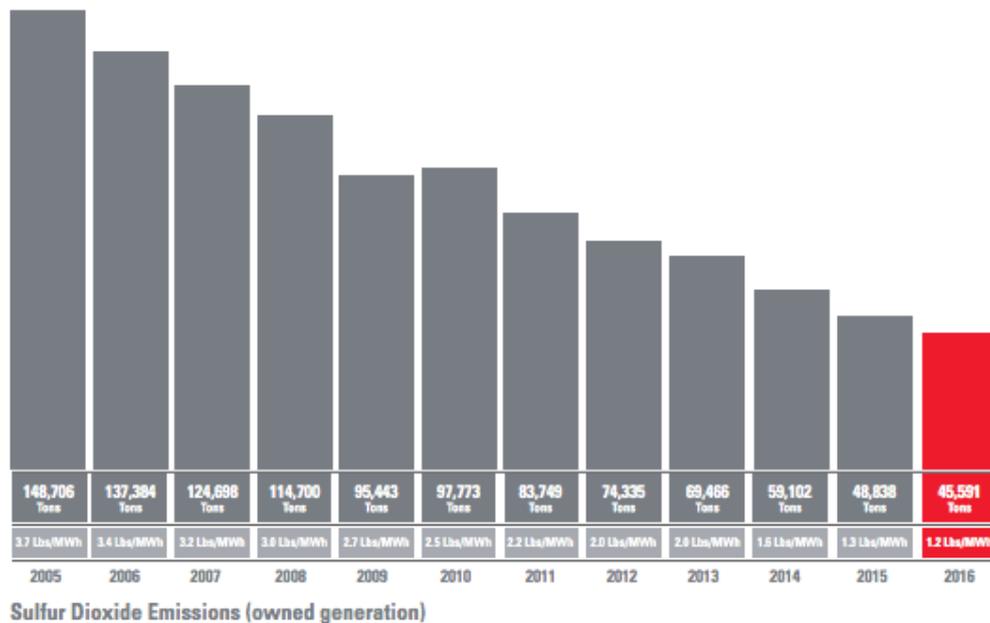
*Image 26: Colorado's previous years Sulfur Dioxide emissions*

67
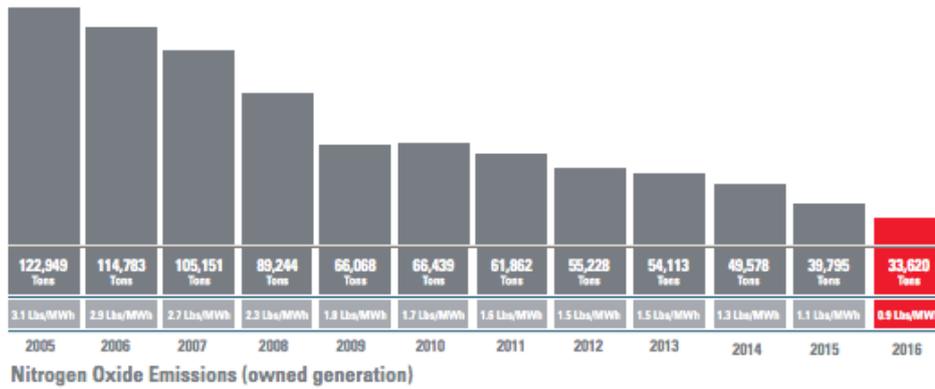
*Image 27: Colorado's previous years Nitrogen Oxide emissions*

These two charts are interesting and enrichment, but we are placing the focus on the first chart that involved the total generation. We do this because our concern is to reduce the emissions of hazard substances and greenhouse gases, and we don't pay attention on who or what is producing those emissions.

In first place, we can make a chart with the approximate values from the first chart until 2030 and draw a trend line for the next years.
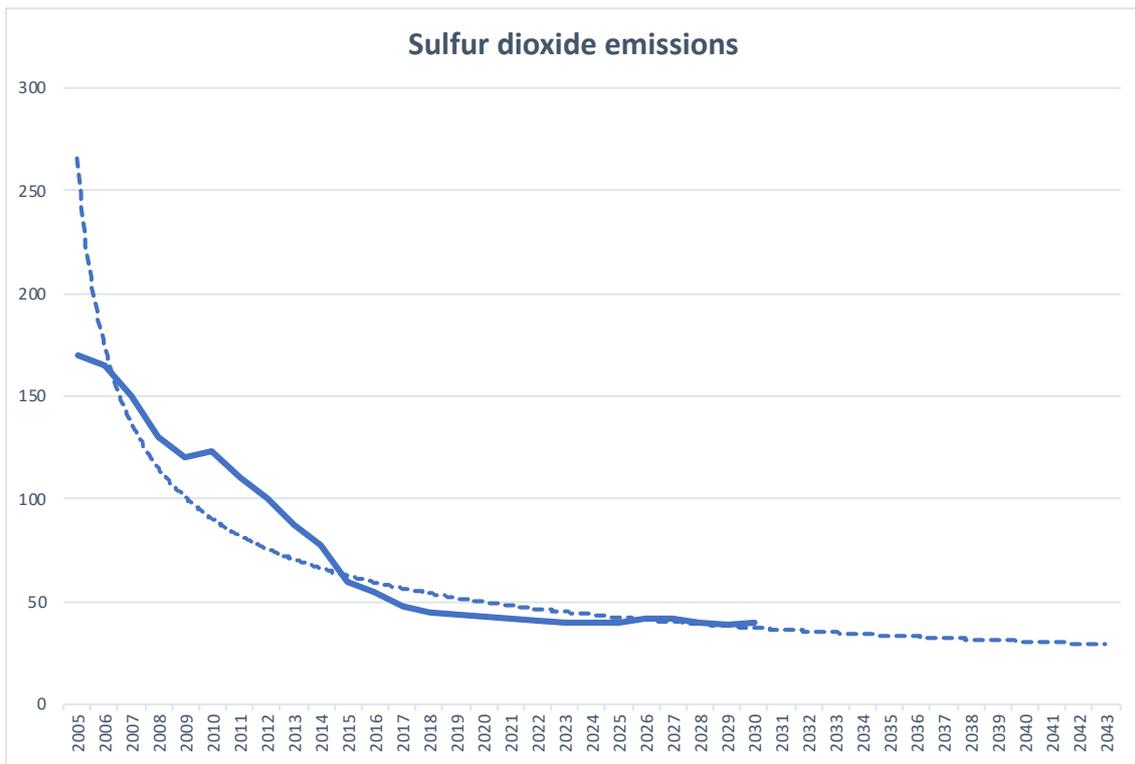


*Figure 12: Sulfur dioxide emissions*

With the approximate values of the emissions of sulfur dioxide after completing the tendency for the next years, and with the energy calculated in the previous section 7.2, we can determine the amount of emissions of sulfur dioxide measured in lbs.

| Year | Lbs/Mwh | MWh | Lbs | Year | Lbs/Mwh | MWh | Lbs |
|---|---|---|---|---|---|---|---|
| 2019 | 44.00 | 1623.80 | 71447.20 | 2032.00 | 35.70 | 1623.80 | 57975.48 |
| 2020 | 43.00 | 1623.80 | 69823.40 | 2033.00 | 34.96 | 1623.80 | 56763.59 |
| 2021 | 42.00 | 1623.80 | 68199.60 | 2034.00 | 34.25 | 1623.80 | 55616.86 |
| 2022 | 41.00 | 1623.80 | 66575.80 | 2035.00 | 33.58 | 1623.80 | 54529.78 |
| 2023 | 40.00 | 1623.80 | 64952.00 | 2036.00 | 32.95 | 1623.80 | 53497.46 |
| 2024 | 40.00 | 1623.80 | 64952.00 | 2037.00 | 32.34 | 1623.80 | 52515.57 |
| 2025 | 40.00 | 1623.80 | 64952.00 | 2038.00 | 31.77 | 1623.80 | 51580.21 |
| 2026 | 42.00 | 1623.80 | 68199.60 | 2039.00 | 31.22 | 1623.80 | 50687.92 |
| 2027 | 42.00 | 1623.80 | 68199.60 | 2040.00 | 30.69 | 1623.80 | 49835.56 |
| 2028 | 40.00 | 1623.80 | 64952.00 | 2041.00 | 30.19 | 1623.80 | 49020.31 |
| 2029 | 39.00 | 1623.80 | 63328.20 | 2042.00 | 29.71 | 1623.80 | 48239.60 |
| 2030 | 40.00 | 1623.80 | 64952.00 | 2043.00 | 29.25 | 1623.80 | 47491.14 |
| 2031 | 36.49 | 1623.80 | 59258.75 | 2044.00 | | | 0.00 |
| Total | 1487545.62 | | | | | | |

*Table 34: Sulfur Dioxide emissions from Coorstek Demand with current fixtures*

The total emission of sulfur dioxide if we don't make the substitution of fluorescent fixtures to LED fixtures is 1,487,545.62 lbs or 674.74 tons of sulfur dioxide.

Same procedure can be carried out, this time using the energy savings also calculated in section 7.2, to obtain the following results.

| Year | Lbs/Mwh | MWh | Lbs | Year | Lbs/Mwh | MWh | Lbs |
|---|---|---|---|---|---|---|---|
| 2019 | 44.00 | 20.240 | 890.56 | 2032.00 | 35.70 | 20.240 | 722.64 |
| 2020 | 43.00 | 20.240 | 870.32 | 2033.00 | 34.96 | 20.240 | 707.53 |
| 2021 | 42.00 | 20.240 | 850.08 | 2034.00 | 34.25 | 20.240 | 693.24 |
| 2022 | 41.00 | 20.240 | 829.84 | 2035.00 | 33.58 | 20.240 | 679.69 |
| 2023 | 40.00 | 20.240 | 809.60 | 2036.00 | 32.95 | 20.240 | 666.82 |
| 2024 | 40.00 | 20.240 | 809.60 | 2037.00 | 32.34 | 20.240 | 654.58 |
| 2025 | 40.00 | 20.240 | 809.60 | 2038.00 | 31.77 | 20.240 | 642.93 |
| 2026 | 42.00 | 20.240 | 850.08 | 2039.00 | 31.22 | 20.240 | 631.80 |
| 2027 | 42.00 | 20.240 | 850.08 | 2040.00 | 30.69 | 20.240 | 621.18 |
| 2028 | 40.00 | 20.240 | 809.60 | 2041.00 | 30.19 | 20.240 | 611.02 |
| 2029 | 39.00 | 20.240 | 789.36 | 2042.00 | 29.71 | 20.240 | 601.29 |
| 2030 | 40.00 | 20.240 | 809.60 | 2043.00 | 29.25 | 20.240 | 591.96 |
| 2031 | 36.49 | 20.240 | 738.64 | 2044.00 | | | 0.00 |
| Total | 18541.65 | | | | | | |

*Table 35: Sulfur Dioxide savings from Coorstek demand with LED fixtures*

The results show that with the implementation of LED lights we avoid the emission 18,541.65 lbs or 8.41 tons of sulfur dioxide. Logically, the percentage of emissions reduced is around 6, like it was for the percentage of savings in energy and in carbon emissions. It is the same percentage also for the next steps, since for all of them we are using the exact same values of energy, and no matter the multiplier, the percentage does not change.

$$Total\ emission\ of\ SO_2\ after\ improvement = 674.74 - 8.41$$
$$= 666.33\ tons\ of\ SO_2$$

Nitrogen oxides are conformed by seven gases. Some of the most hazardous gases are nitric oxide and nitrogen dioxide. These gases are responsible among other things of smog, acid rain when they react with sulfur dioxide, health issues and finally, they also contribute to climate change, as they are greenhouse gases.
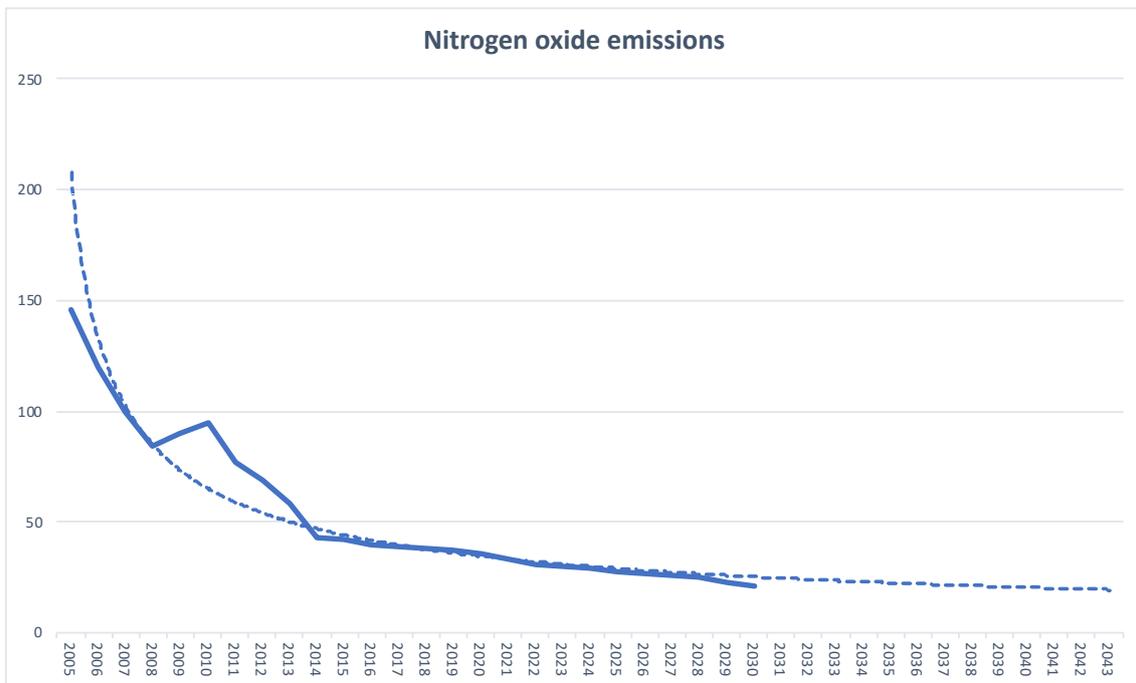


*Figure 13: Nitrogen Oxide emissions*

Again, we repeat the procedure and draw the trend line for the incoming years that help us to complete the tables below.

| Year | Lbs/Mwh | MWh | Lbs | Year | Lbs/Mwh | MWh | Lbs |
|------|---------|------|------|------|---------|------|------|
| 2019 | 37.00 | 1623.80 | 60080.60 | 2032 | 21.00 | 1623.80 | 34099.80 |
| 2020 | 36.00 | 1623.80 | 58456.80 | 2033 | 21.00 | 1623.80 | 34099.80 |
| 2021 | 33.00 | 1623.80 | 53585.40 | 2034 | 21.00 | 1623.80 | 34099.80 |
| 2022 | 31.00 | 1623.80 | 50337.80 | 2035 | 20.50 | 1623.80 | 33287.90 |
| 2023 | 30.00 | 1623.80 | 48714.00 | 2036 | 20.50 | 1623.80 | 33287.90 |
| 2024 | 29.00 | 1623.80 | 47090.20 | 2037 | 20.50 | 1623.80 | 33287.90 |
| 2025 | 28.00 | 1623.80 | 45466.40 | 2038 | 20.50 | 1623.80 | 33287.90 |

| 2026 | 27.00 | 1623.80 | 43842.60 | 2039 | 20.50 | 1623.80 | 33287.90 |
|------|-------|---------|----------|------|-------|---------|----------|
| 2027 | 26.00 | 1623.80 | 42218.80 | 2040 | 20.00 | 1623.80 | 32476.00 |
| 2028 | 25.00 | 1623.80 | 40595.00 | 2041 | 20.00 | 1623.80 | 32476.00 |
| 2029 | 23.00 | 1623.80 | 37347.40 | 2042 | 20.00 | 1623.80 | 32476.00 |
| 2030 | 21.00 | 1623.80 | 34099.80 | 2043 | 20.00 | 1623.80 | 32476.00 |
| 2031 | 21.00 | 1623.80 | 34099.80 | 2044 |       |         | 0.00 |
| Total | 994577.50 |     |          |      |       |         |          |

*Table 36: Nitrogen Oxide emissions from Coorstek Demand with current fixtures*

Once again, if we make no action on the building, in the next 25 years 994,577.5 lbs of nitrogen oxides will go into the atmosphere, or what is the same, 451.13 tons of NO$_x$

| Year | Lbs/Mwh | MWh | Lbs | Year | Lbs/Mwh | MWh | Lbs |
|------|---------|-----|-----|------|---------|-----|-----|
| 2019 | 37.00 | 20.240 | 748.88 | 2032 | 21.00 | 20.240 | 425.04 |
| 2020 | 36.00 | 20.240 | 728.64 | 2033 | 21.00 | 20.240 | 425.04 |
| 2021 | 33.00 | 20.240 | 667.92 | 2034 | 21.00 | 20.240 | 425.04 |
| 2022 | 31.00 | 20.240 | 627.44 | 2035 | 20.50 | 20.240 | 414.92 |
| 2023 | 30.00 | 20.240 | 607.20 | 2036 | 20.50 | 20.240 | 414.92 |
| 2024 | 29.00 | 20.240 | 586.96 | 2037 | 20.50 | 20.240 | 414.92 |
| 2025 | 28.00 | 20.240 | 566.72 | 2038 | 20.50 | 20.240 | 414.92 |
| 2026 | 27.00 | 20.240 | 546.48 | 2039 | 20.50 | 20.240 | 414.92 |
| 2027 | 26.00 | 20.240 | 526.24 | 2040 | 20.00 | 20.240 | 404.80 |
| 2028 | 25.00 | 20.240 | 506.00 | 2041 | 20.00 | 20.240 | 404.80 |
| 2029 | 23.00 | 20.240 | 465.52 | 2042 | 20.00 | 20.240 | 404.80 |
| 2030 | 21.00 | 20.240 | 425.04 | 2043 | 20.00 | 20.240 | 404.80 |
| 2031 | 21.00 | 20.240 | 425.04 | 2044 |       |        | 0.00 |
| Total | 12397.00 |     |        |      |       |        |        |

*Table 37: Nitrogen Oxide savings from Coorstek demand with LED fixtures*

The installation of LED fixtures prevent 12,397 lbs or 5.62 tons of NO$_x$ from polluting the air.

$$Total\ emission\ of\ NO_x\ after\ improvement = 451.13 - 5.62$$
$$= 445.51\ tons\ of\ NO_x$$
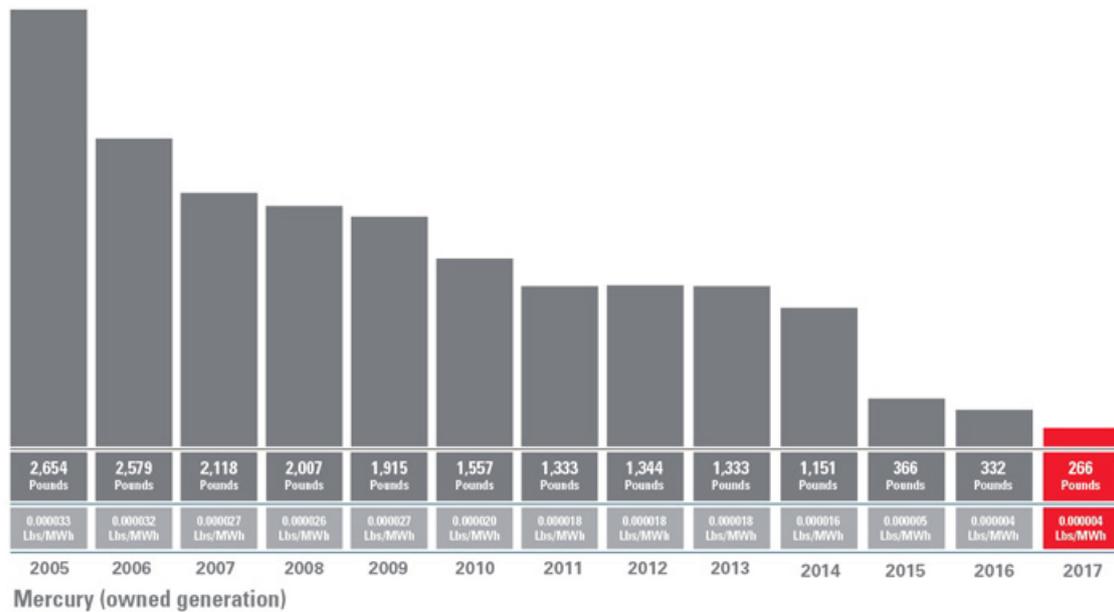
*Image 28: Colorado's previous years Mercury emissions*

The amount of mercury that Coorstek demand of energy releases to the atmosphere is not going to be studied as it is going to be a really low value compared to the previous ones and there is no available information on the emissions beyond 2017.

However, we can calculate the approximate amount of mercury saved just avoiding the use of fluorescent types of lamps. Fluorescent lamp that use 25 to 40 watts of electricity contains an average 6mg of mercury (20). Knowing the number of fluorescent lamps that we have avoid using, and the number of times they would have been replaced, we can make a precise approximation.

$$Grams\ of\ Mercury\ Saved$$
$$= 0.005$$
$$* (A_1 \& A_5 * Number\ of\ times\ changed + A_2$$
$$* Number\ of\ times\ changed + B_1 * Number\ of\ times\ changed)$$
$$= 0.005 * (314 * 4 + 258 * 4 + 158 * 2) = 13.03\ g\ of\ Mercury$$

*Equation 32: grams of mercury avoided in lamps production*

Even though the quantity obtained is very little, we could not have known a priori. Our task is to calculate all the factors involved, no matter the weight or relevance this could have. We can conclude that the mercury saved in matter of fixtures is insignificant and does not affect much in a local scale

# 9. CONCLUSIONS

The main goal of this study is to demonstrate that even brand-new buildings equipped with the latest technologies can be improved towards being more energetically efficient and consequently, a more environmentally friendly space. Global warming is a major challenge that new generations of engineers have to face. Young engineers have been instilled with this concern for the protection and care for the environment. I belong to this new breed of engineers and hence, I share the same passion to change the world, or at least, make my contribution.

After successfully completing this study, the principal objectives set at the beginning have been achieved. It has been proved that a building constructed in the last year that take advantage of cutting-edge technology, does not always mean that is the more efficient solution with the technologies available. A simple change such as installing LED lamps instead of the existing fluorescent lamps can make a meaningful improvement. Also, this small contribution to the environmental cause is destined to give a strong lead to others who want to follow a similar path and might be uncertain of obtaining results. The aim of this project is not to change the world by oneself. Instead, we want to inspire other engineers so that we can all join forces and contribute with our grain of sand.

Regarding the results, we have reached improvements not only in terms of energy savings, and consequently, in savings concerning the emissions released to the atmosphere. It is remarkable that we have achieved this in the most profitable way, as it has been proved that this optimization of the building incurs in great economic savings during the period under review. The values are even more impressive if we consider more years, but technologies are constantly changing, and there might be important breakthroughs in the future.

There is one thing that needs to be highlighted about the results obtained. We have calculated the consequences of the upgrades made. However, it is important to point out that the improved performance of 1.24% in the energy efficiency and 11.14% in the total costs is the outcome of changing just three types of fixtures in the building. In the entire building there are 23 types of fluorescent fixtures and many other LED fixtures. If we find a proper alternative LED fixture for those 19 fluorescent fixtures remaining, the improvements could be extraordinary. This fact reinforces the idea that is not that complicated to reduce the energy efficiency of a building. Merely by changing less than 35% of the building fixtures, and equipping Coorstek Center with 100% LED lamps, the performance is substantially enhanced. Below, the table with the fluorescent fixtures is provided.

| Type of light | Alternative Fixture | Type of light | Alternative fixture |
|---------------|---------------------|---------------|---------------------|
| A1 | YES | G2 | NO |
| A2 | YES | G3 | NO |
| A5 | YES | G4 | NO |
| B1 | YES | K1 | NO |
| C1 | NO | K2 | NO |
| C2 | NO | K3 | NO |
| C3 | NO | K4 | NO |
| C4 | NO | S1 | NO |

| | | | |
|---|---|---|---|
| C7 | NO | S2 | NO |
| F1 | NO | S3 | NO |
| F2 | NO | V2 | NO |
| G1 | NO | | |

*Table 38: Types of fluorescent fixtures in the building*

As it has been mentioned numerous times, the aim of this project is to stimulate efforts towards solving the environmental issue. If we improve every home, building and industry by 1.24%, which is the final result that we obtain with those simple changes, the electricity generation decreases, and here is what we can achieve:

| Area | Emission Type | Current Emission (Million metric tons) | Reduction in Emissions (Million metric tons) |
|---|---|---|---|
| **United States** | | | |
| | $CO_2$ | 1,763 | 21.8612 |
| | $SO_2$ | 1.9 | 0.02356 |
| | $NO_x$ | 1.8 | 0.02232 |
| **World** | | | |
| | $CO_2$ | 30,027.81 | 372.34 |
| | $SO_2$ | 31.75 | 0.3937 |
| | $NO_x$ | 70 | 0.868 |

*Table 39: U.S and World emissions with same savings percentage*

The numbers shown above are only related to electricity generation in the United States (21) (22) and in the global picture (23), disregarding the emissions related to transportation, human activities such as residential activity, agriculture or goods produced in industries. For the sulfur dioxide and nitrous oxides, there is not many sources available with the global information we are looking. However, we use iopscience article (24) and statista (25), make realistic approximations for the year 2019 and translate those number to the units we are using. In some cases, we need the GPW (26) multiplier to convert the MMTCDE (million metric tonnes of carbon dioxide emission) to the unit we are seeking.

In the table, we can see that with that little global energy reduction, we can avoid 373.2 million metric tons of greenhouse gases and 393.7 thousand metric tons of sulfur dioxide, which is toxic and a great risk for human health. Therefore, we have accomplished the initial objective, and the small improvement applied in Coorstek Center can make a notorious difference in a big scenario as well. Results are consistent and really close to what the scientific article *The environmental benefits of LED lighting* (29) predicts.

# 10. FUTURE WORK

At the start of this project, one of the goals that we set was to achieve a better qualification in the LEED certificate, in order to improve the current status. With this work, in cooperation with my two colleagues from ICAI, Cristina Olivié and Diego Montalvo, we expected to succeed in this task. One single enhancement of the building from any of us, may not be enough to reach the Platinum Level, but hopefully with the joint effort from the three of us, we can help Mines to achieve this.

In this project, I expected to calculate the number of points we could achieve with the improvements. However, this is not possible to do it, since some requirements cannot be met in the range of time available constrains our capabilities. In order to calculate the credits given, we need a baseline performance of the building, but we don't have that information, since the building is completely new and is still in its first year of life. A second requirement is a measurement and verification plan of one year, for which a calibrated simulation is needed. Therefore, we are not able to see if the improvements work in reality as they do in theory. That is work for the future if they desire to continue with this work.

Moreover, the in chapter 5 we calculated the reduction of loads in several panelboards, leaving extra margin for future implementations. So, another study that could be developed is the connection of new loads to these panelboards or resizing or them.

# 11. RESOURCES

With the intention of developing a quality project, it is mandatory to meet the requirements established by the legislation. The information on different websites like the National Electrical Code (NEC), documentation regarding LEED certification and the energy consumption which can be found in the website Energy Cap, will provide us enough information about the topic.

Moreover, as it was mentioned before in this paper, there will be a great gather of information about the building and campus. For this, a considerable amount of documentation on the electric systems, load profiles and energy bills of the facilities will be needed. All these documents and plans are provided by Dr. Sen and Emily Royal.

Next, once the data is collected, it will be time to analyze the results, for which various software programming tools will be of great help. These computer programs, such as Ampl, are really helpful for optimization problems. Another tools like Excel are used in tandem.

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# 13. APPENDICES

## Appendix A
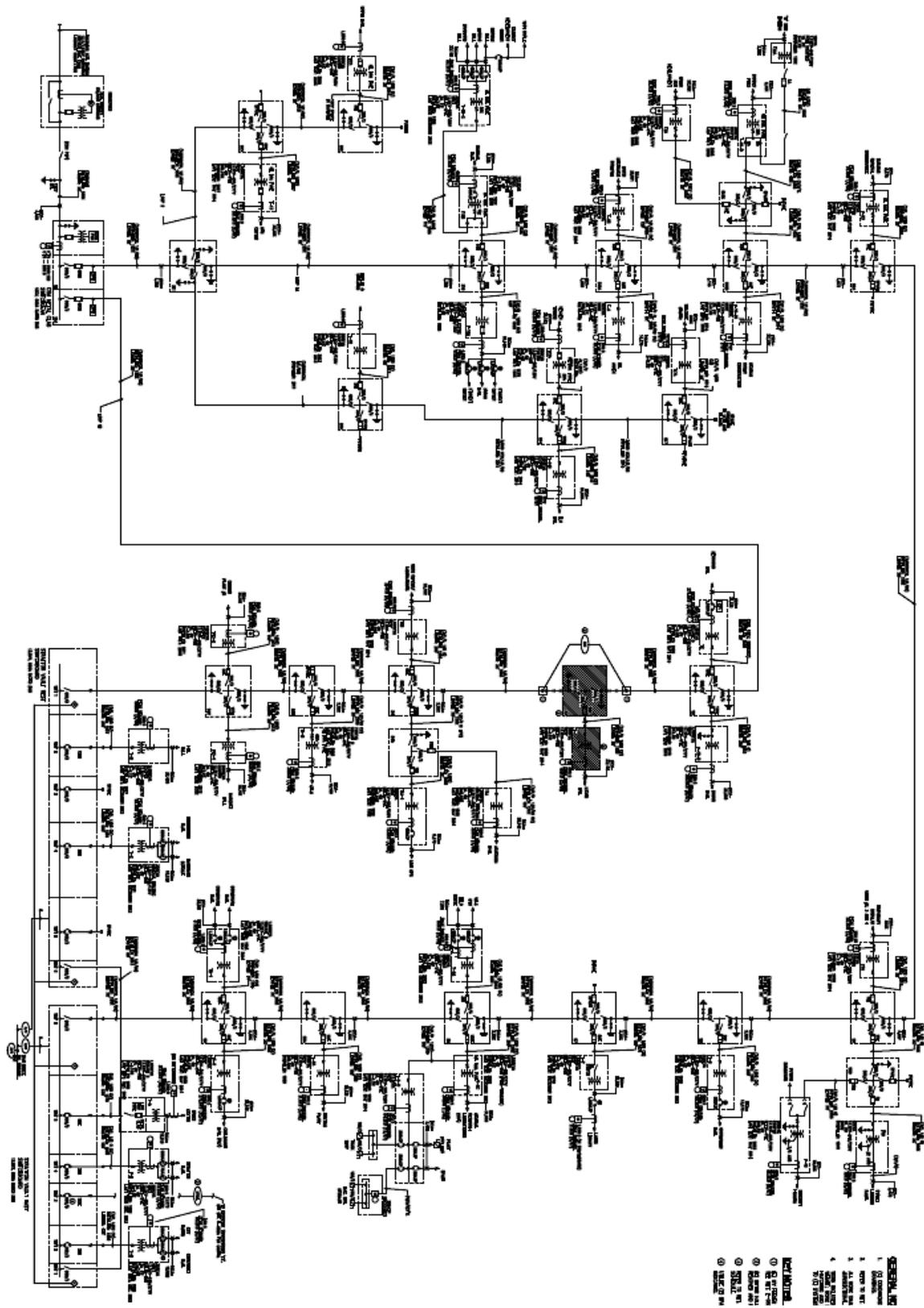
# Appendix B

| Building | Transformer Ratings (Delta-Solidly Grded Wye) | Transformer Rating (kVA) | Transformer impedance (%) | Phase, wire | Peak Demand (kW) | Area |
|---|---|---|---|---|---|---|
| Health Wellness | 13.2kV-208V | 300 | 3.6 | 3φ,4w | X | 1 |
| Rec. Center | 13.2kV-480V | 1,000 | 5.75 | 3φ,4w | 361.8 | 1 |
| Maple Hall | 13.2kV-208V | 500 | 3.9 | 3φ,4w | X | 1 |
| Randall Hall | 13.2kV-208V | 112.5 | 3.35 | 3φ,4w | 26.4 | 1 |
| Morgan Hall | 13.2kV-208V | 300 | 3.6 | 3φ,4w | 83.2 | 1 |
| Student Center | 13.2kV-208V | 1,000 | 5.4 | 3φ,4w | 416 | 1 |
| Elm Hall | 13.2kV-480V | 1,500 | 5.75 | 3φ,4w | X | 1 |
| Weaver Towers | 13.2kV-208V | 500 | 4.4 | 3φ,4w | 172.8 | 1 |
| GRL Annex | 13.2kV-480V | 750 | 5.6 | 3φ,4w | X | 1 |
| Earth Mechanics Institute | 13.2kV-480V | 1500 | 5.8 | 3φ,4w | 74.4 | 1 |
| Welcome Center | 13.2kV-480V | 300 | X | 3φ,4w | X | 1 |
| Stadium Under Construction | 13.2kV-480V | 1,000 | X | 3φ,4w | X | 1 |
| Creex Side Development | 13.2kV-480V | 500 | 4.55 | 3φ,4w | X | 1 |
| Darden Field | 13.2kV-480V | 300 | 2.4 | 3φ,4w | 113.2 | 1 |
| M Sign Lighting | 7.62kV-240V | 15 | X | 1φ,3w |  | 1 |
| Building General Maintenance | 13.2kV-208V | 75 | 3.1 | 3φ,4w | 70.4 | 1 |
| Berthoud Hall | 13.2kV-480V | 1,500 | 5.8 | 3φ,4w | 276.5 | 2 |
| Brown Hall | 13.2kV-480V | 3,000 | 5.4 | 3φ,4w | 300.9 | 2 |
| Meyer Hall | 13.2kV-208V | 300 | 3.6 | 3φ,4w | 165 | 2 |
| USGS Offices Laboratories | 13.2kV-480V | 1,000 | 5.91 | 3φ,4w | 347 | 2 |
| Alderson Hall | 13.2kV-480V | 1,500 | 5.8 | 3φ,4w | 325 | 2 |
| Unit Ops | 13.2kV-208V | 150 | 2.28 | 3φ,4w | 15.6 | 2 |
| CTLM | 13.2kV-480V | 750 | 6.3 | 3φ,4w | 389 | 2 |
| Chiller Plant | 13.2kV-480V | 1,000 | 5.8 | 3φ,4w | X | 2 |
| Marquez Hall | 13.2kV-480V | 2,000 | 5.6 | 3φ,4w | X | 2 |
| Hill Hall | 13.2kV-480V | 2,000 | 6.1 | 3φ,4w | 680 | 4 |
| Engineering Hall-Materials Science | 13.2kV-208V | 300 | 4.9 | 3φ,4w | 95.7 | 4 |
| Green Center | 13.2kV-480V | 1,000 | 4.16 | 3φ,4w | 312.2 | 3 |
| Stratton Hall | 13.2kV-480V | 500 | 4.4 | 3φ,4w | 18.9 | 3 |
| Chauvenet Hall | 13.2kV-480V | 300 | 3.6 | 3φ,4w | 90.2 | 3 |
| Coolbaugh Hall (old) | 13.2kV-480V | 1,000 | 5.32 | 3φ,4w | 270.9417 | 1 |
| Heating Plant | 13.2kV-480V | 300 | 3.46 | 3φ,4w | 31.6 | 1 |
| Hazardous Materials Storage | 13.2kV-208V | 112.5 | 3.3 | 3φ,4w | 54.2 | 1 |
| General Research Laboratories | 13.2kV-480V | 1,500 | 6 | 3φ,4w | 342 | 1 |
| Field House-Volk Gym | 13.2kV-480V | 500 | 7.42 | 3φ,4w | 161 | 1 |
| Lakes Library | 13.2kV-480V | 1,000 | 5.47 | 3φ,4w | 213 | 1 |
| Guggenheim Hall | 13.2kV-480V | 500 | 4.4 | 3φ,4w | 115.3 | 1 |
| Sorority Houses | 13.2kV-208V | 300 | 3.8 | 3φ,4w | 62.8 | 1 |
| Street Lightning Panel | 13.2kV-240V | 50 | 3 | 1φ,3w | X | 1 |
| Temporary Modular Units | 13.2kV-208V | 75 | 3.1 | 3φ,4w | X | 1 |

**Appendix C**



ELECTRICAL ONE-LINE DIAGRAM
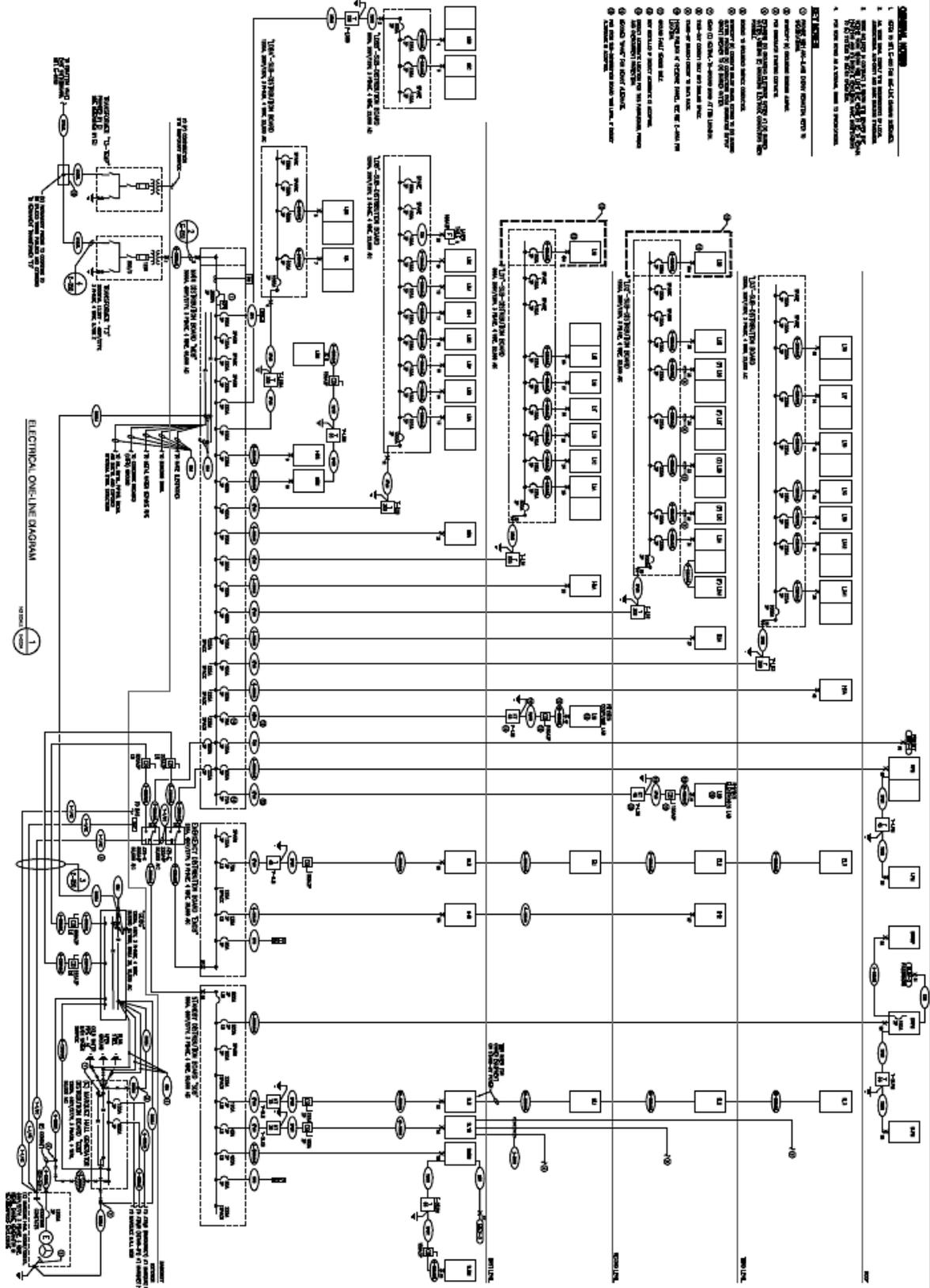
**Appendix D**

| Floor | Panelboard | Type of light | Number of units | Power per unit (W) | Total power (W) |
|-------|-----------|---------------|-----------------|--------------------|-----------------|
| Basement | HBA4 | A1 | 4 | 28 | 112 |
| Basement | | A2 | | 28 | 0 |
| Basement | | A5 | | 28 | 0 |
| Basement | HBA8 | B1 | 50 | 28 | 1400 |
| Basement | HBA12 | A1 | 12 | 28 | 336 |
| Basement | HBA10 | B1 | 16 | 28 | 448 |
| 1st Floor | H1A4 | A1 | 24 | 28 | 672 |
| 1st Floor | H1A8 | A2 | 48 | 28 | 1344 |
| 1st Floor | | A5 | | 28 | 0 |
| 1st Floor | H1A6 | B1 | 48 | 28 | 1344 |
| 1st Floor | H1A6 | A1 | 14 | 28 | 392 |
| 1st Floor | H1A8 | A1 | 6 | 28 | 168 |
| 1st Floor | H1A10 | A2 | 60 | 28 | 1680 |
| 2nd Floor | H2A6 | A1 | 50 | 28 | 1400 |
| 2nd Floor | H2A6 | A2 | 15 | 28 | 420 |
| 2nd Floor | | A5 | | 28 | 0 |
| 2nd Floor | | B1 | | 28 | 0 |
| 2nd Floor | H2A8 | A1 | 36 | 28 | 1008 |
| 2nd Floor | H2A2 | A1 | 18 | 28 | 504 |
| 2nd Floor | H2A2 | A2 | 36 | 28 | 1008 |
| 3rd Floor | H3A4 | A1 | 20 | 28 | 560 |
| 3rd Floor | H3A2 | A2 | 15 | 28 | 420 |
| 3rd Floor | H3A12 | A5 | 12 | 28 | 336 |
| 3rd Floor | H3A8 | B1 | 28 | 28 | 784 |
| 3rd Floor | H3A6 | A1 | 84 | 28 | 2352 |
| 3rd Floor | H3A2 | A1 | 26 | 28 | 728 |
| 3rd Floor | H3A4 | A2 | 6 | 28 | 168 |
| 3rd Floor | H3A8 | A2 | 51 | 28 | 1428 |
| 3rd Floor | H3A10 | A2 | 27 | 28 | 756 |
| 3rd Floor | H3A10 | A1 | 8 | 28 | 224 |
| 3rd Floor | H3A10 | B1 | 8 | 28 | 224 |
| 3rd Floor | H3A12 | B1 | 8 | 28 | 224 |

**Appendix E**

| Floor | Panelboard | Type of light | Number of units | Power per unit (W) | Total power (W) |
|---|---|---|---|---|---|
| Basement | HBA4 | A1 - Alternate | 2 | 40 | 80 |
| Basement | | A2 - Alternate | | 68 | 0 |
| Basement | | A5 - Alernate | | 40 | 0 |
| Basement | HBA8 | B1 - Alternate | 25 | 42 | 1050 |
| Basement | HBA12 | A1 - Alternate | 6 | 40 | 240 |
| Basement | HBA10 | B1 - Alternate | 8 | 42 | 336 |
| 1st Floor | H1A4 | A1 - Alternate | 12 | 40 | 480 |
| 1st Floor | H1A8 | A2 - Alternate | 16 | 68 | 1088 |
| 1st Floor | | A5 - Alernate | | 40 | 0 |
| 1st Floor | H1A6 | B1 - Alternate | 24 | 42 | 1008 |
| 1st Floor | H1A6 | A1 - Alternate | 7 | 40 | 280 |
| 1st Floor | H1A8 | A1 - Alternate | 3 | 40 | 120 |
| 1st Floor | H1A10 | A2 - Alternate | 20 | 68 | 1360 |
| 2nd Floor | H2A6 | A1 - Alternate | 25 | 40 | 1000 |
| 2nd Floor | H2A6 | A2 - Alternate | 5 | 68 | 340 |
| 2nd Floor | | A5 - Alernate | | 40 | 0 |
| 2nd Floor | | B1 - Alternate | | 42 | 0 |
| 2nd Floor | H2A8 | A1 - Alternate | 18 | 40 | 720 |
| 2nd Floor | H2A2 | A1 - Alternate | 9 | 40 | 360 |
| 2nd Floor | H2A2 | A2 - Alternate | 12 | 68 | 816 |
| 3rd Floor | H3A4 | A1 - Alternate | 10 | 40 | 400 |
| 3rd Floor | H3A2 | A2 - Alternate | 5 | 68 | 340 |
| 3rd Floor | H3A12 | A5 - Alernate | 6 | 40 | 240 |
| 3rd Floor | H3A8 | B1 - Alternate | 14 | 42 | 588 |
| 3rd Floor | H3A6 | A1 - Alternate | 42 | 40 | 1680 |
| 3rd Floor | H3A2 | A1 - Alternate | 13 | 40 | 520 |
| 3rd Floor | H3A4 | A2 - Alternate | 2 | 68 | 136 |
| 3rd Floor | H3A8 | A2 - Alternate | 17 | 68 | 1156 |
| 3rd Floor | H3A10 | A2 - Alternate | 9 | 68 | 612 |
| 3rd Floor | H3A10 | A1 - Alternate | 4 | 40 | 160 |
| 3rd Floor | H3A10 | B1 - Alternate | 4 | 42 | 168 |
| 3rd Floor | H3A12 | B1 - Alternate | 4 | 42 | 168 |

**Appendix F**

**Effective October 1, 2018**

ELECTRIC RATE ADJUSTMENTS PER kWh/kW AS APPLICABLE

| Schedule | Charge Type | Charge Amount | GRSA -4.19% | Earnings Sharing Adjustment (ESA) -0.05% | Purchased Capacity Cost Adjustment (PCCA) | Demand Side Management Cost Adjustment (DSMCA) | Electric Commodity Adjustment (ECA) | Transmission Cost Adjustment (TCA) | Clean Air Clean-Jobs Act (CACJA) | Renewable Energy Standard Adjustment (RESA) 2.00% | Total Monthly Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Residential (R) | Service and Facility per Month | 5.41 | (0.0419) | (0.0005) | - | - | - | - | - | 0.10361 | 5.28 |
| | Winter Energy per kWh | 0.05461 | (0.0419) | (0.0005) | 0.00433 | 0.00198 | 0.03581 | 0.00152 | 0.00287 | 0.00198 | 0.10078 |
| Residential Energy Time-Of-Use (RE-TOU) | Service and Facility per Month | 5.41 | (0.0419) | (0.0005) | - | - | - | - | - | 0.10361 | 5.28 |
| | Winter On-Peak Energy per kWh | 0.08880 | (0.0419) | (0.0005) | 0.00433 | 0.00198 | 0.04065 | 0.00152 | 0.00287 | 0.00273 | 0.19911 |
| | Winter Shoulder Energy per kWh | 0.05413 | (0.0419) | (0.0005) | 0.00433 | 0.00198 | 0.04065 | 0.00152 | 0.00287 | 0.00206 | 0.10524 |
| | Winter Off-Peak Energy per kWh | 0.04440 | (0.0419) | (0.0005) | 0.00433 | 0.00198 | 0.02784 | 0.00152 | - | 0.00162 | 0.08268 |
| Small Commercial (C) | Service and Facility per Month | 10.43 | (0.0419) | (0.0005) | - | - | - | - | - | 0.19976 | 10.19 |
| | Winter Energy per kWh | 0.04256 | (0.0419) | (0.0005) | 0.00380 | 0.00181 | 0.03581 | 0.00137 | 0.00261 | 0.00173 | 0.08799 |
| Residential Demand (RD) | Service and Facility per Month | 12.01 | (0.0419) | (0.0005) | - | - | - | - | - | 0.23002 | 11.73 |
| | Winter Demand per kW | 7.76 | (0.0419) | (0.0005) | 0.47 | 0.22 | - | 0.17 | 0.33 | 0.17242 | 8.79 |
| | Energy per kWh | 0.01974 | (0.0419) | (0.0005) | - | - | 0.03581 | - | - | 0.00109 | 0.05580 |
| Residential Demand - Time Differentiated Rates (RD-TDR) | Service and Facility per Month | 5.41 | (0.0419) | (0.0005) | - | - | - | - | - | 0.10361 | 5.28 |
| | Distribution Demand per kW | 3.65 | (0.0419) | (0.0005) | - | - | - | - | - | 0.06990 | 3.57 |
| | Winter Generation & Transmission Demand per kW | 6.81 | (0.0419) | (0.0005) | 0.94 | 0.34 | - | 0.33 | 0.63 | 0.17523 | 8.94 |
| | On-Peak Energy per kWh | 0.00461 | (0.0419) | (0.0005) | - | - | 0.04065 | - | - | 0.00090 | 0.04596 |
| | Off-Peak Energy per kWh | 0.00461 | (0.0419) | (0.0005) | - | - | 0.02784 | - | - | 0.00065 | 0.03290 |
| Secondary General (SG) | Service and Facility per Month | 34.40 | (0.0419) | (0.0005) | - | - | - | - | - | 0.65863 | 33.60 |
| | Distribution Demand per kW | 5.63 | (0.0419) | (0.0005) | - | - | - | - | - | 0.10763 | 5.50 |
| | Winter Generation & Transmission Demand per kW | 9.82 | (0.0419) | (0.0005) | 1.34 | 0.62 | - | 0.48 | 0.91 | 0.25607 | 13.01 |
| | Winter Energy per kWh | 0.00461 | (0.0419) | (0.0005) | - | - | 0.03581 | - | - | 0.00080 | 0.04102 |
| Secondary General Low-Load Factor (SGL) | Service and Facility per Month | 34.40 | (0.0419) | (0.0005) | - | - | - | - | - | 0.65863 | 33.60 |
| | Distribution Demand per kW | 5.63 | (0.0419) | (0.0005) | - | - | - | - | - | 0.10763 | 5.50 |
| | Winter Energy per kWh | 0.12293 | (0.0419) | (0.0005) | 0.01677 | 0.00770 | 0.03581 | 0.00563 | 0.01130 | 0.00390 | 0.19913 |
| Primary General (PG) | Service and Facility per Month | 322.00 | (0.0419) | (0.0005) | - | - | - | - | - | 6.16694 | 314.51 |
| | Distribution Demand per kW | 3.86 | (0.0419) | (0.0005) | - | - | - | - | - | 0.07393 | 3.77 |
| | Winter Generation & Transmission Demand per kW | 9.55 | (0.0419) | (0.0005) | 1.29 | 0.59 | - | 0.47 | 0.90 | 0.24790 | 12.64 |
| | On-Peak Energy per kWh | 0.00458 | (0.0419) | (0.0005) | - | - | 0.04248 | - | - | 0.00094 | 0.04781 |
| | Off-Peak Energy per kWh | 0.00458 | (0.0419) | (0.0005) | - | - | 0.02970 | - | - | 0.00068 | 0.03477 |
| Transmission General (TG) | Service and Facility per Month | - | (0.0419) | (0.0005) | - | - | - | - | - | - | Customer Specific |
| | Winter Generation & Transmission Demand per kW | 8.26 | (0.0419) | (0.0005) | 1.16 | 0.53 | - | 0.43 | 0.83 | 0.21720 | 11.08 |
| | On-Peak Energy per kWh | 0.00441 | (0.0419) | (0.0005) | - | - | 0.04162 | - | - | 0.00092 | 0.04676 |
| | Off-Peak Energy per kWh | 0.00441 | (0.0419) | (0.0005) | - | - | 0.02910 | - | - | 0.00067 | 0.03599 |

# Appendix G

Effective June 1, 2018

**ELECTRIC RATE ADJUSTMENTS PER KWH/KW AS APPLICABLE**

| Schedule | Charge Type | Charge Amount | GRSA -4.19% | Earnings Sharing Adjustment (ESA) 0.12% | Purchased Capacity Cost Adjustment (PCCA) | Demand Side Management Cost Adjustment (DSMCA) | Electric Commodity Adjustment (ECA) | Transmission Cost Adjustment (TCA) | Clean Air Clean-Jobs Act (CACJA) | Renewable Energy Standard Adjustment (RESA) 2.00% | Total Monthly Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Residential ( R) | Service and Facility per Month | 5.41 | (0.0419) | 0.0012 | - | - | - | - | - | 0.10380 | 5.29 |
| | Summer Energy Tier I per kWh | 0.05461 | (0.0419) | 0.0012 | 0.00433 | 0.00183 | 0.02986 | 0.00152 | 0.00287 | 0.00186 | 0.09466 |
| | Summer Energy Tier II per kWh | 0.09802 | (0.0419) | 0.0012 | 0.00433 | 0.00183 | 0.02986 | 0.00152 | 0.00287 | 0.00271 | 0.13811 |
| Residential Energy Time-Of-Use (RE-TOU) | Service and Facility per Month | 5.41 | (0.0419) | 0.0012 | - | - | - | - | - | 0.10380 | 5.29 |
| | Summer On-Peak Energy per kWh | 0.13814 | (0.0419) | 0.0012 | 0.00433 | 0.00183 | 0.03387 | 0.00152 | 0.00287 | 0.00354 | 0.18048 |
| | Summer Shoulder Energy per kWh | 0.08420 | (0.0419) | 0.0012 | 0.00433 | 0.00183 | 0.03387 | 0.00152 | 0.00287 | 0.00250 | 0.12769 |
| | Summer Off-Peak Energy per kWh | 0.04440 | (0.0419) | 0.0012 | 0.00433 | 0.00183 | 0.02320 | 0.00152 | 0.00287 | 0.00153 | 0.07787 |
| Small Commercial ( C) | Service and Facility per Month | 10.43 | (0.0419) | 0.0012 | - | - | - | - | - | 0.20011 | 10.21 |
| | Summer Energy per kWh | 0.08512 | (0.0419) | 0.0012 | 0.00390 | 0.00168 | 0.02986 | 0.00137 | 0.00261 | 0.00242 | 0.12350 |
| Residential Demand (RD) | Service and Facility per Month | 12.01 | (0.0419) | 0.0012 | - | - | - | - | - | 0.23042 | 11.75 |
| | Summer Demand per kW | 10.08 | (0.0419) | 0.0012 | 0.47 | 0.20 | - | 0.17 | 0.33 | 0.21679 | 11.06 |
| | Energy per kWh | 0.01974 | (0.0419) | 0.0012 | - | - | 0.02986 | - | - | 0.00098 | 0.04978 |
| Residential Demand - Time Differentiated Rates (RD-TDR) | Service and Facility per Month | 5.41 | (0.0419) | 0.0012 | - | - | - | - | - | 0.10380 | 5.29 |
| | Distribution Demand per kW | 3.65 | (0.0419) | 0.0012 | - | - | - | - | - | 0.07003 | 3.57 |
| | Summer Generation & Transmission Demand per kW | 9.73 | (0.0419) | 0.0012 | 0.94 | 0.31 | - | 0.33 | 0.63 | 0.23088 | 11.77 |
| | On-Peak Energy per kWh | 0.00461 | (0.0419) | 0.0012 | - | - | 0.03387 | - | - | 0.00077 | 0.03906 |
| | Off-Peak Energy per kWh | 0.00461 | (0.0419) | 0.0012 | - | - | 0.02320 | - | - | 0.00055 | 0.02817 |
| Secondary General (SG) | Service and Facility per Month | 34.40 | (0.0419) | 0.0012 | - | - | - | - | - | 0.66000 | 33.66 |
| | Distribution Demand per kW | 5.63 | (0.0419) | 0.0012 | - | - | - | - | - | 0.10802 | 5.51 |
| | Summer Generation & Transmission Demand per kW | 14.02 | (0.0419) | 0.0012 | 1.34 | 0.57 | - | 0.48 | 0.91 | 0.33499 | 17.08 |
| | Summer Energy per kWh | 0.00461 | (0.0419) | 0.0012 | - | - | 0.02986 | - | - | 0.00069 | 0.03497 |
| Secondary General Low-Load Factor (SGL) | Service and Facility per Month | 34.40 | (0.0419) | 0.0012 | - | - | - | - | - | 0.68000 | 33.66 |
| | Distribution Demand per kW | 5.63 | (0.0419) | 0.0012 | - | - | - | - | - | 0.10802 | 5.51 |
| | Summer Energy per kWh | 0.17561 | (0.0419) | 0.0012 | 0.01677 | 0.00710 | 0.02986 | 0.00593 | 0.01130 | 0.00479 | 0.24421 |
| Primary General (PG) | Service and Facility per Month | 322.00 | (0.0419) | 0.0012 | - | - | - | - | - | 6.17789 | 315.07 |
| | Distribution Demand per kW | 3.86 | (0.0419) | 0.0012 | - | - | - | - | - | 0.07406 | 3.78 |
| | Summer Generation & Transmission Demand per kW | 14.26 | (0.0419) | 0.0012 | 1.29 | 0.54 | - | 0.47 | 0.90 | 0.33759 | 17.22 |
| | On-Peak Energy per kWh | 0.00458 | (0.0419) | 0.0012 | - | - | 0.03540 | - | - | 0.00080 | 0.04059 |
| | Off-Peak Energy per kWh | 0.00458 | (0.0419) | 0.0012 | - | - | 0.02476 | - | - | 0.00058 | 0.02973 |
| Transmission General (TG) | Service and Facility per Month | - | (0.0419) | 0.0012 | - | - | - | - | - | - | Customer Specific |
| | Summer Generation & Transmission Demand per kW | 12.32 | (0.0419) | 0.0012 | 1.16 | 0.48 | - | 0.43 | 0.83 | 0.29437 | 15.01 |
| | On-Peak Energy per kWh | 0.00441 | (0.0419) | 0.0012 | - | - | 0.03469 | - | - | 0.00078 | 0.03970 |
| | Off-Peak Energy per kWh | 0.00441 | (0.0419) | 0.0012 | - | - | 0.02426 | - | - | 0.00057 | 0.02906 |

## Appendix H

```
set I;      # Type of light fixture
set H;      # Hours
set D;      # Days
set M;      # Months
set Y;      # Years
set Yi within Y;
set Yf within Y;

param lprice{i in I};     # Price of buying a LED light fixture i
param fprice{i in I};     # Price of buying a Fluorescent light fixture i
param fixed;              # Monthly fixed Charge
param rate{M,H};          # Energy rate depending on month and hour
param DR{m in M};         # Demand Rate depending on the month
param redpower{i in I};   # Reduction of power per LED light fixture i
param redenergy{i in I};  # Reduction of energy per LED light fixture i in a day
param lreplcost{i in I};  # Annual cost of replacing a LED light fixture i
param freplcost{i in I};  # Annual cost of replacing a Fluorescent light fixture i
param lreplace{Y,I} default 0;     # LED fixture i needs a replacement yes(1) or no(0)
param freplace{Y,I} default 0;     # Fluorescent fixture i needs a replacement yes(1) or no(0)
param maxkW{Y,M} default 0;        # Maximum peak of power consumption each month of every year
param kWh{Y,M,D,H} default 0;      # Energy consumption in kWh for each hour day month and years
from 2019 to 2022

param kWhn{M,D,H} default 0;       # Energy consumption in kWh for each hour day and month for
remaining years

var L{i in I}>=0;        # LED light fixture i
var F{i in I}>=0;        # Fluorescent light fixture i

minimize Cost: sum{y in Yi} (sum{m in M} (sum{d in D} (sum{h in H} rate[m,h]*kWh[y,m,d,h]
        - sum{i in I} rate[m,16]*redenergy[i]*L[i])
        + DR[m]*(maxkW[y,m]-sum{i in I}redpower[i]*L[i]) + fixed)
        + sum{i in I} ((lreplace[y,i]*lprice[i]+lreplcost[i])*L[i]
        + (freplace[y,i]*fprice[i]+freplcost[i])*F[i]) )
    + sum{y in Yf} (sum{m in M} (sum{d in D} (sum{h in H} rate[m,h]*kWhn[m,d,h]
    - sum{i in I} rate[m,16]*redenergy[i]*L[i])
        + DR[m]*(maxkW[y,m]-sum{i in I}redpower[i]*L[i]) + fixed)
        + sum{i in I} ((lreplace[y,i]*lprice[i]+lreplcost[i])*L[i]
    + (freplace[y,i]*fprice[i]+freplcost[i])*F[i]) );;

s.t. C1: L[1]+F[1]/2 = 157;
s.t. C2: L[2]+F[2]/3 = 86;
s.t. C3: L[3]+F[3]/2 = 79;
```

## Appendix I

set I:= 1 2 3;
set H:= 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23;
set D:= 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31;
set M:= 1 2 3 4 5 6 7 8 9 10 11 12;
set Y:= 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043;
set Yi:= 2019 2020 2021 2022;
set Yf:= 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043;

param: lprice fprice:=
1 230 172.5
2 310 232.5
3 250 187.5;

param fixed:= 322;

param DR:=
1 16.41
2 16.41
3 16.41
4 16.41
5 16.41
6 21
7 21
8 21
9 21
10 16.41
11 16.41
12 16.41;

param: redpower redenergy lreplcost freplcost :=
1    0.016   0.240   0.525    1.05
2    0.016   0.240   0.525    1.05
3    0.014   0.1225  0.3075   0.6075;

param lreplace:=
2019 1 1
2032 1 1
2019 2 1
2032 2 1
2019 3 1
2042 3 1;

param freplace:=
2026 1 1
2033 1 1
2040 1 1
2026 2 1
2033 2 1
2040 2 1
2030 3 1
2041 3 1;

# Appendix J

| param | rate:= |  | param | rate:= |  | param | rate:= |  |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0.03477 | 5 | 5 | 0.03477 | 10 | 10 | 0.04781 |
| 2 | 0 | 0.03477 | 6 | 5 | 0.02973 | 11 | 10 | 0.04781 |
| 3 | 0 | 0.03477 | 7 | 5 | 0.02973 | 12 | 10 | 0.04781 |
| 4 | 0 | 0.03477 | 8 | 5 | 0.02973 | 1 | 11 | 0.04781 |
| 5 | 0 | 0.03477 | 9 | 5 | 0.02973 | 2 | 11 | 0.04781 |
| 6 | 0 | 0.02973 | 10 | 5 | 0.03477 | 3 | 11 | 0.04781 |
| 7 | 0 | 0.02973 | 11 | 5 | 0.03477 | 4 | 11 | 0.04781 |
| 8 | 0 | 0.02973 | 12 | 5 | 0.03477 | 5 | 11 | 0.04781 |
| 9 | 0 | 0.02973 | 1 | 6 | 0.03477 | 6 | 11 | 0.04059 |
| 10 | 0 | 0.03477 | 2 | 6 | 0.03477 | 7 | 11 | 0.04059 |
| 11 | 0 | 0.03477 | 3 | 6 | 0.03477 | 8 | 11 | 0.04059 |
| 12 | 0 | 0.03477 | 4 | 6 | 0.03477 | 9 | 11 | 0.04059 |
| 1 | 1 | 0.03477 | 5 | 6 | 0.03477 | 10 | 11 | 0.04781 |
| 2 | 1 | 0.03477 | 6 | 6 | 0.02973 | 11 | 11 | 0.04781 |
| 3 | 1 | 0.03477 | 7 | 6 | 0.02973 | 12 | 11 | 0.04781 |
| 4 | 1 | 0.03477 | 8 | 6 | 0.02973 | 1 | 12 | 0.04781 |
| 5 | 1 | 0.03477 | 9 | 6 | 0.02973 | 2 | 12 | 0.04781 |
| 6 | 1 | 0.02973 | 10 | 6 | 0.03477 | 3 | 12 | 0.04781 |
| 7 | 1 | 0.02973 | 11 | 6 | 0.03477 | 4 | 12 | 0.04781 |
| 8 | 1 | 0.02973 | 12 | 6 | 0.03477 | 5 | 12 | 0.04781 |
| 9 | 1 | 0.02973 | 1 | 7 | 0.03477 | 6 | 12 | 0.04059 |
| 10 | 1 | 0.03477 | 2 | 7 | 0.03477 | 7 | 12 | 0.04059 |
| 11 | 1 | 0.03477 | 3 | 7 | 0.03477 | 8 | 12 | 0.04059 |
| 12 | 1 | 0.03477 | 4 | 7 | 0.03477 | 9 | 12 | 0.04059 |
| 1 | 2 | 0.03477 | 5 | 7 | 0.03477 | 10 | 12 | 0.04781 |
| 2 | 2 | 0.03477 | 6 | 7 | 0.02973 | 11 | 12 | 0.04781 |
| 3 | 2 | 0.03477 | 7 | 7 | 0.02973 | 12 | 12 | 0.04781 |
| 4 | 2 | 0.03477 | 8 | 7 | 0.02973 | 1 | 13 | 0.04781 |
| 5 | 2 | 0.03477 | 9 | 7 | 0.02973 | 2 | 13 | 0.04781 |
| 6 | 2 | 0.02973 | 10 | 7 | 0.03477 | 3 | 13 | 0.04781 |
| 7 | 2 | 0.02973 | 11 | 7 | 0.03477 | 4 | 13 | 0.04781 |
| 8 | 2 | 0.02973 | 12 | 7 | 0.03477 | 5 | 13 | 0.04781 |
| 9 | 2 | 0.02973 | 1 | 8 | 0.04781 | 6 | 13 | 0.04059 |
| 10 | 2 | 0.03477 | 2 | 8 | 0.04781 | 7 | 13 | 0.04059 |
| 11 | 2 | 0.03477 | 3 | 8 | 0.04781 | 8 | 13 | 0.04059 |
| 12 | 2 | 0.03477 | 4 | 8 | 0.04781 | 9 | 13 | 0.04059 |
| 1 | 3 | 0.03477 | 5 | 8 | 0.04781 | 10 | 13 | 0.04781 |
| 2 | 3 | 0.03477 | 6 | 8 | 0.04059 | 11 | 13 | 0.04781 |
| 3 | 3 | 0.03477 | 7 | 8 | 0.04059 | 12 | 13 | 0.04781 |
| 4 | 3 | 0.03477 | 8 | 8 | 0.04059 | 1 | 14 | 0.04781 |
| 5 | 3 | 0.03477 | 9 | 8 | 0.04059 | 2 | 14 | 0.04781 |
| 6 | 3 | 0.02973 | 10 | 8 | 0.04781 | 3 | 14 | 0.04781 |
| 7 | 3 | 0.02973 | 11 | 8 | 0.04781 | 4 | 14 | 0.04781 |
| 8 | 3 | 0.02973 | 12 | 8 | 0.04781 | 5 | 14 | 0.04781 |
| 9 | 3 | 0.02973 | 1 | 9 | 0.04781 | 6 | 14 | 0.04059 |
| 10 | 3 | 0.03477 | 2 | 9 | 0.04781 | 7 | 14 | 0.04059 |
| 11 | 3 | 0.03477 | 3 | 9 | 0.04781 | 8 | 14 | 0.04059 |
| 12 | 3 | 0.03477 | 4 | 9 | 0.04781 | 9 | 14 | 0.04059 |
| 1 | 4 | 0.03477 | 5 | 9 | 0.04781 | 10 | 14 | 0.04781 |
| 2 | 4 | 0.03477 | 6 | 9 | 0.04059 | 11 | 14 | 0.04781 |
| 3 | 4 | 0.03477 | 7 | 9 | 0.04059 | 12 | 14 | 0.04781 |
| 4 | 4 | 0.03477 | 8 | 9 | 0.04059 | 1 | 15 | 0.04781 |
| 5 | 4 | 0.03477 | 9 | 9 | 0.04059 | 2 | 15 | 0.04781 |
| 6 | 4 | 0.02973 | 10 | 9 | 0.04781 | 3 | 15 | 0.04781 |
| 7 | 4 | 0.02973 | 11 | 9 | 0.04781 | 4 | 15 | 0.04781 |
| 8 | 4 | 0.02973 | 12 | 9 | 0.04781 | 5 | 15 | 0.04781 |
| 9 | 4 | 0.02973 | 1 | 10 | 0.04781 | 6 | 15 | 0.04059 |
| 10 | 4 | 0.03477 | 2 | 10 | 0.04781 | 7 | 15 | 0.04059 |
| 11 | 4 | 0.03477 | 3 | 10 | 0.04781 | 8 | 15 | 0.04059 |
| 12 | 4 | 0.03477 | 4 | 10 | 0.04781 | 9 | 15 | 0.04059 |
| 1 | 5 | 0.03477 | 5 | 10 | 0.04781 | 10 | 15 | 0.04781 |
| 2 | 5 | 0.03477 | 6 | 10 | 0.04059 | 11 | 15 | 0.04781 |
| 3 | 5 | 0.03477 | 7 | 10 | 0.04059 | 12 | 15 | 0.04781 |
| 4 | 5 | 0.03477 | 8 | 10 | 0.04059 | 1 | 16 | 0.04781 |
|  |  |  | 9 | 10 | 0.04059 | 2 | 16 | 0.04781 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 16 | 0.04781 | | 11 | 18 | 0.04781 | | 7 | 21 | 0.02973 |
| 4 | 16 | 0.04781 | | 12 | 18 | 0.04781 | | 8 | 21 | 0.02973 |
| 5 | 16 | 0.04781 | | 1 | 19 | 0.04781 | | 9 | 21 | 0.02973 |
| 6 | 16 | 0.04059 | | 2 | 19 | 0.04781 | | 10 | 21 | 0.03477 |
| 7 | 16 | 0.04059 | | 3 | 19 | 0.04781 | | 11 | 21 | 0.03477 |
| 8 | 16 | 0.04059 | | 4 | 19 | 0.04781 | | 12 | 21 | 0.03477 |
| 9 | 16 | 0.04059 | | 5 | 19 | 0.04781 | | 1 | 22 | 0.03477 |
| 10 | 16 | 0.04781 | | 6 | 19 | 0.04059 | | 2 | 22 | 0.03477 |
| 11 | 16 | 0.04781 | | 7 | 19 | 0.04059 | | 3 | 22 | 0.03477 |
| 12 | 16 | 0.04781 | | 8 | 19 | 0.04059 | | 4 | 22 | 0.03477 |
| 1 | 17 | 0.04781 | | 9 | 19 | 0.04059 | | 5 | 22 | 0.03477 |
| 2 | 17 | 0.04781 | | 10 | 19 | 0.04781 | | 6 | 22 | 0.02973 |
| 3 | 17 | 0.04781 | | 11 | 19 | 0.04781 | | 7 | 22 | 0.02973 |
| 4 | 17 | 0.04781 | | 12 | 19 | 0.04781 | | 8 | 22 | 0.02973 |
| 5 | 17 | 0.04781 | | 1 | 20 | 0.04781 | | 9 | 22 | 0.02973 |
| 6 | 17 | 0.04059 | | 2 | 20 | 0.04781 | | 10 | 22 | 0.03477 |
| 7 | 17 | 0.04059 | | 3 | 20 | 0.04781 | | 11 | 22 | 0.03477 |
| 8 | 17 | 0.04059 | | 4 | 20 | 0.04781 | | 12 | 22 | 0.03477 |
| 9 | 17 | 0.04059 | | 5 | 20 | 0.04781 | | 1 | 23 | 0.03477 |
| 10 | 17 | 0.04781 | | 6 | 20 | 0.04059 | | 2 | 23 | 0.03477 |
| 11 | 17 | 0.04781 | | 7 | 20 | 0.04059 | | 3 | 23 | 0.03477 |
| 12 | 17 | 0.04781 | | 8 | 20 | 0.04059 | | 4 | 23 | 0.03477 |
| 1 | 18 | 0.04781 | | 9 | 20 | 0.04059 | | 5 | 23 | 0.03477 |
| 2 | 18 | 0.04781 | | 10 | 20 | 0.04781 | | 6 | 23 | 0.02973 |
| 3 | 18 | 0.04781 | | 11 | 20 | 0.04781 | | 7 | 23 | 0.02973 |
| 4 | 18 | 0.04781 | | 12 | 20 | 0.04781 | | 8 | 23 | 0.02973 |
| 5 | 18 | 0.04781 | | 1 | 21 | 0.03477 | | 9 | 23 | 0.02973 |
| 6 | 18 | 0.04059 | | 2 | 21 | 0.03477 | | 10 | 23 | 0.03477 |
| 7 | 18 | 0.04059 | | 3 | 21 | 0.03477 | | 11 | 23 | 0.03477 |
| 8 | 18 | 0.04059 | | 4 | 21 | 0.03477 | | 12 | 23 | 0.03477; |
| 9 | 18 | 0.04059 | | 5 | 21 | 0.03477 | | | | |
| 10 | 18 | 0.04781 | | 6 | 21 | 0.02973 | | | | |

## Appendix K

| param | kWh:= | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2019 | 1 | 1 | 0 | 186.00 | | 2019 | 1 | 2 | 12 | 276.00 |
| 2019 | 1 | 1 | 1 | 240.00 | | 2019 | 1 | 2 | 13 | 162.00 |
| 2019 | 1 | 1 | 2 | 144.00 | | 2019 | 1 | 2 | 14 | 258.00 |
| 2019 | 1 | 1 | 3 | 192.00 | | 2019 | 1 | 2 | 15 | 150.00 |
| 2019 | 1 | 1 | 4 | 192.00 | | 2019 | 1 | 2 | 16 | 186.00 |
| 2019 | 1 | 1 | 5 | 252.00 | | 2019 | 1 | 2 | 17 | 186.00 |
| 2019 | 1 | 1 | 6 | 156.00 | | 2019 | 1 | 2 | 18 | 186.00 |
| 2019 | 1 | 1 | 7 | 210.00 | | 2019 | 1 | 2 | 19 | 180.00 |
| 2019 | 1 | 1 | 8 | 204.00 | | 2019 | 1 | 2 | 20 | 186.00 |
| 2019 | 1 | 1 | 9 | 192.00 | | 2019 | 1 | 2 | 21 | 186.00 |
| 2019 | 1 | 1 | 10 | 228.00 | | 2019 | 1 | 2 | 22 | 180.00 |
| 2019 | 1 | 1 | 11 | 150.00 | | 2019 | 1 | 2 | 23 | 168.00 |
| 2019 | 1 | 1 | 12 | 216.00 | | 2019 | 1 | 3 | 0 | 174.00 |
| 2019 | 1 | 1 | 13 | 132.00 | | 2019 | 1 | 3 | 1 | 162.00 |
| 2019 | 1 | 1 | 14 | 192.00 | | 2019 | 1 | 3 | 2 | 156.00 |
| 2019 | 1 | 1 | 15 | 222.00 | | 2019 | 1 | 3 | 3 | 150.00 |
| 2019 | 1 | 1 | 16 | 126.00 | | 2019 | 1 | 3 | 4 | 150.00 |
| 2019 | 1 | 1 | 17 | 204.00 | | 2019 | 1 | 3 | 5 | 204.00 |
| 2019 | 1 | 1 | 18 | 246.00 | | 2019 | 1 | 3 | 6 | 138.00 |
| 2019 | 1 | 1 | 19 | 168.00 | | 2019 | 1 | 3 | 7 | 168.00 |
| 2019 | 1 | 1 | 20 | 126.00 | | 2019 | 1 | 3 | 8 | 174.00 |
| 2019 | 1 | 1 | 21 | 198.00 | | 2019 | 1 | 3 | 9 | 174.00 |
| 2019 | 1 | 1 | 22 | 222.00 | | 2019 | 1 | 3 | 10 | 168.00 |
| 2019 | 1 | 1 | 23 | 114.00 | | 2019 | 1 | 3 | 11 | 162.00 |
| 2019 | 1 | 2 | 0 | 168.00 | | 2019 | 1 | 3 | 12 | 210.00 |
| 2019 | 1 | 2 | 1 | 186.00 | | 2019 | 1 | 3 | 13 | 132.00 |
| 2019 | 1 | 2 | 2 | 198.00 | | 2019 | 1 | 3 | 14 | 222.00 |
| 2019 | 1 | 2 | 3 | 138.00 | | 2019 | 1 | 3 | 15 | 138.00 |
| 2019 | 1 | 2 | 4 | 162.00 | | 2019 | 1 | 3 | 16 | 228.00 |
| 2019 | 1 | 2 | 5 | 216.00 | | 2019 | 1 | 3 | 17 | 132.00 |
| 2019 | 1 | 2 | 6 | 162.00 | | 2019 | 1 | 3 | 18 | 186.00 |
| 2019 | 1 | 2 | 7 | 234.00 | | 2019 | 1 | 3 | 19 | 222.00 |
| 2019 | 1 | 2 | 8 | 288.00 | | 2019 | 1 | 3 | 20 | 186.00 |
| 2019 | 1 | 2 | 9 | 222.00 | | 2019 | 1 | 3 | 21 | 138.00 |
| 2019 | 1 | 2 | 10 | 156.00 | | 2019 | 1 | 3 | 22 | 222.00 |
| 2019 | 1 | 2 | 11 | 222.00 | | 2019 | 1 | 3 | 23 | 120.00 |
| | | | | | | 2019 | 1 | 4 | 0 | 168.00 |

| 2019 | 1 | 4 | 1 | 174.00 |
|---|---|---|---|---|
| 2019 | 1 | 4 | 2 | 204.00 |
| 2019 | 1 | 4 | 3 | 156.00 |
| 2019 | 1 | 4 | 4 | 114.00 |
| 2019 | 1 | 4 | 5 | 162.00 |
| 2019 | 1 | 4 | 6 | 174.00 |
| 2019 | 1 | 4 | 7 | 174.00 |
| 2019 | 1 | 4 | 8 | 174.00 |
| 2019 | 1 | 4 | 9 | 174.00 |
| 2019 | 1 | 4 | 10 | 162.00 |
| 2019 | 1 | 4 | 11 | 162.00 |
| 2019 | 1 | 4 | 12 | 198.00 |
| 2019 | 1 | 4 | 13 | 120.00 |
| 2019 | 1 | 4 | 14 | 150.00 |
| 2019 | 1 | 4 | 15 | 186.00 |
| 2019 | 1 | 4 | 16 | 120.00 |
| 2019 | 1 | 4 | 17 | 162.00 |
| 2019 | 1 | 4 | 18 | 162.00 |
| 2019 | 1 | 4 | 19 | 198.00 |
| 2019 | 1 | 4 | 20 | 120.00 |
| 2019 | 1 | 4 | 21 | 156.00 |
| 2019 | 1 | 4 | 22 | 198.00 |
| 2019 | 1 | 4 | 23 | 108.00 |
| 2019 | 1 | 5 | 0 | 150.00 |
| 2019 | 1 | 5 | 1 | 144.00 |
| 2019 | 1 | 5 | 2 | 186.00 |
| 2019 | 1 | 5 | 3 | 108.00 |
| 2019 | 1 | 5 | 4 | 144.00 |
| 2019 | 1 | 5 | 5 | 198.00 |
| 2019 | 1 | 5 | 6 | 120.00 |
| 2019 | 1 | 5 | 7 | 162.00 |
| 2019 | 1 | 5 | 8 | 162.00 |
| 2019 | 1 | 5 | 9 | 156.00 |
| 2019 | 1 | 5 | 10 | 156.00 |
| 2019 | 1 | 5 | 11 | 150.00 |
| 2019 | 1 | 5 | 12 | 150.00 |
| 2019 | 1 | 5 | 13 | 150.00 |
| 2019 | 1 | 5 | 14 | 156.00 |
| 2019 | 1 | 5 | 15 | 150.00 |
| 2019 | 1 | 5 | 16 | 156.00 |
| 2019 | 1 | 5 | 17 | 198.00 |
| 2019 | 1 | 5 | 18 | 120.00 |
| 2019 | 1 | 5 | 19 | 156.00 |
| 2019 | 1 | 5 | 20 | 156.00 |
| 2019 | 1 | 5 | 21 | 156.00 |
| 2019 | 1 | 5 | 22 | 156.00 |
| 2019 | 1 | 5 | 23 | 144.00 |
| 2019 | 1 | 6 | 0 | 180.00 |
| 2019 | 1 | 6 | 1 | 108.00 |
| 2019 | 1 | 6 | 2 | 144.00 |
| 2019 | 1 | 6 | 3 | 186.00 |
| 2019 | 1 | 6 | 4 | 108.00 |
| 2019 | 1 | 6 | 5 | 156.00 |
| 2019 | 1 | 6 | 6 | 162.00 |
| 2019 | 1 | 6 | 7 | 198.00 |
| 2019 | 1 | 6 | 8 | 120.00 |
| 2019 | 1 | 6 | 9 | 156.00 |
| 2019 | 1 | 6 | 10 | 186.00 |
| 2019 | 1 | 6 | 11 | 120.00 |
| 2019 | 1 | 6 | 12 | 150.00 |
| 2019 | 1 | 6 | 13 | 192.00 |
| 2019 | 1 | 6 | 14 | 108.00 |
| 2019 | 1 | 6 | 15 | 150.00 |
| 2019 | 1 | 6 | 16 | 150.00 |
| 2019 | 1 | 6 | 17 | 192.00 |
| 2019 | 1 | 6 | 18 | 120.00 |
| 2019 | 1 | 6 | 19 | 168.00 |
| 2019 | 1 | 6 | 20 | 210.00 |
| 2019 | 1 | 6 | 21 | 120.00 |
| 2019 | 1 | 6 | 22 | 162.00 |
| 2019 | 1 | 6 | 23 | 144.00 |
| 2019 | 1 | 7 | 0 | 186.00 |
| 2019 | 1 | 7 | 1 | 150.00 |
| 2019 | 1 | 7 | 2 | 108.00 |
| 2019 | 1 | 7 | 3 | 144.00 |
| 2019 | 1 | 7 | 4 | 192.00 |
| 2019 | 1 | 7 | 5 | 114.00 |
| 2019 | 1 | 7 | 6 | 174.00 |
| 2019 | 1 | 7 | 7 | 162.00 |
| 2019 | 1 | 7 | 8 | 162.00 |
| 2019 | 1 | 7 | 9 | 162.00 |
| 2019 | 1 | 7 | 10 | 198.00 |
| 2019 | 1 | 7 | 11 | 126.00 |
| 2019 | 1 | 7 | 12 | 168.00 |
| 2019 | 1 | 7 | 13 | 210.00 |
| 2019 | 1 | 7 | 14 | 144.00 |
| 2019 | 1 | 7 | 15 | 192.00 |
| 2019 | 1 | 7 | 16 | 174.00 |
| 2019 | 1 | 7 | 17 | 168.00 |
| 2019 | 1 | 7 | 18 | 168.00 |
| 2019 | 1 | 7 | 19 | 168.00 |
| 2019 | 1 | 7 | 20 | 204.00 |
| 2019 | 1 | 7 | 21 | 120.00 |

| 2019 | 1 | 7 | 22 | 168.00 |
|---|---|---|---|---|
| 2019 | 1 | 7 | 23 | 150.00 |
| 2019 | 1 | 8 | 0 | 144.00 |
| 2019 | 1 | 8 | 1 | 132.00 |
| 2019 | 1 | 8 | 2 | 168.00 |
| 2019 | 1 | 8 | 3 | 102.00 |
| 2019 | 1 | 8 | 4 | 138.00 |
| 2019 | 1 | 8 | 5 | 186.00 |
| 2019 | 1 | 8 | 6 | 150.00 |
| 2019 | 1 | 8 | 7 | 114.00 |
| 2019 | 1 | 8 | 8 | 162.00 |
| 2019 | 1 | 8 | 9 | 162.00 |
| 2019 | 1 | 8 | 10 | 156.00 |
| 2019 | 1 | 8 | 11 | 156.00 |
| 2019 | 1 | 8 | 12 | 198.00 |
| 2019 | 1 | 8 | 13 | 156.00 |
| 2019 | 1 | 8 | 14 | 120.00 |
| 2019 | 1 | 8 | 15 | 156.00 |
| 2019 | 1 | 8 | 16 | 156.00 |
| 2019 | 1 | 8 | 17 | 156.00 |
| 2019 | 1 | 8 | 18 | 150.00 |
| 2019 | 1 | 8 | 19 | 144.00 |
| 2019 | 1 | 8 | 20 | 144.00 |
| 2019 | 1 | 8 | 21 | 186.00 |
| 2019 | 1 | 8 | 22 | 108.00 |
| 2019 | 1 | 8 | 23 | 132.00 |
| 2019 | 1 | 9 | 0 | 168.00 |
| 2019 | 1 | 9 | 1 | 96.00 |
| 2019 | 1 | 9 | 2 | 132.00 |
| 2019 | 1 | 9 | 3 | 126.00 |
| 2019 | 1 | 9 | 4 | 132.00 |
| 2019 | 1 | 9 | 7 | 132.00 |
| 2019 | 1 | 9 | 8 | 258.00 |
| 2019 | 1 | 9 | 9 | 150.00 |
| 2019 | 1 | 9 | 10 | 192.00 |
| 2019 | 1 | 9 | 11 | 186.00 |
| 2019 | 1 | 9 | 12 | 228.00 |
| 2019 | 1 | 9 | 13 | 168.00 |
| 2019 | 1 | 9 | 14 | 120.00 |
| 2019 | 1 | 9 | 15 | 162.00 |
| 2019 | 1 | 9 | 16 | 162.00 |
| 2019 | 1 | 9 | 17 | 198.00 |
| 2019 | 1 | 9 | 18 | 120.00 |
| 2019 | 1 | 9 | 19 | 150.00 |
| 2019 | 1 | 9 | 20 | 156.00 |
| 2019 | 1 | 9 | 21 | 150.00 |
| 2019 | 1 | 9 | 22 | 150.00 |
| 2019 | 1 | 9 | 23 | 144.00 |
| 2019 | 1 | 10 | 0 | 138.00 |
| 2019 | 1 | 10 | 1 | 168.00 |
| 2019 | 1 | 10 | 2 | 102.00 |
| 2019 | 1 | 10 | 3 | 138.00 |
| … | | | | |
| 2020 | 7 | 1 | 0 | 176.80 |
| 2020 | 7 | 1 | 1 | 103.64 |
| 2020 | 7 | 1 | 2 | 182.89 |
| 2020 | 7 | 1 | 3 | 188.99 |
| 2020 | 7 | 1 | 4 | 237.76 |
| 2020 | 7 | 1 | 5 | 140.22 |
| 2020 | 7 | 1 | 6 | 188.99 |
| 2020 | 7 | 1 | 7 | 188.99 |
| 2020 | 7 | 1 | 8 | 237.76 |
| 2020 | 7 | 1 | 9 | 140.22 |
| 2020 | 7 | 1 | 10 | 195.08 |
| 2020 | 7 | 1 | 11 | 188.99 |
| 2020 | 7 | 1 | 12 | 243.86 |
| 2020 | 7 | 1 | 13 | 201.18 |
| 2020 | 7 | 1 | 14 | 152.41 |
| 2020 | 7 | 1 | 15 | 201.18 |
| 2020 | 7 | 1 | 16 | 201.18 |
| 2020 | 7 | 1 | 17 | 207.28 |
| 2020 | 7 | 1 | 18 | 262.14 |
| 2020 | 7 | 1 | 19 | 152.41 |
| 2020 | 7 | 1 | 20 | 195.08 |
| 2020 | 7 | 1 | 21 | 182.89 |
| 2020 | 7 | 1 | 22 | 237.76 |
| 2020 | 7 | 1 | 23 | 182.89 |
| 2020 | 7 | 2 | 0 | 134.12 |
| 2020 | 7 | 2 | 1 | 182.89 |
| 2020 | 7 | 2 | 2 | 195.08 |
| 2020 | 7 | 2 | 3 | 201.18 |
| 2020 | 7 | 2 | 4 | 195.08 |
| 2020 | 7 | 2 | 5 | 201.18 |
| 2020 | 7 | 2 | 6 | 201.18 |
| 2020 | 7 | 2 | 7 | 195.08 |
| 2020 | 7 | 2 | 8 | 201.18 |
| 2020 | 7 | 2 | 9 | 195.08 |
| 2020 | 7 | 2 | 10 | 195.08 |
| 2020 | 7 | 2 | 11 | 195.08 |
| 2020 | 7 | 2 | 12 | 195.08 |
| … | … | … | … | … |

## Appendix L

| | | | | | | |
|---|---|---|---|---|---|---|
| 2019 | 1 | 265.2 | | 2021 | 1 | 274 |
| 2019 | 2 | 254.4 | | 2021 | 2 | 257 |
| 2019 | 3 | 266.4 | | 2021 | 3 | 274 |
| 2019 | 4 | 276.6 | | 2021 | 4 | 271 |
| 2019 | 5 | 267 | | 2021 | 5 | 264 |
| 2019 | 6 | 260 | | 2021 | 6 | 255 |
| 2019 | 7 | 260 | | 2021 | 7 | 257 |
| 2019 | 8 | 258 | | 2021 | 8 | 269 |
| 2019 | 9 | 271 | | 2021 | 9 | 272 |
| 2019 | 10 | 269 | | 2021 | 10 | 258 |
| 2019 | 11 | 256 | | 2021 | 11 | 275 |
| 2019 | 12 | 265 | | 2021 | 12 | 257 |
| 2020 | 1 | 258 | | 2022 | 1 | 275 |
| 2020 | 2 | 266 | | 2022 | 2 | 278 |
| 2020 | 3 | 273 | | 2022 | 3 | 265 |
| 2020 | 4 | 263 | | 2022 | 4 | 276 |
| 2020 | 5 | 255 | | 2022 | 5 | 274 |
| 2020 | 6 | 264 | | 2022 | 6 | 271 |
| 2020 | 7 | 260 | | 2022 | 7 | 275 |
| 2020 | 8 | 268 | | 2022 | 8 | 284 |
| 2020 | 9 | 274 | | 2022 | 9 | 265 |
| 2020 | 10 | 260 | | 2022 | 10 | 281 |
| 2020 | 11 | 261 | | 2022 | 11 | 273 |
| 2020 | 12 | 275 | | 2022 | 12 | 266; |

## Appendix M

| param | kWhn:= | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 0 | 193.11 | | 1 | 3 | 8 | 180.65 |
| 1 | 1 | 1 | 249.18 | | 1 | 3 | 9 | 180.65 |
| 1 | 1 | 2 | 149.51 | | 1 | 3 | 10 | 174.42 |
| 1 | 1 | 3 | 199.34 | | 1 | 3 | 11 | 168.19 |
| 1 | 1 | 4 | 199.34 | | 1 | 3 | 12 | 218.03 |
| 1 | 1 | 5 | 261.64 | | 1 | 3 | 13 | 137.05 |
| 1 | 1 | 6 | 161.97 | | 1 | 3 | 14 | 230.49 |
| 1 | 1 | 7 | 218.03 | | 1 | 3 | 15 | 143.28 |
| 1 | 1 | 8 | 211.8 | | 1 | 3 | 16 | 236.72 |
| 1 | 1 | 9 | 199.34 | | 1 | 3 | 17 | 137.05 |
| 1 | 1 | 10 | 236.72 | | 1 | 3 | 18 | 193.11 |
| 1 | 1 | 11 | 155.74 | | 1 | 3 | 19 | 230.49 |
| 1 | 1 | 12 | 224.26 | | 1 | 3 | 20 | 193.11 |
| 1 | 1 | 13 | 137.05 | | 1 | 3 | 21 | 143.28 |
| 1 | 1 | 14 | 199.34 | | 1 | 3 | 22 | 230.49 |
| 1 | 1 | 15 | 230.49 | | 1 | 3 | 23 | 124.59 |
| 1 | 1 | 16 | 130.82 | | 1 | 4 | 0 | 174.42 |
| 1 | 1 | 17 | 211.8 | | 1 | 4 | 1 | 180.65 |
| 1 | 1 | 18 | 255.41 | | 1 | 4 | 2 | 211.8 |
| 1 | 1 | 19 | 174.42 | | 1 | 4 | 3 | 161.97 |
| 1 | 1 | 20 | 130.82 | | 1 | 4 | 4 | 118.36 |
| 1 | 1 | 21 | 205.57 | | 1 | 4 | 5 | 168.19 |
| 1 | 1 | 22 | 230.49 | | 1 | 4 | 6 | 180.65 |
| 1 | 1 | 23 | 118.36 | | 1 | 4 | 7 | 180.65 |
| 1 | 2 | 0 | 174.42 | | 1 | 4 | 8 | 180.65 |
| 1 | 2 | 1 | 193.11 | | 1 | 4 | 9 | 180.65 |
| 1 | 2 | 2 | 205.57 | | 1 | 4 | 10 | 168.19 |
| 1 | 2 | 3 | 143.28 | | 1 | 4 | 11 | 168.19 |
| 1 | 2 | 4 | 168.19 | | 1 | 4 | 12 | 205.57 |
| 1 | 2 | 5 | 224.26 | | 1 | 4 | 13 | 124.59 |
| 1 | 2 | 6 | 168.19 | | 1 | 4 | 14 | 155.74 |
| 1 | 2 | 7 | 242.95 | | 1 | 4 | 15 | 193.11 |
| 1 | 2 | 8 | 299.01 | | 1 | 4 | 16 | 124.59 |
| 1 | 2 | 9 | 230.49 | | 1 | 4 | 17 | 168.19 |
| 1 | 2 | 10 | 161.97 | | 1 | 4 | 18 | 168.19 |
| 1 | 2 | 11 | 230.49 | | 1 | 4 | 19 | 205.57 |
| 1 | 2 | 12 | 286.55 | | 1 | 4 | 20 | 124.59 |
| 1 | 2 | 13 | 168.19 | | 1 | 4 | 21 | 161.97 |
| 1 | 2 | 14 | 267.87 | | 1 | 4 | 22 | 205.57 |
| 1 | 2 | 15 | 155.74 | | 1 | 4 | 23 | 112.13 |
| 1 | 2 | 16 | 193.11 | | 1 | 5 | 0 | 155.74 |
| 1 | 2 | 17 | 193.11 | | 1 | 5 | 1 | 149.51 |
| 1 | 2 | 18 | 193.11 | | 1 | 5 | 2 | 193.11 |
| 1 | 2 | 19 | 186.88 | | 1 | 5 | 3 | 112.13 |
| 1 | 2 | 20 | 193.11 | | 1 | 5 | 4 | 149.51 |
| 1 | 2 | 21 | 193.11 | | 1 | 5 | 5 | 205.57 |
| 1 | 2 | 22 | 186.88 | | 1 | 5 | 6 | 124.59 |
| 1 | 2 | 23 | 174.42 | | 1 | 5 | 7 | 168.19 |
| 1 | 3 | 0 | 180.65 | | 1 | 5 | 8 | 168.19 |
| 1 | 3 | 1 | 168.19 | | 1 | 5 | 9 | 161.97 |
| 1 | 3 | 2 | 161.97 | | 1 | 5 | 10 | 161.97 |
| 1 | 3 | 3 | 155.74 | | 1 | 5 | 11 | 155.74 |
| 1 | 3 | 4 | 155.74 | | 1 | 5 | 12 | 155.74 |
| 1 | 3 | 5 | 211.8 | | 1 | 5 | 13 | 155.74 |
| 1 | 3 | 6 | 143.28 | | 1 | 5 | 14 | 161.97 |
| 1 | 3 | 7 | 174.42 | | 1 | 5 | 15 | 155.74 |
| | | | | | 1 | 5 | 16 | 161.97 |

| | | | |
|---|---|---|---|
| 1 | 5 | 17 | 205.57 |
| 1 | 5 | 18 | 124.59 |
| 1 | 5 | 19 | 161.97 |
| 1 | 5 | 20 | 161.97 |
| 1 | 5 | 21 | 161.97 |
| 1 | 5 | 22 | 161.97 |
| 1 | 5 | 23 | 149.51 |
| 1 | 6 | 0 | 186.88 |
| 1 | 6 | 1 | 112.13 |
| 1 | 6 | 2 | 149.51 |
| 1 | 6 | 3 | 193.11 |
| 1 | 6 | 4 | 112.13 |
| 1 | 6 | 5 | 161.97 |
| 1 | 6 | 6 | 168.19 |
| 1 | 6 | 7 | 205.57 |
| 1 | 6 | 8 | 124.59 |
| 1 | 6 | 9 | 161.97 |
| 1 | 6 | 10 | 193.11 |
| 1 | 6 | 11 | 124.59 |
| 1 | 6 | 12 | 155.74 |
| 1 | 6 | 13 | 199.34 |
| 1 | 6 | 14 | 112.13 |
| 1 | 6 | 15 | 155.74 |
| 1 | 6 | 16 | 155.74 |
| 1 | 6 | 17 | 199.34 |
| 1 | 6 | 18 | 124.59 |
| 1 | 6 | 19 | 174.42 |
| 1 | 6 | 20 | 218.03 |
| 1 | 6 | 21 | 124.59 |
| 1 | 6 | 22 | 168.19 |
| 1 | 6 | 23 | 149.51 |
| 1 | 7 | 0 | 193.11 |
| 1 | 7 | 1 | 155.74 |
| 1 | 7 | 2 | 112.13 |
| 1 | 7 | 3 | 149.51 |
| 1 | 7 | 4 | 199.34 |
| 1 | 7 | 5 | 118.36 |
| 1 | 7 | 6 | 180.65 |
| 1 | 7 | 7 | 168.19 |
| 1 | 7 | 8 | 168.19 |
| 1 | 7 | 9 | 168.19 |
| 1 | 7 | 10 | 205.57 |
| 1 | 7 | 11 | 130.82 |
| 1 | 7 | 12 | 174.42 |
| 1 | 7 | 13 | 218.03 |
| 1 | 7 | 14 | 149.51 |
| 1 | 7 | 15 | 199.34 |
| 1 | 7 | 16 | 180.65 |
| 1 | 7 | 17 | 174.42 |
| 1 | 7 | 18 | 174.42 |
| 1 | 7 | 19 | 174.42 |
| 1 | 7 | 20 | 211.8 |
| 1 | 7 | 21 | 124.59 |
| 1 | 7 | 22 | 174.42 |
| 1 | 7 | 23 | 155.74 |
| 1 | 8 | 0 | 149.51 |
| 1 | 8 | 1 | 137.05 |
| 1 | 8 | 2 | 174.42 |
| 1 | 8 | 3 | 105.9 |
| 1 | 8 | 4 | 143.28 |
| 1 | 8 | 5 | 193.11 |
| 1 | 8 | 6 | 155.74 |
| 1 | 8 | 7 | 118.36 |
| 1 | 8 | 8 | 168.19 |
| 1 | 8 | 9 | 168.19 |
| 1 | 8 | 10 | 161.97 |
| 1 | 8 | 11 | 161.97 |
| 1 | 8 | 12 | 205.57 |
| 1 | 8 | 13 | 161.97 |
| 1 | 8 | 14 | 124.59 |
| 1 | 8 | 15 | 161.97 |
| 1 | 8 | 16 | 161.97 |
| 1 | 8 | 17 | 161.97 |
| 1 | 8 | 18 | 155.74 |
| 1 | 8 | 19 | 149.51 |
| 1 | 8 | 20 | 149.51 |
| 1 | 8 | 21 | 193.11 |
| 1 | 8 | 22 | 112.13 |
| 1 | 8 | 23 | 137.05 |
| 1 | 9 | 0 | 174.42 |
| 1 | 9 | 1 | 99.67 |
| 1 | 9 | 2 | 137.05 |
| 1 | 9 | 3 | 130.82 |
| 1 | 9 | 4 | 137.05 |
| 1 | 9 | 5 | 137.05 |
| 1 | 9 | 6 | 267.87 |
| 1 | 9 | 7 | 155.74 |
| 1 | 9 | 8 | 199.34 |
| 1 | 9 | 9 | 193.11 |
| 1 | 9 | 10 | 236.72 |
| 1 | 9 | 11 | 174.42 |
| 1 | 9 | 12 | 124.59 |
| 1 | 9 | 13 | 168.19 |
| 1 | 9 | 14 | 168.19 |
| 1 | 9 | 15 | 205.57 |
| 1 | 9 | 16 | 124.59 |
| 1 | 9 | 17 | 155.74 |
| 1 | 9 | 18 | 161.97 |
| 1 | 9 | 19 | 155.74 |
| 1 | 9 | 20 | 155.74 |
| 1 | 9 | 21 | 149.51 |
| 1 | 9 | 22 | 143.28 |
| 1 | 9 | 23 | 174.42 |
| 1 | 10 | 0 | 105.9 |
| 1 | 10 | 1 | 143.28 |
| 1 | 10 | 2 | 180.65 |
| 1 | 10 | 3 | 112.13 |
| 1 | 10 | 4 | 161.97 |
| 1 | 10 | 5 | 161.97 |
| 1 | 10 | 6 | 168.19 |
| 1 | 10 | 7 | 168.19 |
| 1 | 10 | 8 | 168.19 |
| 1 | 10 | 9 | 218.03 |
| 1 | 10 | 10 | 168.19 |
| 1 | 10 | 11 | 130.82 |
| 1 | 10 | 12 | 168.19 |
| 1 | 10 | 13 | 211.8 |
| 1 | 10 | 14 | 130.82 |
| 1 | 10 | 15 | 161.97 |
| 1 | 10 | 16 | 161.97 |
| 1 | 10 | 17 | 199.34 |
| 1 | 10 | 18 | 118.36 |
| 1 | 10 | 19 | 161.97 |
| 1 | 10 | 20 | 199.34 |
| 1 | 10 | 21 | 112.13 |
| 1 | 10 | 22 | 143.28 |
| 1 | 10 | 23 | 149.51 |
| 1 | 11 | 0 | 137.05 |
| 1 | 11 | 1 | 143.28 |
| 1 | 11 | 2 | 180.65 |
| 1 | 11 | 3 | 130.82 |
| 1 | 11 | 4 | 199.34 |
| 1 | 11 | 5 | 180.65 |
| 1 | 11 | 6 | 199.34 |
| 1 | 11 | 7 | 180.65 |
| 1 | 11 | 8 | 193.11 |
| 1 | 11 | 9 | 186.88 |
| 1 | 11 | 10 | 242.95 |
| 1 | 11 | 11 | 186.88 |
| 1 | 11 | 12 | 149.51 |
| 1 | 11 | 13 | 205.57 |
| 1 | 11 | 14 | 255.41 |
| 1 | 11 | 15 | 155.74 |
| 1 | 11 | 16 | 199.34 |
| 1 | 11 | 17 | 199.34 |
| 1 | 11 | 18 | 242.95 |
| 1 | 11 | 19 | 199.34 |
| 1 | 11 | 20 | 137.05 |
| 1 | 11 | 21 | 180.65 |
| 1 | 11 | 22 | 218.03 |
| 1 | 11 | 23 | 130.82 |
| 1 | 12 | 0 | 174.42 |
| 1 | 12 | 1 | 174.42 |
| 1 | 12 | 2 | 168.19 |
| 1 | 12 | 3 | 180.65 |
| 1 | 12 | 4 | 236.72 |
| 1 | 12 | 5 | 143.28 |
| 1 | 12 | 6 | 186.88 |
| 1 | 12 | 7 | 168.19 |
| 1 | 12 | 8 | 193.11 |
| 1 | 12 | 9 | 112.13 |
| 1 | 12 | 10 | 193.11 |
| 1 | 12 | 11 | 155.74 |
| 1 | 12 | 12 | 155.74 |
| 1 | 12 | 13 | 118.36 |
| 1 | 12 | 14 | 186.88 |
| 1 | 12 | 15 | 230.49 |
| 1 | 12 | 16 | 143.28 |
| 1 | 12 | 17 | 186.88 |
| 1 | 12 | 18 | 230.49 |
| 1 | 12 | 19 | 143.28 |
| 1 | 12 | 20 | 186.88 |
| 1 | 12 | 21 | 137.05 |
| 1 | 12 | 22 | 174.42 |
| 1 | 12 | 23 | 105.9 |
| 1 | 13 | 0 | 137.05 |
| 1 | 13 | 1 | 174.42 |
| 1 | 13 | 2 | 143.28 |
| 1 | 13 | 3 | 112.13 |
| 1 | 13 | 4 | 155.74 |
| 1 | 13 | 5 | 199.34 |
| 1 | 13 | 6 | 130.82 |
| 1 | 13 | 7 | 168.19 |
| 1 | 13 | 8 | 155.74 |
| 1 | 13 | 9 | 186.88 |
| 1 | 13 | 10 | 149.51 |
| 1 | 13 | 11 | 112.13 |
| 1 | 13 | 12 | 186.88 |
| 1 | 13 | 13 | 112.13 |
| 1 | 13 | 14 | 168.19 |
| 1 | 13 | 15 | 168.19 |
| 1 | 13 | 16 | 155.74 |
| 1 | 13 | 17 | 155.74 |
| 1 | 13 | 18 | 161.97 |
| 1 | 13 | 19 | 199.34 |
| 1 | 13 | 20 | 118.36 |
| 1 | 13 | 21 | 149.51 |
| 1 | 13 | 22 | 143.28 |
| 1 | 13 | 23 | 174.42 |
| 1 | 14 | 0 | 105.9 |
| 1 | 14 | 1 | 137.05 |
| 1 | 14 | 2 | 143.28 |
| 1 | 14 | 3 | 149.51 |
| 1 | 14 | 4 | 205.57 |
| 1 | 14 | 5 | 124.59 |
| 1 | 14 | 6 | 168.19 |
| 1 | 14 | 7 | 168.19 |
| 1 | 14 | 8 | 218.03 |
| 1 | 14 | 9 | 137.05 |
| 1 | 14 | 10 | 211.8 |
| 1 | 14 | 11 | 174.42 |
| 1 | 14 | 12 | 130.82 |
| 1 | 14 | 13 | 168.19 |
| 1 | 14 | 14 | 174.42 |
| 1 | 14 | 15 | 186.88 |
| 1 | 14 | 16 | 168.19 |
| 1 | 14 | 17 | 168.19 |
| 1 | 14 | 18 | 168.19 |
| 1 | 14 | 19 | 205.57 |
| 1 | 14 | 20 | 124.59 |
| 1 | 14 | 21 | 149.51 |
| 1 | 14 | 22 | 180.65 |
| 1 | 14 | 23 | 180.65 |
| 1 | 15 | 0 | 143.28 |
| 1 | 15 | 1 | 105.9 |
| 1 | 15 | 2 | 149.51 |
| 1 | 15 | 3 | 149.51 |
| 1 | 15 | 4 | 174.42 |
| 1 | 15 | 5 | 174.42 |
| 1 | 15 | 6 | 218.03 |
| 1 | 15 | 7 | 130.82 |
| 1 | 15 | 8 | 174.42 |
| 1 | 15 | 9 | 180.65 |
| 1 | 15 | 10 | 218.03 |
| 1 | 15 | 11 | 130.82 |
| 1 | 15 | 12 | 180.65 |
| 1 | 15 | 13 | 186.88 |
| 1 | 15 | 14 | 168.19 |
| 1 | 15 | 15 | 180.65 |
| 1 | 15 | 16 | 174.42 |
| 1 | 15 | 17 | 174.42 |
| 1 | 15 | 18 | 168.19 |

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|---|---|---|---|---|---|---|---|
| 1 | 15 | 19 | 168.19 | 1 | 19 | 6 | 174.42 |
| 1 | 15 | 20 | 211.8 | 1 | 19 | 7 | 124.59 |
| 1 | 15 | 21 | 112.13 | 1 | 19 | 8 | 211.8 |
| 1 | 15 | 22 | 155.74 | 1 | 19 | 9 | 124.59 |
| 1 | 15 | 23 | 143.28 | 1 | 19 | 10 | 211.8 |
| 1 | 16 | 0 | 143.28 | 1 | 19 | 11 | 174.42 |
| 1 | 16 | 1 | 143.28 | 1 | 19 | 12 | 124.59 |
| 1 | 16 | 2 | 180.65 | 1 | 19 | 13 | 218.03 |
| 1 | 16 | 3 | 118.36 | 1 | 19 | 14 | 168.19 |
| 1 | 16 | 4 | 168.19 | 1 | 19 | 15 | 118.36 |
| 1 | 16 | 5 | 168.19 | 1 | 19 | 16 | 224.26 |
| 1 | 16 | 6 | 174.42 | 1 | 19 | 17 | 137.05 |
| 1 | 16 | 7 | 193.11 | 1 | 19 | 18 | 180.65 |
| 1 | 16 | 8 | 186.88 | 1 | 19 | 19 | 205.57 |
| 1 | 16 | 9 | 193.11 | 1 | 19 | 20 | 155.74 |
| 1 | 16 | 10 | 242.95 | 1 | 19 | 21 | 143.28 |
| 1 | 16 | 11 | 143.28 | 1 | 19 | 22 | 105.9 |
| 1 | 16 | 12 | 186.88 | 1 | 19 | 23 | 143.28 |
| 1 | 16 | 13 | 193.11 | 1 | 20 | 0 | 143.28 |
| 1 | 16 | 14 | 193.11 | 1 | 20 | 1 | 143.28 |
| 1 | 16 | 15 | 186.88 | 1 | 20 | 2 | 143.28 |
| 1 | 16 | 16 | 180.65 | 1 | 20 | 3 | 149.51 |
| 1 | 16 | 17 | 199.34 | 1 | 20 | 4 | 168.19 |
| 1 | 16 | 18 | 224.26 | 1 | 20 | 5 | 155.74 |
| 1 | 16 | 19 | 130.82 | 1 | 20 | 6 | 155.74 |
| 1 | 16 | 20 | 174.42 | 1 | 20 | 7 | 155.74 |
| 1 | 16 | 21 | 205.57 | 1 | 20 | 8 | 193.11 |
| 1 | 16 | 22 | 118.36 | 1 | 20 | 9 | 155.74 |
| 1 | 16 | 23 | 155.74 | 1 | 20 | 10 | 149.51 |
| 1 | 17 | 0 | 155.74 | 1 | 20 | 11 | 155.74 |
| 1 | 17 | 1 | 193.11 | 1 | 20 | 12 | 112.13 |
| 1 | 17 | 2 | 118.36 | 1 | 20 | 13 | 199.34 |
| 1 | 17 | 3 | 161.97 | 1 | 20 | 14 | 112.13 |
| 1 | 17 | 4 | 186.88 | 1 | 20 | 15 | 161.97 |
| 1 | 17 | 5 | 174.42 | 1 | 20 | 16 | 193.11 |
| 1 | 17 | 6 | 180.65 | 1 | 20 | 17 | 161.97 |
| 1 | 17 | 7 | 186.88 | 1 | 20 | 18 | 118.36 |
| 1 | 17 | 8 | 186.88 | 1 | 20 | 19 | 193.11 |
| 1 | 17 | 9 | 180.65 | 1 | 20 | 20 | 118.36 |
| 1 | 17 | 10 | 236.72 | 1 | 20 | 21 | 180.65 |
| 1 | 17 | 11 | 137.05 | 1 | 20 | 22 | 149.51 |
| 1 | 17 | 12 | 186.88 | 1 | 20 | 23 | 155.74 |
| 1 | 17 | 13 | 186.88 | 1 | 21 | 0 | 143.28 |
| 1 | 17 | 14 | 180.65 | 1 | 21 | 1 | 105.9 |
| 1 | 17 | 15 | 230.49 | 1 | 21 | 2 | 143.28 |
| 1 | 17 | 16 | 137.05 | 1 | 21 | 3 | 193.11 |
| 1 | 17 | 17 | 180.65 | 1 | 21 | 4 | 168.19 |
| 1 | 17 | 18 | 218.03 | 1 | 21 | 5 | 168.19 |
| 1 | 17 | 19 | 130.82 | 1 | 21 | 6 | 161.97 |
| 1 | 17 | 20 | 174.42 | 1 | 21 | 7 | 124.59 |
| 1 | 17 | 21 | 205.57 | 1 | 21 | 8 | 168.19 |
| 1 | 17 | 22 | 124.59 | 1 | 21 | 9 | 161.97 |
| 1 | 17 | 23 | 168.19 | 1 | 21 | 10 | 205.57 |
| 1 | 18 | 0 | 161.97 | 1 | 21 | 11 | 124.59 |
| 1 | 18 | 1 | 155.74 | 1 | 21 | 12 | 168.19 |
| 1 | 18 | 2 | 155.74 | 1 | 21 | 13 | 186.88 |
| 1 | 18 | 3 | 161.97 | 1 | 21 | 14 | 168.19 |
| 1 | 18 | 4 | 224.26 | 1 | 21 | 15 | 168.19 |
| 1 | 18 | 5 | 180.65 | 1 | 21 | 16 | 168.19 |
| 1 | 18 | 6 | 137.05 | 1 | 21 | 17 | 161.97 |
| 1 | 18 | 7 | 186.88 | 1 | 21 | 18 | 161.97 |
| 1 | 18 | 8 | 186.88 | 1 | 21 | 19 | 230.49 |
| 1 | 18 | 9 | 186.88 | 1 | 21 | 20 | 149.51 |
| 1 | 18 | 10 | 299.01 | 1 | 21 | 21 | 193.11 |
| 1 | 18 | 11 | 193.11 | 1 | 21 | 22 | 230.49 |
| 1 | 18 | 12 | 255.41 | 1 | 21 | 23 | 137.05 |
| 1 | 18 | 13 | 230.49 | 1 | 22 | 0 | 186.88 |
| 1 | 18 | 14 | 255.41 | 1 | 22 | 1 | 224.26 |
| 1 | 18 | 15 | 267.87 | 1 | 22 | 2 | 137.05 |
| 1 | 18 | 16 | 180.65 | 1 | 22 | 3 | 193.11 |
| 1 | 18 | 17 | 180.65 | 1 | 22 | 4 | 205.57 |
| 1 | 18 | 18 | 137.05 | 1 | 22 | 5 | 211.8 |
| 1 | 18 | 19 | 224.26 | 1 | 22 | 6 | 199.34 |
| 1 | 18 | 20 | 137.05 | 1 | 22 | 7 | 199.34 |
| 1 | 18 | 21 | 161.97 | 1 | 22 | 8 | 274.1 |
| 1 | 18 | 22 | 236.72 | 1 | 22 | 9 | 211.8 |
| 1 | 18 | 23 | 155.74 | 1 | 22 | 10 | 218.03 |
| 1 | 19 | 0 | 224.26 | 1 | 22 | 11 | 161.97 |
| 1 | 19 | 1 | 174.42 | 1 | 22 | 12 | 261.64 |
| 1 | 19 | 2 | 118.36 | 1 | 22 | 13 | 149.51 |
| 1 | 19 | 3 | 249.18 | 1 | 22 | 14 | 168.19 |
| 1 | 19 | 4 | 149.51 | 1 | 22 | 15 | 174.42 |
| 1 | 19 | 5 | 224.26 | ... | ... | ... | ... |

## Appendix N

param   maxkWn:=
1       275
2       278
3       265
4       276
5       274
6       271
7       275
8       284
9       265
10      281
11      273
12      266;

## Appendix O

```
model optimization.mod;
data optimization.dat;
data kWh.dat;
data kWhn.dat;
data maxkW.dat;
data rate.dat;
solve;
display L;
display F;
display Cost;
```


## Appendix P

| Imperial | Metric |
|---|---|
| 1 foot | 0.3048 m |
| 1 square foot | 0.0929 square m |
| 1 lb | 0.4636 kg |

| Currency Conversion | |
|---|---|
| 1 dollar | 0.89 euros |