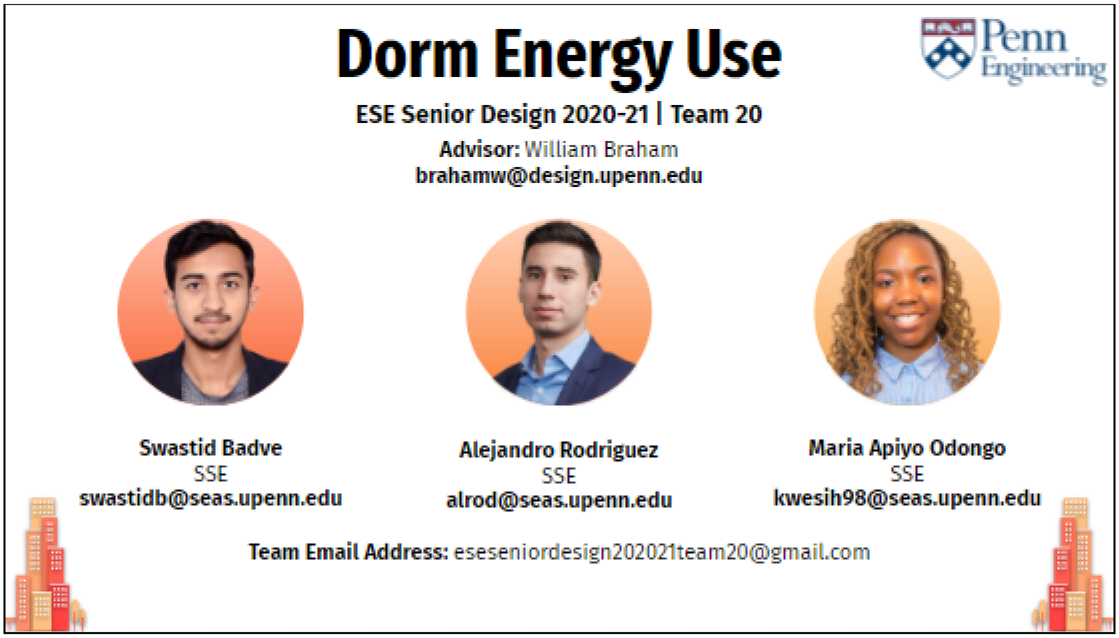
Team 20


Dorm Energy Use
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II. Executive Summary

Our senior design project aims to improve our environment by optimizing people's daily personal energy consumption. We decided to focus on increasing the efficiency of light energy use in indoor spaces, as it is a widespread contributor to overall energy consumption. Within residential buildings, lighting accounts for about 4% of electricity use, accounting for a total consumption of 62 Billion KwH in the U.S. The consumption of 1 KwH corresponds to 0.92 pounds of CO_2 emissions, which means that residential electricity usage contributes 57B of CO_2 emissions, creating a massive negative environmental impact.

Through our research and discussions with our project advisor Professor Braham, the Director of Center for Environmental Building + Design at Penn, we narrowed down 2 key issues that surround energy use. The first issue is that there is little to no data collected on energy use habits at a granular level besides information from utility bills, energy audits etc. Individuals are not generally aware of their energy and carbon footprint, and so it is difficult to adjust behaviours without obtaining clear insights. The second key problem is that there are virtually no direct incentives for reducing waste and being efficient with energy use, especially in residential buildings that charge fixed rates for electricity consumption. In our project, light use and occupancy data is collected through sensors and fed into an incentivization program that awards/penalizes users for their efficient/inefficient energy usage, based on specific criteria and metrics.

The implementation of our project spanned multiple steps. We first needed to determine the specific behaviors we wanted to punish. These behaviours included leaving the lights on when the room is unoccupied and leaving the lights on when there is sufficient natural light coming into the room from outside. Then, we needed to narrow down the relevant metrics we wanted to collect to quantify these behaviors and determine which sensors would allow us to do so. The metrics we settled on were Artificial Lighting Factor and Lighting Occupancy Factor, which give us insights into inefficiency that occurred through the aforementioned behaviours. We also created an allowance for general artificial light level, beyond which energy usage would be considered excessive. We settled on using TSL2591 Luminosity sensors and CCS811 CO_2 sensors connected to Arduino Unos to run our experiments. These would tell us lux (luminosity measurement) and CO_2 levels, which could then be fed into our incentivization program on Python to award/penalise* users.

To calculate the 3 metrics we mentioned above, we needed to differentiate between natural and artificial light, and detect human occupancy in a room. Using the luminosity sensors, we ran multiple control experiments to differentiate between natural light and artificial light, based on the application of the inverse square law for light intensity. Next, we ran control experiments with the CO_2 sensor to identify threshold levels for human occupancy. Once we had established these relationships, we could calculate the relevant metrics and reward/punish individuals based on our incentivisation algorithm. We found that our program did in fact award/punish users fairly in terms of their light usage. Given that this project was implemented inexpensively, we believe that this project could be scaled quickly to be implemented at dorm rooms or other residential buildings in the future.

Note: The utility of rewards falls outside the scope of our project, as the development of the reward or the "PennCoin" is being undertaken by an associated team of PhD students.

III. Overview and motivation of the project:

The main objective of our project is to provide a platform for tracking individual energy consumption in the form of artificial lighting and consequently using the gathered energy use data to incentivize more efficient behaviors that would result in significant energy savings.
We aim to tackle two main problems:

1. The lack of sufficient granular data that maps energy usage to specific modes of consumption, in this case, artificial lighting.
2. The lack of a direct link between overall energy consumption and individual consumption as it relates to daily artificial lighting usage, and the associated carbon footprint.

Inefficient behaviors such as unused lights overnight or in unoccupied spaces are extremely common because of the lack of direct and/or real time insights on individual energy consumption. Assuming a $0.11 per kWh rate, leaving on 10 incandescent bulbs unnecessarily for 1 hour per day could add an extra $24 to electricity bills, in addition to the environmental effects of energy wastage. The most prevalent form of energy usage data is segmented at a collective/building level, thus creating the potential for the inclusion of additional metrics to measure energy use behavior to supplement the current standards used to measure energy efficiency.

We hope to not only grant users a more granular understanding of how their day-to-day behaviors contribute to the overall energy consumption of a space, but to also inspire a spirit of energy conservation with the aim of reducing their associated carbon footprint. This will ideally improve energy efficiency over time and reduce energy waste by comparison to one's own usage, peer usage and a set threshold over which energy consumption will be considered inefficient.

The increasing dilapidation of mother earth as a result of climate change is a direct consequence of carbon emissions into the environment. The recent destructive and sometimes fatal natural disasters are a testament to this. We believe that our project could not come at a better time given the ongoing global conversations surrounding best efforts to combat climate change. A higher quality of life, cleaner air quality, sustainable resources, as well as cost savings are all benefits that lie on the other side of energy conservation.

IV A. Technical Description:

Functional and Performance Requirements:
Input: This refers to the sensors that we use to collect data:

Feature	***Specifications***
Microcontroller	Arduino Uno; input voltage at 7-12V
Light sensors	1. Adafruit TSL2591 luminosity sensor; 3.3-5V; 188 uLux up to

	88,000 Lux 2. Sparkfun AS7265x Triad Spectroscopy Spectral Sensor; 3.3V; accuracy of ±12%; λ = 410 to 950 nm
Light sources	Natural light (sunlight), LED, Fluorescent bulb, Incandescent bulb
Carbon dioxide sensor	KEYESTUDIO CCS811; range of 400 to 8192ppm (parts per million), and various volatile organic compounds (TVOC) ranges from 0 to 1187ppb (parts per billion)

Output: This refers to the Python program used to analyze the collected data and pass it through an incentivization algorithm (shown in appendices).

Operational and Interface Requirements:

The sensors should be placed in optimal positions that ensure the least possible amount of human interference i.e., keep the sensors away from human traffic within a space, ensure minimal obstruction between the sensors and the measured characteristic.

- Placing the light sensor at the window pointing outwards to ensure complete dominance by natural light levels.
- Placing the light sensor mid-room on the ceiling to average lighting level data over a wider range and to account for sensitivities caused by occupant movement relative to the sensor.

Policies and Regulations:

Data privacy and security laws and engineering standards apply to our project given that it involves direct interaction with personal user data and employs the use of technical sensors to measure lighting and carbon dioxide levels. Sufficient lighting thresholds within our project abide by set industry standards for lighting levels in buildings as stipulated by the Illuminating Engineering Society (IESNA). More detail will be provided in subsequent sections highlighting engineering standards.

IV B. What iterations or alternative solutions have you considered?

Firstly, in terms of iterations, we went through multiple distinctive ideas. Two of our key challenges were to differentiate effectively between natural and artificial light, and detect human presence through sensors.

Wavelength differentiation: The first iteration that we used to differentiate between natural light and artificial light was to differentiate between the two on the basis of their differing wavelengths. To work through this experiment, we set up multiple control experiments with varying conditions of light. These varying conditions of light would be measured across ultraviolet, infrared, and visible wavelengths using our AS7265x spectroscopy sensor. These control experiments involved the following conditions: i) only artificial light, ii) only natural light throughout different times of the day, and for differing weather conditions (overcast/sunny), and iii) natural light and artificial light for each of the aforementioned conditions. The goal was to detect a spike in one of the 3 wavelength ranges that could unambiguously differentiate between natural and artificial light. All these experiments were recorded such that there was minimal disturbance. However, the results of this experiment did not yield satisfying results, as the spectrum of natural light and the spectrum of LED lights wavelength existed over similar wavelengths (figure 2 in appendices).

PIR sensor: The second iteration that we used to detect human presence was to utilise a PIR (passing infrared) sensor. The PIR sensor is a widely used sensor, most commonly seen in automatic soap dispensers or automatic lighting systems. At first, the sensor was operating effectively by detecting human presence satisfactorily. However, based on our research, we noticed that the PIR sensor can be overly sensitive. On relatively warmer days, the PIR sensor could be under-sensitive in differentiating the typical heat from bodies and the warmer ambient surfaces, and during colder days, it could be oversensitive. This issue of sensitivity could be remediated by using a more advanced, and expensive PIR sensor. However, given the economic constraints of the project, we chose not to continue utilizing the sensor further and instead utilise the CO2 sensor.

In terms of alternative solutions that we spent time researching on but did not include in our final presentation, there were 2 key solutions that we found were important to reduce inefficient light energy usage.

High-efficiency lighting: LEDs (Light emitting diodes) present a superior solution as compared to incandescent, halogen, and CFL bulbs in terms of reducing inefficient light usage. LED fixtures use 75-80 percent less electricity than incandescent bulbs, and can have a lifespan 25 times longer than that of incandescent light bulbs. Further, LED bulbs also require much less wattage than CFL light bulbs, and last longer and are more robust than halogen bulbs. Beyond the use of LEDs, lighting should also be based on focus points i.e. lighting flux should be concentrated according to the need of the area, based on a person's subjective preferences. For example - lights on study tables can have higher flux, as compared to lights in bedroom side tables, where dimmer lights can be used. Thus, effectively selecting lighting could result in massive energy savings.

Building design: While building design was mostly out of our scope for this project, we thought it presented an interesting practice that could be utilised in the design of residential buildings. In terms of the original planning/design, architects can design buildings to include windows and orient them towards the south or the west to increase access to sunlight. Moreover, the use of paint colors (such as White) that maximize reflectance can be used in the painting of the walls or in the furniture in the room, thus improving the overall utilization of light in the room.

IV C. Were there any societal, environments of economic considerations that influenced the design?

There were various societal and economic considerations that influenced the design of our project. The first had to do with environmental impact which is becoming increasingly important over recent times. Given the context of global warming, there is an urgent need for our society to take everyday actions to conserve energy. As mentioned earlier (in the *Executive*

Summary), there is 57B lbs of CO_2 emissions in the US through residential energy usage. Based on estimates from WSBDC, a 32% reduction in lighting energy consumption can be attained through behavioural changes. Through our project, we hope to nudge users towards these behavioural changes and thus help reduce CO_2 emissions.

Though environmental impact is crucial, economic implications are important to consider if we want to expand its impact at scale. Our project helps reduce energy bills as participants would reduce light energy waste because our program would incentivize them with Penncoin awards or other benefits. If applied on a large scale, there would be significant reduction in energy use costs. However, there would also be significant set up costs as sensors and Arduino hardware would also have to be installed in every room. If the set up costs are too high, then implementing this project may prove ineffective, especially if lightbulbs and energy costs go down. As a result, we aimed to use a combination of affordable sensors, such that the costs would be compensated by the energy cost savings. The economics of this project is explained in the next paragraph.

The total set up cost would be $100 per room. According to a study in Britain, 10% of people leave the lights on when leaving a room at home, which translates into waste of about 836.88 British pounds or about $1,166 of wasted electricity per person (Utility Design, 2018). If we eliminate that 10% of light energy waste, this would translate to an average savings of about $116 per person. This means our project pays for itself in a year, even if we discount it at 10% and leads to long term savings. Our project would not only help the environment but also be a profitable business if applied to the general population.

IV D. Technical description and approach

Experimental approach:

In terms of our approach, we initially performed the iterations mentioned in part (C). When none of them yielded satisfactory results, we performed alternative experiments.

The next experiment we performed was to differentiate between artificial and natural light by factoring out the natural light intensity, and thus detecting the presence of artificial light intensity. This experiment was roughly based on the fundamental principle of the **Inverse Square** law. The Inverse Square law states that the intensity of the light to an observer from a source is inversely proportional to the square of the distance from the observer to the source. This shows that as the distance from a light source increases, the intensity of light is equal to a value multiplied by $1/d^2$. For the purposes of this experiment, we assumed the sunlight entering from the room, from a window, to be identical to a point source. The setup of the project involved the use of the following sensors: i) Luminosity sensor (TSL2591) placed adjacent to the window such that it would detect only natural light ii) Luminosity sensor (TSL2591) placed in the middle of the room (~5 feet away from the window) such that it would detect both natural light and artificial light, and iii) CO_2 sensor placed at the foot of the door to detect any human presence. Within this setup, the first experiment was conducted in the presence of only natural light. Based on the sunlight entering the room, a linear relationship (using linear regression), between the light intensity at the window and the light intensity at the middle of the room was established, as a function of the distance between the 2 sensors. Once this relationship was established, we could factor out the natural light for the mid-room sensor, and thus observe any changes in the ‘delta’ of the light intensity, which would represent the artificial light intensity.

The other experiment involved the use of CO2 sensors to detect human presence. The CCS811 CO2 Sensor was used for this. The normalized CO2 level, for no human presence, was found to be 400 ppm. In this experiment, a CO2 sensor was placed at the foot of the door and the spike in CO2 levels when a human entered the room was observed. Based on experimental data, the threshold level of CO2 for establishing human presence was found to be 420 ppm. The use of both these experiments was to calculate energy efficiency metrics that we had established beforehand, and are talked about in the next section.

Metrics used:

In terms of the metrics, we used 3 primary metrics to calculate the efficiency of energy usage.

1. Artificial Lighting Factor (ALF) = (Time when sufficient natural light and artificial light is detected) / (Time when artificial light is detected)
2. Lighting Occupancy Factor (LOF) = 1 - (Time when artificial light is detected and room is occupied) / (Time when artificial light is detected)
3. Allowance = The 'Artificial Allowance' metrics penalises the use of artificial light beyond a set threshold i.e. 50 Lux more than required, when there is sufficient light (250 Lux) in the room.

Metrics (1) and (2) ranged from 0 to 1, and the goal for the project was to get both these metrics as close to 0 as possible; while metric (3) was a disincentive for using excess artificial light. The numeric values for these metrics were then measured and awarded/penalized based on our incentivisation algorithm (explained in the next section).

Incentivisation methodologies:

The framework for the incentive model was based on the benchmarking of the metrics through 3 different methodologies:

1. Self-benchmarking: Self-benchmarking presents a simple framework that can be run even with a single occupants, as it measures for change in metrics week over week for the same user. The major change focuses on encouraging improvement through self-realization, even though it is not competitive.

2. Peer benchmarking: Peer-benchmarking presents a methodology that measures metrics of users and compares it against one another, setting up a competitive process. While the major constraint for this methodology is the high number of users required, it can also be the most psychologically rewarding for young undergraduates staying in dorm rooms, who are the potential target audience for this study.

3. Threshold based benchmarking: Threshold-based benchmarking is a framework that sets up a maximum threshold of energy usage, and regularly updates students on their daily usage (similar to “Digital well-being” on smartphones) to prevent over usage. This threshold is based on prior data collected. For example: in a single location, the energy efficiency results from December 2019 would allow the team to set up an effective normalized threshold for December 2020.

Note: The utility of rewards falls outside the scope of our project, as the development of the reward or the "PennCoin" is being undertaken by an associated team of PhD students.

IV E. Final status of the project and test results

For the sample room, the light intensity relationship (in Lux) was found to be equal to:

y = 0.506x, (figure 1 in appendices)

where y = light intensity in the middle of the room, and x = light intensity at the window.

Below we can find a set of sample results for one of the users we tested our system on. The rewards were calculated based on the self-benchmarking methodology. The user starts his cycle with 5 PennCoins in his account.

Time	Windowsill	Linear Midroom	Actual Midroom	Artificial	CO2
1100	540.566406	272.986035	272.986035	0	467
1200	543.770629	274.6041676	281.9641676	7.36	456
1300	472.714538	268.029143	279.859143	11.83	465
1400	393.686828	198.8118481	357.8518481	159.04	435
1500	306.341796	154.702607	318.532607	163.83	400
1600	210.178344	106.1400637	279.0900637	172.95	400
1700	204.298965	103.1709773	279.4909773	176.32	400
1800	158.728323	80.15780312	259.3678031	179.21	445
1900	16.975521	8.572638105	190.8826381	182.31	432
2000	0.1088	0.054944	180.744944	180.69	400

```
LOF is  0.5
ALF is 0.14285714285714285
PennCoin Awards for the Day
4
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IV F. Contextualization of results

On a fundamental level, the results do demonstrate a proof of concept for our system. The main goal of the project was to inform a user of his/her inefficient behaviours and thus effectuate a change. While we were able to inform the users of their inefficient behaviours, we did not have enough data or a long enough timeline to observe the change in behaviour that our system created.

In terms of scalability, the sample system we have designed is within the required economics for such a project. Early on in the project, we had decided that the project should be NPV (Net present value) positive within a year. Based on our estimates, as mentioned in part C, our project should be NPV positive within a year. Moreover, if we implement this project at scale, we can expect our costs to go further down, thus making it profitable for any institution or organisation that implements it.

Further, based on the feedback we received on our demo day, another potential direction for us to work more towards would be - understanding the impact of television, laptops, and mobile phones on the artificial light usage. Since a lot of these devices influence the lighting when reading, working etc., the inclusion of these devices adds another layer of complexity in differentiating between natural and artificial light. Based on our recent research, the differentiation of this order of magnitude would require the implementation of an event detection algorithm. An event detection algorithm detects the difference between consecutive data points on the signal time series, and compares it against a detection statistic, which is a threshold. Any point on the time series that has a jump larger than the threshold is identified as an event. This analysis is then coupled with a spectral analysis (in the frequency domain), which allows for the differentiation of natural and artificial light.

IV G. Short Conclusion

Thus, based on the discussion above, we have outlined the benefits and limitations of our project. Going forward, if this project is further worked upon by another team, it will be key to focus on increasing the sample set of the project, and seeing its long term effects on residents.

V. Self learning:

After having learned about Arduino in ESE 111, we had not worked on it much more in the past 3 years or so. Hence, all the team members spent a good amount of time learning Arduino. Furthermore, the running of our experiments required a satisfactory understanding of optics, which we also focussed more on in the latter half of the semester. At the same time, our conversations with our freshman mentees Heyi Liu and Rohan Chhaya were useful, as they brought in different perspectives from their respective majors of electrical engineering and bioengineering.

Beyond this, the learnings and statistical analysis we had gathered from classes like ESE 204 (Decision models), ESE 301 (Engineering probability), ESE 305 (Foundations of data science), ESE 402 (Statistics for data science), and CIS 120 (Programming language and techniques) were key to the implementation of our project.

VI. Ethical and Professional Responsibilities:

Energy efficiency is crucial in reducing the quickly evolving effects of climate change risks. Simple tweaks to our daily behaviors will help us lower our carbon footprint by a significant amount. According to the Energy Efficiency Impact Report of the Business Council for Sustainable Energy, additional investments in energy efficiency could lower U.S. greenhouse gas emissions by an additional 50% by the year 2050. Economically, there exists a tremendous cost-savings potential in reducing our energy waste. The average household spends an average of $264 a year on electricity for lighting, a number that could be lowered significantly. Our project aims to provide an avenue for individual energy use tracking which consequently creates a clear pathway between individual decision-making and energy efficiency. Majority of the time, energy use is spoken of in general/collective terms, but we see great potential in portraying this collective as a collection of individual components i.e. by creating an avenue to track personal energy usage coupled with an incentive to prevent wastage.

One ethical challenge facing our project is privacy. The first is in the context of sensor installation within people's private spaces. Such an endeavour would require explicit consent/permission from the inhabitants/owners. This poses an even greater challenge with the COVID-19 pandemic still in full swing and the health and safety risks involved. For the testing and implementation of our project, we used one of our rooms as a testing site, erasing the need to gain outside permission. In the event that the project would be deployed on a larger scale, a comprehensive yet easy-to-follow step-by-step installation guide would be provided to users to install the sensors themselves. The second is in the context of data collection and storage. Data privacy and security comes to the forefront of such a project. Given that we did not collect swathes of data, we did not encounter this issue. For a larger dataset however, we would only collect data that is relevant to our model, as well as anonymize all other user data that would make individuals easily identifiable.

VII. Meetings:

Throughout the semester, we either met twice a week for 2 hours, or once a week for a span of 4 hours. Our meetings with our faculty advisor Professor Bill Braham were scheduled biweekly. Furthermore, we were also in close coordination with Professor Braham's PhD students - Max Hakkarainen and Alex Waegel.

Our meetings with Max were focussed mostly on identifying and utilizing the appropriate hardware for this project, taking into account the specification, cost, and capabilities of each piece of hardware. On the other hands, our meetings with Alex Waegel were much more high-level as we focussed on how we would conduct our experiments, what our controls could be, and how we could minimize noise in our experiments. Throughout the semester, Professor Braham provided us with innovative ideas to help solve our toughest problems. His vast experience in this field definitely helped in solving the more nuanced problems in this project.

VIII. Proposed schedule with milestones:

The main goal for our project was to accurately record light energy-use habits in individual bedrooms and incentivize practices that are efficient. We were able to implement this successfully, however there were several aspects that we had to roll back on for our project due COVID constraints. We eventually could not access and use a more advanced spectroscopy sensor for testing, since the wrong piece of hardware was ordered and the replacement arrived too late.

	Date	**Milestone**
Meeting with graduate team to narrow down project deliverables and sensors needed	2/9	Narrow down components needed to measure key occupancy and light energy metrics
Put in order for Arduino parts	2/11	Obtained necessary components for Arduino implementation
Developed Python rewards program	Week of 2/18	Incentivize users based of ALF, LOF, and Allowance, using dummy data

Received parts and sent parts back for soldering	3/2	Made sure components were usable
Project brainstorming with Professor Braham, Alex, and Max	3/4	Decided project strategy and Arduino implementation
Set up sensors and met with freshman mentees	Week of 3/8	Made sure light sensors accurately read Lux data and CO2 sensors could accurately ascertain occupancy
Ran control experiments	Week of 3/15 and 3/22	Organized Arduino setup to run experiments in different conditions
Tested out other sensors and potential integration	3/29	Tested PIR sensor and SI1145, in different control conditions
Recorded Demo Day video and Recorded final trailer	4/05 and 4/25	Created script, recorded, and edited video to present

IX. Discussion of teamwork:

Given some of the constraints we faced in the fall semester working virtually, we wanted to build upon our teamwork in order to drive our project effectively. We all decided to be on campus this semester, which was also extremely important since our project required hardware implementation and testing in physical rooms. However, because of covid restrictions, we could only meet in Swastid's room. Swastid played a huge role in setting up the Arduino and testing the sensors in his room, where most of the testing was done. We still faced barriers with the hardware as we did not have access to the lab. We divided up tasks mostly based on our competencies but also came together for a majority of the project as it reduced errors and was more efficient.

The process of ordering and picking up parts also took significant time. We held most of our brainstorming and planning meetings via Zoom for convenience, while most project implementation was done in person. By bringing specific questions beforehand, we were able to run efficient meetings that tackled the issues we had. We communicated with each other via Facebook messenger and coordinated with our advisors via email. Alejandro played a primary role in communicating in the team Slack with TAs and professors to coordinate the ordering and pick up of parts. He also posted software bugs and sought the help of the ESE staff. To keep all our work saved and organized, we continued to build upon our team Google Drive. Maria led the video making (Demo, Trailer) and slide-style parts of our project, helping us deliver our presentations successfully.

X. Budget and justification:

Original Budget (Fall):
Sensors including light sensor, indoor air quality sensor, energy monitor sensor, passing infrared sensor ($200) + Visit to ECA ($50) + Travel expenditure to sensor sites ($50) = $300

Our project took a significant turn from what we envisioned in the fall. At first, we thought we were going to work directly with the graduate team working on incorporating Blockchain rewards with energy sensors installed in dorm rooms. However, this project was delayed and so we decided to create our own light energy incentivization project using smaller sensors, Arduino, and Python. As a result, our updated budget reflects only what was needed to implement the hardware setup, since Python and Arduino software is free to use.

Final Budget (Spring):

Part	Approximate unit cost	Quantity	Source of funding	Subtotal
TSL2591 Light Sensor	$10	2	ESE	$20
KEYESTUDIO CCS811 CO2	$15	2	ESE	$30
Arduino	$25	2	ESE	$50
Total				$100

XI. Standards and Compliance

Given that our project was implemented on a small scale, the engineering standards mentioned below did not impact our current system design. We collected non-critical sensor data i.e., lighting and carbon dioxide levels. On a larger scale however, these standards would have to be integrated into the project:

1. IEEE-P7002: This standard defines the requirements for a systems engineering process for privacy-oriented considerations such as collecting personal user data. It applies to projects involving personal information. A Privacy Impact Assessment (PIA) would be needed at a large scale, both to identify where privacy controls and measures are needed and to confirm if they are in place.
2. IEEE-P1619: This standard defines cryptographic transform and key archival methods to be deployed in data protection to ensure its security.
3. IEEE 2700-2017: This standard provides a common framework for sensor performance specification terminology, units, conditions and limits. This is particularly geared towards sensors with digital I/O interfaces i.e., the light sensors within our project.

XII. Work done since last semester:

Given the COVID caused roadblocks we faced in the fall semester, we wanted to get started with implementing our project plan as soon as possible. First, we met with the graduate team and our advisor to finalize what our hardware and software implementation should look like. We narrowed down the sensors and components needed to measure the relevant metrics, and placed an order for those sensors and components. At the same time, we started working on our incentivisation algorithm using Python. Unfortunately, we faced a major delay as the sensors that needed to be soldered were stuck in a lab that was shut down for some time due to a COVID infection in its vicinity. This led to us reordering our parts.

After finalizing our project plan and receiving the necessary parts, we were able to quickly get started building out the Arduino setup. We first had to learn how to set up the sensors properly and understand the output data. We then tested the sensors under different conditions to understand how they should behave depending on occupancy, natural light, and artificial light presence. We needed to establish benchmarks such as i) CO2 levels which would tell us occupancy and ii) lux levels, which would determine what is deemed sufficient light. After this, we began advanced testing through our Python program based on the linear relationship we observed by putting a light sensor by the windowsill and in the middle of the room. Our program punished light energy waste and rewarded energy efficient practices. We also then needed to record videos of how our project functioned as we met in one of our rooms that had the Arduino setup. After significant testing and optimizing our hardware setup we were able to achieve the key milestone of having a system that worked satisfactorily.

XIII. Discussion and Conclusion

This report discusses Team 20's progress in ESE 450/451 (Senior Design Project). The second semester of our project presented us with the opportunity to pivot into a slightly different trajectory. In Fall 2020, we ventured into the world of making current energy auditing processes more efficient after being introduced to the NREL's JumpIntoStem innovation challenge. Given the amount of expertise that process would require coupled with the tight time frame for the execution of the project, we settled on an incentivization model hinged on the ability to track individual energy consumption in the form of artificial lighting.

The objectives of this project were to create a methodology for granular individual energy use tracking and use the resulting data to incentivise users to cut down on energy wasting behavior by way of the PennCoin. We employed the use of light sensors to measure lighting levels within a space and carbon dioxide levels as a proxy for occupancy within a space. Experiments were conducted to differentiate between artificial and natural lighting such as wavelength differentiation, a passing infrared sensor, high-efficiency lighting and building design. We found the most accurate results from an alternate approach that involved analyzing the relationship between light intensity and distance based on the Inverse Square law. Data was collected in a test bedroom (environment) and fed into a Python program that analyzed user data and awarded PennCoins along self-benchmarking, peer benchmarking and threshold-based benchmarking.

Based on our results, moving forward, we see massive potential in the use of this methodology to both decrease energy consumption and greenhouse gas emissions, while also being economically beneficial to the project owners as well as the residents.

XIV. Appendices

Citations

Utility Design. (2018, July 12). Leaving the lights ON | a study from Utility Design. Retrieved from https://www.utilitydesign.co.uk/blog/leaving-lights-on/

EIA. (2021, February 3). Frequently asked Questions (faqs) - U.S. Energy Information Administration (EIA). Retrieved from https://www.eia.gov/tools/faqs/faq.php?id=99&t=3

WBCSD. (2009, August 9). Transforming the Market: Energy Efficiency in Buildings. Retrieved from https://www.wbcsd.org/contentwbc/download/2067/26086/1

Senseair. (n.d.). Co_2 Sensor vs. Motion Detector. Retrieved from https://senseair.com/knowledge/sensor-technology/technology/co-sensor-vs-motion-detector/

Pew Center. (2011, April). Climate Tech Book. Retrieved from http://large.stanford.edu/courses/2016/ph240/bonanni2/docs/LightingEfficiency.pdf

Hou, Y. (2018, June 7). Reasonable use of artificial lighting in building energy saving. Retrieved from https://aip.scitation.org/doi/pdf/10.1063/1.5041160

Jazizadeh, F., & Wang, J. (2016, May 20). Artificial versus natural light source identification with light Intensity sensors for energy monitoring. Retrieved from https://www.sciencedirect.com/science/article/pii/S1877705816301308

Stanford (2011, April) Lighting Efficiency
http://large.stanford.edu/courses/2016/ph240/bonanni2/docs/LightingEfficiency.pdf

Figure 1.

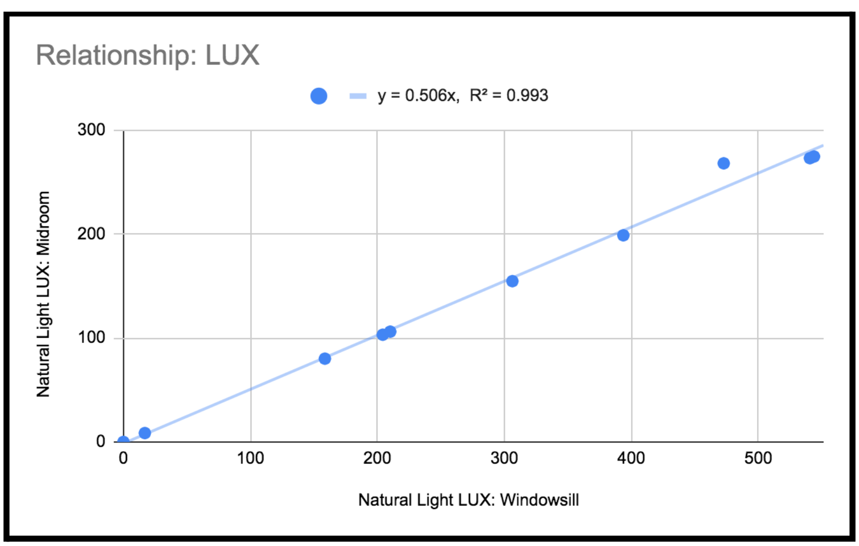

Figure 2.

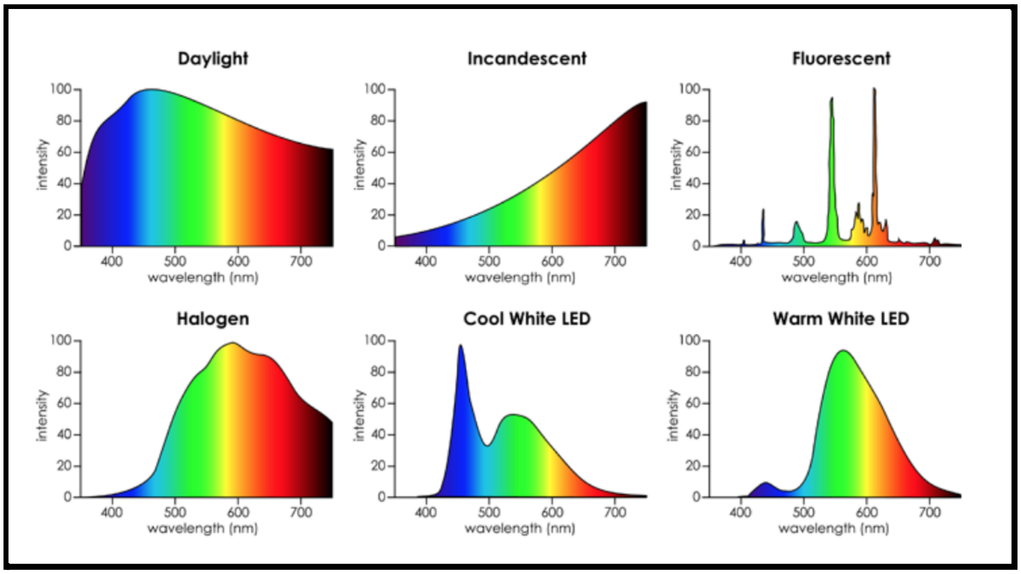

Figure 3.

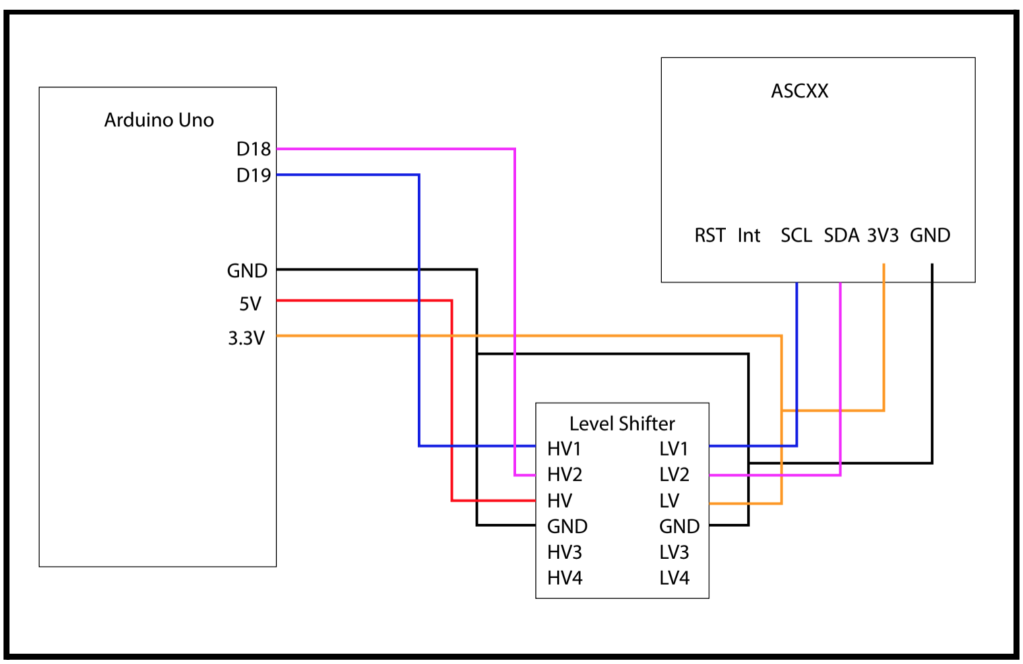

Figure 4.

```
#################################
# Add lighting data to ger data #
#################################

#initialize
ger1 = {'PennCoin': 5, 'LOF': [], 'ALF': []}
occ_light = [0]
art_light = [0]
suff_light = [0]

c = 420.0
d = 10.0
e = 250.0
allowance = 50.0

num_LOF = 0.0
den_LOF = 0.0
num_ALF = 0.0
den_ALF = 0.0

# Get length of sample data
n = len(lux_data.index)

# Loop through data hour by hour
for i in range(1,n):
  #check for artificial lights
  if lux_data['Art'][i] > d:
     den_LOF += 1
```

Figure 5.

```
        #check if occupied
        if lux_data['CO2'][i] > c:
          num_LOF += 1

    if lux_data['Linear Midroom'][i] > e and lux_data['Art'][i] > d:
      num_ALF += 1
    elif lux_data['Art'][i] > d:
      den_ALF += 1


    allowable = e - lux_data['Linear Midroom'][i];
    if allowable > 0:
      allowable = allowable;
    else:
      allowable = -35;
    if lux_data['Art'][i] > (allowable + 50) and lux_data['Actual Midroom'][i] > e:
      ger1['PennCoin'] = ger1['PennCoin'] - 1

  if den_LOF == 0:
    ger1['LOF'] = 0
    print('denominator of LOF is 0')
  else:
    ger1['LOF'] = 1.0 - (num_LOF/den_LOF)

  if ger1['LOF'] <= 0.25 and ger1['LOF'] > 0.0:
    ger1['PennCoin'] = ger1['PennCoin'] + 1
  elif ger1['LOF'] > 0.75:
    ger1['PennCoin'] = ger1['PennCoin'] - 1
```

Figure 6.

```
if den_ALF == 0:
  ger1['ALF'] = 0
  print('denominator of ALF is 0')
else:
  ger1['ALF'] = (num_ALF/den_ALF)

if ger1['ALF'] <= 0.25 and ger1['LOF'] > 0:
  ger1['PennCoin'] = ger1['PennCoin'] + 1
elif ger1['ALF'] > 0.75:
  ger1['PennCoin'] = ger1['PennCoin'] - 1

print("LOF is  " + str(ger1['LOF']))
print("ALF is " + str(ger1['ALF']))
print ("PennCoin Awards for the Day")
print(ger1['PennCoin'])
```