

CE398 FINAL REPORT

Analyzing Energy Efficiency Alternatives: Purdue Wilmeth Active Learning Center (WALC)

Team 7 – Team Sunshine



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Executive Summary

The main purpose of this project is to research and analyze the addition of renewable energy sources to improve the energy efficiency of Purdue's 24-hour campus library. The proposed changes to the Wilmeth Active Learning Center (WALC) will focus on discussing the need for renewable alternatives, optimizing the best system of electricity generation, and comparing whether or not these alternatives are economically viable. In this project, many discrete and economic analysis methods, as mentioned in CE 398 – Civil Engineering Systems Design, have been utilized to create a setup that addresses the three pillars of sustainability.

Founded in 1869, Purdue University has been rapidly developing in innovation, research, and entrepreneurship. Incoming students are continuing to grow in number every academic year with 58,000 students on campus as of Fall 2024. This means the campus needs to be well-equipped with proper housing, transportation, and access to well-maintained study spaces. With temperatures hitting record highs, unhealthy air quality, and heavy rainfall, it is time the school invested more time and budget into utilizing efficient systems. Although Purdue is revamping the campus with renovations of old buildings and the development of new academic/residential buildings, the campus environment and student life will be impacted negatively if the social and environmental aspects of the campus are not addressed.

To help solve the emerging problem of climate change impacting college campuses, the team discussed and researched similar initiatives at other university campuses. By addressing the need for alternative sources, we picked three technologies based on their history, kilowatt-hour generation, and installation impact on students and staff. Next, a discrete optimization analysis was performed at a simulated budget to create the best system with the highest power generation at the lowest cost. Finally, the team considered the economic and aesthetic viability of implementing renewable energies. An economic analysis and a discussion of new designs to improve the functionality of learning spaces helped us reach a conclusion.

Introduction

When it comes to planning infrastructure for any type of population, the need for resiliency, sustainability, and recyclability are crucial tools to consider. This also incorporates the health and safety for the public involved in the system. City planners must consider the best alternatives to meet the criteria and constraints of the end users while maintaining efficiency. As for civil engineers, it is important to identify any problems within the engineering system and determine factors that can be used to improve its input and output.

The objective of this project is to determine through data analysis if there are any changes necessary to improve the energy efficiency of the Wilmett Active Learning Center. This problem falls under the needs assessment and systems operation phases because it is the most widely used library on campus that could be operated differently. Energy efficient libraries on college campuses across the nation are compared to determine the need to incorporate renewable technologies. Solar panels, kinetic energy storage systems, and wind energy are examined while considering factors like installation costs, annual maintenance, impacts of weather, total energy production, and improving campus environment and aesthetics. The network of energy sources is optimized using a discrete analysis approach and an economic analysis.

Statement of Need

Background Information

Climate change is a complex and multifaceted issue that requires global cooperation and action. Greenhouse gases such as carbon dioxide (CO₂) absorb heat in the form of infrared radiation emitted from Earth's surface. As the concentration of these gases in the atmosphere increases, more heat is trapped, leading to global warming. Since the onset of industrial times in the 18th century, human activities have raised atmospheric CO₂ by 50% - meaning the amount of CO₂ is now 150% of its value in 1750 (Wolff, 2020). As a result, the global average surface temperature has risen approximately 1 degree Celsius (33.8 degrees Fahrenheit) since 1900. This warming trend has been accompanied by ocean warming, sea level rise, significant reductions in Arctic Sea ice, and more frequent and intense heat waves, among other climate impacts.

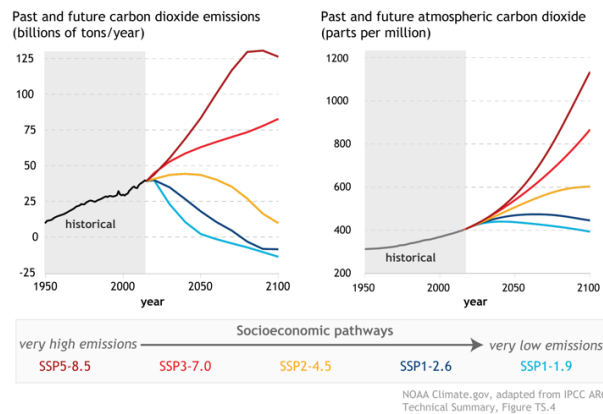


Figure 1: Predicted Atmospheric CO₂ and Emissions Rise



Figure 2: Direct Effect of Climate Change on the Great Barrier Reef

Comprehensive studies have confirmed that the primary driver of this warming is elevated levels of CO₂ and other greenhouse gases (NASA, 2023). If emissions continue, further climate change is inevitable, with substantial increases in global temperatures and notable regional climate shifts. While short-term fluctuations in warming may still occur, the long-term climate trajectory will be determined by the total amount of greenhouse gases released through human activity. The yearly rise and fall of atmospheric CO₂ levels is driven by seasonal changes in large-scale plant photosynthesis. In the springtime of the Northern Hemisphere, plants begin to grow and absorb CO₂ from the atmosphere as part of their natural development, causing CO₂ levels to decrease. By autumn, plant growth slows or halts, and much of the vegetation decomposes, releasing CO₂ back into the air and reversing the trend.

This boom-and-bust cycle of plant growth gives the graph of CO₂ (*Figure 3*) a sawtooth pattern of ups and downs from year to year. On a larger scale, the upward climb of the trend line over the decades is caused by CO₂ emissions, primarily from burning fossil fuels. Thus, the data illustrate both natural factors and human additions of CO₂.

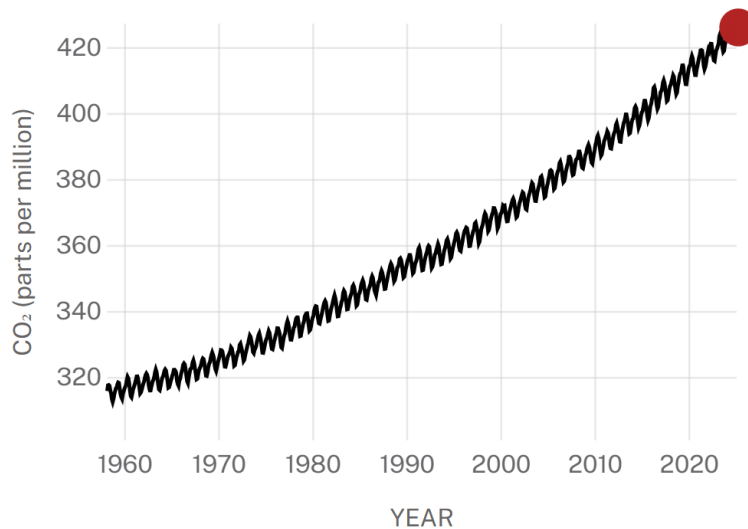


Figure 3: Predicted Atmospheric CO₂ Based on Yearly Trend

One main idea of the project is the discussion of how climate change affects the three main pillars of sustainability: *economic, environmental, and social*. In the context of living conditions and community structure, how do these three pillars specifically impact us? There are major threats to our environment such as biodiversity loss, deforestation, and resource depletion. These effects undermine the ecosystems' ability to regenerate and provide essentials like clean air, water, and food. Socially, climate change is detrimental to mental and public health with the displacement of people due to droughts and floods in vulnerable regions. Finally, the economies of various countries can be impacted by infrastructure damage, reduced productivity, unequal access to healthcare and education.



Figure 4: UN Sustainable Development Goals with Environmental, Social, and Economic Factors

Spreading awareness about these issues is important to provide more resources than what was taken for our future generations to live sustainably. Recognizing the urgent effects of climate change and the need for sustainability, it's time to translate these principles into action by implementing renewable energy sources on college campuses. **Overall, our team is introducing solutions to help Purdue reduce long-term utility costs, minimize the environmental impact, increase the campus reputation, and promote research in sustainable living.**

Current Energy Demand

For this project, our team will focus on the total electricity usage in WALC to compare the best energy efficient alternative to create a healthier campus environment. *Table 1* below shows the general energy consumption of educational buildings including the college/university level at about **17.4 kWh** per square foot with an average of **14.4 kWh** per square foot.

Site electricity consumption									
All buildings using electricity						Distribution of building-level intensities (kWh/square foot)			
	Number of buildings (thousand)	Total floorspace (million square feet)	Floorspace per building (thousand square feet)	Total (billion kWh)	per building (thousand kWh)	per square foot (kWh)	25th percentile	Median	75th percentile
All buildings	5,234	84,869	16.2	1,243	237	14.6	3.8	8.7	17.2
Principal building activity (expanded)									
Education	389	12,239	31.5	134	345	11.0	5.6	9.0	13.7
College or university	27	1,883	69.2	33	1,202	17.4	9.2	14.4	20.0
K-12	232	9,175	39.6	89	386	9.8	5.6	8.3	12.6
Elementary or middle school	189	6,118	32.4	58	306	9.5	5.6	8.0	11.9
High school	43	3,056	71.6	32	740	10.3	6.2	10.5	15.5
Preschool or daycare	68	431	6.4	6	85	13.3	8.0	11.6	16.9
Other classroom education	62	750	12.1	6	100	8.2	2.6	6.6	10.7

Table 1: Site Electricity Consumption – Commercial Buildings (U.S. Energy Information Association)

Energy Consumption Breakdown

Full Year 2024 Usage:

WALC - Wilmeth Active Learning Center	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	TOTAL	kbtu	kbtu/gsf
CHW TNHR	84,575	94,222	71,752	30,620	6,095	881	101	3,988	8,039	22,769	53,577	70,207	446,826	5,361,912	32
ELEC KWH	83,794	97,881	108,071	102,585	94,462	84,254	95,991	99,717	96,675	102,599	81,582	77,032	1,124,643	3,837,282	23
Steam mmbTU	291	303	255	277	289	362	522	294	288	260	294	259	3,694	3,694,158	22
Natural Gas DTH	NO NATURAL GAS												0	0	0
TOTAL														12,893,352	77
										GSF:	168,532		kbtu/GSF:		77

Table 2: WALC Total Energy Usage Based on Each Category (2024)

Full Year 2023 Usage:

WALC - Wilmeth Active Learning Center	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	TOTAL	kbtu	kbtu/gsf
CHW TNHR	90,869	91,869	66,564	19,419	9,072	559	2,108	972	2,798	18,806	36,134	54,931	394,101	4,729,212	28
ELEC KWH	83,031	93,585	102,188	99,116	95,132	87,460	92,781	92,284	94,240	97,205	77,787	76,823	1,091,632	3,724,648	22
Steam mmbTU	288	299	262	282	370	527	483	363	360	254	268	272	4,027	4,027,384	24
Natural Gas DTH	NO NATURAL GAS												0	0	0
TOTAL														12,481,245	74
										GSF:	168,532		kbtu/GSF:		74

Table 3: WALC Total Energy Usage Based on Each Category (2023)

Based on the tables above, if the building consumes a total of 1,124,643 kWh in 2024 and has a total square footage of 170,390 sq. Ft., the total energy efficiency will follow this equation:

$$\text{For the annual } kWh \text{ Per Square Foot} = \frac{\text{Total } kWh}{\text{Total Square Footage}}$$

$$\left(\frac{1,124,643 \text{ kWh}}{170,390 \text{ sq ft.}} \right) = 6.60 \frac{kWh}{sq ft.}$$

For the annual usage in 2023:

$$\left(\frac{1,091,632 \text{ kWh}}{170,390 \text{ sq ft}} \right) = 6.41 \frac{kWh}{sq ft}$$

This daily value is much less compared to the national electricity consumption value of 17.4 kWh in college buildings (*Table I*). This is great since it is less than the generic consumption value, but our team would like to help further improve energy efficiency by producing equal to or greater than the total kilowatt hours WALC produces. The values help our team determine which renewable energy sources could potentially be beneficial to install and maintain over a long period of time. Renewable energy sources are also very important for reducing carbon emissions.

Current Carbon Emissions

As stated earlier in the report, carbon emissions are pivotal to the rising climate. A part of our objective is to reduce the carbon emissions of WALC because its high annual energy usage contributes to high carbon emissions. According to the EPA, Indiana's grid conversion factor from MWh to CO₂ is 1000.1 lb. CO₂/MWh. The equation below demonstrates the annual emissions from WALC in 2024:

$$1,124,643 \text{ kWh} \cdot \left(\frac{1 \text{ MWh}}{1000 \text{ kWh}} \right) \cdot \left(\frac{1000.1 \text{ lb CO}_2}{1 \text{ MWh}} \right) \cdot \left(\frac{1 \text{ ton CO}_2}{1000 \text{ lb CO}_2} \right) = 1,124.755 \text{ tons CO}_2$$

WALC generates over 1,000 tons of carbon dioxide which is equivalent to 1,346,349 miles driven by the average passenger car. Integrating renewable energy would be a great way to reduce this number while improving energy efficiency. The United States is already trending towards integration of renewable energy with 21% of electricity generation coming from renewable sources. However, Indiana is lagging with only 14% of electricity generated by renewable sources and consuming 26 million tons of coal (EIA, 2024).

Current Campus Initiatives

LEED Certifications for buildings provide an opportunity to reduce the carbon footprint with sustainable practices and low energy technologies. According to Purdue's physical facilities website, the current mandate requires that all new buildings, with a budget of \$10 million or greater, are required to meet the silver LEED certification. Purdue has ideas for "retro-commissioning" the most active of the fifty buildings on campus built before 1970. For example, the Facilities building was retro-commissioned in 2002, and the renovations led to a 16% reduction in energy consumption. However, these values are only based on a carbon neutrality study done by Energy Star in 2007. While there is a significant budget and clear goals to pursue carbon neutrality, the efforts have been lackluster.

There has also been an initiative with building green roofs on campus. Green roofs act as a thermal insulator due to the foliage, and it is shown to reduce money spent on heating and cooling. Despite its benefits, only two green roofs have been built in the last 16 years. The first was built on the Data Science and AI building (formerly Schleman Hall) in 2009, and the other was built on Hampton Hall of Civil Engineering in 2012. Hampton's green roof totaled around \$900,000 including \$125,000 raised by civil undergraduates over two years before installment (Austin, 2012). This data shows that there needs to be more things done to increase the awareness of using better technology to reduce the emissions being produced. *Figure 5* below shows the Hampton Green Roof containing a variety of plants.



Figure 5) Hampton Hall Green Roof

Figure 6 below shows the green roof on the Data Science and AI building installed by the Boiler Green Initiative. The roof provides many environmental benefits including stormwater management, improved energy efficiency, heat island effect reduction, and enhancing biodiversity. The modular planters have trays with water channels to conserve stormwater and drain overflow into the gutter systems.



Figure 6) Data Science & AI Building Green Roof

Current Design

This section highlights the current design of the Wilmeth Active Learning Center. Built in 2017, WALC has become one of the busiest buildings on Purdue's campus, offering a crucial space for both students and faculty. The 170,390 sq ft, four-floor facility houses the Library of Engineering and Science (LoES), and 27 classrooms designed for active learning. Throughout the building, study and collaborative spaces are interspersed with classrooms, creating a highly efficient use of space. In the 1920's, the site was home to Purdue's Engineering Administration Building and the campus' North Power Plant. The power plant served as Purdue's sole generator of heat and power (Purdue Physical Facilities, 2019).

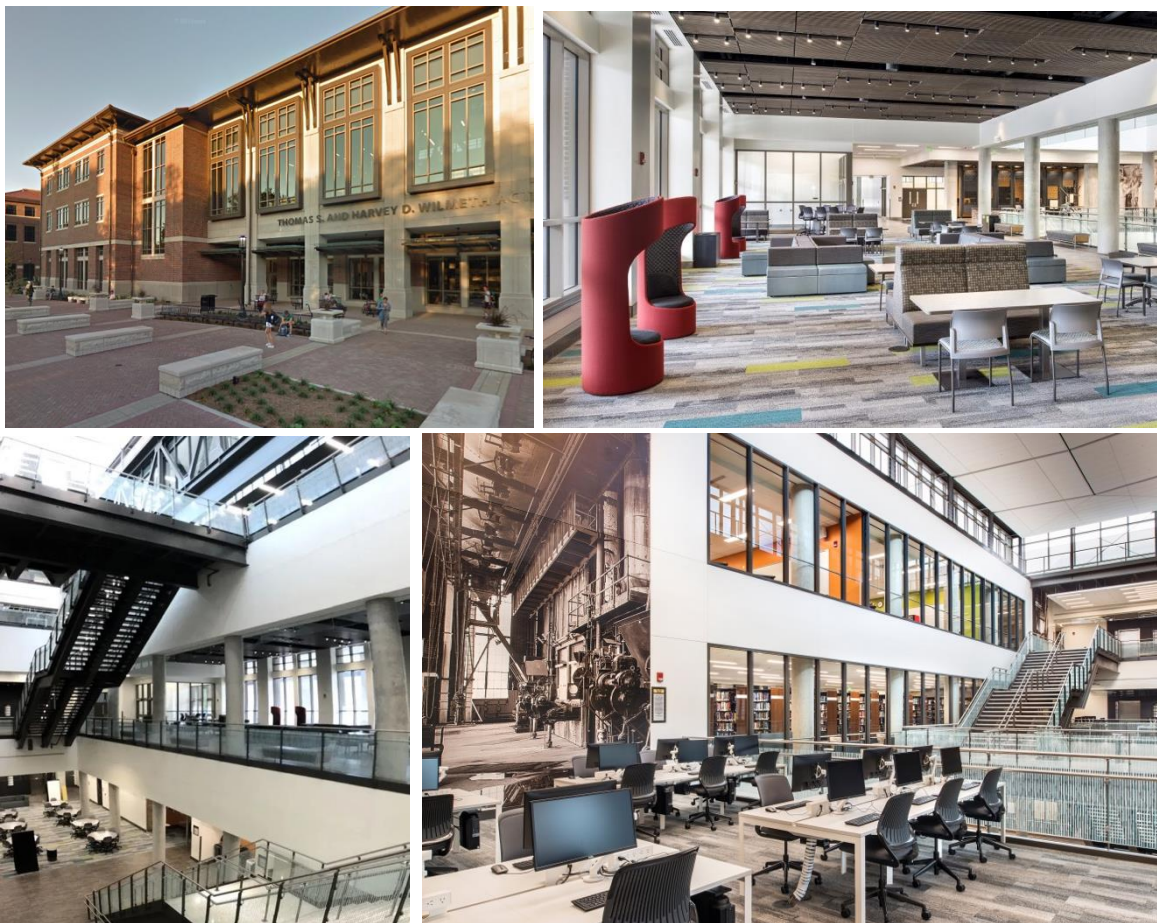


Figure 7) WALC Building: Outside and Inside View

Inside WALC we can find a wide range of study areas, meeting rooms, computer labs, and individual study booths, making it a versatile space for all kinds of learning. Whether you are working on a group project or need a quiet corner to focus on your own, WALC has everything. The design of the building maximizes the use of space with open, well-lit areas that make it a good environment for students. It's not just a place to study, it's also a space to interact, collaborate, and grow and make new connections with people.

The building exemplifies modern architecture and uses simple materials to create a great experience for everyone. As one of the prominent buildings in the whole campus, this facility should be more focused on promoting resilience by incorporating smart lighting, high-performance windows, and energy-efficient HVAC systems. To take WALC's sustainability to the next level, we can combine renewable energy technologies and energy-efficiency into practice. This would transform WALC into a building that generates as much energy as it uses, helping Purdue achieve its long-term sustainability goals.

Other University Campus Renewable Energy Examples

Solar Ray Implementation Example

Georgia Tech's Kendeda Building for Innovative Sustainable Design is Georgia's first and world's 28th project to achieve the Living Building Challenge (LBC) certification (Georgia Tech). This certification recognizes the most rigorous and comprehensive green building standard globally. The building aims to promote restorative relationships to connect people and nature where occupants give more to the environment than they take. Its design focuses on net-positive output in both energy and water annually, incorporating salvaged materials during construction, and diverting more waste from landfills than it generates. To support the local economy, over 50% of the building's materials and services were sourced within a 1,000-kilometer (621-mile) radius. Additionally, the building prioritizes occupant health and wellbeing by using chemically safe materials that could impact human or environmental health.



Figure 8) GA Tech Kendeda Building: Outside and Inside View

The building site is about 58,800 square feet (1.35 acres) in total. This is comprised of approximately 47,000 square feet of programmable space that is mostly enclosed and conditioned. Public learning space includes the 3,600 square foot outdoor porch area and a 1,000 square foot accessible roof deck. Also, there is a 4,300 square foot, private, rooftop garden containing the honeybee apiary, pollinator garden, and blueberry orchard. The remaining space is for loading and bike storage.

The solar arrays on the Kendeda Building have an energy output of 330 kilowatts (kW), and the 917 SunPower solar panels generate about 440,000 kilowatt-hours (kWh) annually. The actual Energy Use Intensity (EUI) has an approximate value of 18,000 British thermal units per square foot yearly (BTU/sf/yr) before factoring onsite solar. This makes the building 80% more efficient than a comparable, conventionally built higher education building in Atlanta. In terms of renewable energy values, the photovoltaic system supplies over 200% of the building's annual energy needs, far exceeding the 105% LBC requirement (Georgia Tech).

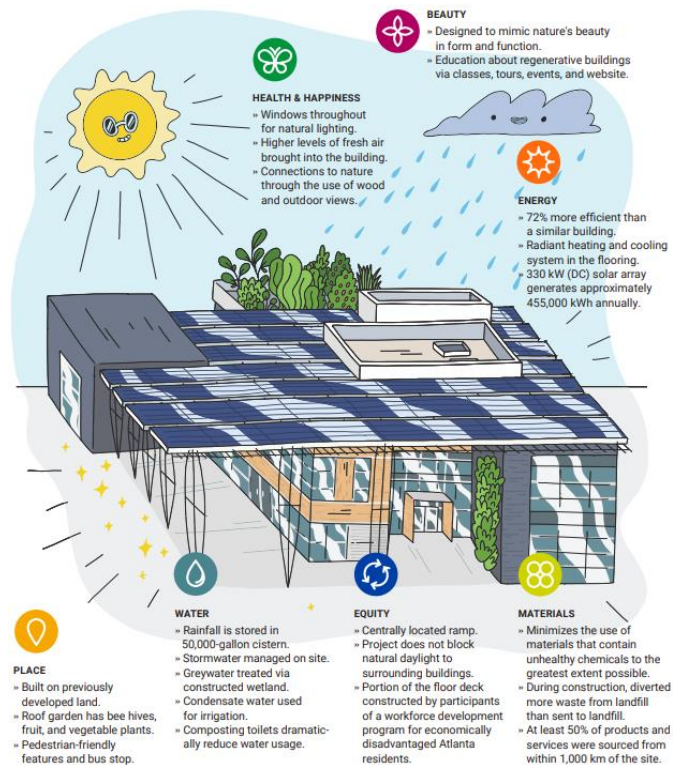


Figure 9) Kendeda Building: Net Positive Output Infographic

Piezoelectric Flooring Implementation Example

Several universities have explored integrating piezoelectric flooring as a renewable energy source on their campuses. For instance, research scientists at Georgia Tech are looking into piezoelectric tiles in high-traffic areas to capture energy from footsteps and power nearby lighting. Their hypothesis is that placing these systems in high-traffic areas, they can produce a significant amount of electricity storage needs (Tibbetts, 2017). The only challenge is that the electricity generated **was not enough** for big energy needs. Since this approach is successful on a small scale, it is a promising idea to help with campus sustainability goals when combined with other renewable energy resources.



Figure 10) UK Based Company, Pavegen - Piezoelectric Tiles (Oxford Street)

Pavegen is a company that also works on the research of piezoelectric integration. One project incorporated Siemens' cloud-based platform, MindSphere, into their walkway installation at the University of Birmingham, UK. This advanced integration allows for real-time monitoring of key performance metrics and analytics for the Pavegen system. With MindSphere, the University can measure and analyze the energy produced by student foot traffic offering insight into the walkway's effectiveness and impact (University of Birmingham).

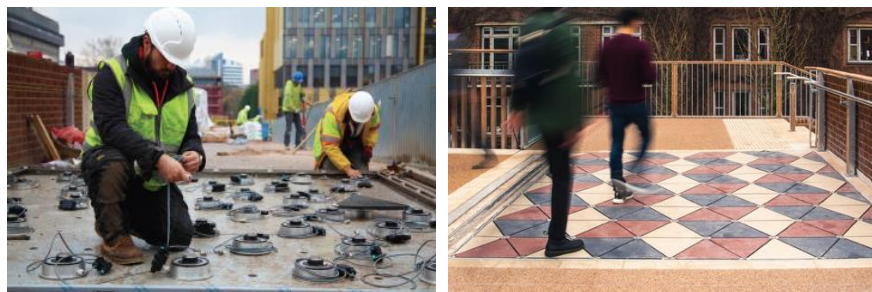


Figure 11) Pavegen Tiles at the University of Birmingham

Wind Turbine Implementation Example

Universities have implemented various types of wind turbines on their campuses as part of hands-on energy projects for their students. In 2010, the University of Delaware and Gamesa Technology Corporation installed two-megawatt utility scale wind turbines at the Hugh R. Sharp Campus in Lewes. This turbine generates enough energy to meet the campus' needs and powers approximately 100 homes in Lewes. It also serves as a research and educational resource for anyone interested in wind energy.



Figure 12) University of Delaware Wind Turbine

The State University of New York at Potsdam (SUNY Potsdam) installed its first campus wind turbine in October 2021. The 3.5 kW turbine, produced locally by Ducted Wind Turbines, supports the college's renewable energy goals and provides an educational resource for students. It can produce up to 12 kW in strong winds and is used for hands-on learning in environmental studies courses. The Ducted Wind turbines can produce more than twice the energy of a conventional open bladed wind turbine of the same rotor diameter.

Appalachian State University in North Carolina operates the 152 feet tall Broyhill Wind Turbine, the largest turbine in the state when it was installed in 2009. Located on the highest point on campus, the turbine has an annual average output of 110,000 kWh per year with a total installation cost of \$533,000. This project was backed by the student-led ASU Renewable Energy Initiative with generous support from New River Light & Power Company (Appalachian State University).

Plans and Considerations

In this section, our research investigates the hypothetical implementations and corresponding energy output of each selected alternative energy source. The team found ways to implement solar, wind, and piezoelectricity while reducing interference with the current structure and stakeholders.

Roof Solar Arrays

Background Information

Solar Panels consist of photovoltaic cells that convert a certain portion of sunlight directly into electricity using semiconductors like silicon. This is important when discussing the crystalline structure formed by silicon, phosphorus, and other atoms binding together in the solar cell. The energy from the photons free electrons within the semiconductor material which creates direct current (DC) electricity. Wiring connected to the positive and negative sides of the cell harnesses the electrical current using wires that are connected to the panel which carry the electricity to an inverter. At this point, the electricity can be converted into alternating current. Linking all the cells into panels can help provide either all or a portion of the power needed for a home or business to run.

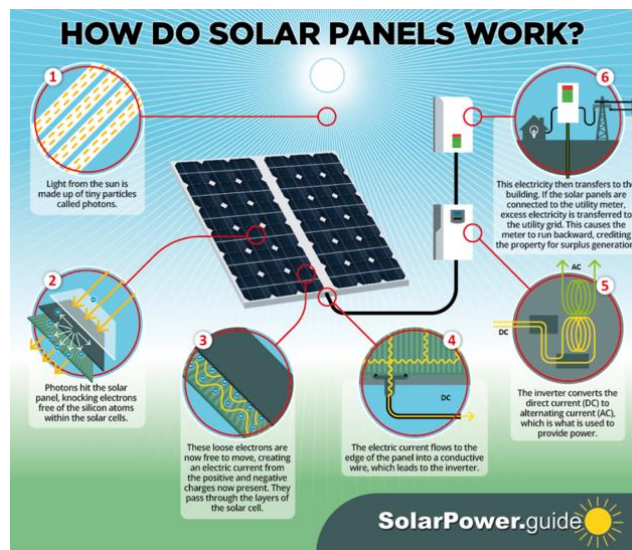


Figure 13) Solar Panel Infographic

Research Study

Solar panels were picked because of their long history of being integrated into established buildings. A big inspiration for how to install solar arrays in WALC came from the Fort Wayne campus. The campus received a \$135,000 grant from EBSCO Solar to implement solar panels on Kettler Hall. The grant program has initiatives to help university libraries implement solar arrays in order to reduce environmental footprints and decrease electricity costs. The research process included **measuring the roof's solar exposure and tracking the sun's path during various times of the year**. About 114 solar panels now generate 61,000 kilowatt-hours of power annually which is enough for the labs in the building producing. This endeavor is also saving 47 tons of CO₂ which is equivalent to planting 1,100 trees annually (Purdue Fort Wayne). We reapplied this methodology to the Wilmeth Active Learning Center to see how much energy it would generate in West Lafayette's climate. The average solar panel surface area is estimated to be 1.5 square meters with an efficiency of converting solar radiation into energy at about 15%. Using the values from National Renewable Energy Lab database, Indiana's average radiance and output is summarized in *Table 4* below:

Month	Solar Radiation Per Day [kWh/m ²]	Solar Radiation Per Month [kWh/m ²]	Solar Energy Per Month - 1 Panel [kWh]	Solar Energy Per Month - 20 Panels [kWh]
January	2.87	88.87	20.02	400.37
February	3.68	114.08	25.67	513.36
March	4.82	149.42	33.62	672.39
April	5.36	166.16	37.39	747.72
May	5.97	185.07	41.64	832.82
June	6.49	201.19	45.27	905.36
July	6.26	194.06	43.66	873.27
August	6.12	189.72	42.69	853.74
September	5.55	172.05	38.71	774.23
October	4.21	130.51	29.36	587.39
November	3.07	95.17	21.41	428.27
December	2.26	70.06	15.76	315.37

Table 4) Average Solar Radiance in Indiana (National Renewable Energy Lab Database)

Possible Implementation

We used Google Earth and its tools to help us properly measure the square footage of the roof.

Figure 14 below shows the panel placement that was decided based on the structural weight, maintenance safety, and electrical configuration of the panels.

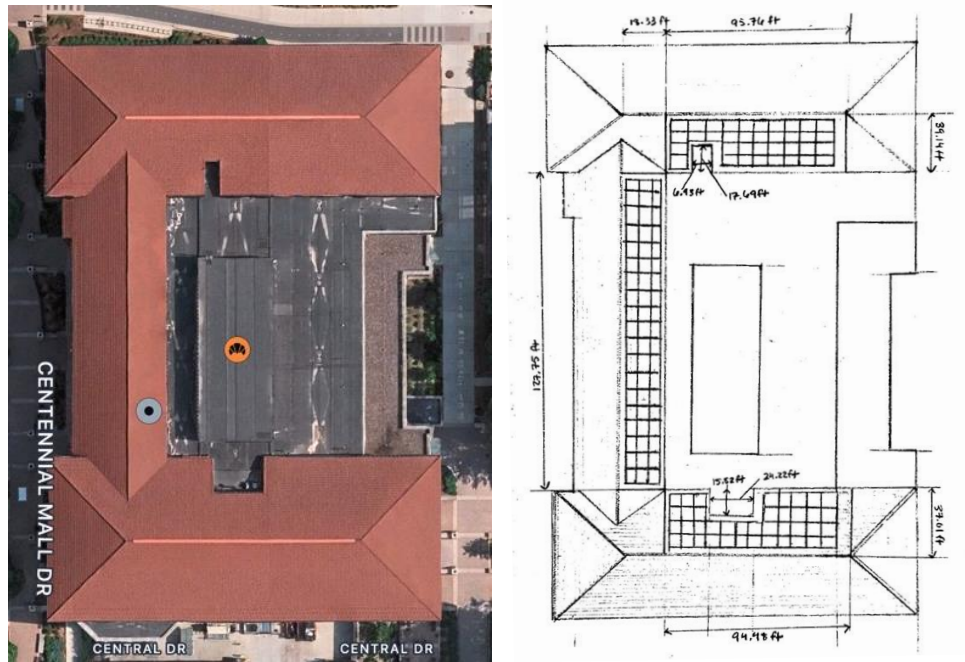


Figure 14) WALC Rooftop with Hypothetical Solar Panel Placement

Energy Generation Calculation

For a high-efficiency solar installation on a library roof, monocrystalline panels are the optimal choice. These panels offer higher efficiency – typically around 18-23%, compared to 15-18% for polycrystalline (GreenMatch). They also offer a long lifespan of 25-30+ years, which is sufficient for this project (Huawei). It is recommended that all panels face the same direction with minimal shading in a series connection to ensure peak energy generation. This approach increases the system voltage, which reduces energy loss through wiring and pairs well with MPPT (Maximum Power Point Tracking) inverters that perform better at higher voltages. A series configuration is especially efficient when combined with monocrystalline technology as it allows the system to operate at a higher voltage and lower current, minimizing resistive losses and improving overall performance.

Based on the research, the hypothetical energy generation based on the roof square footage from the drawing and average energy generation:

- *Total Usable Roof Area = 9,080.65 ft²*
- *Monocrystalline Panel Efficiency = ~20%*
- *System Efficiency (Inverter + losses) = 85%*
- *Total Efficiency = 0.2 * 0.85 = 17%*
- *Average Solar Irradiance Per Day in Indiana = 4.72 kWh/m²*
- *Typical Panel Size = 17.5 ft² (5.4 ft * 3.25 ft)*

Estimation

1) Convert kWh/m²/day to W/m²: (Average Over 24 hours)

$$4.72 \frac{kWh}{m^2 \cdot day} \cdot \left(\frac{1000 W}{1 kW} \right) \cdot (24 hr) \cdot (1 day) = 113,280 \frac{W}{m^2}$$

2) Convert W/m² to W/ft²

$$113,280 \frac{W}{m^2} \cdot \left(\frac{0.092903 m^2}{1 ft^2} \right) = 10,524.05184 \frac{W}{ft^2}$$

3) Average Power Available per ft²

$$10,524.05184 \frac{W}{ft^2} \cdot 0.17 = 1,789.0888128 \frac{W}{ft^2}$$

4) Multiple By Total Roof Area

$$1,789.0888128 \frac{W}{ft^2} \cdot 9080.65 ft^2 = 16,246,089.328 W \cdot \left(\frac{1 kW}{1000 W} \right)$$

$$= 16,246.0893 kW$$

This is the effective power capacity, adjusted for Indiana's average irradiance and efficiency

5) Estimated Monthly Energy

$$16,246.0893 \text{ kW} \cdot \left(\frac{1 \text{ day}}{24 \text{ h}}\right) = 676.9204 \text{ kWh} \cdot \left(\frac{24 \text{ h}}{1 \text{ day}}\right) \cdot \left(\frac{30 \text{ days}}{1 \text{ month}}\right)$$
$$= 487,382.68 \frac{\text{kWh}}{\text{month}}$$

6) Estimated Annual Energy

$$487,382.68 \frac{\text{kWh}}{\text{month}} \cdot 12 \text{ months} = 194,953.072 \frac{\text{kWh}}{\text{year}}$$

7) Number of Panels

$$\frac{1 \text{ panel}}{17.5 \text{ ft}^2} \cdot 9080.65 \text{ ft}^2 = 518.89 \approx 519 \text{ panels}$$

Based on the calculations, we have found that adding a total of 519 panels on the roof WALC would provide an estimated annual generation of **194,953 kWh/year**. This output could provide about 1/4th of the annual electricity consumption of the building in 2024. This value may seem small, but it can help save funds and overall carbon footprint in the long run.

Piezoelectric Flooring

Background Information

Piezoelectric systems convert mechanical energy from foot traffic into electricity and generate between 0.1 and 0.5 watts per square foot (Aburumman, 2024). In areas with high foot traffic, like university buildings, this technology can be highly effective. *Figure 15* demonstrates how piezoelectric flooring generates energy from foot traffic through the piezoelectric effect. The material between the two plates is a piezoelectric ceramic. When the material bends under the compressive force of the plates, the ceramic disc's charge balance is changed. This imbalance produces a small charge that can be stored and used by the circuit it is connected to.

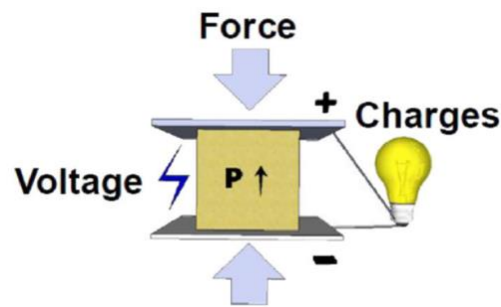


Figure 15) The Piezoelectric Effect

Research Study

As stated above, the piezoelectric effect provides a consistent charge if the foot traffic remains consistent. Piezoelectric tiles were chosen for this study because of the 24-hour operating time of WALC. The research article by Aburumman explores how piezoelectric energy generation is directly related to the available area. This case study explores how piezoelectric tiles could be applied at the four main entrances of the library. The article also compared the energy generation potential of piezoelectric flooring with alternative solutions like solar panels. If piezoelectricity is combined with solar panels, then it could provide stable energy output for the Wilmeth Active Learning Center.

Possible Implementation

Since WALC has thousands of people passing through its four main entrances daily, it can provide plenty of foot traffic. This section calculates a hypothetical installation of the piezoelectric flooring at these four entry points.



Figure 16) WALC Rear Entrance with Hypothetical Piezoelectric Flooring Placement

Energy Generation Calculation

Based on the assumptions from the study, the hypothetical energy generation with a door width to double door length:

- *West Entrance Doorway: 18ft x 6 ft -- totaling 108 Sq. Ft per entrance.*
- *East Entrance Doorway: 19.5ft x 6 ft -- totaling 117 Sq. Ft per entrance.*
- *Total Area: 4 West Doorways + 4 East Doorways = 900 Sq. Ft*
- *Energy Generation Per Square Foot: Average (~ 0.3 watts/sq ft)*

Estimation

1. Energy generated per square foot per day:

$$0.3 \text{ Watt} \times (1 \text{ hour} / \text{day}) = 0.3 \text{ Watt-hours} / \text{day per sq. ft.}$$

2. Energy generated from 900 square feet per day:

$$0.3 \text{ Watt-hours} / \text{day per sq. ft.} \times 900 \text{ sq. ft.} = 270 \text{ Watt-hours} / \text{day}$$

3. Annual Energy Generation (Assuming 300 days for the academic year):

$$270 \text{ Watt-hours} / \text{day} \times 300 \text{ days} = 81,000 \text{ Watt-hours} / \text{year} = \mathbf{81 \text{ kWh} / \text{year}}$$

4. Efficiency Percentage

$$(\text{Energy Generated by Piezoelectric Flooring} / \text{Total Electricity Consumption}) \times 100$$

$$\text{Percentage} = (81 \text{ kWh} / 1,124,643 \text{ kWh}) \times 100$$

$$\mathbf{\text{Percentage} \approx 0.0072\%}$$

The system could generate 81 kWh per year of electricity from foot traffic at entrances. Dividing this value by the 2024 total year electricity consumption would give us an efficiency of 0.0072% which is not viable for this building.

Flower Turbines

Background Information

Flower Turbines are vertical axis wind turbines that are shaped like tulips. Their unique shape makes them aerodynamic and highly efficient, even in low-wind conditions. They work by using the cup shape around the blades to capture wind. With this captured wind, the blades are pushed to convert torsion into electricity. When clustered together in a 'bouquet,' they can increase each other's kilowatt-hour generation, making them ideal for energy generation in limited space. This works by producing a wind funnel because the captured air is being pushed into the nearby turbine. The European company of the same namesake as their product aims to solve the aerodynamic and design problems faced by small wind energy systems. These turbines produce virtually no sound, are durable, and activate at low speeds.



Figure 17) Visual Example of Flower Turbines and their Function

Research Study

Flower Turbines were chosen because they integrate into existing infrastructure with minimal disruption to urban settings. Due to the sheer size of the WALC, it would need wind farms to power it alone. However, the turbines could still be used in tandem with the solar panels like the piezoelectric tiles. The base cost for a bouquet of 10 turbines is \$118,300. Since they have a 20-year lifespan, this is a long-term investment for renewable energy (Flower Turbines). Over the course of two decades, the wind turbines will help reduce energy costs and support Purdue's commitment to sustainability. Not only will the turbines help WALC reduce its energy consumption, but their design will also enhance the building's

aesthetics. These turbines will integrate seamlessly with the environment, creating a visually pleasing and energy-efficient addition to the building.

Possible Implementation

We decided to place the wind turbines next to the skylight since it would not interfere with the solar panel placement. Due to the live and dead load of the wind turbines, placing them on top of the skylight could lead to additional hazards.

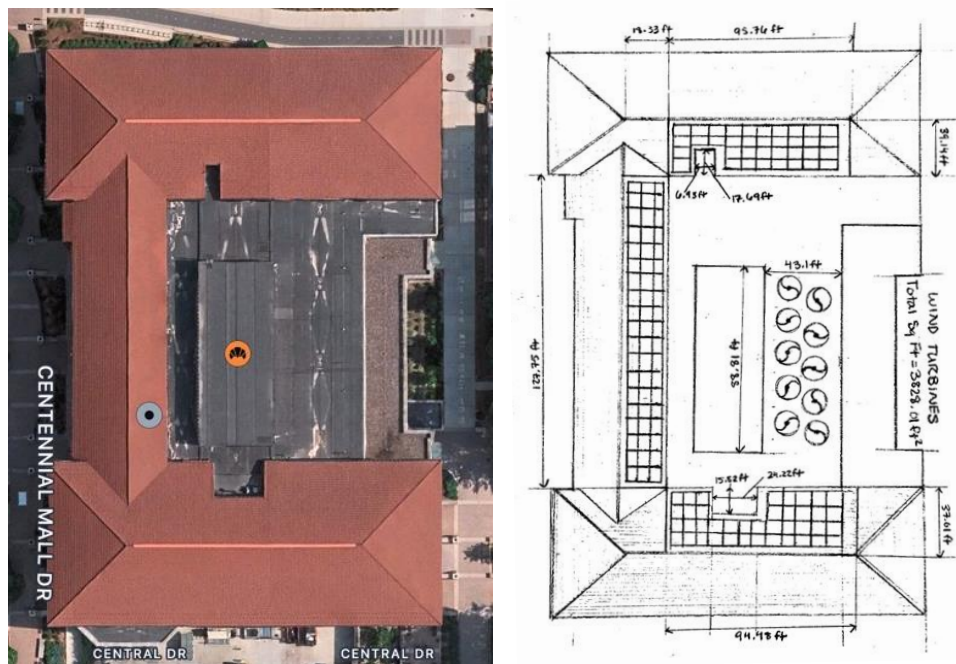


Figure 18) WALC Rooftop with Flower Turbine Placement

Energy Generation Calculation

With an average wind speed of 10.4 mph in West Lafayette, the turbines are projected to generate a good supply of power (Weatherspark). Using the values from *Table 5*, the energy generated was calculated based on the average monthly wind speed to determine the monthly kWh generated in *Table 6* below.

All in One Power Curve for each of 10 turbines

		watts								
m/s	mph	1m Tulip	2m Tulip	3m Tulip	5m Tulip	2m AL13	4m AL13	6m AL13	8m AL13	
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
0.5	1.1	0.0	0.2	0.5	1.7	0.4	0.9	1.4	1.9	
1.0	2.2	0.2	1.6	3.6	13.5	3.5	7.3	11.1	15.6	
1.5	3.4	0.5	5.5	12.3	45.6	12.0	24.5	37.6	52.5	
2.0	4.5	1.3	13.0	29.2	108.0	28.3	58.1	89.2	124.4	
2.5	5.6	2.5	25.3	57.0	210.9	55.4	113.4	174.2	243.0	
3.0	6.7	4.4	43.7	98.4	364.5	95.6	196.0	300.9	419.9	
3.5	7.8	6.9	69.5	156.3	578.8	151.9	311.2	477.9	666.8	
4.0	8.9	10.4	103.7	233.3	864.0	226.7	464.5	713.3	995.3	
4.5	10.1	14.8	147.6	332.2	1,230.2	322.8	661.3	1,015.6	1,417.2	
5.0	11.2	20.3	202.5	455.6	1,687.5	442.8	907.2	1,393.2	1,944.0	
5.5	12.3	27.0	269.5	606.4	2,246.1	589.4	1,207.5	1,854.3	2,587.5	
6.0	13.4	35.0	349.9	787.3	2,916.0	765.2	1,567.6	2,407.4	3,359.2	
6.5	14.5	44.5	444.9	1,001.0	3,707.4	972.8	1,993.1	3,060.9	4,271.0	
7.0	15.7	55.6	555.7	1,250.2	4,630.5	1,215.0	2,489.4	3,822.9	5,334.3	
7.5	16.8	68.3	683.4	1,537.7	5,695.3	1,494.5	3,061.8	4,702.1	6,561.0	

Table 5) Flower Turbines – All in One Power Curve (Flower Turbines)

Month	Wind Speed (mph)	Power Output (W)	Monthly Energy (kWh)
January	12.1	606.4	451.162
February	12.0	606.4	407.501
March	12.3	606.4	451.162
April	12.1	606.4	436.608
May	10.4	332.2	247.157
June	8.7	233.3	167.976
July	7.6	156.3	116.287
August	7.4	156.3	116.287
September	8.6	233.3	167.976
October	10.3	332.2	247.157
November	11.5	455.6	328.032
December	11.7	455.6	338.966
Average	10.4	398.36	264.689

Table 6) Average Wind Speed in Indiana with corresponding Power Output (Weatherspark)

Table 6 above records that the average kilowatt-hours generated per month was 264.689 kWh. To find the average amount of kWh generated per year, we multiply this number by 12 months.

$$264.689 \frac{kWh}{month} \cdot 12 \frac{months}{year} = 3,176.268 \frac{kWh}{year}$$

As a result, the average kWh generated per year by each wind turbine would be 3,176.268 kWh.

This value would be multiplied by 10 because *Table 5* shows the power output for each wind turbine.

$$3,176.268 \frac{kWh}{year} \cdot 10 \text{ turbines} = 31,762.68 \frac{kWh}{year}$$

Thanks to the “bouquet” effect of the turbines, their energy output increases exponentially to **31,762.68**

kWh annually.

Design and Analysis

Overview

The team conducted a knapsack analysis to determine the most optimal setup of solar panels, piezoelectric flooring, flower turbines, or some combination of the three to install. The discrete analysis includes a full installation cost breakdown to compare with the total income per kWh generated yearly. After creating the optimal setup using Microsoft Excel Solver, we construct an economic analysis on the chosen energy sources. By calculating the benefit cost ratio, we will demonstrate if the set-up is economically viable. This method directly relates the present cost of the system to the present benefits of the system.

Cost Estimation

In this section, every cost used for both analysis procedures are recorded and explained.

Installation Costs

For solar panels, we found that it costs \$6-12 per square foot. (Wigness 2024). For this analysis, we assumed \$9 per square foot. Although solar panels use the most space, its installation costs are calculated as:

$$\frac{9}{ft^2} \cdot 9080.65 ft^2 = 81,725.85$$

Piezoelectric flooring typically costs about £80 (or \$103) per square foot to install (Hopkins 2024). So, for 900 square feet of flooring, the total installation cost would be:

$$\frac{\$103}{sq.ft.} * 900 sq.ft. = \$92,700$$

Finally, the installation costs for wind turbines are outlined on the products section of the Flower Turbines' website. It costs the most to install with a base price of \$118,300. All these sources need a structural assessment, electrical/grid integration, and permitting fees to be added into the WALC. We decided to set this at a base price because all three installations will require about the same number of hours to install, and our calculations could be simplified. This price would sit at \$18,000 which is \$5,000 for the assessment, \$10,000 for the electrical integration, and \$3,000 for the permits. The only additional set up cost would come from the solar panels. Since they must cut and mount the panels onto roof tiles, the process will add an extra \$15,000. The total installation costs for each renewable source are summarized in *Table 9*.

Power Generation Income

Using the average annual kilowatt-hours generated by each source, we can calculate the amount of money each source will save for WALC. As of February 2024, the commercial electricity in Indiana is 12.56 cents per kilowatt-hour (EIA). This calculation is done by multiplying this factor by the kWh generated per year.

For solar panels:

$$194,953 \frac{kWh}{year} \cdot 12.56 \frac{cents}{kWh} \cdot \left(\frac{1 \text{ dollar}}{100 \text{ cents}} \right) = \$24,486 \text{ per year}$$

For piezoelectric tiles:

$$81 \frac{kWh}{year} \cdot 12.56 \frac{cents}{kWh} \cdot \left(\frac{1 \text{ dollar}}{100 \text{ cents}} \right) = \$10 \text{ per year}$$

For flower turbines:

$$31,762.68 \frac{kWh}{year} \cdot 12 \frac{cents}{kWh} \cdot \left(\frac{1 \text{ dollar}}{100 \text{ cents}} \right) = \$3,812 \text{ per year}$$

Annual Maintenance Costs

The maintenance costs would come into play during the economic analysis of the desired setup of renewable energy. For the solar panels, the estimated cost of annual maintenance would be \$1,480. Roof Gnome published an article in November of 2024 calculating the high-end cost of maintaining the panels would be \$740 (Magerl, 2024). However, it is unclear if this number is for residential or commercial panels, so the team doubled this cost. This is more reasonable because it puts the solar panels in range of the maintenance costs of the flower turbines. Piezoelectric tiles are hard to calculate maintenance costs for because they either require simple cleaning or a replacement of the materials and components to maintain efficiency. This is among the reasons why it was not chosen for the final system for implementation in the library. Finally, the last cost to find was for the flower turbines. The manual for the 3M Flower turbine explained that its maintenance is like that of a car. It only requires a visual inspection and a change of grease every two years. (Flowerturbine.com). After finding the price of a 50kg container of oil to be around \$424, we can assume that the cost of yearly maintenance would only come out to be \$1,272. (Melkib) We found this number by multiplying the price of the oil by 3 to account for the labor involved. Although the oil only needs to change every two years, we set this as the yearly cost to build up an automatic allowance for any replacements.

Salvage Value

The final cost to be calculated for the renewable energies was the salvage value. This is the amount of money that Purdue would receive at the end of the lifespan of these technologies. Unfortunately, calculating the exact salvage value of each source would be very difficult. Due to the degradation of the technology and unknown market value 20 years down the road, it is impossible to estimate a salvage value that would accurately demonstrate the benefit of adopting renewables. To get around this, the team decided to calculate the amount of money Purdue could receive from tax breaks and add that as an estimated salvage value. This would not only simplify the math, but it would give a more

realistic picture of the benefits of using renewable energy. For both solar and wind, they would fall under the IRS' Modified Accelerated Cost Recovery System (MACRS). According to an online source, this system would allow Purdue to receive a portion of the costs of the depreciating value of the system through tax breaks (Cohen, 2024). The article also provides an example table that we will use to find the estimated salvage value for the panels and turbines. We opted for this simple calculation because it is hard to find out how Purdue University conducts their taxes. For both calculations the adjusted depreciation value will always be:

$$\text{Initial Cost} \cdot (1 - 0.15) = \text{Depreciation Value}$$

For solar panels:

$$\$114,700 \cdot (1 - 0.15) = \$97,495$$

For flower turbines:

$$\$136,300 \cdot (1 - 0.15) = \$115,855$$

Now, the tables can be constructed by taking a decreasing percentage of this value over a 6-year period.

Base Depreciation Value		\$97,495
Year	Depreciation Rate	Annual Depreciation Amount
1	32%	\$31,198
2	20%	\$19,499
3	19.20%	\$18,719
4	11.52%	\$11,231
5	11.52%	\$11,231
6	5.76%	\$5,616
Total	100%	\$97,495

Table 7) Solar Panel Depreciation Value through MACRS

Base Depreciation Value		\$115,855
Year	Depreciation Rate	Annual Depreciation Amount
1	32%	\$37,074
2	20%	\$23,171
3	19.20%	\$22,244
4	11.52%	\$13,346
5	11.52%	\$13,346
6	5.76%	\$6,673
Total	100%	\$115,855

Table 8) Flower turbine Depreciation Value through MACRS

Both depreciation values are fully paid back at the end of the estimated 6-year period. Therefore, the salvage value for the panels and the turbines will be the same as their base depreciation values. The piezoelectric tiles were left out of this calculation because they are still being researched.

Discrete Knapsack Analysis

The knapsack analysis is a discrete optimization method that allows us to determine the best set up for these renewable energy alternatives. To do this, we inserted the expected costs (installation) and the expected energy benefits (power generation income) into Microsoft Excel. Our objective for this analysis was to maximize the benefits created with this system. Then, we added a budget of \$260,000 to constrain the results. Using the Math Solver extension the results came out to be building twice as many solar panels as initially proposed.

Renewable Alternatives for WALC - Discrete Optimization					
Source	Expected Cost (\$)	Expected Energy Benefits (\$)	Decision	Actual Costs	Actual Benefits
Solar Panels	\$114,700	\$24,468	2	\$229,400	\$48,936
Wind Turbines	\$136,300	\$3,812	0	\$0	\$0
Piezoelectric Tiles	\$110,700	\$10	0	\$0	\$0
Objective Function			Total	\$229,400	\$48,936
Maximize Benefit			Budget	\$260,000	
$\sum_{i=1}^3 x_i \cdot r_i$					
Constraints					
$\sum_{i=1}^3 x_i \cdot c_i \leq 2.5$					

Figure 19) The First Result of the Discrete Knapsack Analysis

Although this result fits within the criteria, there is not enough space on the roof to successfully implement this solution. To remedy this, we established another constraint to set the decision variable of the solar panels equal to 1. This is modeled as:

$$x_1 = 1$$

This fixed the problem and gave us the final combination of implementing both solar panels and flower turbines as a final solution!

Renewable Alternatives for WALC - Discrete Optimization						
Source	Expected Cost (\$)	Expected Energy Benefits (\$)	Decision	Actual Costs	Actual Benefits	
Solar Panels	\$114,700	\$24,468	1	\$114,700	\$24,468	
Wind Turbines	\$136,300	\$3,812	1	\$136,300	\$3,812	
Piezoelectric Tiles	\$110,700	\$10	0	\$0	\$0	
Objective Function			Total	\$251,000	\$28,280	
Maximize Benefit			Budget	\$260,000		
$\sum_{i=1}^3 x_i \cdot r_i$						
Constraints						
$\sum_{i=1}^3 x_i \cdot c_i \leq 2.5$						

Figure 20) The Final Result of the Discrete Knapsack Analysis

Economic Analysis

Now that we have the optimal setup of renewables, we can perform the economic analysis on the solar panels and the wind turbines. Assuming a 5% interest rate, we calculated the benefit cost ratio for both sources over a lifespan of 20 years. A sample calculation for both sources is available in Appendix A, and the compound interest sheet we used is in Appendix B. The results showed that solar panels would yield a profit while wind turbines would not with a BCR of 2.57 and 0.6 respectively. Overall, this makes the system economically viable if only the solar panels are installed.

Summary Table

	Solar Panels	Piezoelectric Tiles	Flower Turbines
Total Installation Cost (\$)	114,700	110,700	136,300
Annual Power Generation Income (\$/yr)	24,468	10	3,812
Annual Maintenance Costs (\$/yr)	1,480	N/A	1,272
Salvage Value (\$)	97,495	N/A	115,855
Discrete Optimization Budget (\$)	260,000		
Lifespan (years)	20	N/A	20
Benefit Cost Ratio (BCR)	2.57	N/A	0.6

Table 9) Summary of Values from Discrete and Economic Analysis

Aesthetics and Interactive Design

Universities should also prioritize making their learning spaces welcoming and refreshing! Incorporating ideas that help with mental health can help increase cognitive performance and keep emotional well-being in check. We see so many students sitting outside on the grass or at picnic tables when the weather is just right! This is a great way to decompress and take a break after working for so long. There are picnic tables in the front and back of WALC, but the only issue is that there are no umbrellas or outlets to help students stay outside longer. We can install folding umbrellas that have small solar panels to charge lights or phones – which can also be stored away for the winter months. These umbrellas can also use bright colors as shown in *Figure 21* below.

The backside of WALC's seating area also uses a large space, but there are also no shades or charging stations. A cool implementation would be to add a Pergola that has sunscreens and small solar panels to help cover the area when it is sunny. Adding windchimes or string lights could make the place more inviting for students or visitors to enjoy the outdoors!



Figure 21) Aesthetic design additions to front and back seating area of WALC

Every design should make a lasting impact! Imagine walking through the entryway of a building and seeing inspirational quotes or cool designs on the wall to help boost your day even if the weather seems gray. What if you walk in and see a vertical garden wall that also smells good? This is a great way to add more color and purpose to a building by bringing in a touch of nature while also improving air quality. Introducing bright, energizing colors throughout WALC can instantly lift the atmosphere. From colorful furniture and art installations to accent walls, it will make the building feel lively and welcoming, creating a space that students will enjoy being in.



Figure 22) Aesthetic design additions to the interior of WALC

To create a more engaging experience, we can design the building to be interactive for students. For example, adding piezoelectric flooring with glowing tiles or transparent sections that light up when stepped on would let users see the impact of their movements. While solar panels and flower turbines operate in the background, students could still connect with the technology through digital displays showing real-time energy data inside the building. This helps them visualize how everyday actions – like walking – can positively contribute to energy generation. It is also a creative way to promote sustainability while helping students learn about renewable energy in a hands-on and memorable way.

Final Recommendations

Based on thorough calculations and design analyses of each energy alternative, our team recommends implementing solar panels on the rooftop of WALC as the optimal energy source. Referring to Table 9, solar panels have a higher Benefit Cost Ratio of 2.57 - therefore justifying their performance over a lifespan of 20 years. The building is already energy efficient, but considering the long-term financial benefits, there will be lower annual energy costs and potential incentives for using renewable energy as a campus investment. With this, WALC can become a model for sustainability, thus raising Purdue's prestige as a leader in green technology which will help to gain more research funding and support for future energy-efficient initiatives. Also, the integration of solar energy will help the environmental and social pillars of sustainability. A project like this will reduce the library's carbon footprint and influence student-led projects across campus.

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Appendix A

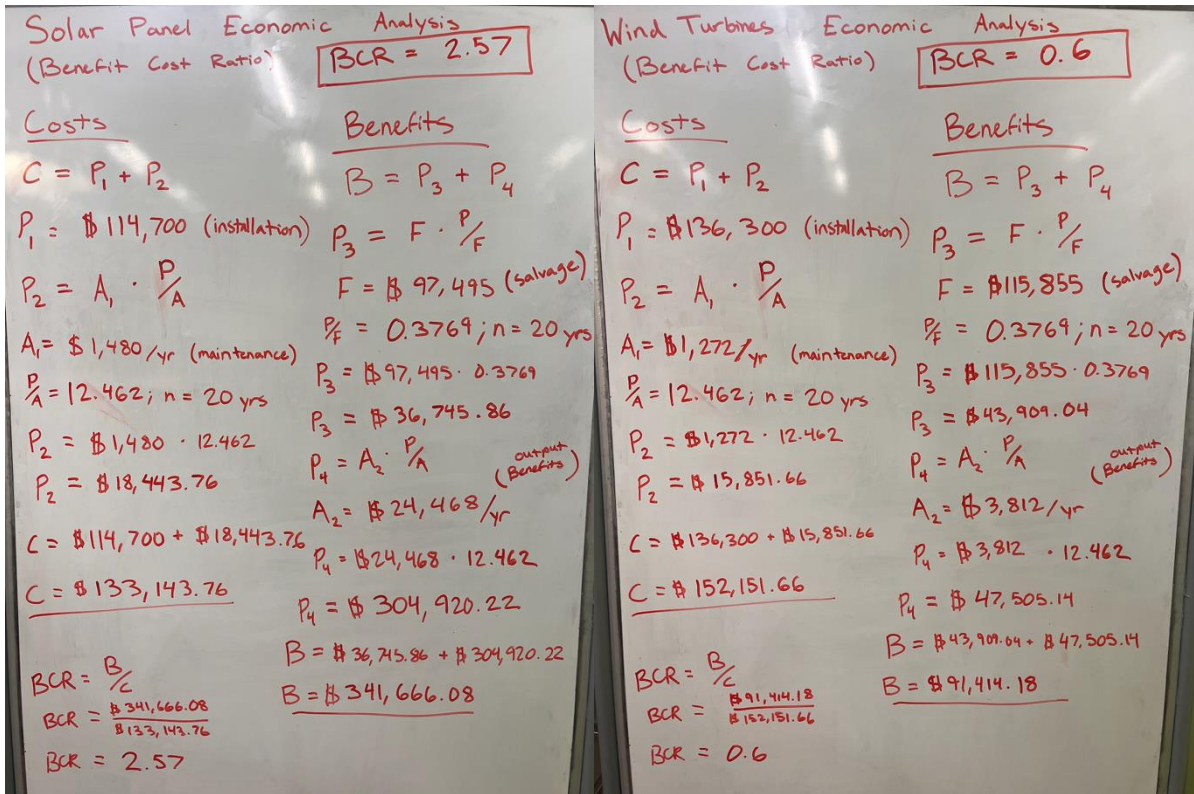


Figure 23) Calculations of the Benefit Cost Ratio

Appendix B

5%		Compound Interest Factors						5%	
n	Single Payment		Uniform Payment Series				Arithmetic Gradient		n
	Compound Amount Factor	Present Worth Factor	Sinking Fund Factor	Capital Recovery Factor	Compound Amount Factor	Present Worth Factor	Gradient Uniform Series	Gradient Present Worth	
	Find F Given P F/P	Find P Given F P/F	Find A Given F A/F	Find A Given P A/P	Find F Given A F/A	Find P Given A P/A	Find A Given G A/G	Find P Given G P/G	
1	1.050	.9524	1.0000	1.0500	1.000	0.952	0	0	1
2	1.102	.9070	.4878	.5378	2.050	1.859	0.488	0.907	2
3	1.158	.8638	.3172	.3672	3.152	2.723	0.967	2.635	3
4	1.216	.8227	.2320	.2820	4.310	3.546	1.439	5.103	4
5	1.276	.7835	.1810	.2310	5.526	4.329	1.902	8.237	5
6	1.340	.7462	.1470	.1970	6.802	5.076	2.358	11.968	6
7	1.407	.7107	.1228	.1728	8.142	5.786	2.805	16.232	7
8	1.477	.6768	.1047	.1547	9.549	6.463	3.244	20.970	8
9	1.551	.6446	.0907	.1407	11.027	7.108	3.676	26.127	9
10	1.629	.6139	.0795	.1295	12.578	7.722	4.099	31.652	10
11	1.710	.5847	.0704	.1204	14.207	8.306	4.514	37.499	11
12	1.796	.5568	.0628	.1128	15.917	8.863	4.922	43.624	12
13	1.886	.5303	.0565	.1065	17.713	9.394	5.321	49.988	13
14	1.980	.5051	.0510	.1010	19.599	9.899	5.713	56.553	14
15	2.079	.4810	.0463	.0963	21.579	10.380	6.097	63.288	15
16	2.183	.4581	.0423	.0923	23.657	10.838	6.474	70.159	16
17	2.292	.4363	.0387	.0887	25.840	11.274	6.842	77.140	17
18	2.407	.4155	.0355	.0855	28.132	11.690	7.203	84.204	18
19	2.527	.3957	.0327	.0827	30.539	12.085	7.557	91.327	19
20	2.653	.3769	.0302	.0802	33.066	12.462	7.903	98.488	20
21	2.786	.3589	.0280	.0780	35.719	12.821	8.242	105.667	21
22	2.925	.3419	.0260	.0760	38.505	13.163	8.573	112.846	22
23	3.072	.3256	.0241	.0741	41.430	13.489	8.897	120.008	23
24	3.225	.3101	.0225	.0725	44.502	13.799	9.214	127.140	24
25	3.386	.2953	.0210	.0710	47.727	14.094	9.524	134.227	25

Figure 24) CE 398 Compound Interest Factors Worksheet