Impact analysis of sustainable home systems and features

Civil Engineering 421:

Environmental Sustainability Engineering

Closing the Housing Gap—Fall 2017

FURNACE SYSTEMS

Introduction:

In Dane County, Wisconsin, there is a great need for affordable and worker's housing throughout the region. To combat this issue, public-private partnerships are developed where the Dane County Affordable Housing Fund provides funding and assistance to the developers willing to construct or renovate affordable housing complexes. Recently, the Dane County Board of Supervisors agreed to provide two million dollars per year from 2015 to 2018 solely for the development of affordable housing. All operations within Dane County adhere to the county's adopted sustainability principles, and with the budget constraints associated with affordable housing projects, the sustainability of these buildings is not merely a choice but a requirement to keep these projects affordable and feasible.

Affordable housing focuses on building multi-family housing that is integrated into the community as large apartment complexes, as this is cost and space effective. With the public private partnership there is the ability to have standard market price apartments in the same building as subsidized units. This way, they can provide non-discriminatory housing as well as construct complexes that have a much smaller carbon footprint than building several smaller homes. Thus, apartment complexes with upwards of forty to fifty units in one building are the most economically feasible for these projects. Existing complexes are located throughout the Dane County area and are designed to be conveniently located around major employers, public transit, and other attractions. Occasionally, these complexes share building space that is open to retailers or private businesses. The existing Union Corners development is being used as a reference for features to include within this project (Milewski, 2016).

The crux of the proposal revolves around the furnace systems being installed in Dane County's affordable housing projects. Different heating options for large apartment complexes will be compared, and the most sustainable option will be determined in terms of the environmental, economic, and societal constraints faced in multi-family living. The ultimate goal of this project is to give our community partner, the Dane County Housing Initiative, information on alternative heating systems for future housing projects and the ability to evaluate the respective sustainability for any heating options they might consider as newer technology enters the market. With these tools, Dane County can work to create the most sustainable multi-family communities.

Question:

When looking into building the large apartment complexes proposed by Dane County, there exist multiple factors revolving around furnace selection that must be compared. The first important factor is whether the furnace should be centralized or if each apartment should have its own smaller unit. This can affect heat usage rates and the overall efficiency of the system (Lstiburek, 2006). The next factor that should be addressed is which type of fuel the furnace should use. Traditional furnace systems use natural gas or coal but new systems can take advantage of electric or geothermal energy, which has a smaller impact on the environment and can increase our overall efficiency.

There are benefits and drawbacks to having a centralized system that will be weighed as a process of the research. The ultimate goal in the end will be to determine if centralized systems outweigh the individual furnaces in terms of cost and benefits. When looking into the difference between the two systems it is important to take into account the need for sub-monitoring units when heat is paid for by the individual tenant. It is also important to realize that in centralized systems the furnace would not be turned off for an individual apartment being vacant for an extended period of time. There are multiple factors that will be involved in comparing the two styles including, cost, carbon footprint, and accessibility.

When comparing the energy sources for different furnaces, it is important to look at the feasibility of each option. For example, solar options were not explored because during peak winter heating needs, the output of a solar heating system would not be able to fill the energy demand. Similarly, wind powered furnaces require a lot of land dedicated to electricity production, which is not always a readily available resource for communities. That being said, the choices for energy sources were narrowed down to electricity, geothermal heat, and gas. With all of the options being reasonable choices to implement in Wisconsin, the best option will be determined which for the case of multi-family unit housing located in the South Central

Wisconsin region. Cost, accessibility, energy consumption, and overall sustainability will be weighed for each option.

After looking into each factor of furnace selection the benefits and costs of each option will be compared, ultimately answer the underlying question by determining if the cheapest option is best, the most sustainable option is best, or if there is a happy medium that satisfies both constraints.

Methods

The analysis of each heating system option will be based on the three tenets of sustainability. The environmental, economic, and social costs and benefits of each option will be accounted for. Our final recommendations will come from the result of a balanced analysis of each area.

When judging the environmental impact of a heating option, there are a number of factors to consider. Each system has initial manufacturing costs but the greatest impact of a system is determined by its energy use over its lifetime. An effective way to determine a furnace's energy efficiency is with its AFUE rating. This value is a measure of heating output compared to energy input of each furnace. Standards dictate the acceptable minimum rating for different models and typical gas furnaces operate around 90% efficiency (U.S. GPO, 2017). Entirely electric furnaces and can reach nearly 100% efficiency but their effectiveness may not be optimal while geothermal heat pumps can surpass 400% efficiency.

The energy source for each heating option is also important to consider. Many traditional furnaces used in residential buildings make use of natural gas as fuel to provide heat. Natural gas, while it produces less emissions than crude oil, is still a fossil fuel and is unsustainable indefinitely. Newer furnaces can be entirely electric and are not dependent on fossil fuels. However, if the production of electricity comes from coal or natural gas plants, this option can have a greater overall impact than a traditional furnace. Large power plants are not efficient at converting fuel into energy so that 100% AFUE rating is misleading in an electric furnace's overall impact (MGE Power Sources, 2017). Heat pumps operate by transferring the natural heat of the earth to buildings. Because of its independence from fossil fuels, this could be the most sustainable energy source of all of the options at hand but some heat pumps can have limited effectiveness in colder weather depending on their orientation (Heat Pump Systems, 2016). In order to avoid seasonal efficiency dropoffs, the systems need to be dug to a significant depth such that the ground temperature remains constant year round.

When weighing each heating option, the overall energy consumption of each system and the emissions produced by different fuel sources will be analyzed. The annual equivalent CO_2 consumption will be determined for each system.

From an economic perspective, there are three major costs associated with a furnace system. Purchase and installation costs, regular energy consumption during operation, and maintenance and upkeep costs are the areas that will be weighed when determining the best furnace option. Each cost is paid for by a different entity which could make it difficult to compare the options. For example, installation cost is paid by Dane County's chosen contractor, the operational costs are paid by the resident, and maintenance is the responsibility of the building's owner. For the most part, operation costs correlate directly with energy consumed so minimizing one factor should reduce the other as well. The lifetime costs will be measured and compared to determine the cost benefit relation between different options.

Determining a sustainable furnace system is primarily an environmental and economic issue but there are still social factors to address that could make one option preferable over another. For example, a system that operates according to a resident's exact needs is preferred over one that cannot. Control of temperature in independent units is a feature that could be improved by individual systems over a central option. Noise created and the size of each unit can also determine the desirability of different systems. Safety can also differ depending on each fuel source. Overall, social factors are not as critical to our scope but they are still important to consider for a fully sustainable solution.

Expected Results:

After researching the many available furnace options, geothermal heat pumps appear to present the best option for the given scenario. We discovered that in general, geothermal heat pumps are superior to conventional furnaces in every facet except for initial installment costs.

With that being said, depending on the situation, some buildings might not be able to afford high initial costs, however in a large scale project such as this Dane County installment we expect that the energy return over time will outweigh the initial cost (DOE, 1998). At first, heat pumps appeared impractical given the typical climate of Wisconsin because most heat pumps are reliant on air temperature. After the research showed that geothermal heat pumps utilize the earth's temperature rather than the air temperature this idea was accepted as one of the more feasible options.

Preliminary estimates expect the carbon footprint of geothermal to be the lower of the two options due to conventional furnaces being fueled by natural gas and the emissions that coincide with burning the natural gas. Geothermal pumps have no secondary emissions beyond what is required to generate the electricity to power the pump. Because they make use of an external energy source, they can have efficiencies approaching 400% whereas conventional furnaces are not capable of surpassing 100% (ClimateMaster, 2016). An electric furnace would also be another option that would approach a low carbon footprint but it is dependent on how the electrical energy is generated. Large power plants are typically inefficient and generating electricity to power a furnace would require more resources than directly sourcing the furnace. Purely electric and geothermal furnace systems are similar in their carbon footprint being dependent on the origin of the electrical power but overall, geothermal pumps use less electricity than electric furnaces and therefore we expect them to be the best option for Dane County to pursue.

Comparison

Early in the decision making stages, independent units were found to be the most effective option for heating large residential buildings. Large furnaces capable of heating several thousand square feet are great for commercial or office spaces but the independent control for each unit is critical towards social acceptance of furnace systems.

In comparing the different furnace systems, three specific models were selected to represent each category. These were selected through market research and balanced cost, efficiency, and output capability. The specific properties of each model is detailed in Table 1 below.

Table 1: Furnace Comparison Data

	MRCOOL Multi-Speed Gas Furnace	Revolv 23kW Electric Furnace	MHP 5 Ton Geothermal Heat Pump
Cost	$986	$687	$2895
AFUE Efficiency	95%	100%	COP: 4
Heating Capacity (BTU/hr)	78,000	75,000	63,000
Dimensions	35” x 29.5” x 17.5”	20” x 60.63” x 24.5”	26” x 24” x 43”

The minimum capacity rating was determined by the maximum expected heating needs during a Wisconsin winter. For a unit with 1,200 to 1,600 sqft, a desired temperature of 75℉ and an outside temperature of 0℉, the output required is approximately 70,000 BTU/hr depending on the insulative properties of the building (AC Direct, 2017). While this heating rate will not commonly be required throughout the year, it was essential to design around this scenario.

Environmental

The environmental analysis assumes that each apartment will use 17,000 kWh of energy per year to heat their space. This value is derived from the typical space heating energy consumption trends for Wisconsin households as detailed in a U.S Energy Information Administration report (U.S. EIA, 2009). The model apartment complex included 60 units, totalling 1,020,000 kWh of energy per year to heat the entire building.

It is assumed for the electric furnace system that the electricity is supplied by the Madison Gas and Electric company. Despite having invested in wind, solar, and biogas energy, most of MGE’s electricity is provided by coal or natural-gas fired power plants. According to the information provided by MGE’s 2016 Environmental and Sustainability Report, their most current emissions rate is 1.587 lbs CO_2 / kWh generated (MGE, 2016). This number was used to compute the amount of emissions generated by the kWh requirement to heat our multi-family complexes. The electric furnace is rated as 100% efficient, as all electricity is directly going to make heat. Thus, to find the total emissions produced from the model building's yearly heating consumption, the total kWh of energy is multiplied by MGE's emission rate, totalling 734.25 metric tons of carbon dioxide released into the atmosphere per year. This was by far the most environmentally impactful option, and right away it was clear that electric furnace systems have serious disadvantages.

The analysis of the geothermal system followed the same protocol as the electric system, as geothermal systems use electricity to circulate the refrigerant through the system. The amount of electricity required to do this, however, is much smaller than that required to heat the entire space. Instead, only about a quarter of the energy required to heat the building is used (Klaassen, 2006). This comes out to a total of 255,000 kWh of energy to run the geothermal system for the whole year. The same emissions rate from MGE was used to calculate the emissions contributed from this, and the total emissions came out to 183.56 metric tons of CO2 released per year.

The natural gas emissions analysis takes into account the electricity required to run the system as well as the emissions generated from the furnace's operation and use of natural gas. There is not much electricity required to run the system; only 19838 kWh per year (NYSERDA, 2013) . Still, this amounts to about 14.28 metric tons of CO2 per year just from the electricity provided by MGE. The rest of the CO2 emissions were calculated using data from the U.S. EPA's greenhouse gases equivalency calculator, which states that a natural gas furnace releases about 0.0053 metric tons of CO2 per therm (EPA, 2017). To find the number of therms, the total amount of kWh per year was converted from 1,020,000 kWh to 34804 therms. For the natural gas system, however, efficiency plays more of a role. It was assumed that because the complex would be new, the highest efficiency furnace would be selected. Thus, this model looks at natural gas furnaces with a 95% AFUE rating. With this number, it was found that to get 34804 therms of heating, about 36635 therms would need to be used by the system. With this number and the estimated emission rates provided by the EPA, it was determined that the natural gas being used would contribute 194.2 metric tons of CO2 per year. Paired with the system's electricity use, the natural gas furnace has a total annual emissions rate of 208.4 metric tons of CO2 per year.

It is clear that the geothermal heating system results in the lowest amount of annual emissions overall. Additionally, there are many factors that were not considered in the environmental analysis. The main factor that was neglected was the environmental cost of sequestering the materials to manufacture as well as run the system. For natural gas, this could have made a large difference, as a newer technology being used to harvest natural gas, fracking, is currently under scrutiny for having serious environmental implications. However, due to the relatively short amount of time that fracking has been in operation and the extent to which these implications are unknown, it is difficult to give a quantitative assessment for damages caused by natural gas harvesting. As for the materials used to manufacture these systems, the overlap in materials and methods used for furnace construction suggests that for each option the cost of manufacture would be relatively similar and thus insignificant to the analysis.

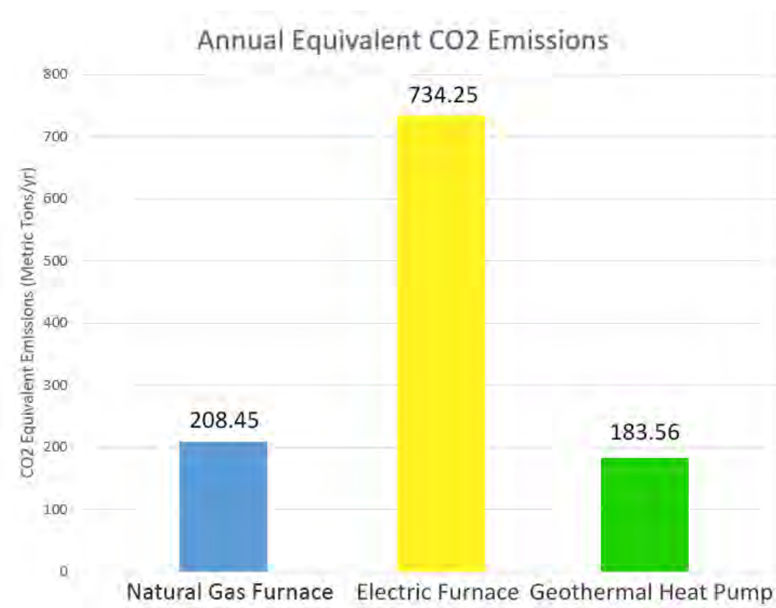

Figure 1: Annual CO_2 equivalence comparison between natural gas, electric, and geothermal furnaces

Economic

Cost is a critical deciding factor towards determining an optimal furnace system. Both initial and operational expenses were considered to find the life cycle costs of each furnace option. Each value builds on the assumption that the project would house 60 families and that each unit would have an independent heating unit.

The initial costs of each system includes both the purchase price of each unit and the installation costs. While large development projects can usually negotiate improved rates by purchasing units in bulk from wholesale distributors, the retail prices were compared because they were the most consistent and widely available. Electric furnace units are the least expensive option at $687 per unit while the gas furnace stands at $986. The geothermal unit is significantly more at $2895 per unit but it also has the greatest expected lifetime at 40 years. Over this 40 year period, the electric furnace would need to be replaced once and the natural gas furnace would be replaced twice, overall bringing the long term purchase prices much closer together.

Installation expense is another factor that could vary greatly depending on the contractor's rates but generally, electric furnaces are the least expensive to install because all that is required is ductwork and a connection to an electric line. Natural gas furnaces are more complex and require ducts and electrical connections as well as a natural gas source. This can be even more costly in a multi level apartment complex. Geothermal heat pumps are the most costly because they require significant planning and vertical pumps require deep drilling. These costs can be reduced when working with a new project because retrofitting requires working around existing structures and obstacles. At $15,000 to $25,000 per unit, this is the largest commitment to be addressed while selecting furnace options.

The expenses associated with running each system depends on electricity and natural gas rates as well as each model's efficiency. MGE's current rates for the two resources were considered as well as the associated connection fees. The lifetime purchase, installation, and operational costs are plotted in Figure 2 below as a factor of time.

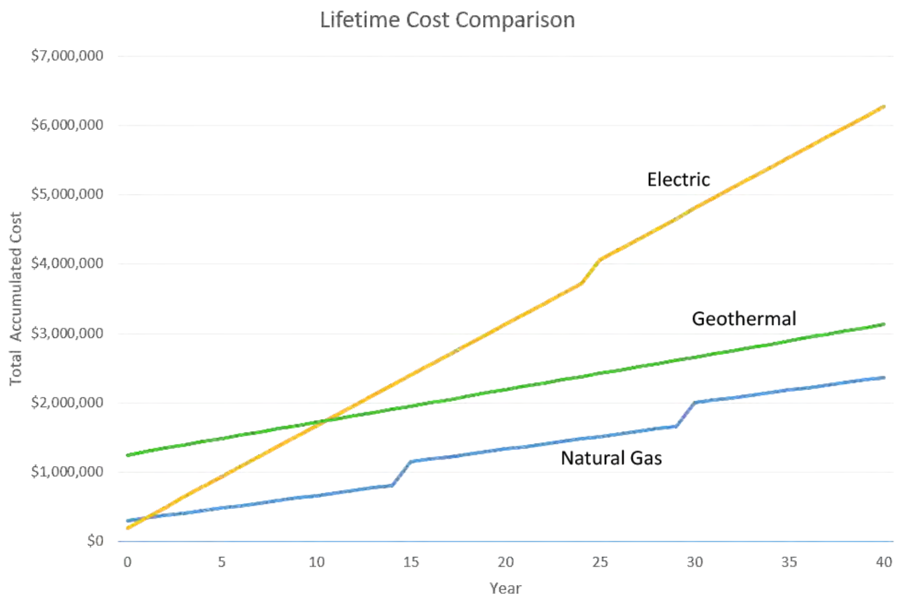

Figure 2: 40 year cost comparison between geothermal, electric, and natural gas furnaces

As seen within the graph, even with an effective efficiency of 400%, the cost of electricity required to power a geothermal pump is still bested by the low cost of power provided by natural gas. At 13.03¢/kWh, electrical energy is far more expensive for the relative power output. Natural gas is priced at 11.67¢/therm which equates to 0.4¢/kWh. Natural gas furnaces still require electricity to power the motor and fan to circulate air and the annual consumption for the building was found to be 19,800 kWh (NYSERDA, 2013). Even with this electricity requirement and the inefficiency in the natural gas system, the annual heating costs for the entire building were the lowest in natural gas furnaces at $36,296/year. The annual cost for geothermal systems came to $46,894 while purely electric options came to $146,535. These costs reflect the current overwhelming popularity of natural gas furnaces throughout the state.

Social

The social aspects of furnace selection are important to consider when comparing different options. Factors such as aesthetics, safety, accessibility, and noise can make one choice more desirable over another.

The aesthetics of the three choices have similarities as well as important differences. All three options are encased by a steel box with varying sizes. In apartment complex projects size is an important factor to take into account given the restrictive footage that apartments consist of. The smallest of the three options volumetrically is the gas furnace which would be optimal for small units.

Safety is important to discuss with furnaces as they will be directly implemented into each family's residence. Natural gas furnaces differ from geothermal and electrical in the manner that the safety concern is not simply wiring issues that lead to electrical fires. In natural gas furnaces that are not functioning at peak performance, incomplete combustion of the natural gas can occur producing carbon monoxide. Carbon monoxide leaks can be extremely dangerous and fatal if not resolved quickly. The increased risk of the natural gas systems is dangerous to overlook as each unit will have its own furnace which leads to each family being reliable for their own system.

Accessibility of furnaces is a new and developing field with the implementation of wireless controlled thermostats and individually controlled rooms. In comparison of the actual furnace units each can be fitted for zone control in the apartments. The efficiency of controlling different zones of the apartment depend more on the ductwork and piping of the apartment more than the actual furnace itself.

The noise levels of each furnace are also important to compare as loud furnaces can be disruptive to quiet homes. The geothermal furnace excels in this facet as the sound levels range from the hum of a refrigerator to the sound of a running dishwasher. The sound a geothermal furnace makes as it circulates the refrigerant through the ground and building is less disruptive than the forced air options that have loud fans to move the heated air throughout the building (Brown, 2016).

Discussion:

After consideration of the environmental, economical, and social outlooks for the three furnaces, it was determined that a geothermal system was the optimal choice for the new development. Geothermal was chosen despite its high initial costs due to its uncapped potential.

The highest cost in a geothermal system lies in the installation process. In this project there is an added benefit of working on a new site and costs can be reduced by working on such a large scale. Residents currently pay approximately 30% more annually for geothermal heating opposed to natural gas however natural gas rates could continue to rise as the finite resource is consumed and rates will converge. Environmentally, geothermal furnaces have the lowest environmental impact of the three options with potential to further lower its impact in the future. The low impact of geothermal will continue to decrease over time as MGE has set emission goals to produce less than 1.21 lbs CO_2/kWh and increase their dependence on renewable energy 30% by 2030. On a social basis, there is not a great difference between the three options except for the reduced noise level of geothermal systems and increased risk in natural gas systems. The geothermal system drew eyes once again as it is a more compatible system to have in each individual unit to promote safety and increase habitability.

Conclusion:

In the United States, the current market favors the choice of a natural gas furnace. Natural gas is a fuel in relative abundance and at present it's price is attractive for use within home heating systems. The future must be considered, however, when projects of this magnitude are planned. It is likely that multi-family complexes built now will have a lifetime of over 100 years and with new construction technologies, it's possible these buildings could last upwards of 150 years. This makes the consideration of alternative heating systems highly important and the geothermal option is decidedly the option with the most convincing longevity. The decision on furnace systems for the complex will ultimately come down to the developers in charge of the project, but it is the goal of this project to show that there are alternative options available that provide their own advantages and disadvantages in terms of sustainability.

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Appendix: Calculated Emissions and MGE Expense Data

		Units
Annual Use:	17000	kWh / apt
Apartments:	60	apts
Use for building:	1020000	kWh (per yr)
kWh to BTU:	3480382800	BTU (per yr)
BTU to therms:	34803.828	therms (per yr)

Calculate CO2 Emissions		
Natural Gas Furnace:	0.0053	Metric Tons CO2 / therm
Real Therms:	34803.83	therms (per yr)
AFUE Efficiency:	0.95	A higher efficiency is assumed
Therms for Building:	36635.61	therms (per yr)
CO2 Emissions from Gas:	0.0053	Metric Tons CO2 / therm
Total building emissions:	208.4491	Metric Tons CO2 (per yr)
Electricity Required	19838	kWh (per year)
CO2 Emissions from Electricity:	14.28042	
https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculat		
http://www.taitem.com/wp-content/uploads/tt_furnace_electricity_use_201305		
Electric Furnace:		
kWh for building:	1020000	kWh (per yr)
MGE stated emission rate:	1.587	lbs CO2 / kWh
lbs CO2 emitted:	1618740	lbs CO2 (per yr)
Metric ton conversion:	734.249	Metric Tons (per yr)
https://www.mge.com/environment/stewardship/responsibility-report.htm		
Geothermal System:		
Coefficient:	4	uses 1/4 the energy
kWh for building:	1020000	kWh (per yr)
Actual kWh used:	255000	kWh (per yr)
MGE stated emission rate:	1.587	lbs CO2 / kWh
lbs CO2 emitted:	404685	lbs CO2 (per yr)
Metric ton conversion:	183.5622	Metric tons CO2 (per yr)

	Calculating Costs			
	Electricity		Natural Gas	
Connection Cost	0.62466	$/day	$0.7195	$/day
Electricity Cost	0.13025	$/kWh	$0.1167	$/therm

INSULATION

1. Introduction

Housing has been recognized as a basic human right by the Board of Supervisors for Dane County, WI. However, there is currently a large gap between the number of housing units available at an affordable price and the number of units needed. This affordable housing gap is not unique to Dane County or even Wisconsin, but the Dane County Housing Initiative (DCHI) has been tasked with tackling this issue at the local level. According to the 2015 Housing Needs Assessment, the DCHI has found that around 65,000 households in Dane County live in housing which is considered "unaffordable" because they spend more than 30% of their income on housing (Paulsen, 2015). This gap has grown substantially over the past two decades due to relatively stagnant incomes, rising housing costs, and a large population growth rate in the region. The lack of affordable housing negatively impacts the workforce and can lead to higher employee turnover, which in turn can increase business costs and reduce regional competitiveness. To help combat this, the Dane County Housing Authority (DCHA) distributes 1,211 vouchers through the Department of Housing and Urban Development to eligible families amounting in over $6 million in rental subsidies each year (Paulsen, 2015). As the DCHA continues to increase its housing availabilities, they are interested in finding sustainable development opportunities that may help provide a better life to the current generation of families without compromising the needs of future generations. The Dane County Board Office has partnered with the University of Wisconsin - Madison's Environmental Sustainability Engineering course to help understand some sustainable development options that may be available to them. One of these topics of discussion is to do an analysis on the most sustainable form of insulation.

Wisconsin is known for its diverse weather which makes heating and cooling of homes especially difficult to manage. For a house to maintain a reasonably comfortable internal temperature year-round, air conditioners and heat furnaces are virtually unavoidable. Air conditioners and heating systems can be both economically and environmentally costly. In fact, in a typical U.S. house, heating and cooling account for 48% of the energy used (Insulation, 2017). In Dane County, this percentage is even higher. This makes insulation in Madison and its surrounding areas crucial. Insulation is used in every home to resist the transfer of thermal heat, helping to cut back on dependence of an air conditioner or heating system. Using the optimal type of insulation could benefit Dane County economically, environmentally, and socially. Before analyzing these different factors, it is helpful to understand exactly how insulation works.

2. Goal and Scope

The goal of this project, through analysis of the three paradigms of sustainability, is to propose the most optimal insulation material. The research focuses on wall insulation for inner houses in Madison, Wisconsin.

3. Background of Insulation

There are three basic mechanisms of heat flow that insulation aims to prevent. The most important of these three mechanisms is conduction (the way heat moves through a substance). Different materials have been used to hamper the energy flow but generally, good insulators are bad conductors. Less dense materials are also better insulators as atoms are spaced further apart, making it harder for heat to flow. These two characteristics are a good way to begin the search for well functioning insulation. A numerical value, called the R-value, is used to show the resistance to conductive heat flow. A high R-value represents an insulator that resists conductive flow of heat effectively, while insulation with a low R-value does not do as good of a job in restricting heat flow. R-value depends on the type, thickness, and density of material being used. Sometimes insulation systems are made of more than one material. The R-value of multilayer insulation systems is the R-value of the individual layers added up. Convection and radiation are the other two types of heat flow. When designing an insulation system, convection and radiation are secondary to conduction. To counter heat that is transferred through radiation, which travels in a straight line and heats particles and in its path that are capable of absorbing energy, a simple layer is placed on the front or back of the insulation system, designed to reflect radiant heat energy. Overall, insulation systems can be most easily analyzed on performance by the R-value.

Using the R-value to quantitatively compare current and alternative insulators will prove helpful in choosing the ideal material. (Thermal Insulation, 2017)

3.1 Current insulation

Due to the diversity of both climates and types of homes across the country, there is a huge variety of insulation types on the United States market. Deciding on the type of insulation to use depends on where in the country and where in the house the insulation has to be installed.
The most widely used insulation types in the US and in Wisconsin on the market right now are: fiberglass/rockwool, cellulose, and spray foam.

Fiberglass or rockwool

Fiberglass or rockwool insulation can be either blown-in (good at retrofit), which is literally blown into the walls and attic of a house through a large hose, or batt-insulation (commonly used for new buildings), which is manufactured in blankets of various sizes and thicknesses (see ***figure 1***). This material has a relatively high R-value, is inexpensive and easy to install, and is non-flammable and highly resistant to moisture damage, which is why this type of insulation is very popular for a lot of homeowners. Although this type of insulation has a lot of advantages, it is made from fibers that can irritate the skin, are possibly cancerous, and can enter the respiratory system and cause damage. Safety equipment is therefore necessary and it is not advised to stay in the home while it is being installed.

Figure 1 Fiberglass insulation roll mat[1]

[1]Scott, R. (2015, September 08). How Insulating Your Home Can Save You Money. Retrieved from https://scottleeheating.com/how-insulating-your-home-can-save-you-money/

Cellulose insulation

Cellulose insulation material is manufactured from old newspapers (see ***figure 2***). The papers are sorted and ground into insulating cellulose flakes which come in both bales and blown-in forms. The path from newspaper to insulation material requires little energy and no water. (Energy.gov, 2017)

Figure 2 Cellulose insulation[2]

Spray foam

Spray foam insulation (see ***figure 3***) is petroleum based and has little or no recycled content. The installation requires a professional with special equipment in order to measure, mix and spray the insulation. This type of insulation is effective in reducing air leaks and is often used in areas where this is critical although it can be used in all structures. The cost of using this is quite high compared to fiberglass and the waste generated cannot be reused or recycled. There have also been The Center for Disease Control and Protection is currently studying the risks of using this type of insulation (Spray Polyurethane Foam (SPF): A Sustainable Insulation Choice? , 2017) but has not concluded anything yet.

[2]Ringler, A. (2017, February 20). Home. Retrieved from http://www.retrofoamofmichigan.com/what-is-cellulose-insulation-material/ and Chicago Tribune, Sun-Times and Crain's leaders on the future of print media. (n.d.). Retrieved from http://www.chicagonow.com/candid-candace/2016/02/chicago-tribune-sun-times-and-crains-leaders-on-the-future-of-print-media/

Figure 3 Spray foam insulation[3]

3.2 Alternative insulation

There are many alternative insulation solutions on the market some of which are listed here: denim, sheep wool, hemp, and straw insulation.

Denim insulation

The company 'Bonded Logic' has developed the material and owns patents to the manufacturing process. The insulation is called Ultratouch and contains 80 percent post-consumer recycled fibers from denim (see ***figure 4***). (Bonded Logic, 2017)

Figure 4 Denim insulation[4]

Sheep wool insulation

All natural insulation from sheep (see ***figure 5***) is perfectly safe to install and has excellent insulation properties. Sheep's wool is also resistant to pests, fire, and mold. It can hold large quantities of water, which is an advantage for use in some walls. (Sheep wool insulation, 2017)

[3] Spray Foam Insulation. (2017, June 14). Retrieved from https://www.planswift.com/blog/spray-foam-insulation/
[4] Reprinted from BUY Jeans for Men (5116) in indore, India from MOVE ON FASHION. (n.d). Retrieved from http://moveonfashion.com/jeans-for-men-5116-/p21# and
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Figure 5 Sheep wool insulation[5]

Hemp insulation

Hemp/flax (see ***figure 6***) are natural fibers and have been used throughout history. Because of its vast properties, it is often used as ropes, sails and also clothing. It has great strength and is naturally resistant to mold and harsh weather conditions. (American Lime Technology, 2017)

Figure 6 Hemp insulation[6]

Straw insulation

Straw bales used for insulation are made from a waste product. Typically, when farmers have harvested wheat, the stalks simply become a disposal problem. By baling the straw, farmers can gain money by selling them for home construction. Straw bale (see ***figure 7***) is also an excellent insulation and building material. (Energy.gov, 2017)

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[5]

[6]Reprinted from Dowdey, S. (2010, October 05). Sheep's Wool Insulation: A Sweater for Your House. Retrieved from https://www.stufftoblowyourmind.com/blogs/sheeps-wool-insulation-a-sweater-for-your-house.htm and G., Products, E., & Wadsworth, C. (2017, October 28). Black Mountain 16″ Natural Sheep Wool Insulation. Retrieved from http://eco-buildingproducts.com/product/16-sheeproll-natural-wool-insulation-roll/?v=7516fd43adaa

Figure 7 Straw insulation[7]

3.3 Quantitative R-value background

As previously mentioned, the R-value of insulation is one quantitative way to compare the performance of various materials. Typically, less material is needed for insulations with high R-values. ***Table 1*** lists the R-value per square inch of the seven insulations we choose to analyze.

Table 1. R-value of insulation based on material type

Insulation Type:	Fiberglass (Batt) (AiDomes, Aug 2016)	Cellulose (Blown) (AiDomes, Aug 2016)	Spray Foam (Polyurethane) (AiDomes, Aug 2016)	Denim (Batt) (Build Direct, 2017)	Sheep Wool (energy.gov, 2017)	Hemp (energy.gov, 2017)	Straw (energy.gov, 2017)
R-value (per inch)	3.14	3.70	6.25	3.5	3.5	3.5	2.7

4. Methods

In order to best assess these different housing insulation options for use in Dane County, each type of insulation will be analyzed using the three main paradigm of sustainability: economic, environmental, and social (see ***figure 8***). Each paradigm will require unique assessment methods for comparing insulation types. In order to make the comparisons relative, the 'industry standard' insulation will serve as the baseline to which the other types of insulations will be compared.

[7] Reprinted from The Man Who Brought Hemp to Kentucky. (2016, May 11). Retrieved from https://modernfarmer.com/2015/01/man-brought-hemp-kentucky/ and Warm, K. M. (1970, January 01). Hemp Insulation - The Green Alternative. Retrieved from http://www.keepmewarm.com/2016/09/hemp-insulation-green-alternative.html

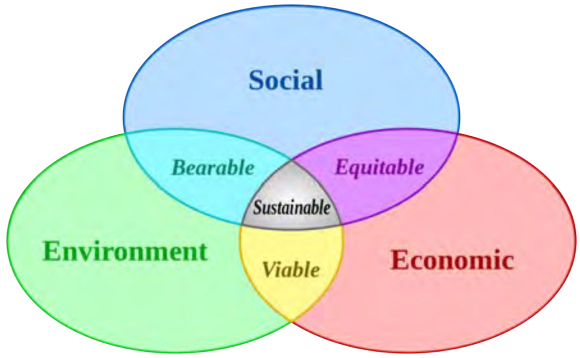

Figure 8 The three paradigm of sustainability[8]

4.1 Economics

Economic sustainability is important in determining the feasibility of the use of a product. To begin comparing the insulation types from a financial perspective, some assumptions must be made to standardize the analysis.

First, insulation is installed in different ways and must meet various requirements depending on the location within the building. For the purposes of this analysis, insulations will be assumed to be installed in a wall to the required R-value for the state of Wisconsin. According to the Energy Conservation Code, Dane County falls into Climate Zone 6 which suggests wall insulation to meet an R-value of 20 (IECC, 2009). This assumption makes this analysis applicable to a wider variety of building types versus assuming the insulation being installed in a crawl space or attic.

The second assumption used in this analysis is that the insulation will be installed in a new-construction development. While older buildings can often be renovated and re-insulated, the installation method and insulation type can be highly situation dependent making it difficult to compare the financial aspects.

The third assumption is that a new development will always have some sort of insulation. This means that the types of insulation will be compared to each other rather than compared to a building without insulation.

The fourth and likely most important assumption is that each insulation type would be installed by a professional. This assumption is important for two reasons. First, it means that the cost of installation must be included in the financial analysis as opposed to a homeowner doing it

[8] V., H., G., T., P., N., & D., B. (n.d.). Straws. Retrieved from https://www.feedipedia.org/node/60 and Straw-Bale Walls for Northern Climates. (n.d.). Retrieved from http://www.greenbuildingadvisor.com/blogs/dept/guest-blogs/straw-bale-walls-northern-climates

themselves. Second, this assumption places the insulation types on a more equal playing field. The effectiveness of an insulation type is highly dependent upon the installation. If an insulation is installed incorrectly, it can completely void many of the benefits of the insulation. While it is true that some insulations expand to fill gaps better than others and therefore may offer long-term energy savings, for the purposes of this analysis it is assumed that each insulation is installed perfectly and to the proper R-value. This analysis therefore negates any possible energy savings associated with using different types of insulation. However, being that a realistic home would experience some energy loss over time, this is addressed qualitatively in the results and discussion section.

The fifth assumption is that all insulation will last the same amount of time. This assumption seems to hold true as it is unlikely to replace the insulation in a household if it was installed properly to begin with. Part of this assumption covers the fact that some insulation will settle overtime, therefore reducing its effective thermal resistance. This is usually accounted for at installation by using thicker insulation than initially required.

Using the above assumptions, it was possible to compare upfront costs of installing the different types of insulations at a normalized level.

4.2 Environmental

The environmental cost associated with a product is often overlooked, but is one of the key components of sustainable development. One of the most effective methods of determining the environmental impacts of a certain product or service is to use a life cycle assessment (LCA) tool. These tools will take into account all of the inputs and outputs of a product in four main stages of its life cycle: raw material procurement, manufacturing, use, and end of life. An LCA can be used to look at single indicator or multiple indicator impact categories. For the purposes of this analysis, a multiple indicator LCA will be used. The useful indicators in this analysis are greenhouse gases and energy consumption. Other research papers also analyze hazardous waste and toxic releases, eutrophication potential, land use, and water withdrawals however this is not included in this analysis. Previous research yielded process LCAs, which provided a detailed look at the life cycle stages of each insulation option. These LCAs provided a common ground for which to compare the various insulation options based on different environmental impacts assessed throughout the life cycle of the product.

4.3 Social

Compared to the environmental and economic analyses, the social assessment was quite qualitative. That being said, part of the social analysis depended on the personal values of the homeowner or insulation installation crew. Overall social costs of insulation include the safety of the installation and manufacturing processes, and any toxic effects on human and animal health. The assumption that the insulation would be installed professionally eliminated many of the risks usually associated with inexperienced installers.

5. Results

5.1 Economics

Quantitative Financial Analysis

Insulation costs are highly dependent upon a few specific variables. The first variable of importance is the total area in need of insulation. For a given wall, this can be found by multiplying the width by the height of the wall. To normalize this variable, each insulation can be compared on a per square-foot cost. Another variable of importance is the thickness of the insulation needed to reach the required R-value. The overall thermal resistance of a cross section of insulation is a linear function of the depth of the insulation, although this function changes based on the insulation material. For instance, fiberglass batt insulation usually has an R-value of 3.14 per inch of thickness (AiDomes, 2016) . To normalize this variable, each insulation was compared to each other using a thickness of a unit R-value. To summarize, the costs of each insulation material were analyzed on a costs per square-foot per unit R-value ($/[sq. ft. x R-value]). As this value is a little abstract, it was multiplied by the required R-value of 20 for walls in the state of Wisconsin to obtain a normalized cost per square foot (IECC, 2009). In this analysis, installation costs were also added into the normalized cost to obtain a total cost per square foot of insulation required (see ***Table 2***).

Table 2. Cost per square foot of installed R20 insulation by type

	Fiberglass Batt [1, 2]		Blown Cellulose [4, 5]		Spray Foam [4]		Denim Batt [6]		Sheep Wool Batt [7,8]		Hemp Batt [9]		Straw	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Material cost [$/(sq. ft. x R-value)]	$0.0174	$0.0344	$0.0074	$0.0204	$0.1070	$0.1750	$0.0643	$0.0643	$0.1455	$0.1654	$0.2115	$0.2115	--	--
Material Cost - R20 [$/sq. ft.]	$0.35	$0.69	$0.15	$0.41	$2.14	$3.50	$1.29	$1.29	$2.91	$3.31	$4.23	$4.23	--	--
Installation Cost [3] [$/sq. ft.]	$0.28	$0.65	$0.28	$0.65	--	--	$0.28	$0.65	$0.28	$0.65	$0.28	$0.65	--	--
Total Cost [$/sq. ft.]	$0.62	$1.34	$0.42	$1.06	$2.14	$3.50	$1.56	$1.94	$3.19	$3.96	$4.51	$4.88	--	--

Sources: [1] (MNSHI, 2017), [2] (Home Depot, 2017a), [3] (Attic Insulation, 2017), [4] (Improvement Center, 2017), [5] (Insulation-Guide, 2017), [6] (Home Depot, 2017b), [7] (Wadsworth, 2017), [8] (Good Shepherd Wool, 2016), [9] (Riha, 2016)

The information from ***Table 2*** was converted into a column chart (see ***figure 9***) to visually show the difference in upfront cost of the installed insulation materials.

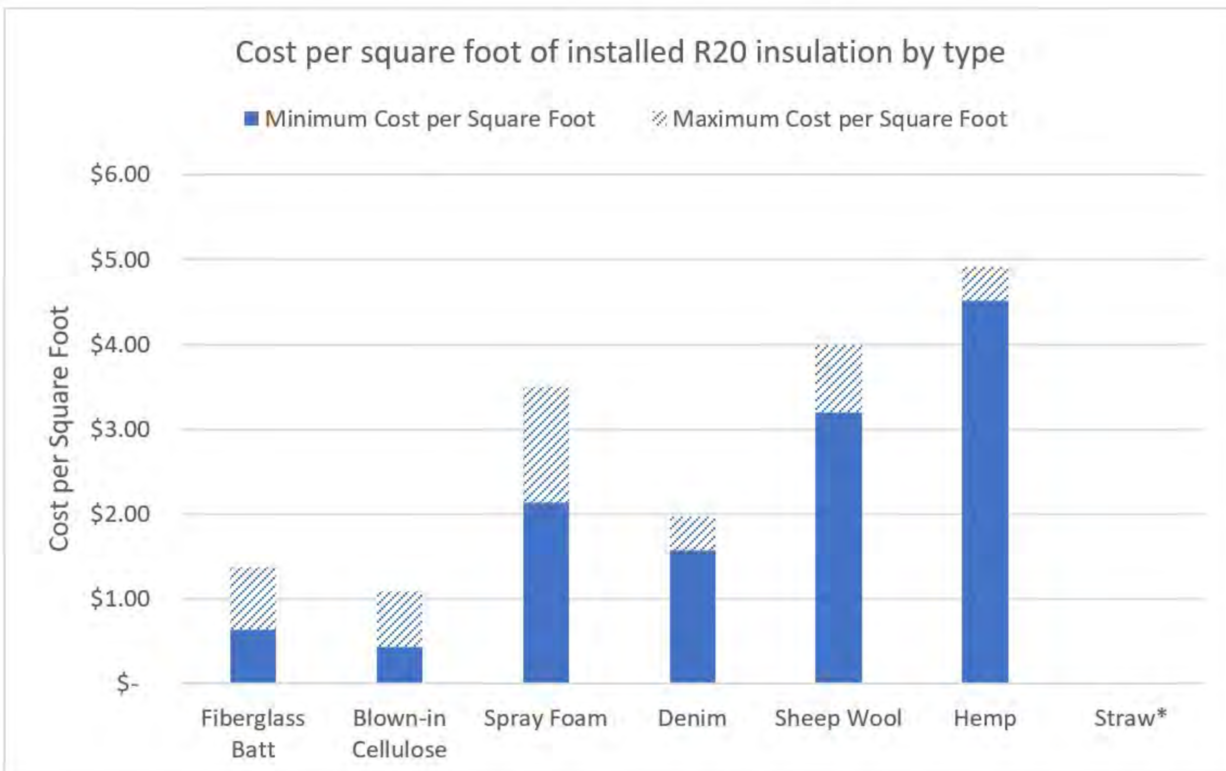

Figure 9 Cost per square foot of installed R20 insulation by type developed from Table 2.

Using ***figure 9***, it is easy to develop a ranking of the most financially sustainable insulation materials. Given the assumptions listed above, a cheaper upfront cost equates to a more economically sustainable material choice. Therefore, the following list shows a ranking of the most economically sustainable insulation options.

1. Blow-in Cellulose

2. Fiberglass Batt
3. Denim Batt
4. Spray Foam
5. Sheep Wool
6. Hemp
7. Straw*

Straw is a unique insulation in that it cannot be used in a typical wood frame home, instead it would be a major component of the design and construction. In fact, the straw is sometimes even used as a structural element in the home. One of the unique construction requirements when using straw bales is that the walls need to be at least 18 inches wide to accommodate the bales. This can be viewed as a practical design element as well as a positive aesthetic feature. However, the thick walls also cut into valuable livable area in the home thereby making it smaller than that of a typically framed home. These unique design constraints make it impractical to compare in the same way as various other types of insulation. While not difficult, the construction techniques are unconventional and therefore would require a knowledgeable contractor in addition to likely extra effort in obtaining building code approval. Overall, it is typical for a straw bale building to cost 10-12% more than a conventional building (Strawbale.com, 2013).

Issue with Assumptions Made

While it is convenient to make assumptions in order to normalize the results and create a quantitative comparison between materials, it is not necessarily realistic. Two important issues that these assumptions ignore is the degradation of materials over time and the failure to install the insulation properly. Both of these issues can be hard to quantify as they are completely situational. They do, however, contribute to this financial analysis in a slightly different manner.

The purpose of insulation is to restrict the flow of heat through a structure and it is necessary in reducing the amount of energy needed to maintain a comfortable climate within the home. If the insulation is not installed properly or begins to degrade over time, then it loses its capability of restricting the flow of heat and can end up costing the homeowner more money in energy costs. For instance, batt insulation is usually quite cheap and can be installed by a homeowner, but it can be difficult to install perfectly. Any gaps or improper placement of the insulation can lead to areas susceptible to the flow of heat and essentially negating the benefits of the insulation. Spray foam, on the other hand, is usually professionally installed and it expands upon installation to fill up any potential voids. One potential solution is to use batts for the large sections of the walls and to spot fill hard to manage areas with spray foam.

It is also well known that some insulation degrades over time. For instance, blown-in insulation can lose as much as 20% of its initial R-value due to settling (NAIMA, 2017). This is usually accounted for upon installation by ensuring that extra insulation is placed into the cavity so that the insulation meets the required R-value upon settling. However, if this is not properly addressed upon installation, it can cause weaker R-values in the home than initially intended. On the other hand, sheeps wool insulation likely expands slightly over time having the opposite effect and increasing its insulative effect.

As with all insulation, the resistance value of a straw bale can be grossly degraded by the presence of moisture within the walls. Straw bales, however, face the additional challenge of rot and insect infestation if not properly installed.

5.2 Environmental

Life Cycle Assessment (LCA)

Based on the economic assessment Cellulose and Denim insulation was chosen, a more thorough analysis will be presented in regard to life cycle assessment of fiberglass and these two products. The two types are also seen as the most realistic option for Dane County to choose. The other materials will however still be part of the assessment and all the materials are compared with fiberglass insulation.

The ISO 1404 standard (International Organization for Standardization, 2006) states that there are four phases of a life cycle assessment (see ***figure 10***) to consider:

1. **Goal and scope definition** (defines the purpose of the LCA, identifies assumptions and boundaries and defines the scope)
2. **Inventory analysis** (the impacts of energy, materials, emissions, etc. are identified, classified and quantified)
3. **Impact assessment** (the environmental impacts of the product/process/activity are assessed)

4. **Interpretation** (the results are interpreted and products compared, opportunities for environmental improvement identified and conclusions are made)

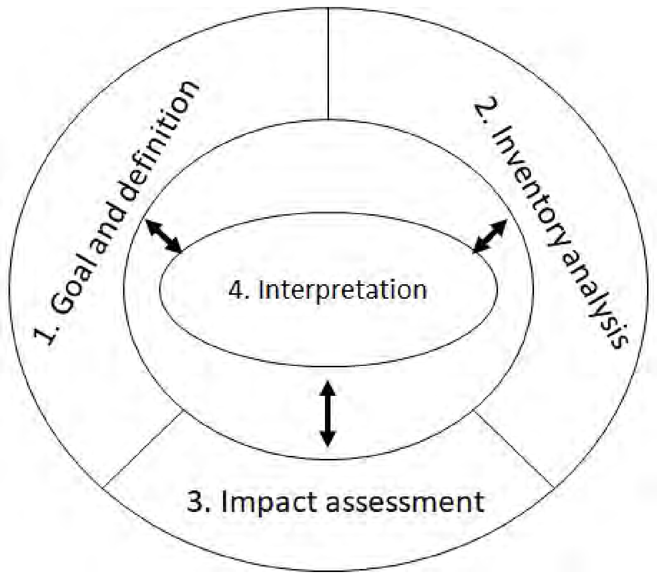

Figure 10 The four phases of a life cycle assessment

Goal and scope

The goal and scope of this assessment is to compare the environmental impacts from fiberglass insulation and the alternative insulation materials.

Analysis

The analysis will be based on the three materials mentioned above, fiberglass as the baseline material, cellulose as an alternative and denim as another alternative to fiberglass. The production processes of these materials will now be presented, each of these steps requires energy etc. and it is the base for finding the environmental impacts of each material.

Production process of fiberglass insulation:

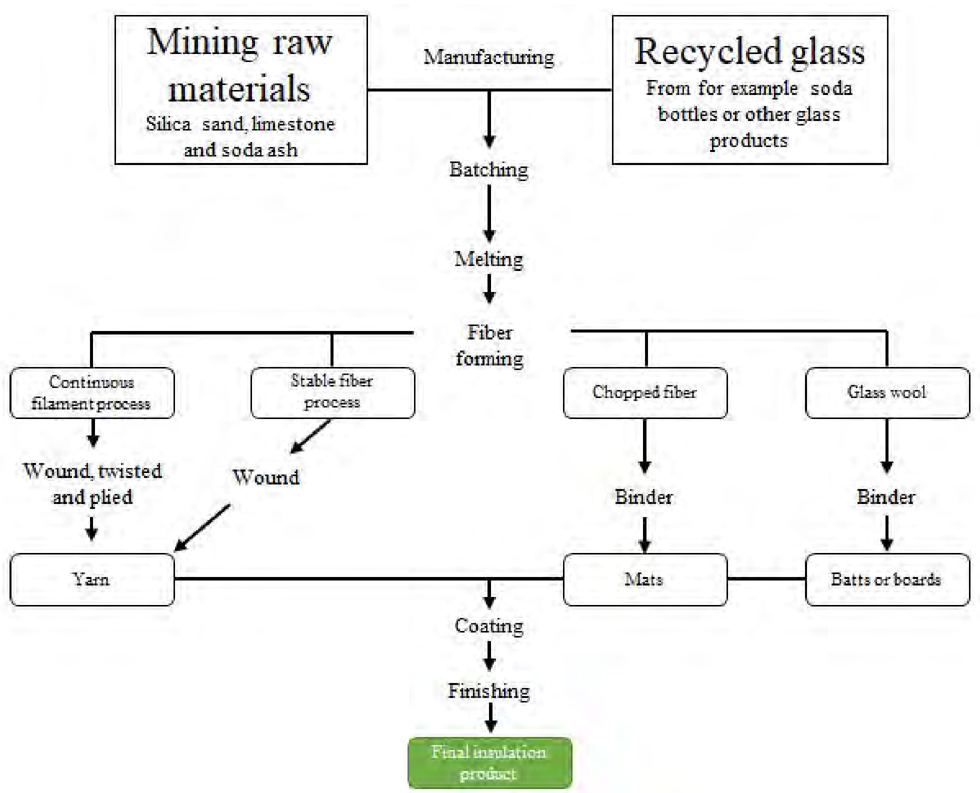

Figure 11 Production process of fiberglass insulation[9]

1. Mining the raw materials Silica sand, limestone and soda ash. This process requires a lot of energy and water. Most fiberglass insulation contains a fair amount of recycled glass from soda bottles or other glass products.
2. When the batch is prepared it is put into a furnace for melting, from there the molten material is transferred to forming equipment.
3. Fiber forming is done in four different types of fiber processes depending on which type is desired for the final product, fiberglass comes in yarn, mats, batts or boards.
4. Coating, the fiberglass is now coated to strengthen the fiber, reduce fiber abrasion and to protect against static electricity.
5. The fiberglass is now formed into various shapes, depending on usage this could be rolls, mats or boards and is now ready for the consumer.

[9]How fiberglass is made - material, used, processing, components, dimensions, composition, product, industry. (n.d.). Retrieved December 6, 2017, from http://www.madehow.com/Volume-2/Fiberglass.html

Production process of cellulose insulation:

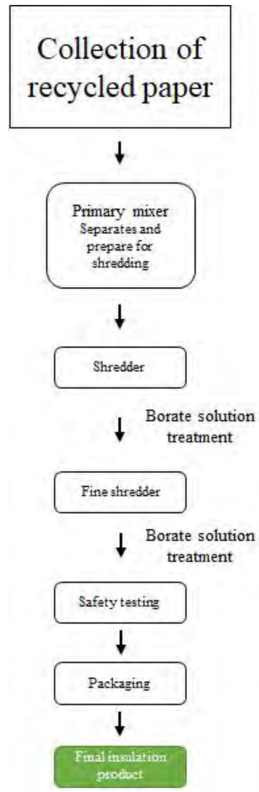

Figure 12 The production process of cellulose insulation[10]

1. Recycled paper is collected in all types, this can be waste products from paper production or waste from offices.
2. The primary mixer will separate and remove all metals using magnets, this process prepares the paper for the first coarse shredding.
3. First coarse shredder will shred the paper into small bits of paper, after shredding the cellulose will be treated with a borate solution to make it fire and pest resistant.
4. The fine shredder will shred the cellulose into even smaller bits and the cellulose will undergo another borate solution treatment.
5. The material is now ready for safety testing, here the material is exposed to various tests such as thermal testing, an example is the testing of a lit cigarette that burns out in the material, the material must withstand the heat from this and not catch fire.
6. The material is now packed and ready for the consumer.

[10] Production of cellulose insulation - YouTube. (n.d.). Retrieved December 6, 2017, from https://www.youtube.com/watch?v=Ug8cPtmd3ow

Production process of denim insulation:

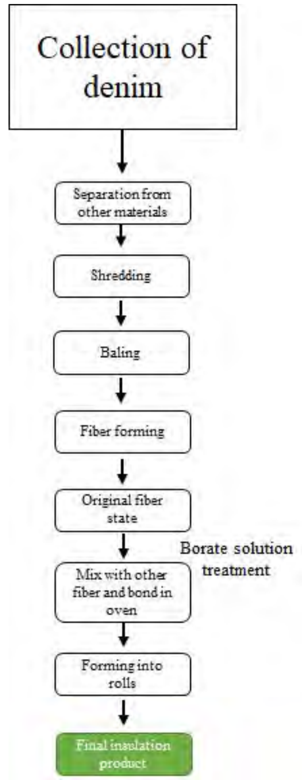

Figure 13 The production process of denim insulation[11]

1. Recycled denim is collected both from the production of jeans and from consumers.
2. The material is separated from other materials that might be in the collected denim. Buttons, zippers etc. are removed.
3. The denim is now shredded into smaller pieces and baled.
4. A processor now unweaves the denim, returning the textile to its original fiber state.
5. The material is treated for fire and pest resistance.
6. The material is now mixed with other fibers and bond in an oven.
7. The material is formed into rolls, packed and ready for the customer.

Assessment

The environmental assessment is based on the scientific review and comparative analysis written by (Schiavoni, S., D'alessandro, F., Bianchi, F., & Asdrubali, F. , 2016). By doing a lot of desk

[11] How Denim Insulation Is Made - How Denim Insulation Works | HowStuffWorks. (n.d.). Retrieved December 6, 2017, from https://home.howstuffworks.com/denim-insulation1.htm

research, it was clear that LCA's are calculated and evaluated in many different ways, finding information that could be compared was difficult, but this article was the most thorough and best represented article found. This analysis relates to energy consumption and global warming potential of several insulation materials, some of the materials are analyzed through a Cradle to grave approach and others are analyzed through a Cradle to gate approach.

The Cradle to grave approach is the full LCA from extraction of resources to use phase and disposal phase, meaning that all inputs and outputs are considered for all the phases of the life cycle. The Cradle to gate approach is a partial assessment of a product life cycle from extraction of resources to the factory gate without the use phase and disposal phase.

A functional unit must be defined when doing an LCA, the primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related. In this case the functional unit is defined as the mass of material needed to obtain a thermal resistance of $1 \frac{m^2K}{W}$ for a $1\ m^2$ panel (Schiavoni, S., D'alessandro, F., Bianchi, F., & Asdrubali, F. , 2016).

LCA results

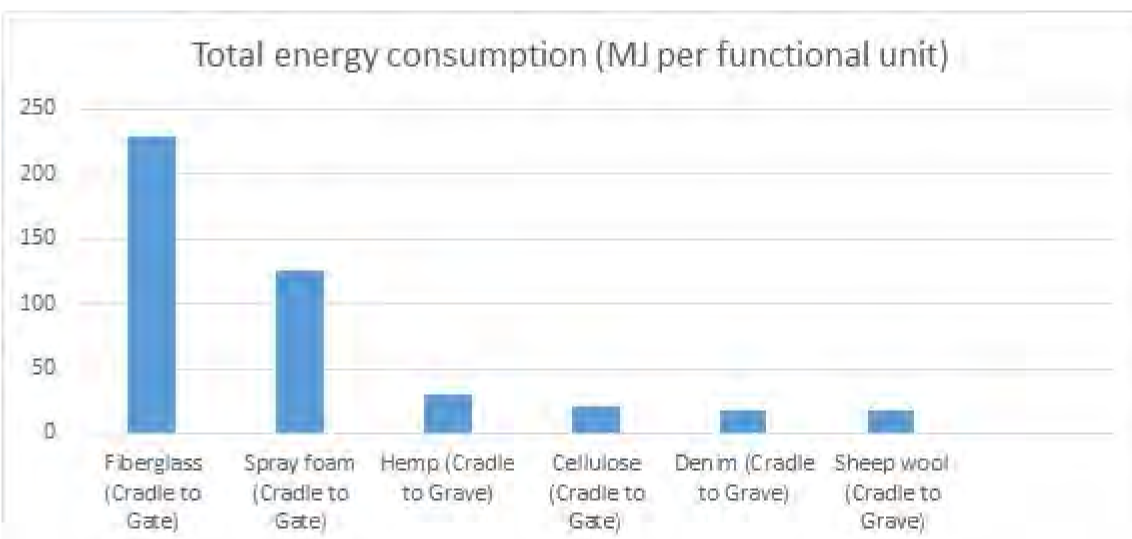

Figure 14 The total energy consumption in MJ per functional unit of respectively fiberglass, spray foam, hemp, cellulose, denim and sheep wool insulation materials

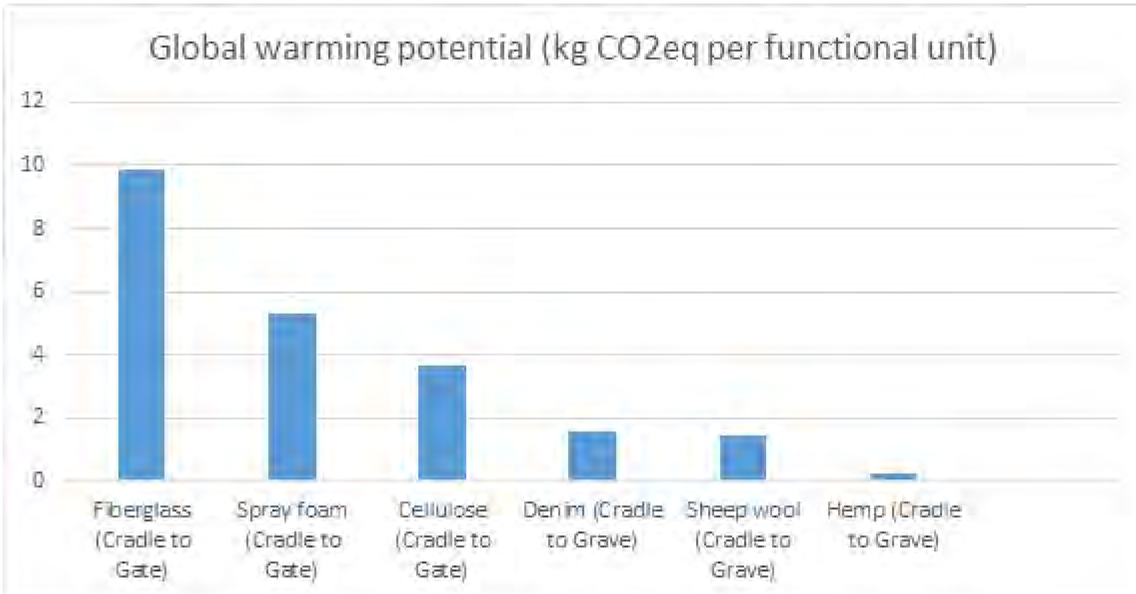

Figure 15 The global warming potential in MJ per functional unit of respectively: fiberglass, spray foam, cellulose, denim, sheep wool and hemp insulation materials

Below is the ranking of each of the insulation options.

1. Sheep wool
2. Hemp
3. Denim
4. Cellulose
5. Spray foam
6. Fiberglass batt

Insulation materials analyzed through the cradle to gate approach (Schiavoni, S., D′alessandro, F., Bianchi, F., & Asdrubali, F. , 2016) states that fiberglass is by far the worst performing insulation material, spray foam is the second worst performing and cellulose insulation is the best performing materials in regard to embodied energy and global warming potential using the cradle to gate approach, unfortunately the lack of available data in their study suggests that there should be more research done in this area to find the most environmentally friendly material.

Insulation materials analyzed through the cradle to grave approach

Comparing the data evaluated from the cradle to gate approach, hemp insulation is characterized by having the highest amount of embodied energy, but it also has the lowest global warming potential. Sheep wool insulation has the lowest value of embodied energy and has a low global warming potential value. Denim scores highest in global warming potential and second highest in embodied energy of the all the materials analyzed through cradle to grave.

Interpretation

The depth and strength of an LCA is based on answering the questions in the four phases of the life cycle. A full LCA includes actual environmental impact data that has been gathered on the product's entire life cycle. These LCA’s are very time consuming, costly, and only achievable once the products are in use and has gone through all phases of its life cycle.

Comparing the two approaches Cradle to grave and Cradle to gate is probably not the best way to go but there is still a lot of research that must be done to get complete and better comparable numbers.

5.3 Social

The social costs of insulation were difficult to quantitatively analyze, unlike the economic and environmental costs, but for a system to be sustainable, it must fulfil all three parts of the paradigm. Much of the social aspect was tailored towards human health. Although some of the production practices were taken into account, the uncertainty in where and how some materials would be produced if used made it hard to put much weight on that element.

Fiberglass, the most common insulation, is made by spinning glass fibers into insulation. If the fiberglass comes into contact with human skin during the production or installation process, small shards of glass will penetrate the skin. These cuts leave no long term effects and can be avoided to some extent with proper equipment. The real cause for concern with fiberglass is the release of styrene, which can cause cancer and penetrate organs and tissues when in the respiratory system via inhalation. (Fiberglass Insulation Hazards, 2015)

Cellulose is another common type of insulation that emanates surprising health effects. The most common mistake in installing cellulose insulation is assuming the specific cellulose needs to be dampened. The amount of water added depends on the type of cellulose. Failing to read the instructions and 'eyeballing' the necessity of water can result in a release of ammonium sulfate or sulfuric acid, which is toxic to the human body. Assuming Dane County will hire professionals to install the insulation allows us to focus on potential effects of properly installed cellulose insulation. Boric acid can be discharged through a leak in the insulation cover, causing potentially serious damage to the abdominals, liver, lungs, and kidneys. (9 Pros and Cons of Cellulose Insulation, 2015)

Spray foam, when installed correctly, is a safe insulative choice. Once installed, isocyanates and polyols react to form polyurethane. This installation requires the occupants of the house to evacuate until the reaction is complete. The effects of inhaling excess volatile organic compounds given off by the insulation are still unclear. (EPA Raises Health Concerns with Spray Foam Insulation, 2016)

Denim may be slightly complicated to install due to the compression preciseness it must obtain to be effective, but unlike the three common insulation materials previously mentioned, denim is almost entirely safe. There are no itchy or cancerous fibers, just recycled denim. The only potential harm comes from the boric acid which acts as a fire retardant. A base of boric acid is added to any insulation, so should not be accounted for in the comparison of various insulation options. (The Good and the Bad of Denim Insulation, 2017)

Hemp and straw are the only two insulation options which are one hundred percent natural, explaining the extremely low social/health costs. They are both easy to install as well as non-toxic and non-irritants to the touch. No chemicals are given off during the installation process or use phase. (Insulation Types - Insulation, 2017) (The Pros and Cons of Straw Bale Wall Construction, 2017)

Lastly, wool insulation health effects are for the most part minor but can have severe consequences. Wool must be sprayed with borax, an antifungal chemical used mainly as an insect repellant. Inhalation of borax can cause minor complications such as a rash, nausea, or diarrhea. Inhalation of borax in extreme amounts can affect reproduction and development (tested on animals, assumed to occur in humans). As wool comes directly from sheep, we must also think about the cleanliness of the sheep. Organophosphates are used on sheep herds to protect them from scab mites. An active ingredient in organophosphates is linked to poor farmer health. Once the wool is fully processed into insulation, most of the organophosphates appear to be gone but the presence can still be potentially harmful. (Devil or Angel?, 2017)

By comparing the costs of all seven materials, the following list was attain, ranking the insulation types from least to most socially costly.

1) Hemp
2) Straw
3) Denim
4) Sheep's Wool
5) Spray Foam
6) Cellulose
7) Fiberglass

6. Discussion/Conclusion

Conducting the methods section, as previously proposed, led to a series of results that were thoroughly interpreted. Within each sustainability paradigm investigated (social, economic, and environmental), there are unique materials that prove to be the most sustainable option based on the various methods and analyses used. For this reason, each analysis technique was used to develop a ranked list of sustainable housing insulation materials for each sustainability paradigm. Once each paradigm had a ranked list of materials, the overall "winner" was be deduced by comparing the rankings between materials. The most difficult point in our research was deciding whether a weight system should be used, valuing one paradigm higher than another. After much thought, we thought the most effective result would be derived from an equally weighted system. Using different weights is essentially estimating personal values, something with is extremely variable. To create the bar graph below (see **fig. 16**), we began by assigning a value to each material (in respective paradigms).

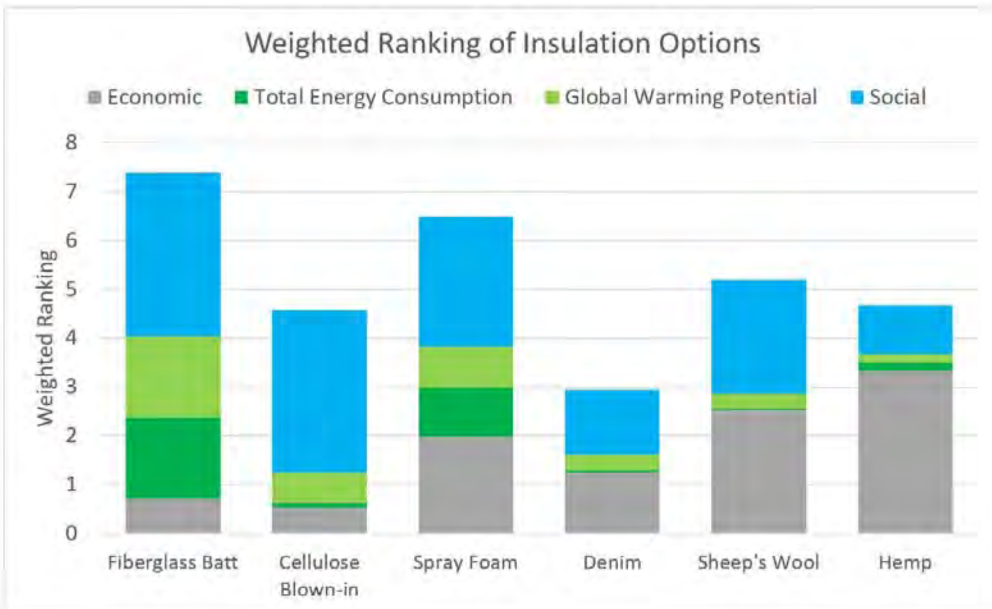

Fig. 16. Weighted ranking based on results of decision matrix (*Table 3*)

Table 3. Decision matrix for sustainable insulation options

Material Options	Economic (V_econ)	Environmental (V_env) Tot. Energy Cons.	Environmental (V_env) Glob. Warm Pot.	Social (V_soc)	Total (V_total)	Overall Ranking
Fiberglass Batt	2.1	10	10	10	7.4	**6**
Cellulose Blown-in	1.6	0.5	3.8	10	4.6	**3**
Spray Foam	6.0	6	5	8	6.5	**5**
Denim	3.8	0.3	1.9	4	3.0	**1**
Sheep's Wool	7.6	0.2	1.8	7	5.2	**2**
Hemp	10.0	1	1	3	4.7	**4**
Straw	--	--	--	--	--	**--**
Paradigm Weight (W)	**33%**	**33%**		**33%**		
		50%	50%			
		Environmental Category Wt. (ECW)				

The material with the largest negative impact was given the value of 10 in the respective category. The value associated with the other materials in that category were then scaled appropriately with respect to the maximum value of 10. For example, a material that has half the social cost as fiberglass (the largest social impact) was given a five. This ranking system gave the highest possible value in each category a 10. Using the equation below, a total value was obtained for each of the materials by combining the values for each of the pillars of sustainability.

$$V_{Total} = [V_{Econ} \times W_{Econ}] + [(V_{TEC} \times CW_{TEC} + V_{GWP} \times CW_{GWP}) \times W_{Env}] + [V_{Soc} \times W_{Soc}]$$

This equation was used for determining the weighted value of each insulation option with respect to the three pillars of sustainability, where *V* is the respective value associated with each pillar of sustainability, *W* is the paradigm weight, and *CW* is the category weights associated with the environmental theme. The subscripts correspond to the various category and theme names.

Using the comparisons available in ***Figure 16*** and ***Table 3***, an overall ranking was determined. Using the criteria described, it was found that the recycled denim material is the most sustainable insulation option for use in Dane County.

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LIGHTING

Introduction

The purpose of this report is to compare Compact Fluorescent Lighting (CFL) and Light Emitting Diode (LED) light bulbs to determine which would be the most sustainable option for Dane County affordable housing developments. In 2012, the Dane County government passed a resolution to become "more environmentally, socially, and economically sustainable in its planning, management, and policy making" (Dane County, 2012). Furthermore, the primary objective of Dane County affordable housing developments is to reduce the housing gap among Dane County residents. While lighting is a component of housing that is often taken for granted, it plays an important role in the comfort and productivity of people's lives. The goal of this study is to determine what types of lightbulbs Dane County residents should use in their public housing units to support the sustainability and equity goals of the Dane County government.

This study will focus on the key sustainability paradigms of environmental, social, and economic factors that contribute to the overall sustainability of light bulbs, specifically CFL and LED light bulbs. CFL and LED light bulbs were chosen because they are the most prevalent in today's market since the U.S. Energy Independence and Security Act was released in 2007. The environmental factors that this study will focus on are the use and disposal, or the cradle to grave, of one unit of light bulbs in terms of greenhouse gas emissions, overall energy use, and material disposal. The social component of this study will focus on the preferences of the residents and user safety. For the economic consideration, the main factors will be the upfront cost of purchasing the lightbulb as well as the long term cost efficiency based on lifetime of the light bulbs. These criteria are discussed in the following sections.

Methods

In order to measure the full effects of the different lighting options a mix of different evaluation methods were utilized. The full evaluation matrix can be found in the results section as *Table 1*. Each criteria, as listed in the project scope, were weighed and evaluated based on the system explained in *Table A1* and *Table A2* in the Appendix. To evaluate the environmental impacts of the different light bulbs a literature review was used, adding perspective as to how the data applies to Dane County. To measure the brightness and social impact of the light bulbs, the light bulbs were compared in terms of lumens. A breakdown of the comparative lumens for different types of lightbulbs can be seen in *Figure A1*. Lumens are defined as "a unit of luminous flux in the International System of Units, that is equal to the amount of light given out through a solid angle by a source of one candela intensity radiating equally in all directions" ("What Are Lumens? Lumens Chart, Definition & Bulb Facts at Lumens", 2017.) Additionally, literature was reviewed in order to measure potential residents' preference for lumenosity. Data for economic impacts was obtained from observed market costs of the product as well as electricity costs in Dane County. Comparatively, watts were used to describe and measure the energy use of the product.

Criteria for Evaluation

This report evaluates sustainability paradigms based on a series of criteria. This criteria was generated considering the most relevant interests of Dane County. These criteria are included in the evaluation matrix and the list of descriptions are found below:

1. **Resident Preference**

The preference of the housing residents was evaluated. Since residents are the main parties affected by the lighting and will be the main users of them, their preference is ranked very high in the weighing of the criteria. The information for this was based on literature review of preference data from other studies that have been performed. Examples of reports used for this analysis include EPA's Energy Star, University studies, and the Department of Energy.

2. **User Safety**

Safety is always a concern for household products. This criteria will include usage safety as well as direct concerns from harmful materials, especially rare metals, in the bulbs.

3. **Bulb Cost**

The costs of the bulbs must also be weighed. With the volume of light bulbs that are needed, this will be a large cost for the purchaser of the lightbulbs. The cost of the light bulb is considered to be of high importance as a goal for affordable housing is to provide low cost options for their residents.

4. Running Cost

Use cost, or the cost associated with the lights being turned on, is the highest cost associated with the project, and is dependent on the bulb power. This is rated very highly in the decision matrix due to the equity goals of Dane County.

5. Disposal Cost

Although the costs associated with disposal are low, it is still an important consideration especially because residents are responsible for this cost.

6. Greenhouse Gas (GHG) Emissions

Greenhouse gas emissions are a major external environmental cost of power generation, especially during the use phase of the lightbulbs. Due to the sustainability resolution, this is considered important in the overall assessment.

7. Materials and Disposal

Proper disposal of lightbulbs is important for keeping contaminants from entering the environment. However, it is unrealistic to assume that all the bulbs will be properly disposed of, especially when proper recycling resources are not typically free of cost. The primary consideration for disposal effects is the materials used, especially the potentially hazardous rare metals that can be toxic to the environment. Although these are important considerations, a light bulb is a relatively small electronic good and is manufactured with small amounts of material. For this reason, the weight of this criteria is relatively low.

Results

Based on the sources found in the references section, the results for each evaluation criteria were obtained:

1. Resident Preference

Lighting plays an effect on people's productivity level, as well as the psychological and physical well being of a resident-- though further research needs to be done onto what extent lighting affects these psychological and physical attributes (Energy Star, 2014). In the Dangol et al., 2015 article, a comparison of LEDs vs fluorescent lamp (FL) was conducted. While this life cycle assessment only examines the differences between FLs and LEDs, it allows for a comparable examination of how people prefer different lighting options. In conclusion, the LED lighting system was preferred based on color and lighting capacity. FL has higher lumens than CFLs. As such, it is reasonable to infer that LEDs are preferred to CFLs, though there is a high variance in individual preference.

Because of the higher preference for LEDs rather than CFLs, the LEDs lighting preference will be ranked with a 2 and the CFL will be ranked as a 1, as shown in the decision matrix under Table 1.

2. User Safety

User safety is always a key concern when dealing with household items. CFLs have historically been considered more hazardous than LEDs because CFLs have a small amount of mercury in them. As shown in *Figure A8* (Lim, Kang, Ogunseitan, & Schoenung, 2012), CFLs have a higher amount of toxic metals than LEDs. Most notably, CFLs have more chromium and mercury. In high doses or chronic exposure, chromium exposure can be fatal. Chromium is a carcinogen and exposure can also damage respiratory, reproductive, and cardiovascular system ("ATSDR - Public Health Statement", 2017.) Effects of mercury exposure include death, and immune, nervous, and digestive system damage.("WHO | Mercury and health," 2017.) However, there is more silver in LEDs than CFLs. Silver exposure alone has minimal harmful effects; however silver compounds, such as silver oxide or nitrate, can have damaging respiratory effects and can cause skin irritation ("ATSDR - Public Health Statement," 2017). In the case of both light bulbs, the amount of toxic metals is small (respectively all metals used in the light bulbs range between 1.0e -16 and 1.0e - 10). It is unlikely that a resident would experience any of these symptoms given the small amounts of these metals but given the severity of the consequences due to exposure of these metals it is best to error on the side of caution. When comparing LEDs and CFLs, LEDs have less of these toxic materials and therefore have higher user safety.

As LEDs have less toxic materials than CFLs, they will be ranked as a 2 and CFLs will be ranked as a 1.

3. Bulb Cost

Based on online prices from a number of popular retailers, the costs of individual CFL and LED bulbs are quite comparable. *Table A3* shows prices of bulbs from these stores. The average prices for 60 watt equivalent bulbs are $3.50 per CFL bulb and $3.38 per LED bulb. The costs per bulb vary based on manufacturer, retailer, and bulb type.

The price difference of bulbs is low, however, it should be noted that the prices of LEDs are falling as technology improves.

Because of the low price difference, the rating in the matrix will be a 2 for both bulb types because they are both relatively cost effective, yet could be improved with lower costs.

4. Running Cost

Madison Gas and Electric provides power to the Madison area. The current rates are approximately 13 cents per kilowatt-hour. This value will be used to convert power usage to a dollar amount ("Residential Electric Rates - Madison Gas and Electric - Madison, Wisconsin," 2017.)

A 60-Watt incandescent bulb has an output of about 500-700 lumens. An 800 lumen LED and CFL are approximately 10W and 13W, respectively. At an estimate of 3 hours of runtime per day and 1,095 hours/year, this gives approximately 10W x 1,095 hours/year = 10,950 Whr = 11.0 kWh and 13W x 1,095 hours/year = 14,235 Whr = 14.2 kWh annually.

For an annual cost per bulb, the CFL bulbs will use slightly more power because of their lower light to power usage ratio. The estimated costs for one bulb annually are:

LED: 11.0 kWh x $0.13 = **$1.42/year**

CFL: 14.2 kWh x $0.13 = **$1.85/year**

At an estimate of 45 bulbs per household (Dakks, 2007) and 13 cents per kilowatt-hour, annual household power costs are shown in *Table A4* in the Appendix.

For quantifying the running costs into the matrix, LEDs will be rated a 3 and CFLs a 2 because of the slight energy efficiency advantage characteristic of LEDs.

5. Disposal Cost

In Madison, homeowners are required to bring back CFLs to participating stores for recycling. Because of the mercury content, these bulbs are banned from regular municipal waste and landfills. The recycling typically requires the owner to pay a small fee, dependent on the location. There is also a time cost related to this.

LED lights also contain harmful substances, however, they are not required to be recycled and can be disposed of in regular municipal waste, which is ultimately lesser cost to the consumer. (City of Madison, 2017.)

Barring the probability of homeowners disposing of CFLs in municipal waste, which surely occurs and causes other issues, the use of CFLs in Madison results in a charge for recycling. Because of this varying additional cost, CFLs in the matrix will be rated a 1 and LEDs will be rated a 3.

6. Greenhouse Gas (GHG) Emissions

One important observation from literature review was the changes and improvements seen in LED lighting technologies over recent years. The most recent reliable and extensive LCA of LEDs and CFLs is from 2012 by the U.S. Department of Energy. In *Figure A2* and *Figure A3* it can be seen that there is a distinction between older and newer versions of LEDs, with newer

LEDs showing greatly reduced environmental impacts. These improved environmental impacts are based on projections of what the possibilities for the LED technology could be, however are not based on observed data. Based on more recent data (Shahzad et al., 2015), there have been many updates to LED lighting technology, which have overall increased the efficacy of this technology, and it is projected to continue to improve in the coming years. This environmental assessment was based on the most recent data as much as possible as the newer technology is what will be encountered by most consumers.

The primary source of Greenhouse Gas Emissions and other environmental impacts for both CFL and LED light bulbs comes from the use phase. This can be seen in *Figure A3* and *Figure A4* in the Appendix which compare the environmental impacts in the different phases of a light bulb's life cycle. Furthermore, *Figure A5* breaks down the impacts from the use phase into the different environmental compartments. Based on these results, the main consideration for this criteria is the environmental impact of the electricity and greenhouse gases expended during the use of these light bulbs.

Based on projected LED technologies shown in *Figure A2* and *Figure A3* as well as the more recent data observed in *Figure A6*, it can be seen that LED light bulbs produce less harmful environmental impact than CFL light bulbs. While both still produce greenhouse gases, all data shows that LEDs produce about half as much over their lifetime. Therefore, for the evaluation matrix, LEDs will be given a score of 2, and CFLs will be given a score of 1.

7. Materials and Disposal

Whether the resident or the building manager handles the light bulbs, it is likely that they will be thrown in the trash. There is no convenient or totally effective way to recycle CFLs or LEDs. Therefore, the end of life for each of these light bulbs if expected to be in a landfill.

Figure A7 shows an internal view of both CFL and LED light bulbs. While these light bulbs look very different, they each contain similar materials. The primary material of concern for both light bulbs is the rare metals that could potentially be hazardous to the environment once disposed of in a landfill. From a recent study (Lim, Kang, Ogunseitan, & Schoenung, 2012), it was found that both light bulbs contain metals that are hazardous to the environment including aluminum, copper, gold, lead, silver, and zinc. While both contain large amounts of harmful metals, CFLs contain higher levels of highly toxic metals such as lead, zinc, and mercury, as can be seen in *Figure A8*. These metals are of particular concern as they are both difficult to substitute and are very scarce. This makes CFLs a less suitable option when considering the impacts of disposal, however neither light bulb is ideal. Because of this, in the Evaluation Matrix, CFLs will be given a score of 0 and LEDs will be given a score of 1.

Table 1: Evaluation matrix for compact fluorescent light bulbs and light emitting diode light bulbs.

Evaluation Matrix - Energy Efficient Lighting						
			Compact Fluorescent Light Bulb (CFL)		**Light Emitting Diode Light Bulb (LED)**	
	Criteria	**Weight (1-3)**	**Rating (0-3)**	**Score**	**Rating (0-3)**	**Score**
Social Viability	Resident Preference	2	1	2	2	4
	User Safety	2	1	2	2	4
Economic Viability	Bulb Cost	3	2	6	2	6
	Running Cost	3	2	6	3	9
	Disposal Cost	1	1	1	3	3
Environmental Viability	Greenhouse Gas Emissions	2	1	2	2	4
	Disposal Effects	1	0	0	1	1
Totals:				**19**		**31**

Overall, the Evaluation Matrix in *Table 1* allows for a quantitative interpretation of the qualitative analysis performed in this LCA. Based on the results shown in the evaluation matrix, as well as the qualitative analysis above, it is recommended that LED light bulbs be used.

Discussion and Conclusion

The analysis shows that for all three paradigms of sustainability: social, economic, and environmental, LEDs are the most sustainable option. Social impacts taken into account were the user safety and resident preference. While both LEDs and CFLs have a small amount of toxic metals, LEDs have less. Despite these being small amounts, risk should be limited and therefore the LEDs should be used. Preference among different lighting options is highly variable. However, as shown in the Dangol et al. (2015), study, LEDs were generally preferred. This shows that LEDs are more socially sustainable than CFLs based on criteria used in this report. Economically, the bulbs had a small difference in individual costs. However, LEDs had a slightly lesser running cost. CFLs also require recycling in the City of Madison, which typically results in a fee. The environmental effects of lighting based on projected LED technologies shown in *Figure A2* and *Figure A3* as well as the more recent data observed in *Figure A6*, it can be seen that LED light bulbs produce less harmful environmental impact than CFL light bulbs. While both still produce greenhouse gases, all data shows that LEDs produce about half as much over their lifetime, and LEDs are only expected to continue to improve in the coming years.

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Appendix

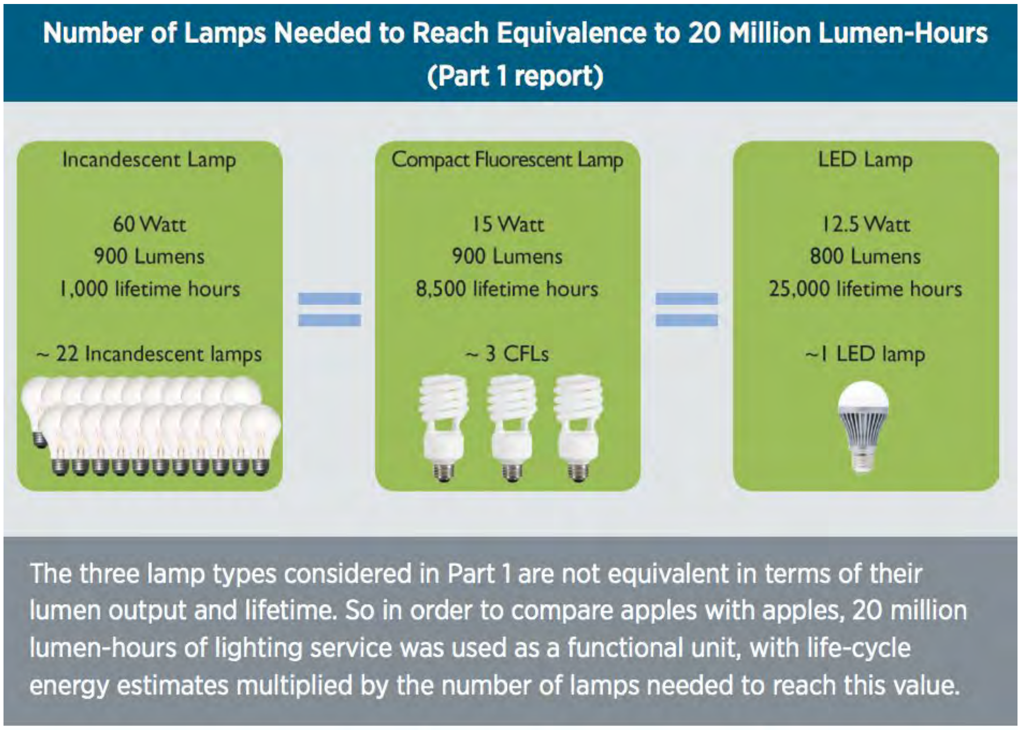

Figure A1: Figure comparing different types of light bulbs and the number of light bulbs needed to produce equivalent lumens

Table A1: Scale used for evaluation matrix weighting.

Weight	Qualitative Meaning
1	Not very important
2	Important
3	Top priority

Table A2: Scale used for evaluation matrix rating.

Rating	Qualitative Meaning
0	Bad
1	Neither bad or good

2	Good
3	Great

Table A3: Current prices for individual light bulb at popular convenience stores. These prices are for 60 watt equivalent individual bulbs, which is about 900 lumens each. Some prices are derived from packs of multiple light bulbs.

	Menards	Target	Walmart	Average
CFL	$4.99	$4.50	$1.00	$3.50
LED	$4.99	$3.75	$1.385	$3.38

Table A4: Comparison table of annual costs for LEDs and CFLs based on assumptions stated above:

Annual Costs of Compared Light Bulbs (USD)		
	LED	**CFL**
Per bulb:	$1.42	$1.85
Per 45-bulb household:	$63.90	$83.25
Per 1000 households:	$63,900	$83,250

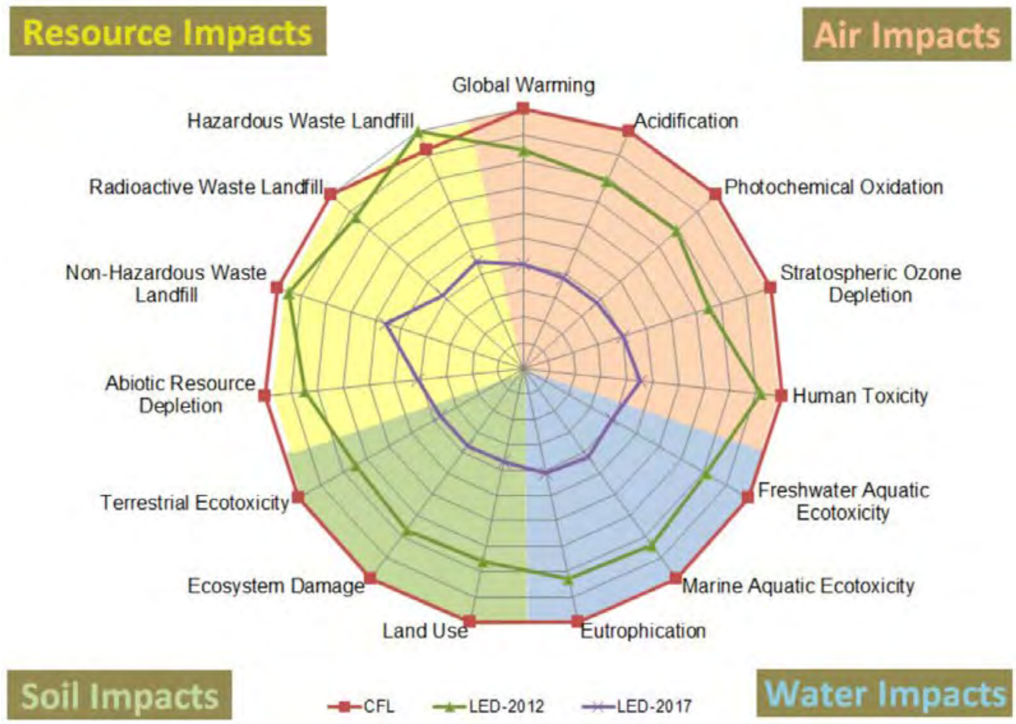

*Figure A2: Web chart showing environmental impacts of different types of light bulbs (*https://www1.eere.energy.gov/buildings/publications/pdfs/ssl/lca_factsheet_apr2013.pdf).

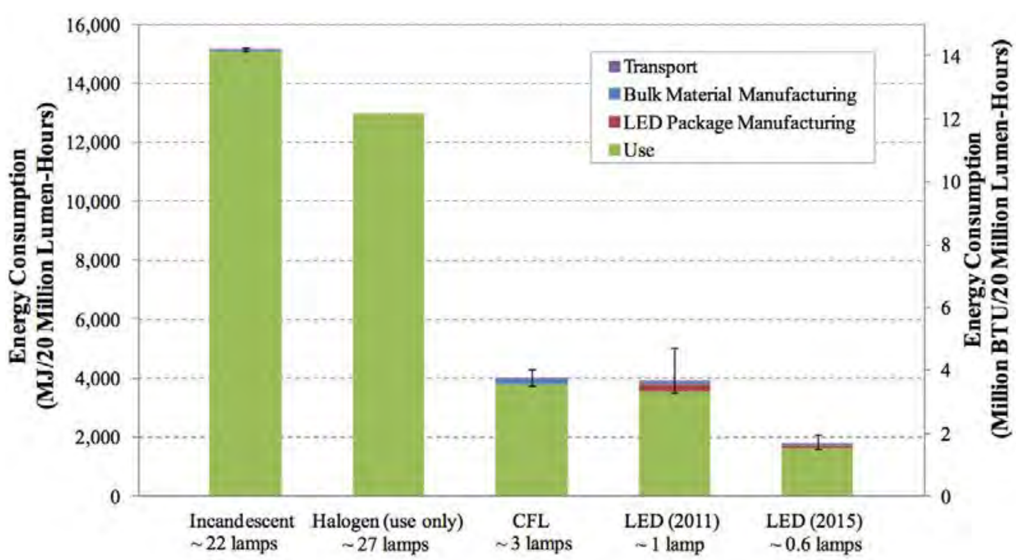

Figure A3: Energy Consumption for different life cycle stages for different types of lightbulbs (https://www1.eere.energy.gov/buildings/publications/pdfs/ssl/2012_LED_Lifecycle_Report.pdf).

Table A5: Impacts of LED's and CFL's under different impact categories. (http://www.sciencedirect.com/science/article/pii/S2212827114004405).

		Ecosystem quality			Human health					Resources	
		acidification & eutrophication	Eco-toxicity	land occupation	carcinogenic	climate change	ionising radiation	ozone layer depletion	respiratory effects	fossil fuels	mineral extraction
LED	Manufacturing	2.81E-2	2.07E-1	3.11E-2	1.66E+0	5.10E-2	2.40E-3	2.38E-5	2.05E-1	3.64E-1	1.62E-1
	Use	7.07E-1	5.52E-1	3.46E-1	1.72E+0	2.00E+0	1.27E-2	1.71E-4	4.50E+0	1.40E+1	3.68E-2
	End-of-life	9.28E-5	1.58E-1	7.46E-6	7.10E-4	2.01E-3	2.88E-7	1.46E-8	3.35E-4	2.25E-4	6.89E-6
CFL	Manufacturing	1.91E-2	1.37E-1	2.27E-2	8.95E-1	3.24E-2	1.60E-3	1.36E-5	1.53E-1	2.40E-1	2.29E-1
	Use	6.18E-1	4.83E-1	3.03E-1	1.51E+0	1.75E+0	1.11E-2	1.50E-4	3.94E+0	1.22E+1	3.22E-2
	End-of-life	9.66E-5	9.66E-5	3.35E-5	1.08E-3	9.77E-5	2.32E-6	6.68E-8	4.56E-4	9.33E-4	1.42E-5

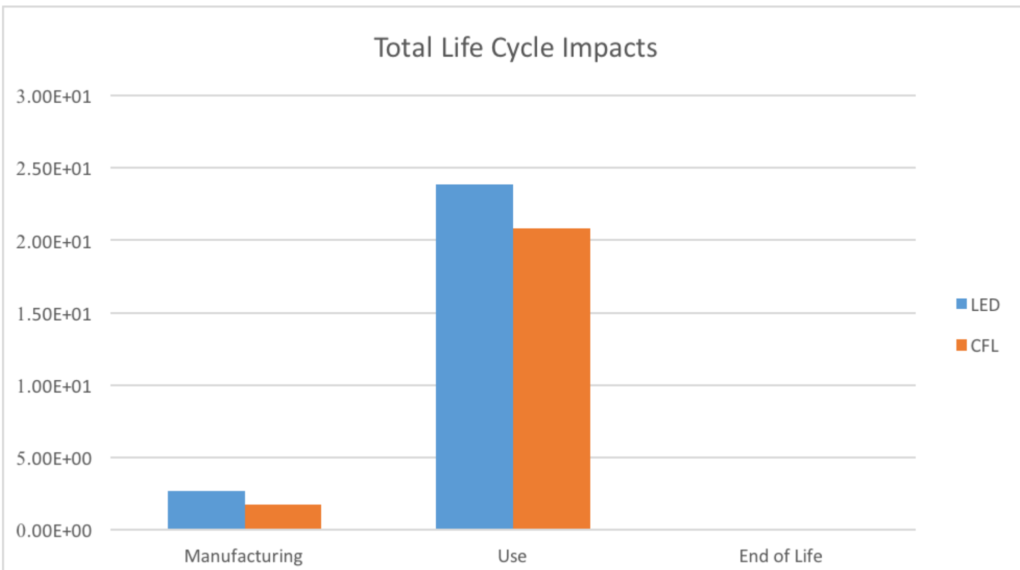

Figure A4: Sum of life cycle impacts for different types of lightbulbs using data from Figure A5 obtained on 2012.

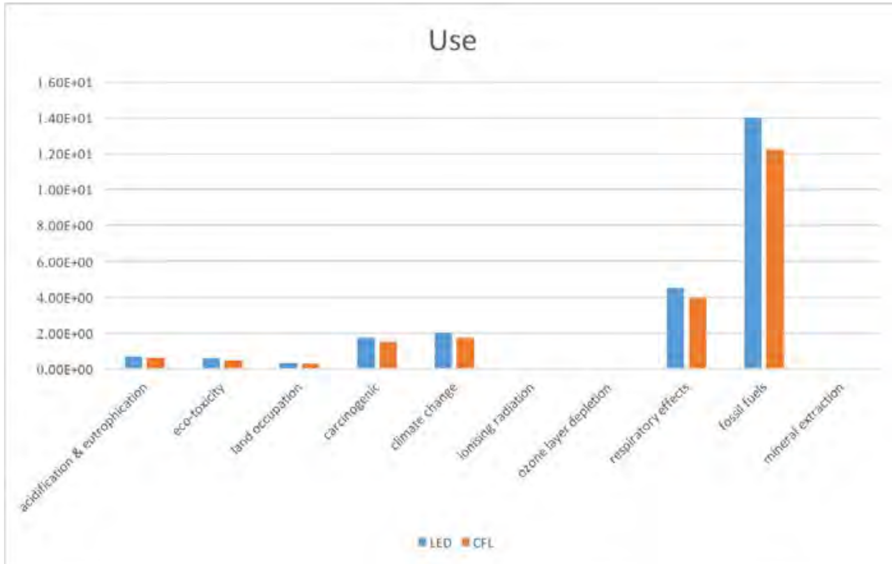

Figure A5: Impacts of different light bulbs in use phase based on data in Table A4 obtained in 2012.

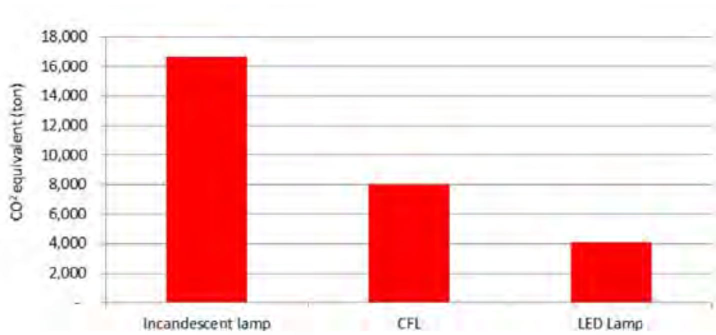

Figure A6: Cumulative life cycle impacts of different light bulbs based on data obtained in 2015. (https://www.researchgate.net/profile/Khurram_Shahzad8/publication/282288413_Comparative_life_cycle_analysis_of_different_lighting_devices/links/562c86ff08aef25a2441d196.pdf).

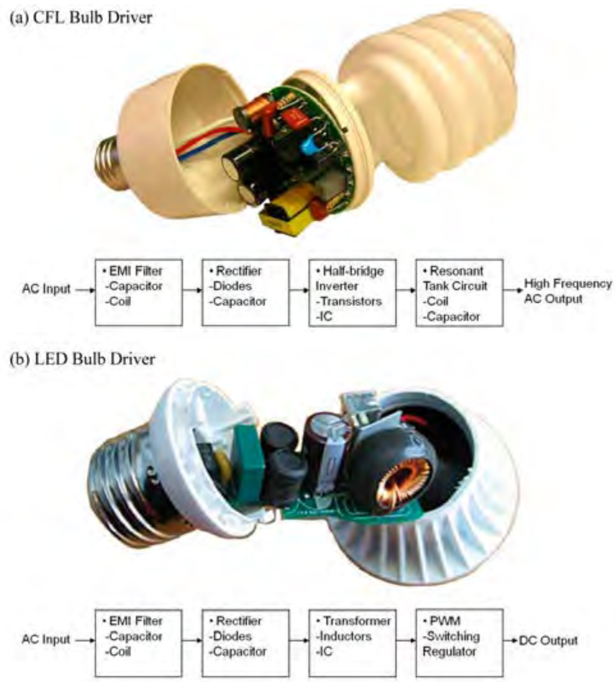

Figure A7: Internal components of CFL (a) and LED (b) lightbulbs.

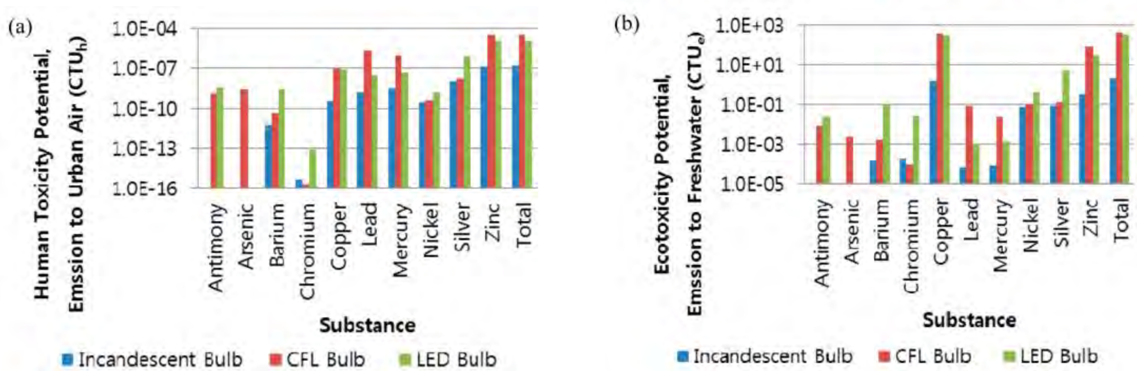

Figure A8: Human Toxicity (left) and Ecotoxicity (right) potential of different metal components of Incandescent (blue), CFL (red), and LED (green) light bulbs. (http://pubs.acs.org/doi/pdf/10.1021/es302886m).

PASSIVE TECHNOLOGIES

Executive Summary

Dane County is interested in implementing passive housing technology in affordable housing units. As a guide, this report compares passive housing technologies to conventional systems. Passive housing aims to address inefficiencies in conventional systems include A/C, heating, windows, insulation, and flooring. It is a systems perspective of these functional units with the intent to reduce energy loss and optimize heat gain.

The feasibility of passive housing technologies are assessed through economic, environmental, and social criteria. The economic investigation consists of payback period analysis. Environmental impacts are analyzed using Economic Input-Output Life Cycle Assessment and peer-reviewed literature. Social considerations are addressed through a weighting system of functionality, overall well-being, and community growth justified by literature. These criteria are combined into a final recommendation tailored to Dane County's affordable housing needs. Please use this report as a guide in future affordable housing planning projects.

Motivation

Dane County's population is growing at a faster rate than all other counties in the state of Wisconsin. Dane County is witness to a quarter of Wisconsin's annual population growth, as well as three quarters of its growth over the period of 2008 to 2012. There are over 66,000 cost-burdened households, defined as spending more than 30 percent of income on housing. Additionally, 33 percent of renters are not able to afford a two-bedroom apartment at current market price (Dane County Closing the Housing Gap Project Team).

Population growth in Dane County is paired with housing deficit. A housing deficit is a gap between the the housing units needed and the units available at an affordable price. This pressures residents to live in housing that is unaffordable, overcrowded, substandard, in disrepair, or fall victim to homelessness (Office of the Dane County Board, 2017). There is currently 64,526 cost-burdened households in Dane County (Municipalities, 2015). For those that apply for a Section 8 Housing Voucher, the wait list may be over two years.

Dane County is looking to address these housing issues while incorporating sustainability. They have taken the initiative to invest $2 million with private investments and federal matching grants from 2015 to 2018 (Office of the Dane County Board, 2017). This three year investment has provided 275 additional units for the community (The Cap Times, 2017).

Dane County's Guiding Sustainability Principles are comprised of: reducing the contribution to fossil fuel dependence and wasteful use of scarce metals and minerals, reducing the contribution to dependence upon persistent chemicals and wasteful use of synthetic substances, reducing the contribution of encroachment upon nature and harm to life-sustaining ecosystems, and reducing the contribution to conditions that undermine people's ability to meet their basic human needs (Dane County Board, Res 103, 2012).

To assist Dane County in their pursuit of sustainable affordable housing, passive housing technologies will be explored in depth. The three paradigms of sustainability are used as framework in this comparison of conventional and passive housing: environmental, economic, and social. The wellbeing of the Dane County community hinges on affordable housing to accommodate those with housing insecurities. It is the goal of this report to consider all parties, motivations, and priorities of stakeholders equally.

Literature Review

This section is a discussion of existing passive housing technologies, including their benefits, features and an overview of conventional housing for comparison. Many of the features discussed are found in most passive housing units, and will most likely be considered in Dane County's decision process.

Conventional House Design

Most homes in the United States do not fall under the category of "passive." Traditionally-built homes were focused on aesthetics and function rather than potential for energy efficiency and cost-effectiveness.. Before touching on the features of passive housing, the general details of an average, traditional home are discussed.

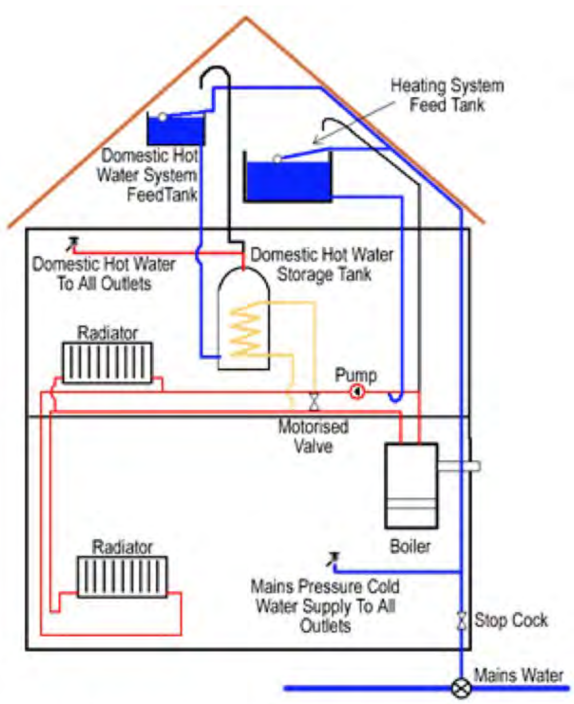

Figure 1. Conventional Heating System layout.

The air-tightness of a house is commonly determined by the air-change rate. This is the number of times that air in the home exchanges with outside air each hour. If the volume of air that enters and leaves the house in an hour is equal to the heated air volume within the house, it has one air change per hour. Most homes have an air change rate of one, two or even up to four. These numbers are significantly higher than that of a passive home, as will be specified later.

Conventional homes tend to have less efficient windows than passive housing design, but in using conventional windows, there are measures one can take to increase the efficiency and keep costs low. This can be done by adding storm windows, caulking and weather-stripping, using window treatments or coverings. Adding storm windows can reduce air leakage and improve comfort. Caulking and weather-stripping can reduce air leakage around windows. Window treatments or coverings can reduce heat loss in the winter and heat gain in the summer. Most window treatments, however, aren't effective at reducing air leakage or infiltration.

Traditional homes usually use fiberglass, cellulose, or foam for insulation. All of these have their advantages and disadvantages, but strictly looking at performance, foam insulation is best. Once applied, foams become rigid and have an R-value range from R-6 to R-7 (Maynard, 2016). R-values are essentially a rating system for how well insulation performs. The higher the number, the higher the performance. As will be discussed further on, the best conventional insulation falls well short of passive housing standards.

Passive House Design

Air Flow and Heat Exchange

In order to optimize a passive building's efficiency, airtightness and ventilation are crucial in design. Passive buildings are designed so that most air exchange with the exterior of the building is done by controlled ventilation through a heat-exchanger. This is done to minimize heat loss or gain, depending on the desired temperature, and to prevent uncontrolled air leaks. The airtightness of a passive house is generally checked with a pressure test. The allowable air-change rate should not exceed 0.6 times a room's volume per hour and the pressure differential should be limited to 50 Pascals. (IPHA, 2016)

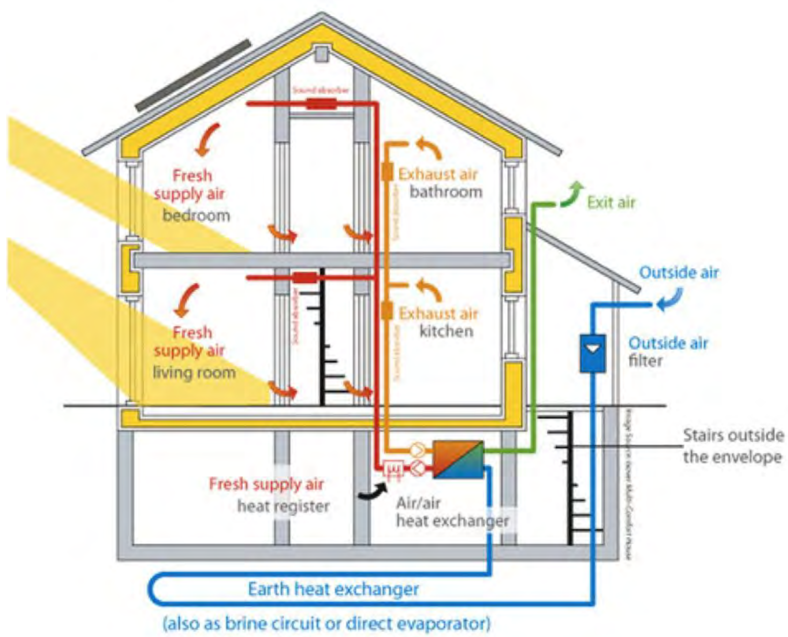

Figure 2. General passive heating system layout.
(Australian Passive House Association, 2017)

Ventilation units with heat recovery are beneficial to energy savings, as they ensure that the warmth carried by the exhaust air from the system is not wasted. It is instead transferred to the incoming fresh air without the two airstreams mixing. In hot conditions, heat exchangers can also work in reverse so that the heat carried by the incoming air is transferred to the exhaust air and is pre-cooled before entering the home. Heat exchange systems can also have a built in bypass to the heat exchanger, which is very valuable in places like Wisconsin, where the days and nights can vary greatly in temperature. A ventilation system with heat recovery allows fresh air to enter the building in a controlled manner. It is important that the fresh air entering the building not exceed 30 m^3 per hour per person (IPHA, 2016). Any air exchange value much over this rate will make the air uncomfortably dry.

Position of Sun and Building

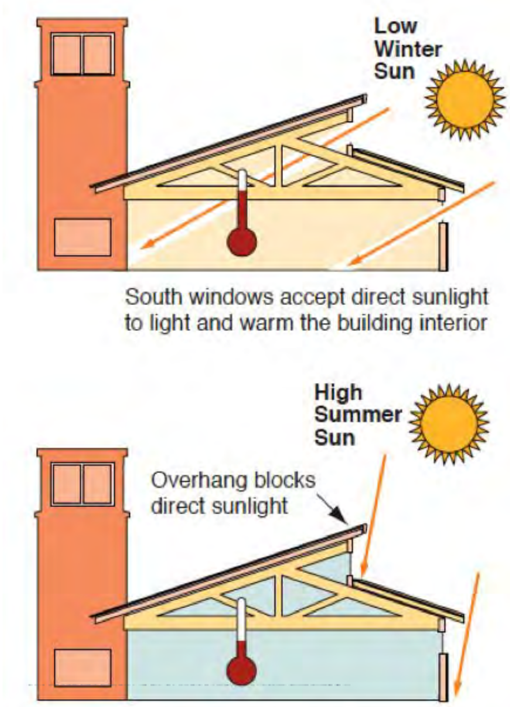

Figure 3. Demonstration of overhang.
(Green Passive Solar Magazine)

Windows on the South side (in the northern hemisphere) of buildings receive the sun's energy and contribute to warming a passive solar building during the winter. Relative to the horizon, the sun has a lower trajectory and less intensity in the winter, so it is advantageous to capture maximum sunlight. In summer, passive solar houses rely on shading to keep the building cool. Figure 3 shows an overhang that shades the south-facing windows from high summer sun without compromising the reception of low winter sun. Positioning a building along the east-west direction with its longest and most exposed exterior facing the south allows buildings to effectively utilize the sun's heat energy. An ideal position would be within 5 degrees of due south. Applying these two features - building direction and window overhang - into the construction of a building, results in heating and cooling costs of a tenant or homeowner to decrease by 85% on average. (Green Passive Solar, 2017)

Windows

South-facing windows are important for a passive solar design and building. The U-value of a window assembly refers to the rate of heat loss through the window. The lower the U-factor, the greater a window's resistance to heat flow, and the better its insulating properties (Measuring Performance, 2017). To be effective, south-facing windows should have a solar heat gain coefficient (SHGC) of greater than 0.6 in order to maximize solar heat gain during the winter. They also should have a U-factor of 0.35 or less to reduce conductive heat transfer, and a high visible transmittance for good visible light transfer. Doing this allows the sun's energy to be absorbed and distributed through the building. In cooling climates, particularly effective strategies include the use of north-facing windows and shaded south-facing windows. Windows with low SHGCs are more effective at reducing cooling loads. A benefit that is presented by not only facing the windows south, but also increasing their size optimally, is increasing the amount of daylighting within the building. With more natural light coming into the building, there is less need for artificial lighting, thus lowering energy costs. Triple-paned windows tend to be at the top of efficiency standards, but double-paned windows are standard on passive housing units.

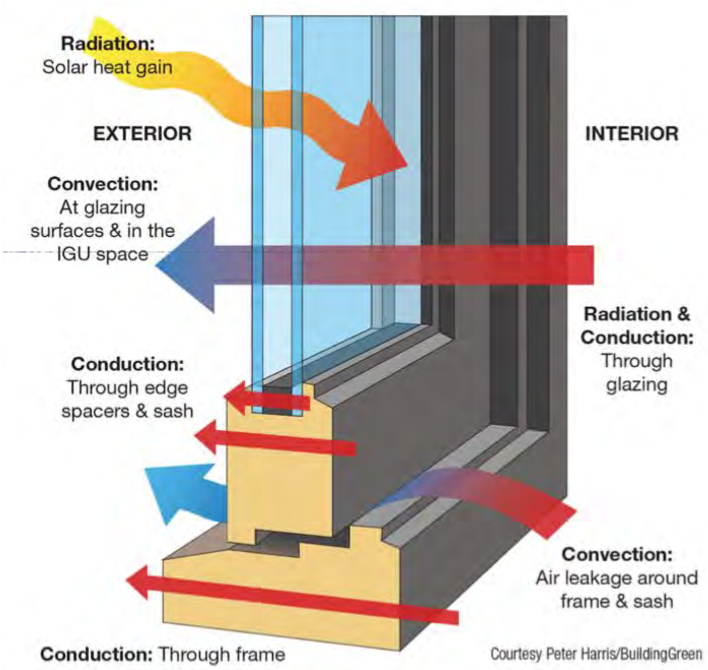

Figure 4. Window Thermal Transfer.
(Home Power Magazine)

Insulation

When developing a passive design, insulation is used in combination with thermal mass. Thermal mass is a dense material that can store and radiate heat. It is recommended that a passive solar house have insulation on the outside of the thermal mass so the heat stored within the mass can be utilized to keep the inner temperature warm and stable. There are also building materials that incorporate insulation within its structure. These types of building materials include Structural Insulated Panels (SIPS) and Insulated Concrete Forms (ICFs) (Green Passive Solar, 2017). Insulation levels of passive houses are generally in the range of R-40 to R-60 for walls, R-60 to R-90 for roofs, and R-30 to 50 for slabs. Passive homes tend to have much more insulation than a traditional home. This is done to mitigate any heat or cold leaks, which is absolutely crucial for design. Thermal bridges are also accurately accounted for in the calculation methodology. A thermal bridge is an element or location with less insulation or reduced insulation performance relative to the adjacent areas of the building. This means the element or location provides a path of least resistance or a "bridge" for heat to move through the building. In cold climates, this means additional heat will be lost through these specific locations. In hot climates, a thermal bridge will allow unwanted additional heat to pass through the thermal envelope into the building (Passipedia). Thermal bridges are ideally minimized with proper insulation.

Figure 5. Structure insulated panels.
(QUACENT)

Methods

This report uses economic, environmental, and social feasibility tools to assess the benefits of each system. Calculations are based on an average unit in a newly constructed 60 unit apartment building in Madison. The cost to build a 1000 sqft conventional unit is $80,000, based on data from 2013 and adjusted for inflation to the present (Waier, 2013). The cost of construction for a passive apartment is an additional 16%, which makes a passive unit roughly $12,800 more to construct (Audenaert, 2010). The total cost to construct a 60 unit apartment is

$4,800,000 and $5,568,000 for a conventional and passive complex respectively. The time scale which is used for analysis includes construction and use, but does not include end-of-life. Results are based on average passive systems across the industry, not specific designs.

Economic feasibility is the primary design consideration due to the rigid budget and pressure from growing housing demand. This report compares the costs of passive systems with conventional systems by implementing a payback period analysis. Payback period is the time needed to recover an investment. In this context, the investment is the additional construction costs for passive systems in the US. Two payback period analyses are conducted: the first payback period analysis (figure 6) assumes constant energy use and price over time. Energy usage in conventional homes is a constant 103 million Btu per home per year (U.S. EIA, 2009), and energy usage in passive homes is 67% less (Audenaert, 2010). The price of natural gas in Madison is constant at $0.5370 per therm (MG&E, 2017). The second scenario, shown in figure 7, includes the changing price of natural gas as predicted by the World Bank in 2016. These values are in nominal US dollars, which is the current dollar prices at the time of production.

Economic analyses neglect social and environmental costs which may eventually burden Dane County and its residents. Dane County implemented Guiding Sustainability Principles in Resolution 103 in October 2012, which includes the goal to "reduce and eventually eliminate Dane County government's contribution to fossil fuel dependence and to wasteful use of scarce metals and minerals." Passive housing design is one method to pursue this notion of environmentalism put forth by Dane County.

Environmental consequences of passive housing designs are considered during the supply chain and use phase. End of life impacts are not considered. An Economic Input-Output Life Cycle Assessment (EIO-LCA), will be used to determine baseline environmental impacts of conventional systems and passive systems. This method estimates the materials energy, and emissions subsequent to activities in an industry, in this case residential permanent site single- and multi-family structures (EIO-LCA, 2002). Carnegie Mellon's EIO-LCA tool provides the baseline impact of conventional systems in terms of energy, Joules (J), in the supply chain.

Peer-reviewed literature and statistics from the U.S. Department of Energy is used to quantify the change in energy consumed from conventional and passive housing technologies during 30 years of use. From *Household Energy Use in Wisconsin,* the average household consumed $1.09x10^{11}$ *J per year*. Passive technologies utilize three times less energy than conventional technologies (Audenaert, 2010). From the *Drivers of U.S. Household Energy Consumption, 1980-2009,* energy consumption increases about 2.56% each year. These parameters, when input into a compound interest formula, will estimate the amount of energy consumed by both passive and conventional technologies over 30 years.

There are consequences to building a sustainable passive apartment complex. The following questions are difficult to quantify: Is the home layout familiar and comfortable? Will the residents and community feel proud of their home? How might these new designs influence community and green spaces nearby? What impact does this have on the health of the residents? Answers to these questions are best quantified by a rating system including the criteria of *functionality, overall well-being, and community growth* applied in the final decision process. These values will be determined by peer-reviewed literature.

Results

Economic Analysis

Keeping the price of natural gas and energy use constant, the payback period is 33 years. On page 10, figure 6 depicts the costs of conventionally heating a single unit compared to the cost of passive housing using energy use data from US EIA and present natural gas price from MGE. Though the installation of passive housing is $12,500 more than conventional, the passive series converges on conventional, showing the annual savings that passive housing provides to residents. Conventional system residents pay an annual energy cost of $533 per unit, while residents of passive housing pay an an average of $180. This calculation depicts the "worst case scenario" which does not account for inevitable fluctuations in energy use and cost.

A second payback period analysis shown in figure 7 is conducted to consider these parameters. This plot accounts for forecasted price growth of domestic natural gas, which the World Bank predicts will double by 2030. The payback period is 18 years as indicated by the dashed line in figure 7. At this time, additional passive housing investments are paid off and become of economic benefit to the community. The additional construction costs of passive systems are $12,500 per unit, which is afforded by the Dane County Affordable Housing Fund. Economic benefit will not be to the Fund, but rather to the residents.

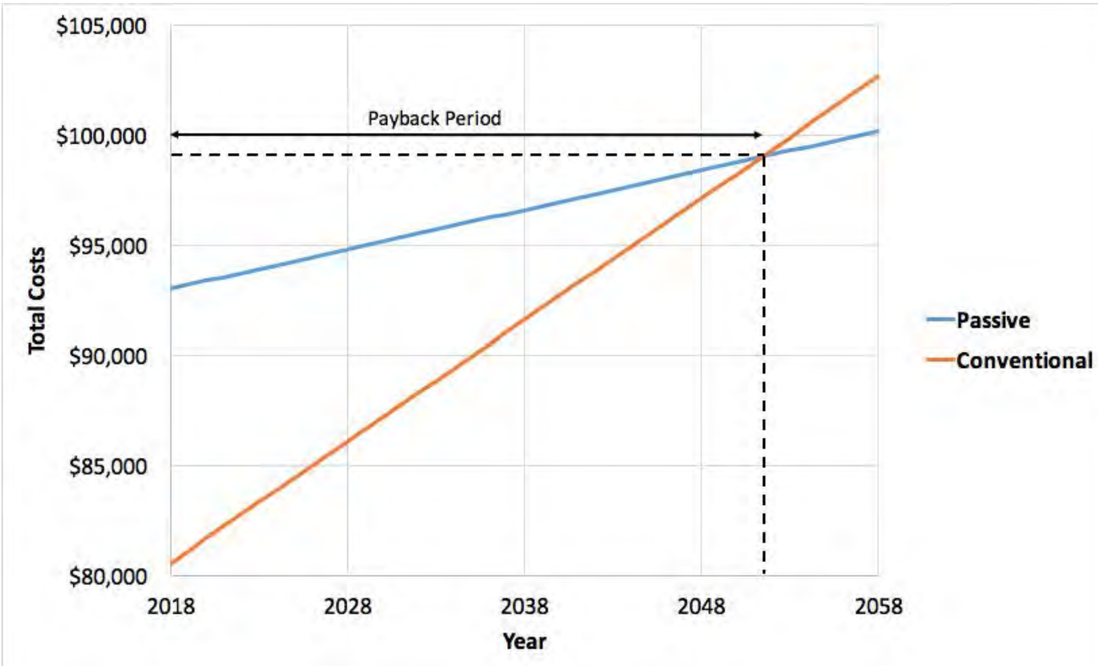

Figure 6. Total cost for a single unit with steady energy use and cost.

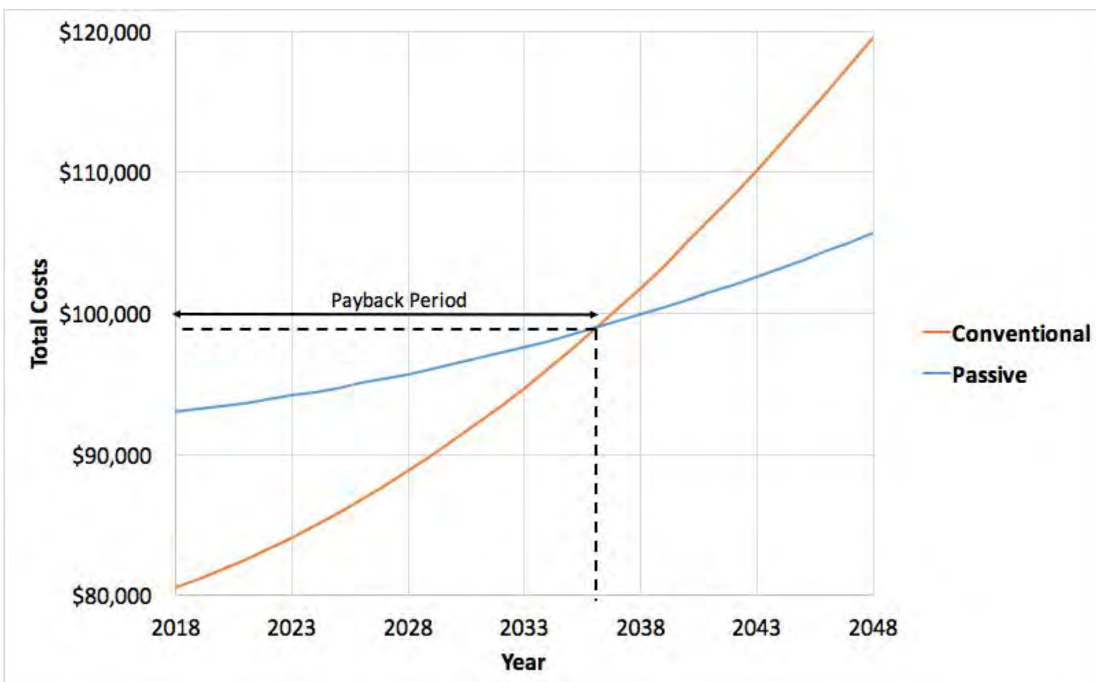

Figure 7. Total costs adjusted for forecasted rise in energy use and natural gas cost.

Environmental Analysis

Carnegie Mellon EIO-LCA

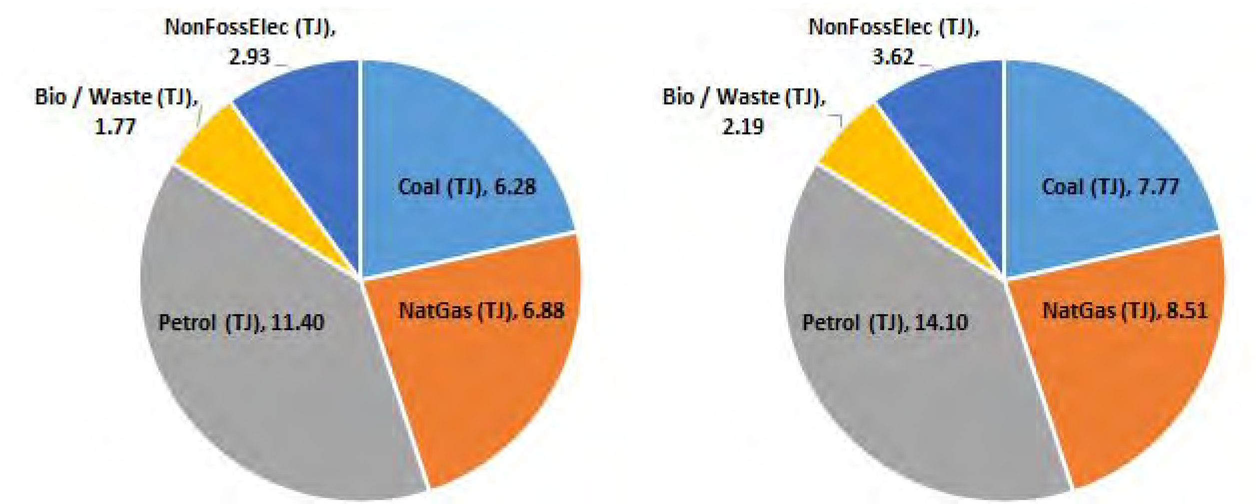

Figure 8. Energy (TJ) Used in Conventional (left) and Passive (Right) Technologies in Residential Permanent Site Single- and Multi-Family Structures (EIO-LCA, 2002)

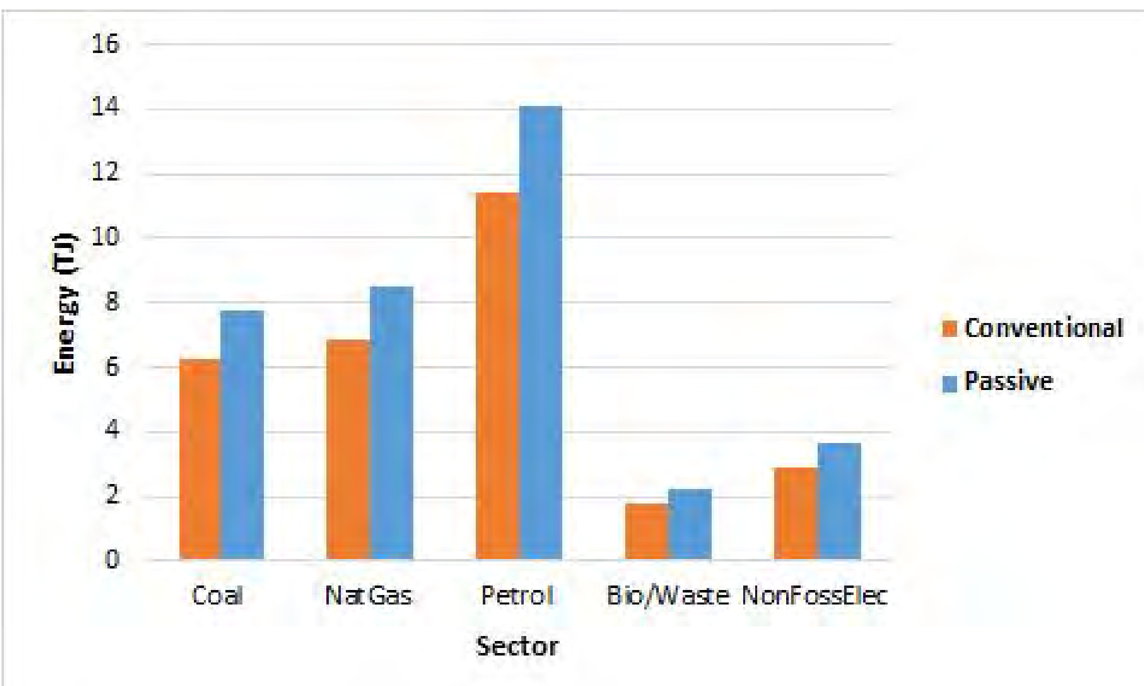

Figure 9. Comparison of Energy (TJ) Used in Conventional and Passive Technologies in Residential Permanent Site Single- and Multi-Family Structures (EIO-LCA, 2002)

The EIO-LCA tool provides guidance on the relative impacts from different types of products, materials, services, or industries with respect to resource use and emissions from beginning to end of the supply chain. It relies on the economic value of each system in the value of the dollar in 2002, therefore the system has a greater cost and impact today. Since the conventional 60-unit apartment system is $3.282 million and the passive 60-unit apartment system is $4.061 million, the passive system will have a greater environmental impact as shown in Figures 8 and 9.

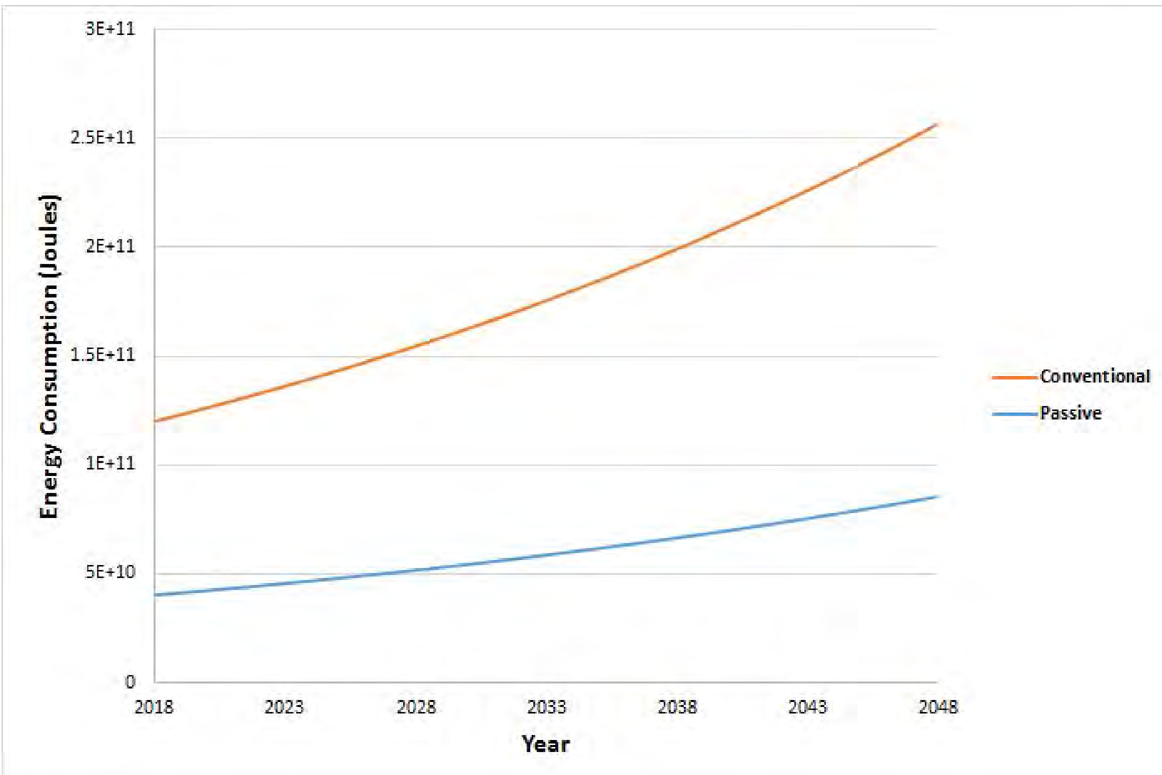

Figure 10. Energy Consumption Change Over Time Comparison of Conventional and Passive Technology Homes (EIA, 2015; EIA, 2009)

Figure 10 accounts for the energy consumption of conventional and passive technology apartment unit. In 2018, the figure shows passive energy consumption is about three times less than conventional energy consumption. Due to the compounding interest of 2.56%, the rate of the conventional energy consumption increases faster over the 30 year time frame of the use phase. A passive home consumes $2.25x10^{12}$ J less energy than a conventional technology home over the 30 year period.

Efficacy of Results

Figures 6-10 rely on economic data from European passive houses. The application of these measurements to apartment buildings in the United States requires assumptions. The statistics on homes within the U.S. relied on utilizing the European data to determine what a passive system would cost, and the energy it would require. There are a number of factors which complicate the accuracy of that assumption, including specific design choices of heat transfer, passive solar efficiency, and sizing of the system. A passive apartment building has fewer exposed walls per unit compared to a single family house, which may lessen heat loss. On the contrary, air flow and exchange may be limited between apartment units where this is not a problem in single-family houses. These design quandaries are not within the scope of this project, thus, the data presented is meant as a guide.

Using apartment unit averages normalizes many of these factors. The cost of energy, on average, is $553 annually for Wisconsin homes (EIA, 2009). Using the MGE Average Energy Use and Cost tool, this value was compared to affordable housing units in Madison. A 76-unit low income housing apartment community in Monona averaged $445 per year, but other similar apartment units had higher energy costs.

Social Analysis

The social impacts involved in designing and building passive housing systems may not be obvious on the surface, but are nonetheless an important aspect in creating living space that is comfortable and practical. Living in a sustainable environment has shown to be beneficial to both health and productivity. These benefits can be seen at different levels: buildings, the community, and society in general. At a building level, research on the benefits of sustainable design has focused on three primary topics: health, comfort, and satisfaction. Although these topics are separate, they are very much integrated within each other. Health issues are the focus of epidemiologists and public health professionals. Comfort is studied by researchers with expertise in building science and physiology, while well-being and psychosocial processes are studied by environmental and experimental psychologists. These three aspects of social impacts of sustainability will be taken into account in this analysis.

The environment within a building can have both negative and positive impacts on the occupants' quality of life. Negative impacts include illness, fatigue, discomfort, and stress resulting from poor indoor air quality, thermal conditioning, and lighting. Minimizing these problems by incorporating sustainable design often improves health and performance. Improved indoor air quality and increased control of ventilation have strong positive effects. In addition to reducing risks and discomforts, passive buildings should also contain features and attributes that create positive psychological and social experiences. Although less research has been done on health-promoting environments, emerging evidence shows that certain sustainable building features, including increased personal control over indoor environmental conditions, access to daylight and views, and connection to nature, are likely to generate positive states of well-being and general overall health (Fisk, 2000).

Many studies have found high levels of air-quality problems and occupant illnesses in office buildings (Brightman and Moss 2001). Studies have begun to show the relationships between the building environment and illness symptoms in three main areas: sick building syndrome (SBS), asthma and allergies, and communicable and respiratory diseases (Fisk 2000). SBS symptoms include headache, fatigue, dizziness, irritations of the skin, eyes, and nose, and difficulty breathing. A large review study of the links between health, perceived air quality, and ventilation found that ventilation rates lower than 10 L/s per person were associated with statistically significant worsening of symptoms in a range of building types (Fisk, 2000). Ventilation and air circulation are important, but sometimes overlooked, features of sustainable buildings. Designing for ample ventilation in passive housing can mitigate these problems significantly.

Psychological effects such as comfort, satisfaction, and well-being are created processes that interpret environmental information in terms of its effect on current needs, activities, and preferences. These senses of the environment around the occupant of a building affects work performance and productivity, stress, and well-being (Heerwagen, 1984). Because of the variability in psychological responses, the same environmental conditions can affect people in different ways, as well as affect the same person differently over time, depending on context. Occupant comfort and satisfaction with building conditions are a major focus of evaluating a building's effect on the psychology of the occupants. Efforts to improve comfort and satisfaction are important because discomfort has negative consequences, for example, in a work setting, which includes work effectiveness, job satisfaction, and quality of worklife. The benefits include reduced stress, improved emotional functioning, increased communication, and an improved sense of belonging (Groenewegen, 2006).

Conclusion

A final recommendation combines economic, environmental, and social arguments. Results suggest that passive housing in Dane County is a viable and practical solution for sustainable affordable housing.

Economic priority is motivated by high population growth and portion of cost-burdened households in Dane County (Dane County Housing Initiative). As depicted in figure 7, it will take 18 years to recoup the investment in constructing a passive housing system. The investment made by the Dane County Affordable Housing Fund will be recovered by residents, who save \$373 on energy costs the first year, growing to \$1300 by 2048. This is a 67% reduction in energy costs. While 18 years is a substantial period, the immediate benefit to residents justifies this investment.

Environmental considerations are weighed second-highest because of the nature of this project and the inquiry made by Dane County. From figures 8 and 9, the energy consumption in Joules of a passive housing system is about 23.7% greater than a conventional housing system from beginning to end of the supply chain with consuming $6.93x10^{12}J$ more. However, the calculated total energy consumed from the EIO-LCA is a course estimate for the relative impacts and relies on the dollar amount of each system. Figure 10 shows that during the use phase the energy consumed over time by a passive housing system is $2.25x10^{12}J$ less than a conventional housing system over the 30 year period, which is roughly $7.5x10^{9}J$ of energy saved each year. The trendlines of energy consumed is based on the average electricity use in Wisconsin and the national increase in energy consumption. Since the EIO-LCA is a course model that estimates the energy consumed by a system in the supply chain phase, it is considered not as heavily as the calculation of energy consumed during the use phase for the environmental analysis.

The social aspects of passive housing in this analysis point in a positive direction. A thorough literature review of the social aspects shows the mental and physical health gains resulting for designing for passive housing. A greener living space, paired with optimal ventilation, will result in happier and healthier residents, which in turn will benefit production in the workforce. Based on this research, an investment in passive housing is overwhelmingly a beneficial decision socially.

Passive housing opens opportunities to empower the Dane County community. Residents living in these spaces will be healthier, happier and liberated from high monthly energy costs. A thorough analysis of available peer-reviewed literature indicates minimal development of passive housing in the United States, especially in apartment buildings. As a developing industry, passive housing will likely become cheaper in the future, making it easier to implement. This lack of development in the industry opens up another opportunity: to become the Nation's leader in passive and sustainable affordable housing.

From the sustainability assessment, it is recommend that passive housing is pursued by Dane County in affordable housing. Specific designs may vary in degree of efficiency and should be assessed individually. It is important moving forward that Dane County be skeptical of the efficiency of a passive housing technology system, and that a more thorough analysis be completed with each design.

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SOLAR PANELS

Background

Solar energy is a growing renewable energy source due to the large quantity availability and the push back against fossil fuels. The amount of energy from the Sun that hits the Earth in one hour is more energy than the whole world uses in a year and thus has the capability to produce power without diminishing resources [1]. Contrastingly, traditional fossil fuel power plants used to generate electricity deplete natural resources and have large carbon footprints.

Solar power is the conversion of sunlight directly into electricity. This process occurs in small, square semiconductors called photovoltaic (PV) cells. They are made from thin film layers of silicon and other conductive materials. When particles of light, also called photons, hit the cells, chemical reactions within the cell release electrons, generating an electric current. An inverter converts the direct current (DC) to alternating current (AC) which can be used for powering household appliances or sold to the utility grid. The photovoltaic process can be seen in Figure 1.

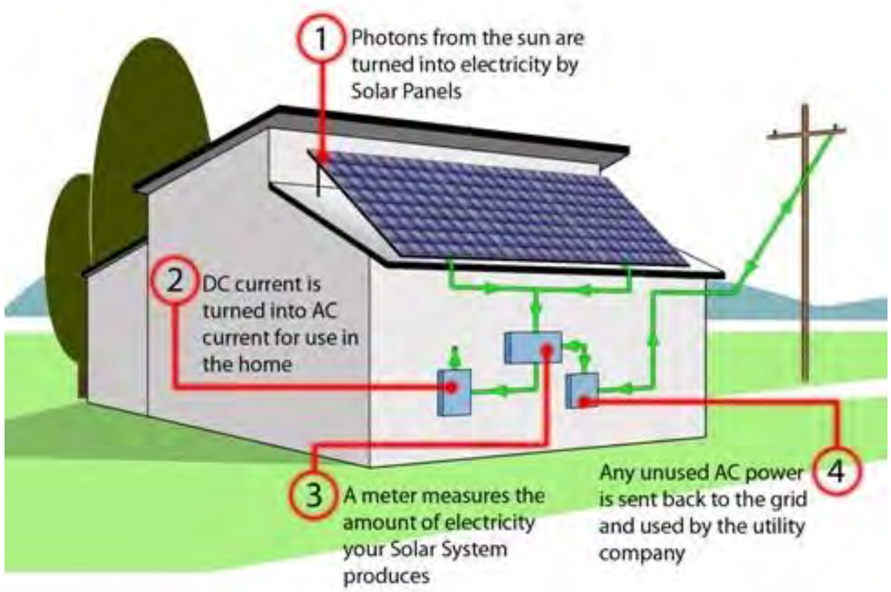


Figure 1. Conversion of sunlight into usable power [2].

The Dane County Housing Authority in Wisconsin asked a group of students at the University of Wisconsin if solar panels could be beneficial over traditional electricity in a low-income housing project. In 2012, the Dane County Board adopted Guiding Sustainability Principles as part of Resolution 103. One principle aims to “reduce and eventually eliminate

Dane County government's contribution to fossil fuel dependence" [3]. Another has the goal of eliminating conditions that hinder people from meeting their basic human needs.

The team researched the feasibility of a PV system to provide electricity for an affordable housing development in the Madison area using average housing data. Using research and generated data, the team weighed the environmental, economic, and societal impacts of using solar panels against conventional electricity generation. Based upon the results of our analysis, Dane County is provided with a final recommendation on the incorporation of solar panels into the housing development.

Methods and Assumptions

Property

In 2015, Dane County purchased the Messner property at 1326 E Washington Avenue with the intent to create a homeless day center, but is now scheduled to be redeveloped into mixed-income affordable housing [4]. Units to be included are market rate units as well as units for very low-income residents, earning less than 50 percent of the county's median income, and extremely low-income residents, making less than 30 percent of the local median income.

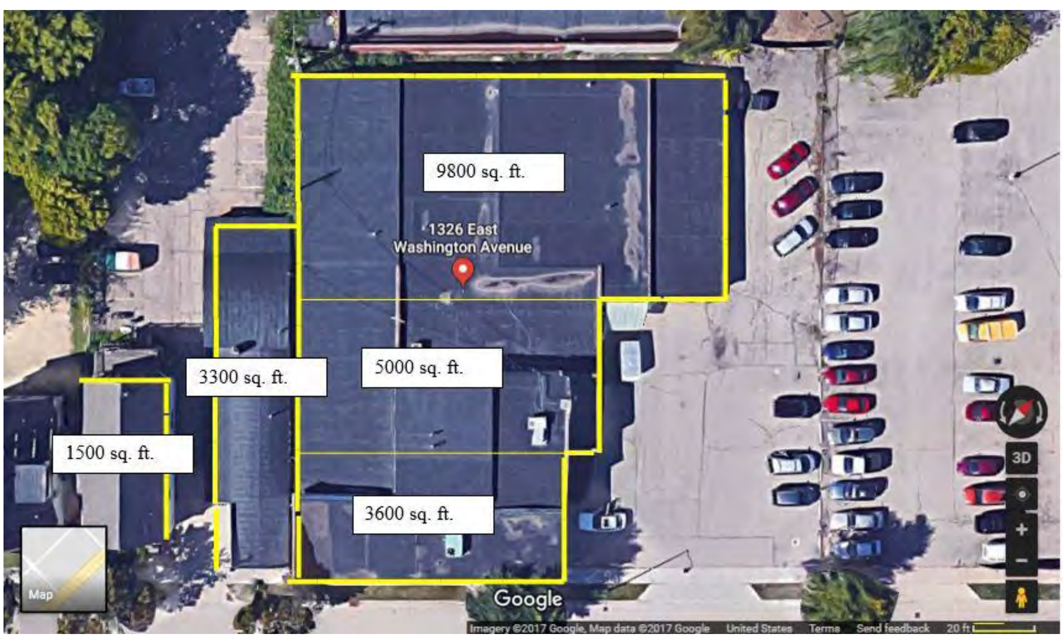


Figure 2. 1326 E Washington Ave, Madison, WI 53703 and attached properties.

The property is comprised of the two-story main building in addition to two smaller buildings. Roof sizes of the buildings were estimated using the aerial image and from scale from Google

Maps. The combined roof size was estimated to be about 23,000 ft², seen in Figure 2, and is be used as reference in an analysis model.

The Dane County Housing Initiative website has housing examples, one of which is Parmenter Circle. Using the same method, the roof size of Parmenter Circle was found to be just over 25,000 ft² with four stories. There are 50 apartment units within the example housing complex with twice as many floor levels. For the duration of the project, 40 apartment units is used as a conservative number, with an average of 1,000 square feet for each unit.

The analysis tool used to calculate captured energy is the National Renewable Energy Laboratory's System Advisor Model (SAM). SAM includes built in weather data, so the team used the region "Madison Dane Co Regional Arpt" for the typical meteorological years of 1991-2005 (TMY3) as this is the most recent and accurate weather data near Dane County.

Energy Use

In Wisconsin, the average annual electricity usage per household is ~9,000 kWh with an average of 2,605 square feet, equating to about 3.5 kWh/ft² [5]. Using 1,000 sq. ft. as the mean apartment size for the 40 units in the proposed housing complex, a conservative value of 280,000 kWh annually was calculated for the total building usage.

PV System

A detailed photovoltaic SAM performance model was analyzed for a distributed residential system. The module chosen is the Talesun Solar TP660AM240 to be rack mounted on the roof of the buildings. It is made of monocrystalline silicon and has a 250 W power rating with an 80% power output warranty of 25 years [6]. The desired array size was chosen to be 250 kWdc to meet or exceed the electricity demand of the building for more than 25 years with a 0.7% degradation rate per year, seen in Figure 3. This nameplate capacity requires 984 modules which occupy 17,200 square feet, under the limit of the 23,000 square foot rooftop space.

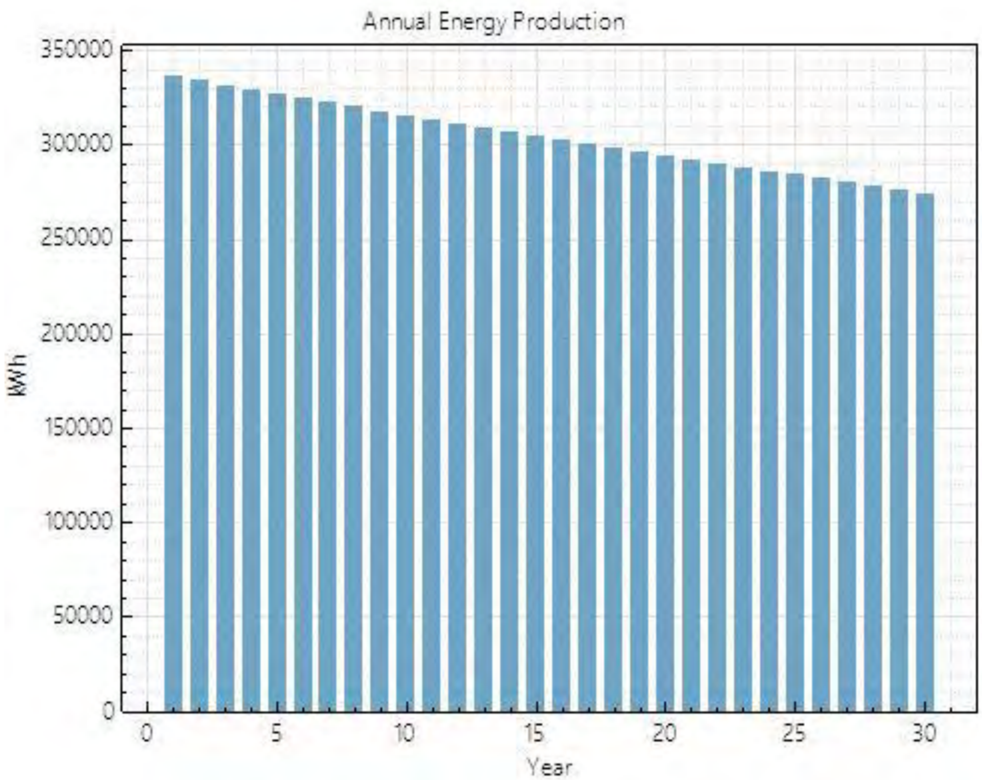


Figure 3. Annual Energy Production over 30 years predicted with SAM.

To keep the costs low, the modules are in a fixed position, not tilting to allow for tracking. A standard 240V inverter was chosen to match the 240V of the module. Generic loss values and electricity demand loads were used in the analysis module, which can be seen in Appendix A.

Social Aspects

In Dane County, 32.8% of all households are cost-burdened, meaning they spend more than 30 percent of their income on housing [4]. Additionally a third of all renters are unable to afford a two-bedroom apartment at market rate [4]. These circumstances create a housing gap in Dane County which is expected to increase with the county experiencing more growth than anywhere else in the state.

Social outcomes and effects of solar panels cannot be quantified with numbers and values. Because the housing project is to assist low-income consumers, literature regarding income levels is utilized to provide an analysis.

Environmental Considerations

A standard Life Cycle Assessment (LCA) tool is The Economic Input-Output Life Cycle Assessment (EIO-LCA) method from Carnegie Mellon University. The tool estimates the materials and energy required and the environmental emissions resulting from certain processes or activities. Due to the massive growth of the solar energy sector within the last decade, the EIO-LCA model based on 2002 data was determined to be too out-of-date for the scope of the project. Instead, the team decided to use more relevant and recent literature.

Madison Gas and Electric's (MGE) electricity sources from 2016 are shown in Figure 4 [7]. MGE receives electricity generated from coal, gas/oil, other purchased sources, and renewables. The other purchased sources of electricity also vary in their generation. Given that 88% of the electricity generated by MGE came from non-renewables, any reduction of carbon emissions from the transition to a PV system would be reflected in the life-cycle environmental performance of the team's proposed PV system.

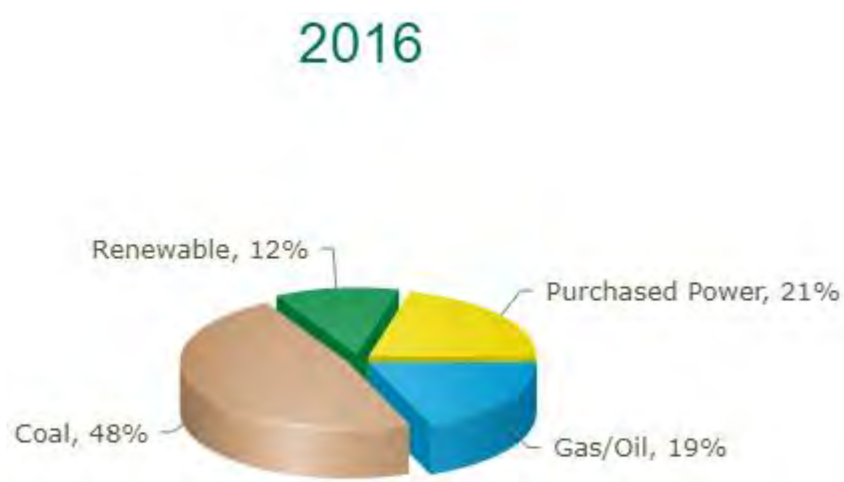


Figure 4. MGE's electricity sources.

In order to quantify the possible environmental benefits of using solar panels instead of conventional electricity, a life cycle assessment was researched. Nearly all greenhouse gas emissions from the life cycle of a PV system are generated from the production of the materials and devices used within it. Over 50% of greenhouse gas emissions are generated within the operational stage for the coal, natural gas and oil fuel cycles [8]. The longer a PV system is active, the more greenhouse gases will be reduced. The LCA results for the team's proposed PV system strongly depends on the current available electricity mix.

The Environmental Payback Time (EPBT) is a basic metric of the performance of a PV system throughout its lifetime. EPBT measures the time it takes for a PV system to produce the amount of electricity that could be generated by the current electric mix, while considering the amount of primary energy that is used to produce the PV system. Using the embodied energy of the individual components and applying it to the PV system, both the energy required to make the team's PV system and the EPBT were calculated [9,10].

Energy return on investment (EROI) is another metric used to evaluate the effectiveness of a PV system. EROI puts one unit of energy into the system and returns the energy that is generated. This ratio gives a representation of the effectiveness of the energy system and is deduced from literature.

To calculate the carbon emissions eliminated by switching to a PV system, greenhouse gas emission values were used in coordination with the information taken from MGE in Figure 4. It was assumed that the 21% of power purchased from outside sources would result in 59% of the electricity was provided by coal and 29% of power would be provided by natural gases. The other 12% of renewables were assumed to produce no carbon emissions. These values were multiplied by 280,000 kWh per year and then multiplied by 30 years to get the tons of Carbon emissions that would be consumed if the team's PV system was not pursued. Using a PV system does not produce carbon emissions. Carbon emissions of 194 and 112.5 g carbon emissions/kWh from coal and gas, respectively, were used to calculate the amount of carbon emissions that would be eliminated by switching to a PV system [11].

Economic Specifications

The financial analysis was conducted over a period of 30 years with a simple cash model. As previously stated, the panels include a performance warranty over 25 years, so it is reasonable to assume that the panels can continue producing electricity at a similar rate for at least 5 years beyond the warranty period. In calculating the net present value, an annual discount rate of 5% was used. This value seemed like an acceptable rate of return, given that the Dane County Housing Authority has funds set aside to invest in new housing projects, rather than invest in more lucrative opportunities.

The current electric rate for MGE is $0.134/kWh, and the rate has increased at an average of 0.5%/year over the past 5 years [12]. This growth rate was used to determine the utility rate in future years, which was then incorporated into the value of the energy produced by the solar system in future years. Both maintenance costs and salvage value of the system were neglected in the team's analysis.

When determining potential financial incentives for the PV system, the team was required to make more assumptions. Many possible incentives require application and approval. Table 1 below shows details the incentive programs that the team chose to include.

Table 1. Table of potential financial incentives [13].

Incentive Program	Incentive Rate	Estimated Amount of Incentive
Renewable Energy Competitive Incentive Program	$0.25/kWh	$84,048.25
Multifamily Energy Savings Program	$0.08/kWh	$26,895.44
Residential Renewable Energy Tax Credit	30% of cost	$212,645.10
Renewable Rewards Program	12% of cost ($2,400 max)	$2,400.00
	Total Incentives =	**$325,988.79**

The Renewable Rewards Program is a Wisconsin rebate program that rebates 12% of the cost up to $2,400 for residential or $4,000 for business. The new housing program may qualify as a business, but to be conservative the team chose $2,400 as the maximum rebate. It is unclear if the Multifamily Energy Savings Program includes solar PV, but it may be possible to qualify under either the Energy Management Systems/Controls or the Custom categories.

Results

SAM

With all parameters entered (Appendix A), SAM creates a table summarizing the output performance of the first year, some of which can be seen in Table 2.

Table 2. SAM Summary

Metric	Value
Annual energy (year 1)	336,193 kWh
Electricity bill without system (year 1)	$2,146
Electricity bill with system (year 1)	-$8,753
Net savings with system (year 1)	$10,899
Net capital cost	$708,817

The summary provides what the building would pay for electricity using conventional electricity generation purchased from MG&E and what the building receives from selling excess solar energy production to the utility company. These values are also calculated for the lifetime of the system in Appendix B.

One common trend in solar energy production is a higher yield in summer months. This is due to longer days and more sunlight in May, June, and July. Days are shorter during the winter and thus have less hours of sunlight to produce electricity, which can be seen in Figure 5.

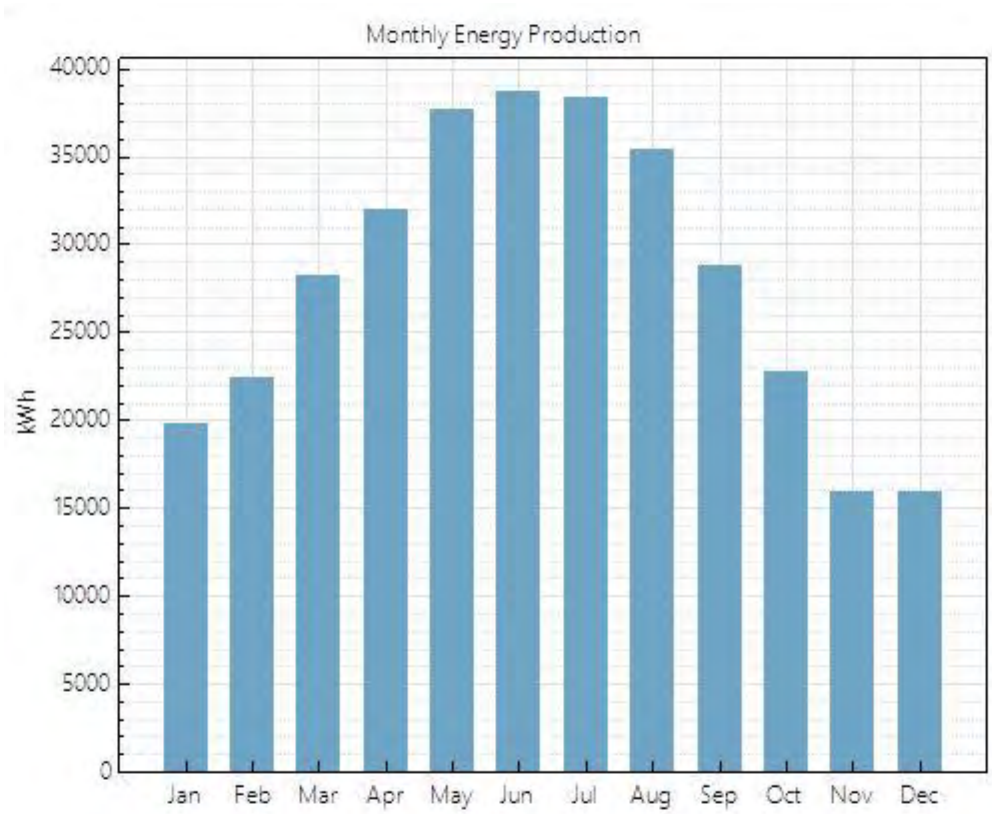


Figure 5. Monthly Energy Production for year 1, predicted in SAM.

<u>Social</u>

Assuming a fairly consistent use of energy across users, low-income consumers pay a larger percentage of their income to energy than higher-income consumers because the price of electricity does not change. Due to installation costs of solar panels that do not apply to existing electricity, low-income consumers conventionally have less opportunity for solar power because it has been found that the number of solar installations correlates with income level as seen in Figure 6 [14].

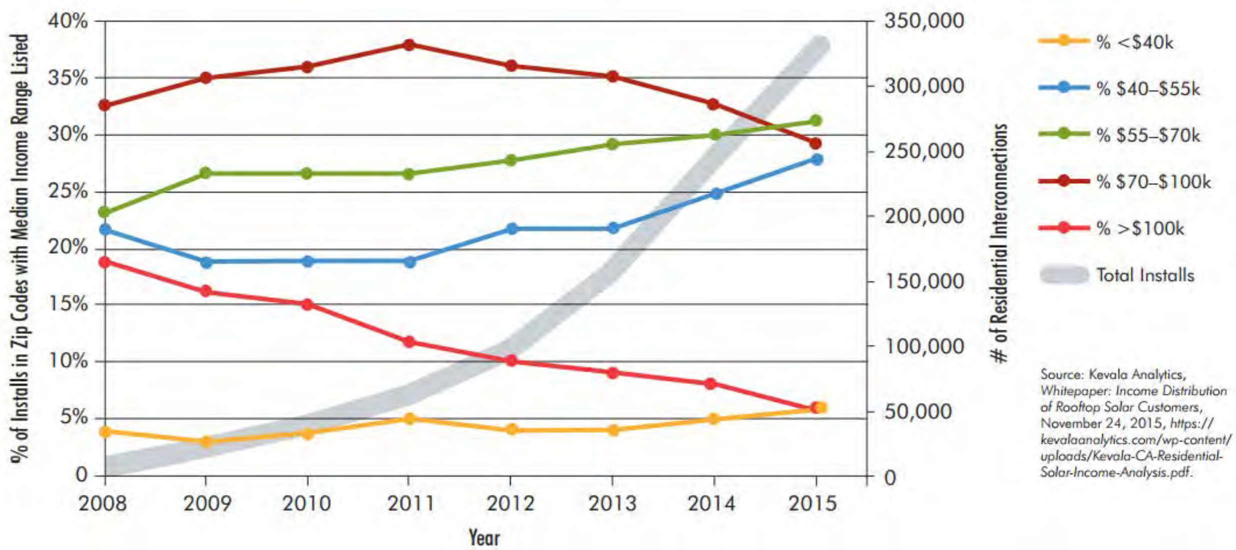


Figure 6. Household Income and Solar Adoption in California (2008–2015) [14].

LCA

Using the embodied energies combined with the specifics provided by the manufacturer of the solar panel, the EPBT was calculated, see Appendix C, to produce the value of 1.611 years. The EROI for a similar PV system in Perrysberg, Ohio was 33. An EROI around this would be expected in the team's proposed solar system. Throughout a 30 year period, 1,361.92 tons of carbon emissions would be eliminated by using the team's PV system, calculated in Appendix C.

Financial

The financial analysis used the previously stated assumptions and values from SAM, from which the following economic values were calculated using equations in Appendix D:

- Net present value = $369,509.00
- Benefit/Cost ratio = 1.521
- Payback period = 10.45 years

Figure 7 shows a cash flow diagram over 30 years for the system.

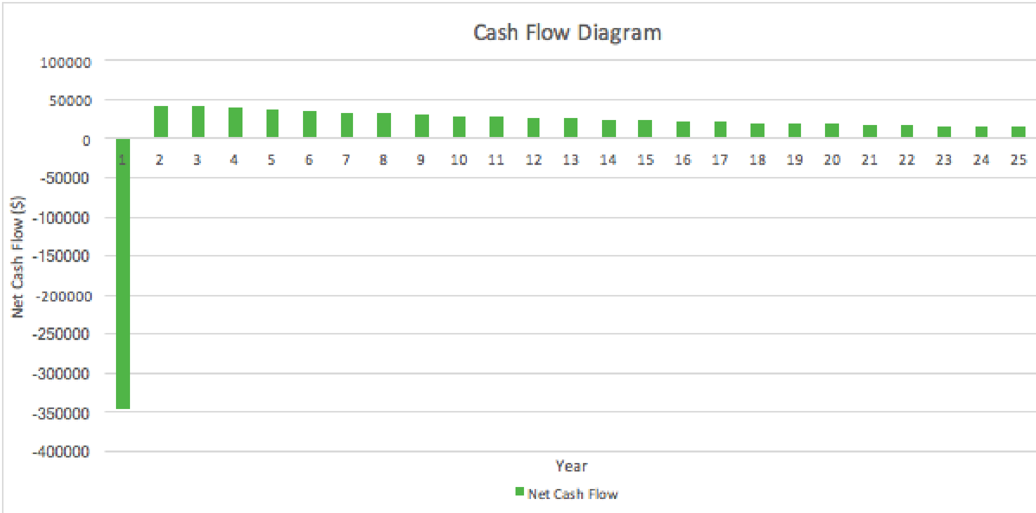


Figure 7. Cash flow diagram.

Discussion

Social

Low-income consumers may generally lack the savings necessary to finance a solar panel system or not have ownership of the roof in a rental. There are large upfront costs that take time to be returned; for someone struggling financially, this could make other tasks, such as paying for groceries or loans, difficult to do in the beginning.

Contrary to the purchasing trends, it is the low-income consumers that would benefit most from saving money on their energy bill because they pay a larger percentage of their income to energy than higher-income consumers. An affordable housing development with an installed solar panel array providing all the electricity that units need would allow for that cost burden to be taken away from the residents. If residents were previously unable to save significant amounts of money, saving around $100/month from their old electricity bills would provide an avenue for financial growth.

The utilization of a PV system provides residents with a technology once inaccessible to them, while allowing them an opportunity to save money for a house, education, or any number of investments for the future. Because of these reasons, the team determined the proposed project is sustainable from a social perspective and recommends that the Dane County Housing Authority continue their research into the installation of a solar system.

Environmental

The LCA of the PV system provided the information the team needed to make a recommendation to Dane County. Choosing to use a PV system would result in the elimination of 1,361.92 tons of carbon emissions, which equates to 292 passenger vehicles driven for one year, or 153,249 gallons of gasoline consumed [15]. Eliminating the emissions generated by energy consumption would help to reduce the total environmental impact of the housing project through the future. Figure 6 shows the relationship between household income and solar adoption. This figure shows that the residents in the affordable housing would most likely not live in a building that utilized green energy in its construction. Thus, the use of a PV system in this development would reduce the carbon footprint of a group of people that would have normally consumed from non-green energy sources.

A majority of the emissions produced by PV systems occurs in the raw material acquisition and manufacturing processes. LCAs have been performed to discover areas for improvement. The LCA talked about the purification process in the creation of crystalline Si PV modules. The energy required in the purification of crystalline Si accounts for 45% of the primary energy used in fabricating Si modules [8]. This is one area where PV systems can reduce their environmental impact. By reducing the energy required to purify crystalline Si, the amount of embodied energy in the system can be reduced.

Throughout the lifetime of the PV system, carbon emissions would be reduced. Even while the EPBT of 1.611 years makes up for the energy consumed in the creation of the PV system, carbon emissions are drastically lower than using traditional electric sources. The team sees the overwhelming environmental benefits provided by using a PV system throughout its life cycle as a strong reason to justify the use of a PV system in the affordable housing development.

Economic

The net present value and benefit/cost ratio of the project reflect that the purchase and installation of the solar system is an economically viable decision. Although a B/C ratio of 1.521 isn't especially high, it still shows that the benefits of the PV system outweigh the costs over 30 years.

Upon first analysis, the payback period indicates that the project may be less economically viable. An investment opportunity with a payback of over 7 years isn't usually a sign of a wise investment. However, the Dane County Housing Authority is likely more equipped to absorb the initial negative cash flows than a business which relies on profits. The payback period is also significantly outweighed by the 30 year lifespan of the proposed solar system; Appendix D displays the continued positive cash flows well past the payback period. Additionally, the projections for system performance are quite reliable and all system components are warrantied, so the risk of inaccurate future cash flow projections is minimal. Considering all of these factors, the team determined that the payback period isn't ideal, but still reflects economic viability.

There are also other possible tools that could improve the economic prospects of the project which weren't considered. One possible avenue that the Housing Authority could follow is a Power Purchasing Agreement (PPA). In a PPA, the building owner allows a 3rd party investor to place a solar PV system on the owner's property. The energy produced by the system is then sold to the building owner at a fixed rate. This means that costs up front would be much lower. Often times, a PPA makes a solar system much more economically viable for non-corporate entities, as a 3rd party could take advantage of other incentives, further reducing the overall cost.

Other possible factors include the utilization of loans and/or bonds. Because the system would be purchased by a government entity, it is very possible that low interest rate loans and bonds could be used as a funding source. Depending on the loan, this could reduce the payback period of the system. Additionally, the system could easily produce power beyond the 30 years included in our analysis. Any additional years of production would equate to increased cash flows, which would improve both the net present value and the benefit/cost ratio of the system.

The team recommends that the Dane County Housing Authority continues with the project based on the analysis that shows generally favorable economics. They should follow their standard procedure for financing and sourcing funds for a new project, and they should look further into the possibility of a PPA. There are solar developers in the Madison area who can provide further analysis in these areas, including the arrangement of a PPA with a 3rd party investor.

Conclusion

Upon completion of a sustainability analysis, the team found many positive results from the installation of the proposed PV system. The solar photovoltaic system would lower the carbon footprint of the housing project while also creating new opportunities to help residents with lower income. Free energy could be generated for over 30 years, and with a qualified economic research team, the upfront financial load could potentially be decreased. Additionally, the Dane County Housing Authority could meet the Guiding Sustainability Principles using this technology. As the proposed project meets requirements for each of the 3 paradigms of sustainability, the team recommends that the Dane County Housing Authority continues with and conducts additional research for the implementation of a PV system.

Appendices

Appendix A: SAM Inputs

Files in Library

Search for: [ ] Name

Name	Station ID	Latitude	Longitude	Time zone	Elevation
USA WI La Crosse Municipal Arpt (TMY3)	726430	43.867	-91.25	-6	198
USA WI Lone Rock Faa Ap (TMY3)	726416	43.2	-90.183	-6	219
USA WI Madison (TMY2)	14837	43.1333	-89.3333	-6	262
USA WI Madison Dane Co Regional Arpt [isis] (TMY3)	726410	43.13	-89.33	-6	262

CEC Performance Model with Module Database

Search for: [ ] Name

Name	I_mp_ref	V_mp_ref	A_c	N_s	I_sc_ref	V_oc_ref	gam
Tainergy Tech TKSG-31501	8.57	36.72	1.773	72	8.91	45.91	-0.4
Taiwan Semiconductor Manufacturing TS-230P4-AD	7.58	30.36	1.624	60	8.10	36.42	-0.4
Taiwan Semiconductor Manufacturing TS-235P4-AD	7.68	30.60	1.624	60	8.23	36.72	-0.4
Taiwan Semiconductor Manufacturing TS-240P4-AD	7.83	30.72	1.624	60	8.32	36.84	-0.4
Taiwan Semiconductor Manufacturing TS-245P4-AD	7.94	30.84	1.624	60	8.43	37.08	-0.4
Taiwan Semiconductor Manufacturing TS-250P4-AD	8.03	31.14	1.624	60	8.50	37.32	-0.4
Talesun Solar TP660AM225	8.35	30.1	1.624	60	8.78	37.7	-0.4
Talesun Solar TP660AM240	8.35	30.1	1.624	60	8.78	37.7	-0.4

Temperature Correction

(●) Nominal operating cell temperature (NOCT) method

( ) Heat transfer method

Refer to Help for more information about CEC cell temperature models.

NOCT method parameters

Mounting standoff: Ground or rack mounted

Array height: Two story building height or higher

Inverter CEC Database

Search for: [ ] Name

Name	Paco	Vac	Mppt_low	Mppt_high	Vdco	Vdcmax
SMA America: SB3300U 240V [CEC 2006]	3300	240	200	400	248.9285714	0
SMA America: SB3800TL-US-22 (208V) 208V [CEC 2013]	3800	208	250	480	398.6683333	600
SMA America: SB3800TL-US-22 (208V) 208V [CEC 2014]	3850	208	175	480	400.884	600
SMA America: SB3800TL-US-22 (240V) 240V [CEC 2013]	3800	240	250	480	398.4966667	600
SMA America: SB3800TL-US-22 (240V) 240V [CEC 2014]	3850	240	175	480	401.4343333	600

System Sizing

(●) Specify desired array size

Desired array size: 250 kWdc

DC to AC ratio: 1.20

( ) Specify modules and inverters

Modules per string: 7

Strings in parallel: 2

Number of inverters: 1

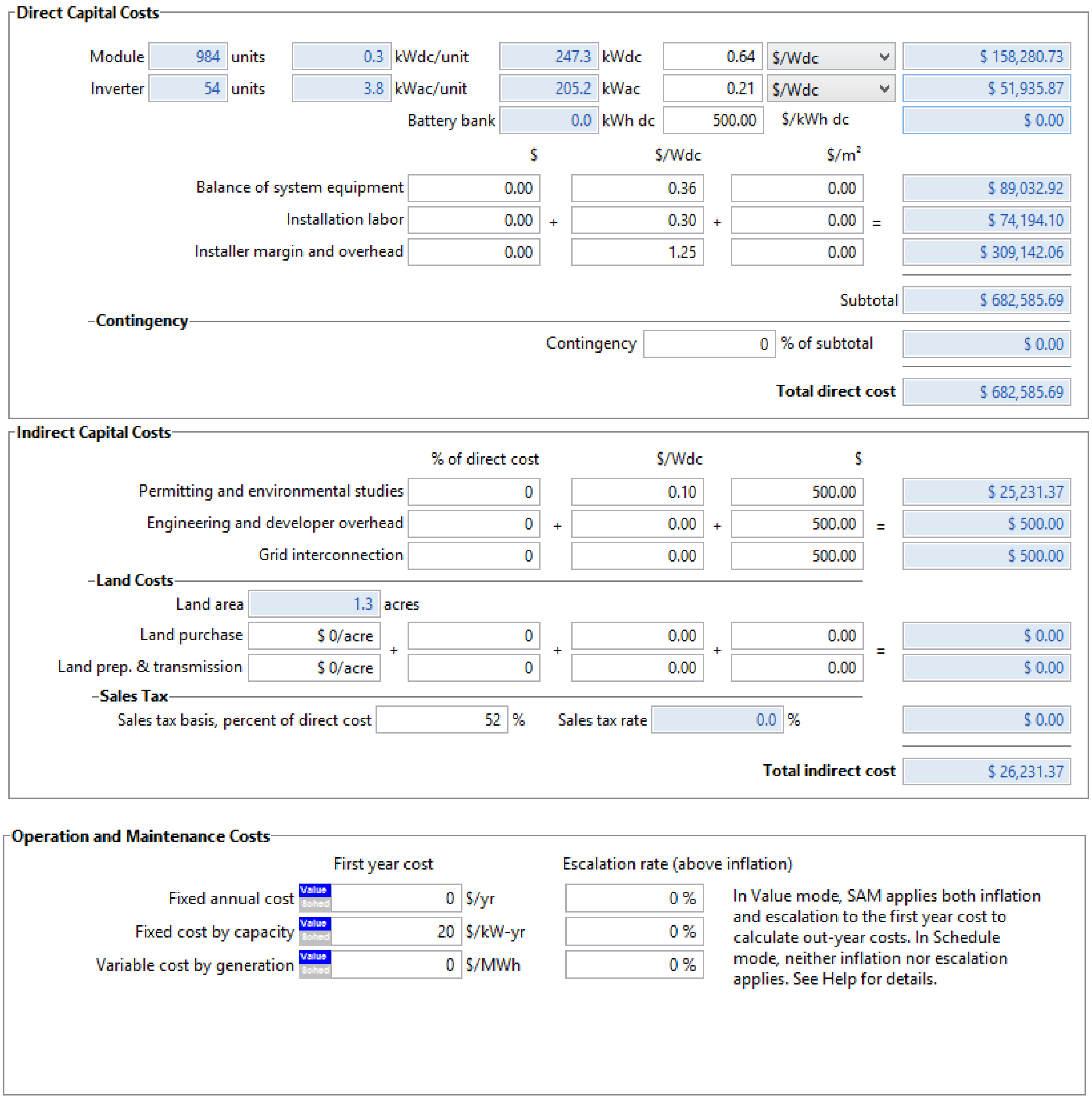
PV simulation over one year

System Performance Degradation

Degradation rate [Value / Sched] 0.7 %/year

Applies to the system's total annual AC output.

In Value mode, the degradation rate applies to the system's total annual kWh output for the previous year starting in Year 2. In Schedule mode, each year's rate applies to the Year 1 value. See Help for details.



Direct Capital Costs

Module	984	units	0.3	kWdc/unit	247.3	kWdc	0.64 $/Wdc	$ 158,280.73
Inverter	54	units	3.8	kWac/unit	205.2	kWac	0.21 $/Wdc	$ 51,935.87
				Battery bank	0.0	kWh dc	500.00 $/kWh dc	$ 0.00

	$		$/Wdc		$/m²		
Balance of system equipment	0.00		0.36		0.00		$ 89,032.92
Installation labor	0.00	+	0.30	+	0.00	=	$ 74,194.10
Installer margin and overhead	0.00		1.25		0.00		$ 309,142.06
					Subtotal		$ 682,585.69

Contingency

Contingency	0	% of subtotal	$ 0.00
		Total direct cost	$ 682,585.69

Indirect Capital Costs

	% of direct cost		$/Wdc		$		
Permitting and environmental studies	0		0.10		500.00		$ 25,231.37
Engineering and developer overhead	0	+	0.00	+	500.00	=	$ 500.00
Grid interconnection	0		0.00		500.00		$ 500.00

Land Costs

Land area	1.3 acres								
Land purchase	$ 0/acre	+	0	+	0.00	+	0.00	=	$ 0.00
Land prep. & transmission	$ 0/acre		0		0.00		0.00		$ 0.00

Sales Tax

Sales tax basis, percent of direct cost	52 %	Sales tax rate	0.0 %	$ 0.00
			Total indirect cost	$ 26,231.37

Operation and Maintenance Costs

	First year cost		Escalation rate (above inflation)
Fixed annual cost (Value / Sched)	0	$/yr	0 %
Fixed cost by capacity (Value / Sched)	20	$/kW-yr	0 %
Variable cost by generation (Value / Sched)	0	$/MWh	0 %

In Value mode, SAM applies both inflation and escalation to the first year cost to calculate out-year costs. In Schedule mode, neither inflation nor escalation applies. See Help for details.

Residential Loan Type

- ( ) Standard loan — Standard loan interest payments are not tax deductible.
- (•) Mortgage — Mortgage interest payments are tax deductible.

Loan Parameters

Debt fraction	100	%	Net capital cost	$ 708,817.06	
Loan term	25	years	Debt	$ 708,817.06	
Loan rate	5	%/year	WACC	3.26	%

The weighted average cost of capital (WACC) is displayed for reference. SAM does not use the value for calculations.

For a project with no debt, set the debt fraction to zero.

Analysis Parameters

Analysis period	30	years	Inflation rate	2.5	%/year
			Real discount rate	5.5	%/year
			Nominal discount rate	8.14	%/year

Tax and Insurance Rates

			Property Tax		
Federal income tax rate (Value)	30	%/year	Assessed percentage	100	% of installed cost
State income tax rate (Value)	7	%/year	Assessed value	$ 708,817.06	
Sales tax	0	% of total direct cost	Annual decline	0	%/year
Insurance rate (annual)	0.5	% of installed cost	Property tax rate	0	%/year

Salvage Value

Net salvage value	0	% of installed cost	End of analysis period value	$ 0

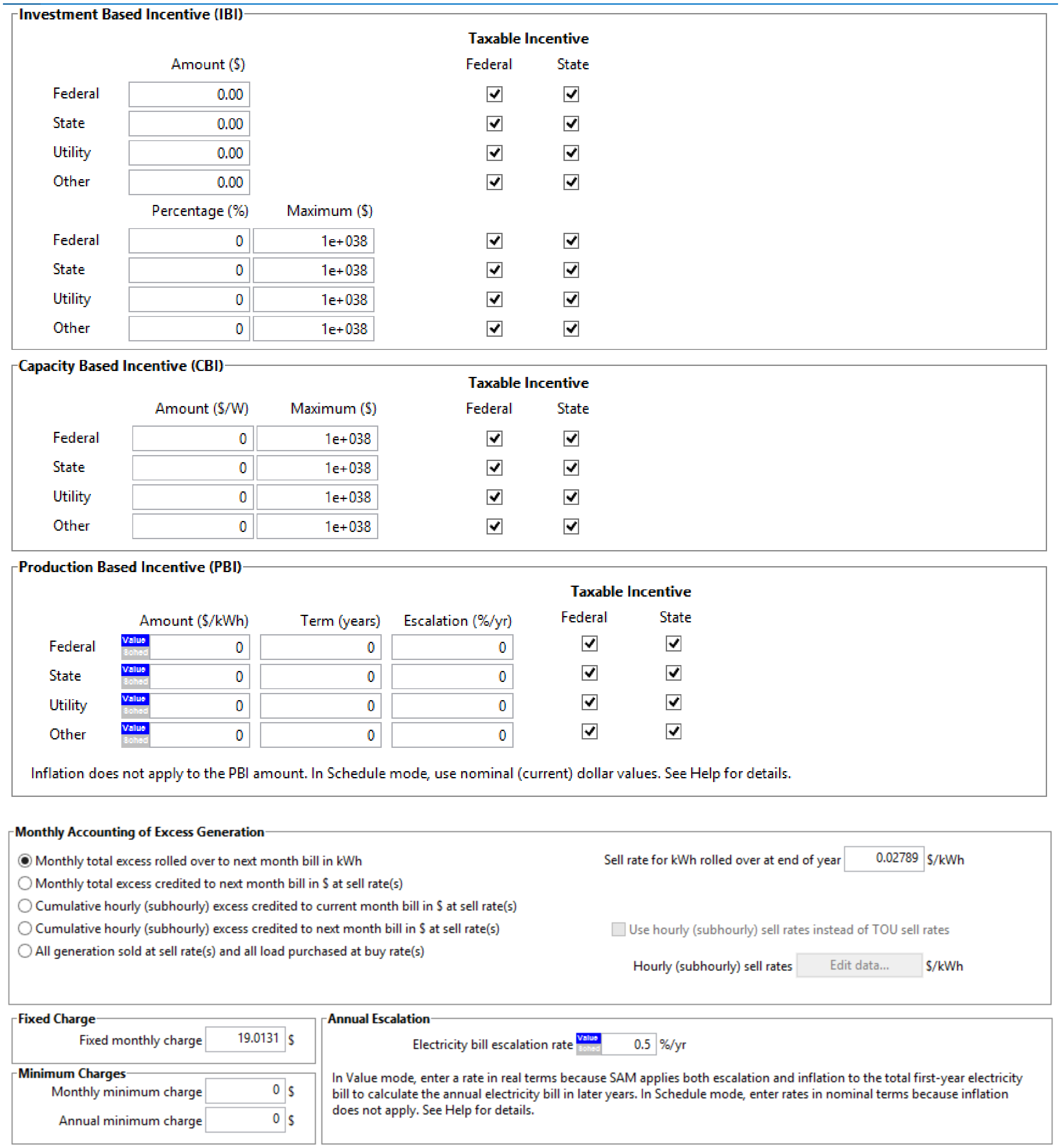
Investment Tax Credit (ITC)

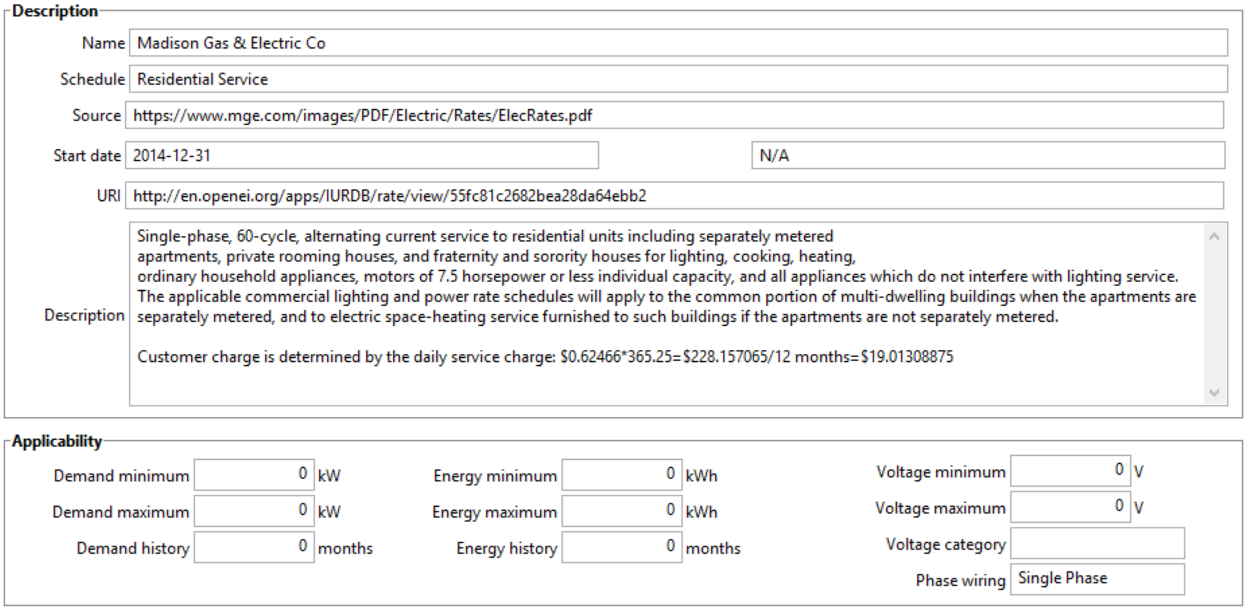
	Amount ($)	
Federal	0.00	
State	0.00	
	Percentage (%)	**Maximum ($)**
Federal	30	1e+038
State	12	2400

Production Tax Credit (PTC)

	Amount ($/kWh)	Term (years)	Escalation (%/yr)
Federal (Value)	0	10	0.00
State (Value)	0	10	0.00

Inflation does not apply to the PTC amount. In Schedule mode, use nominal (current) dollar values. See Help for details.


Investment Based Incentive (IBI)
Taxable Incentive
Amount ($)
Federal
State
Federal 0.00
State 0.00
Utility 0.00
Other 0.00
Percentage (%)
Maximum ($)
Federal 0 1e+038
State 0 1e+038
Utility 0 1e+038
Other 0 1e+038
Capacity Based Incentive (CBI)
Taxable Incentive
Amount ($/W)
Maximum ($)
Federal
State
Federal 0 1e+038
State 0 1e+038
Utility 0 1e+038
Other 0 1e+038
Production Based Incentive (PBI)
Taxable Incentive
Amount ($/kWh)
Term (years)
Escalation (%/yr)
Federal
State
Federal 0 0 0
State 0 0 0
Utility 0 0 0
Other 0 0 0
Inflation does not apply to the PBI amount. In Schedule mode, use nominal (current) dollar values. See Help for details.
Monthly Accounting of Excess Generation
Monthly total excess rolled over to next month bill in kWh
Monthly total excess credited to next month bill in $ at sell rate(s)
Cumulative hourly (subhourly) excess credited to current month bill in $ at sell rate(s)
Cumulative hourly (subhourly) excess credited to next month bill in $ at sell rate(s)
All generation sold at sell rate(s) and all load purchased at buy rate(s)
Sell rate for kWh rolled over at end of year 0.02789 $/kWh
Use hourly (subhourly) sell rates instead of TOU sell rates
Hourly (subhourly) sell rates Edit data... $/kWh
Fixed Charge
Fixed monthly charge 19.0131 $
Minimum Charges
Monthly minimum charge 0 $
Annual minimum charge 0 $
Annual Escalation
Electricity bill escalation rate 0.5 %/yr
In Value mode, enter a rate in real terms because SAM applies both escalation and inflation to the total first-year electricity bill to calculate the annual electricity bill in later years. In Schedule mode, enter rates in nominal terms because inflation does not apply. See Help for details.

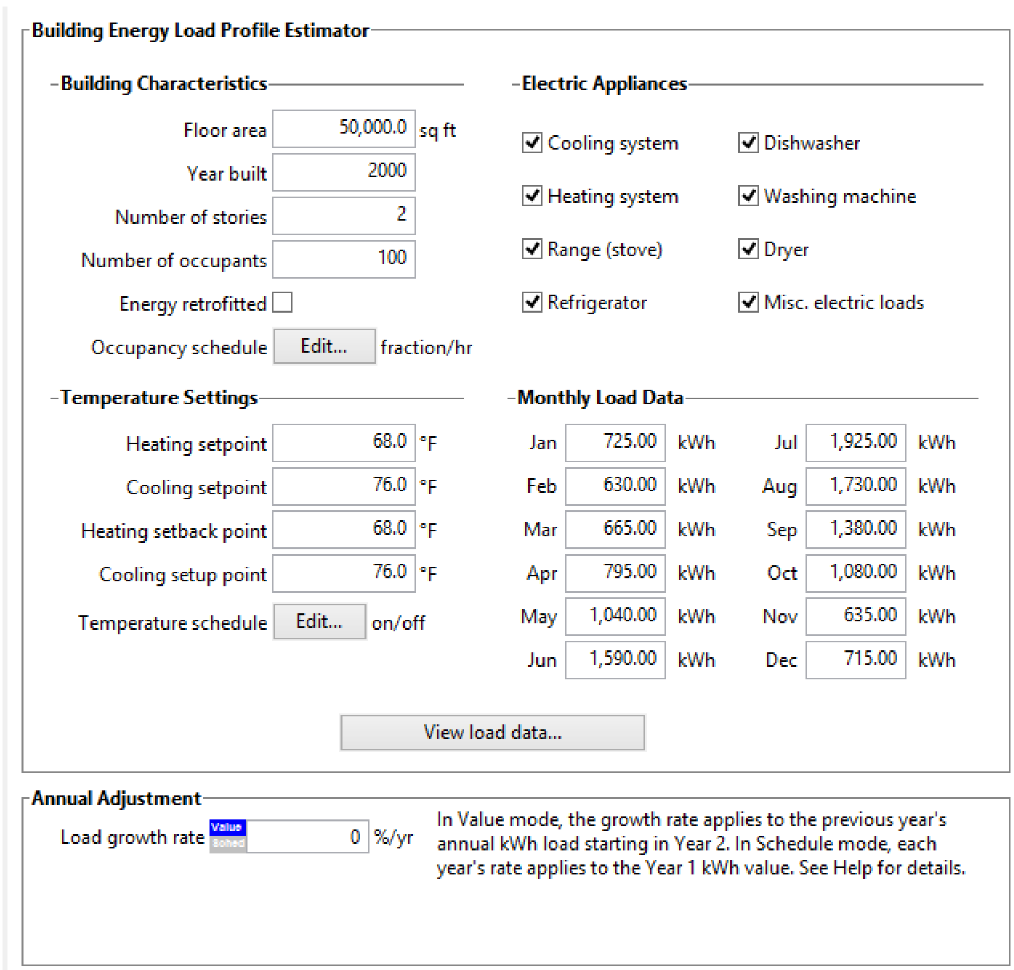


Description

Name	Madison Gas & Electric Co
Schedule	Residential Service
Source	https://www.mge.com/images/PDF/Electric/Rates/ElecRates.pdf
Start date	2014-12-31 / N/A
URI	http://en.openei.org/apps/IURDB/rate/view/55fc81c2682bea28da64ebb2
Description	Single-phase, 60-cycle, alternating current service to residential units including separately metered apartments, private rooming houses, and fraternity and sorority houses for lighting, cooking, heating, ordinary household appliances, motors of 7.5 horsepower or less individual capacity, and all appliances which do not interfere with lighting service. The applicable commercial lighting and power rate schedules will apply to the common portion of multi-dwelling buildings when the apartments are separately metered, and to electric space-heating service furnished to such buildings if the apartments are not separately metered. Customer charge is determined by the daily service charge: \$0.62466*365.25=\$228.157065/12 months=\$19.01308875

Applicability

Demand minimum	0 kW	Energy minimum	0 kWh	Voltage minimum	0 V
Demand maximum	0 kW	Energy maximum	0 kWh	Voltage maximum	0 V
Demand history	0 months	Energy history	0 months	Voltage category	
				Phase wiring	Single Phase



Building Energy Load Profile Estimator

Building Characteristics

Floor area	50,000.0 sq ft
Year built	2000
Number of stories	2
Number of occupants	100
Energy retrofitted	☐
Occupancy schedule	Edit... fraction/hr

Electric Appliances

- ☑ Cooling system
- ☑ Dishwasher
- ☑ Heating system
- ☑ Washing machine
- ☑ Range (stove)
- ☑ Dryer
- ☑ Refrigerator
- ☑ Misc. electric loads

Temperature Settings

Heating setpoint	68.0 °F
Cooling setpoint	76.0 °F
Heating setback point	68.0 °F
Cooling setup point	76.0 °F
Temperature schedule	Edit... on/off

Monthly Load Data

Jan	725.00 kWh	Jul	1,925.00 kWh
Feb	630.00 kWh	Aug	1,730.00 kWh
Mar	665.00 kWh	Sep	1,380.00 kWh
Apr	795.00 kWh	Oct	1,080.00 kWh
May	1,040.00 kWh	Nov	635.00 kWh
Jun	1,590.00 kWh	Dec	715.00 kWh

View load data...

Annual Adjustment

Load growth rate Value Sched 0 %/yr

In Value mode, the growth rate applies to the previous year's annual kWh load starting in Year 2. In Schedule mode, each year's rate applies to the Year 1 kWh value. See Help for details.

Appendix B: SAM Outputs

Time stamp	Energy | (kWh)	Electricity bill without system | ($)	Electricity bill with system | ($)	Value of electricity savings | ($)
1	0	0	0	0
2	336193	2146.26	-8753.02	10899.3
3	333840	2210.65	-8948.01	11158.7
4	331503	2276.97	-9147.3	11424.3
5	329182	2345.28	-9351	11696.3
6	326878	2415.64	-9559.19	11974.8
7	324590	2488.11	-9772	12260.1
8	322318	2562.75	-9989.48	12552.2
9	320061	2639.63	-10211.8	12851.4
10	317821	2718.82	-10439	13157.8
11	315596	2800.39	-10671.2	13471.6
12	313387	2884.4	-10908.5	13792.9
13	311193	2970.93	-11151.1	14122
14	309015	3060.06	-11399	14459.1
15	306852	3151.86	-11652.4	14804.2
16	304704	3246.42	-11911.3	15157.8
17	302571	3343.81	-12176	15519.8
18	300453	3444.12	-12446.5	15890.6
19	298350	3547.45	-12722.9	16270.4
20	296261	3653.87	-13005.4	16659.3
21	294188	3763.48	-13294.2	17057.7
22	292128	3876.39	-13589.3	17465.7
23	290083	3992.68	-13890.9	17883.5

24	288053	4112.46	-14199.1	18311.5
25	286036	4235.84	-14514	18749.9
26	284034	4362.91	-14836	19198.9
27	282046	4493.8	-15164.9	19658.7
28	280072	4628.61	-15501.1	20129.8
29	278111	4767.47	-15844.7	20612.2
30	276164	4910.49	-16195.8	21106.3
31	274231	5057.81	-16554.6	21612.5

Appendix C: LCA Equations

$$EPBT(year) = \frac{Embedded\ (primary)\ energy\ (MJ\ m^2)}{Annual\ \ (primay)\ energy\ generated\ by\ the\ system\ (MJ\ m^2yr^2)}$$

square inches per panel	2160				Support structure	200	KWh/m2
square inches all panels	2592000				Battery	0	KWh/m2
					Inverter	33	KWh/m2
square inches to square meters	1672.25472				misc	125	KWh/m2
Energy requirements MJ/square meter	7692371.712	MJ					
Framed Panel	0.002136772	KWh					
Support structure	334450.944	KWh					
Battery	0	KWh					
Inverter	110368.8115	KWh					
misc	209031.84	KWh					
Total energy to make system	653851.5977	KWh					

	Energy Payback		
157856.4023		Energy used in construction of system - Energy generated by system	
0.611053111	0	247998	
1.611053111	1	-157855	
	2	-563707	
	3	-969557	
	4	-1375406	
	5	-1781254	

	Kwh/year	Coal (g Carbon emissions/ kWh)	Gas/Oil (g Carbon emissions / kWh)			
1 year	280000	194	112.5			
30 years	8400000	1629600000	945000000			
			Total			
			1,235,514,000.00	grams of Carbon emission:		
			1,361.92	tons of Carbon emissions		

Appendix D: Economic Model Calculations

Year	Energy Produced (kWh)	Utility Rate	Value of Energy	System Cost	Incentives	Net Cash Flow
1	336193	$0.1340	$45,049.86	$708,817.00	$325,988.79	-$337,778.35
2	333856	$0.1354	$43,036.75	$0.00	$0.00	$43,036.75
3	331535	$0.1367	$41,113.60	$0.00	$0.00	$41,113.60
4	329231	$0.1381	$39,276.39	$0.00	$0.00	$39,276.39
5	326942	$0.1395	$37,521.28	$0.00	$0.00	$37,521.28
6	324669	$0.1409	$35,844.59	$0.00	$0.00	$35,844.59
7	322412	$0.1423	$34,242.83	$0.00	$0.00	$34,242.83
8	320171	$0.1438	$32,712.65	$0.00	$0.00	$32,712.65
9	317946	$0.1452	$31,250.84	$0.00	$0.00	$31,250.84
10	315736	$0.1467	$29,854.36	$0.00	$0.00	$29,854.36
11	313541	$0.1482	$28,520.28	$0.00	$0.00	$28,520.28
12	311361	$0.1497	$27,245.82	$0.00	$0.00	$27,245.82
13	309197	$0.1512	$26,028.31	$0.00	$0.00	$26,028.31
14	307047	$0.1527	$24,865.20	$0.00	$0.00	$24,865.20
15	304913	$0.1542	$23,754.07	$0.00	$0.00	$23,754.07
16	302794	$0.1558	$22,692.59	$0.00	$0.00	$22,692.59
17	300689	$0.1574	$21,678.54	$0.00	$0.00	$21,678.54
18	298599	$0.1590	$20,709.81	$0.00	$0.00	$20,709.81
19	296523	$0.1606	$19,784.36	$0.00	$0.00	$19,784.36
20	294462	$0.1622	$18,900.28	$0.00	$0.00	$18,900.28
21	292415	$0.1638	$18,055.69	$0.00	$0.00	$18,055.69
22	290382	$0.1655	$17,248.85	$0.00	$0.00	$17,248.85
23	288364	$0.1672	$16,478.07	$0.00	$0.00	$16,478.07
24	286359	$0.1688	$15,741.72	$0.00	$0.00	$15,741.72
25	284368	$0.1706	$15,038.29	$0.00	$0.00	$15,038.29
26	282392	$0.1723	$14,366.28	$0.00	$0.00	$14,366.28
27	280429	$0.1740	$13,724.31	$0.00	$0.00	$13,724.31
28	278479	$0.1758	$13,111.02	$0.00	$0.00	$13,111.02
29	276544	$0.1775	$12,525.14	$0.00	$0.00	$12,525.14
30	274621	$0.1793	$11,965.44	$0.00	$0.00	$11,965.44

$\text{Energy Produced}_{\text{Year 2}} = \text{Energy Produced}_{\text{Year 1}}/1.007$
$\text{Utility Rate}_{\text{Year 2}} = \text{Utility Rate}_{\text{Year 1}}/0.995$
$\text{Value of Energy}_{\text{Year n}} = \text{Value of Energy}_{\text{Year n-1}}/1.05^{n-1}$
Net Present Value = Σ all Net Cash Flows
Benefit/Cost Ratio = $(\Sigma\ (\text{Value of Energy}_{\text{Year n}}) + \text{Incentives})/\text{Cost of System}$

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WINDOWS

Abstract

This paper details window options for affordable housing developments in Dane County, WI. Analyses were undertaken to evaluate the sustainability of various options using the three paradigm of sustainability: economic, environmental, and social impact. Alternative high-performance window schemes were analyzed and compared to existing specifications. Comparisons of embodied energy, life cycle emissions, financial costs of initial implementation, potential savings in life cycle energy costs, and social benefits and costs were made. Results showed that by optimizing window specifications, substantial savings can be made over the lifespan of the window. Payback periods of incremental window system investments were within acceptable limits when specified in the initial build. The financial payback periods for replacement windows were higher, emphasizing the need for sustainable and energy efficient choices at the initial design stage.

1. Introduction

Home to over 500,000 people spread across 33 towns, Dane County, located in South Central Wisconsin, is Wisconsin's second largest county by both area and population (United States Census Bureau, 2017). However, with the largest population growth in the entire state from 2015 to 2016, land availability for housing development is quickly diminishing and the price per acre is skyrocketing (The Capital Area Regional Planning Commission, 2017). This is causing many problems throughout the county, one of which is a rising housing gap. A housing gap is the difference between the number of housing units available at an affordable price, and the number of units that are needed. The growing gap in Dane County is forcing people to live in overcrowded houses, houses they can't afford, and houses falling into disrepair.

In an effort to combat these housing issues, Dane County has invested almost $2 million for the creation of affordable housing (Dane County Housing Initiative (DCHI), 2017). These affordable housing developments will provide mixed-income housing with living conditions that will be the same for all people living there, regardless of their financial situation. With the addition of these new housing developments residents will hopefully be given more opportunities to create stronger community bonds, and have increased access to public amenities and resources. The overall intention of the investment is to establish successful partnerships that will allow for the creation of affordable housing options, and ensure equal opportunity for the entire community.

As part of the partnership between the University of Wisconsin-Madison (UW – Madison) and Dane County, the Dane County Board of Supervisors has reached out to the university with several different projects encompassing many aspects of the new developments including: finding real estate properties to invest in, providing recommendations on existing housing conditions, and researching new sustainable housing technologies. The board has specifically chosen the Environmental Sustainable Engineering class at UW-Madison to help research for several different projects dealing with sustainable housing technologies. These projects encompass a wide range of topics from passive housing designs to energy efficient lighting and furnaces. Through this research, the Dane County Board of Supervisors is hoping to gain knowledge and understanding of different types of sustainable practices they might be interested in implementing in their future undertakings. This report will investigate sustainable low-emissivity, or low-e, window options for Dane County affordable housing.

2. Background

The efficiency of a window refers to its ability to control certain properties like the transfer of heat, the prevention of air leakage, and the transmittance of light into a space. Low-e window efficiency comes from the use of different frame materials, different glazing types (meaning different number of panes), and different types of low-e coatings. Through these options, low-e windows can alter certain characteristics like the rate of heat loss, the fraction of incident solar radiation admitted, and the amount of visible light transmission (Energy Star, 2017). On average, homes in the Midwest lose up to 30 percent of their heating and cooling energy, but with the implementation of low-e windows that number could be cut in half (LAS Enterprises, 2016). Additionally, low-e window schemes can help reduce energy bills by up to 50 percent (LAS Enterprises, 2016). While the use-of low-e windows has the potential to save a considerable amount of money and reduce energy use, finding the most efficient and sustainable option can be a challenge.

The National Fenestration Rating Council (NFRC) is a third-party organization that compares and provides ratings for the energy performance of window, door and skylight products (National Fenestration Rating Council, 2017). Windows are rated in several categories; U-factor, solar heat gain coefficient (SHGC), visible transmittance, and air leakage (National

Fenestration Rating Council, 2017). U-factor is a measure of the ability of a window to keep heat in, and SHGC measures the ability of a window to keep heat out. Visible transmittance refers to the amount of visible light that can pass through a window. Finally, air leakage is a measure, in cubic feet, of air that passes through a square foot of window. In Wisconsin, the climate is classified as "cold" by the Efficient Windows Collaborative due to the significant period of the year when heating is necessary. For this type of climate, window schemes that provide more insulation such as low-e coatings, gas fills, and insulating frames are better because they prevent heat loss (Efficinet Windows Collaborative 1, 2017). Energy Star ratings for windows in the Wisconsin region with superior energy performance are shown in Table 1.

Table 1: Superior energy performance window ratings for a cold climate (Efficinet Windows Collaborative 1, 2017).

Parameter	Rating
U-factor	0 – 0.25
SHGC	0.35 – 0.60
Air Leakage	0 – 0.30
Visible Transmittance	0.40 – 0.60

There are many different factors that affect the efficiency of different windows economically, environmentally, and socially. Analysis of different window schemes should, therefore, be a three pronged attack.

3. Goal

The goal of this project is to provide information and ideas about beneficial and sustainable window technologies to the Dane County Board of Supervisors for use in affordable housing. Focus will be on options that are feasible to implement now rather than undeveloped or untested innovations.

4. Methods

In 2012, Dane County established guiding sustainability principles with the goal of becoming more environmentally, socially, and economically sustainable in its operation, management, and decision making (Dane County Sustainability Work Group, 2016). The Environmental Sustainable Engineering class at UW Madison was selected as a partner for the Dane County Board of Supervisors project due to the focus on sustainability, and the expectation is to provide a comprehensive evaluation of options from a sustainability point of view.

The methodology used to assess and compare each of the window options follows the three paradigm of sustainability: economic impact, environmental impact, and social impact. For the economic assessment, net present value (NPV) and payback period calculations were made in combination from information collected using the online *Window Selection Too* (Efficient Windows Collaborative 2, 2017) l. The environmental assessment utilized information from existing life cycle assessment (LCA) studies and an Economic Input-Output LCA (EIO-LCA) was conducted using the tool developed by Carnegie Mellon (Green Design Institute - Carnegie Mellon University, 2017). Both the EIO-LCA and economic assessments used Sunny Hill Apartments located in Sun Prairie, WI, a Dane County Affordable Housing site, as a basis for assumptions. Finally, the social impacts were compared qualitatively based on literature.

5. Literature Review

5.1 Economic Literature Review

There are many low-e window options on the market that are available to both consumers and developers, and they come in a wide range of materials and finishes. Glazing choices affect how much light can be transmitted, how much of the sun's heat is allowed into interior spaces, and how well the flow of heat is prevented. Coating options and the addition of inert gas fills affect heat transfer as well. All of these additional options, however, add to the window's cost, and some may not be economically justified by their energy savings.

In much of the United States, low-e windows are now standard for new homes. This coating, an almost invisible layer of metal applied to one side of the glass, is used to lower the U-factor of the glazing; that is, it slows heat transfer. In a cold climate like Madison, an SHGC of 0.42 to 0.55 is ideal, as well as a U-factor of 0.30 to 0.39 according to (Holladay, 2017).

To determine which windows to analyze in this study, relevant literature was reviewed that compared several window types. In a study conducted by Menzies & Wherrett (2005), it was found that while multiple-glazed, argon-filled windows recouped their incremental capital cost, krypton-filled windows did not have a reasonable payback period.   This led to the decision not to evaluate krypton- or xenon-filled windows (whose capital cost is even higher) in this study because they are not economically justified even in cold climates where higher performance filling provides higher energy savings. It was also discovered that high SHGC coatings are only justified in hot climates, where it is almost always ideal to keep heat out of the home. Low solar gain coefficient coatings are ideal for cold climates, because they help to retain heat in the home while allowing some heat from the sun to warm the interior during the winter (Holladay, 2017). The conclusion from several studies is that higher specification windows aren't always justified economically, but in a climate like Dane County, argon filled, low-e coatings (preferably with a low solar gain coefficient), and multiple glazed window systems could provide a positive return on investment.

5.2 Environmental Literature Review

One way to assess the environmental impact of a window is through life cycle assessment (LCA). LCA is a holistic approach to evaluating the environmental impacts associated with a product, process or service by analyzing the material and energy flows over its entire life cycle (ISO, 2006). There are many different factors that could contribute to the environmental impacts of a window, but the most commonly analyzed aspects using LCA have been window frame material and inert gas fill.

Salazar & Sowlati (2008) completed a literature review of window LCAs which included studies looking at window material, gas fill, number of panes (the glazing of a window), and low-e coating. All of the studies in the review that looked at window frame materials found wood frames to have a lower embodied energy than the alternative PVC and aluminum options (Citherlet et. al, 2000; Asif, Davidson, & Muneer, 2002; Menzies & Muneer, 2003; Recio et al, 2005). However, a study considering more contemporary frame systems found that PVC, aluminum clad wood, and fiberglass frames are all comparable when it comes to cradle-to-grave emissions (Salazar & Sowlati 2, 2008). Overall the use-phase energy in a window frame life cycle had little effect on the overall environmental impact (Salazar & Sowlati 1, 2008).

In considering different gases for an inert gas fill between window panes, Weir & Muneer (1998) looked at the difference between using argon, krypton, and xenon. They found that argon had the lowest kg of CO_2 at 94.7 for the evaluated scenario followed by krypton with 207.6 kg of CO_2 and then xenon with 1,094.7 kg of CO_2 (Weir & Muneer, 1998). One reviewed LCA looked at several different options for materials and designs of windows including: the number and type of panes, the gas between panes, spacers between panes, and frame material (Citherlet et. al, 2000). The overall conclusion from that study was that although advanced windows have higher environmental impacts during their production, the energy savings during the use phase due to insulation properties significantly offsets the impact from production.

5.3 Social Literature Review

In addition to economic and environmental impacts, windows also have social impacts. Generally, the more panes in a window the less noise can travel through and the sturdier the window will be, which can overall make the inside space quieter and safer (Diez, 2017). Multiple paned windows with certain low-e coatings also decrease the temperature change inside the space creating a higher level of comfort and decreasing energy use (McNutt English, 2017). However, cost increases noticeably with the increase in number of panes. This can put strain on developers and tenants as initial capital costs will be higher, and monthly rent prices could possibly increase. Window size also plays a role in social impacts. An increase in window size can allow extra light to travel into a space, reducing the need for artificial lighting, but often comes at the cost of less privacy (Ruya, 2017). A final social concern is that some low-e windows have reportedly melted the vinyl sidings of adjacent buildings under the right conditions. The combination of a barometric pressure drop (which causes bowing), intense sunlight, and close proximity to other buildings can create a magnifying effect that could potentially melt certain materials (National Association of Realtors, 2017). This, however, is less of an issue for this project given the climate found in the Dane County area; however, it is still something to consider.

6. Economic Analysis

6.1 Economic Assessment

A large concern of the Dane County Board of Supervisors is the overall cost associated with different window options. Both net present value and payback period were utilized to evaluate the economic costs of multiple-glazed windows and the use of low-e coatings. Net present value allowed for a cost comparison between window options in present-day dollars, and payback period analysis was utilized to determine the amount of time before the initial incremental capital cost of the window investment is paid off. These methods highlighted which option or options are reasonable investments for the county to pursue.

Data for window energy costs and savings was gathered for the economic analysis using the *Window Selection Tool: Existing Construction Windows* (Efficient Windows Collaborative 2, 2017). It is "a step-by-step decision-making tool to help determine the most energy efficient window" (Efficient Windows Collaborative 3, 2017). When using this tool, several assumptions and generalizations were made to obtain energy costs and savings data. The location for climate data selected was Madison, WI, assuming the climate conditions would be the same for all of Dane County. Window orientation was assumed to be equal. This takes an average of performance data from all window orientations: north, south, east, and west. Low-e coated windows will have the best performance when facing southward (Efficient Windows Collaborative 3, 2017), but it is not likely that all the windows in the development will face south, so the equal orientation was selected to best represent the entire complex. The next assumption that was made was that the window to floor area ratio was 10%. Heating in a cold climate, such as Dane Co., incurs the largest annual energy cost, and reducing window size is a traditional way to reduce the amount of heat loss (Efficient Windows Collaborative 3, 2017).

Using the Affordable Housing Online website, Sunny Hill Apartments located in Sun Prairie, WI was selected as a model for this calculation. Sunny Hill Apartments is a 56-unit apartment complex consisting of one, two, and three bedroom options (CoStar Group, Inc., 2017). There are eight one-bedroom apartments with an average 571 sq. ft., 40 two-bedroom apartments with an average 864 sq. ft., and eight three-bedroom apartments with an average 1053 sq. ft. (CoStar Group, Inc., 2017). There are four windows in each apartment, and an average of 849 sq. ft. per apartment. Assuming the windows in all of the apartments are the same size, each window would be approximately 21 sq. ft., a reasonable size. The final assumption for the economic data was a typical shading scheme since the actual amount of shading for each apartment may differ based on landscaping and tenants' preferences. All of the assumptions are summarized in Table 2.

Table 2: Description of Window Assessment Tool assumptions made.

Location	Room Orientation	Window-to-Floor Ratio	Shading	Stories	Windows per Apartment	Average ft^2 per Apartment	Area per Window
Madison, WI	Equal	Small (10%)	Typical	1 story	4	849.14	21

Using these assumptions, the *Window Selection Tool* was able to generate a table of different window schemes with annual energy costs, links to different manufacturers, and lists for each of the windows that fit the selected scheme. From this, eight different window schemes (two high solar gain (HSG), two medium solar gain (MSG), two low solar gain (LSG), and two clear) were selected for analysis. The selected window schemes and the manufacturer information are summarized in Table 3.

Table 3: Summary of selected window schemes data collected using the Window Selection Tool.

Panes	Glass	Frame	Annual Energy Cost	Manufacturers	Window type	Capital Cost (Whole Apartment)
3	HSG	Non-metal	$888	Wasco Windows (In Wisconsin)	GENO Frame Triple Pane LoE 180	$169,066.24
2	HSG	Non-metal	$914	Wasco Windows (In Wisconsin)	4500 Frame LoE 180	$128,819.72
3	MSG	Non-metal	$908	Alside by Associated Materials, Inc.	Sheffield Model 0501 Double Hung	$148,310.40
2	MSG	Non-metal	$916	Alside by Associate Materials, Inc.	Performance Series Gold V101 New Construction Double Hung	$88,683.84
3	LSG	Non-meal	$920	NT Window	W140 - Presidential Vinyl Window Slider	$59,797.99
2	LSG	Non-metal	$931	NT Window	E140 - Executive Series Vinyl Slider	$47,315.12
3	Clear	Non-metal	$1,030	-	-	$106,400
2	Clear	Non-metal	$1,089	-	-	$61,600

Though manufacturers were listed for each window type, not all of the window cases were commercially available. Specific manufacturers could not be found that sold non-low-e coated windows as low-e coated windows have become standard in the United States. The capital costs are based on estimates of windows with similar specifications not from new construction. One other point to note is that the window types (e.g. single-hung, double-hung, slider, etc.) are different between the low-e coating levels (LSG, MSG, and HSG). To provide a more accurate capital cost comparison, ideally the window would have the same specifications across the board in terms of frame, size, and style, thereby isolating the variables we are analyzing.

The associated costs (capital and energy) of each window, as well as payback period and net present value, are shown in Table 4. Conservative estimates were used in the analyses for inflation rate and window life. An inflation rate of 2.5% and a time study period of 25 years were used as discount rate and window life span respectively (InerNACHI, 2017).

Table 4: Window system comparisons of energy cost savings per year, payback period, and net present value of savings.

Which to Compare (No low-e, double glazed is baseline)	**Energy Savings** (per year)	**Payback Period**	**NPV of Savings (25 yr. period)**
Baseline v. LSG double-glazed (double)	$158	2.1	$2,830
Baseline v. LSG triple-glazed (triple)	$169	3.2	$2,977
Baseline v. MSG double	$173	6.1	$2,922
Baseline v. MSG triple	$181	11.8	$2,803
Baseline v. HSG double	$175	10.2	$2,779
Baseline v. HSG triple	$201	12.4	$3,079
LSG double v. LSG triple	$11	26.1	$131
LSG double v. MSG double	$15	53.5	$76
LSG double v. MSG triple	$23	81.2	($43)
LSG double v. HSG double	$17	89.4	($67)
LSG double v. HSG triple	$43	52.1	$233
LSG triple v. MSG double	$4	129.0	($55)
LSG triple v. MSG triple	$12	131.7	($174)
LSG triple v. HSG double	$6	205.4	($198)

LSG triple v. HSG triple	$32	61.0	$102
MSG double v. MSG triple	$8	133.1	($119)
MSG double v. HSG double	$2	358.4	($142)
MSG double v. HSG triple	$28	51.3	$157
MSG triple v. HSG double	-$6	58.0	($24)
MSG triple v. HSG triple	$20	18.5	$276
HSG double v. HSG triple	$26	27.6	$299

6.2 Economic Results

From the data gathered in the assessment, potentially justifiable options determined by our review of current literature were compared. Figure 1 shows the payback period for the alternative window systems compared to the baseline window. The LSG coated, double-glazed window had the shortest payback period; however, all of the higher specification windows had payback periods below the 25-year window life time estimate.

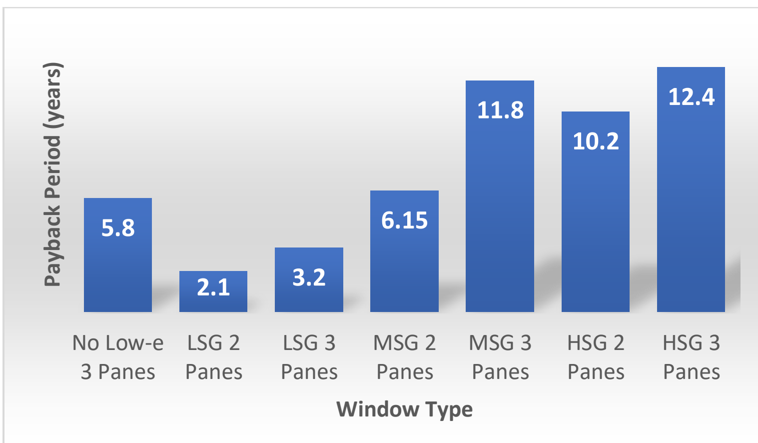

Figure 1: Payback period compared to baseline option (No low-e with two panes).

Figure 2 presents the net present value of savings associated with the higher specification windows compared to a non-low-e coated, double-paned window. When compared to this baseline, most of the window options have similar NPVs over the time study. With the exception of the non-low-e coated option, which is difficult to find commercially anyway, the variation between the savings in all other window schemes is around $200 in total for the 25 years.

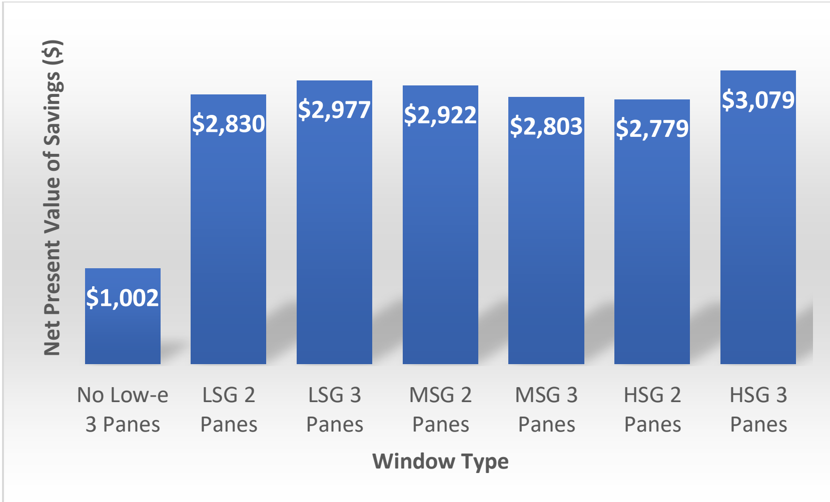

Figure 2: NPV of savings compared to baseline (No low-e with 2 panes).

With such little variation in NPV, along with feasible payback periods from every option, it was decided further analysis was needed. To determine the most feasible option, higher specification windows were then compared incrementally. The option with the shortest payback period, LSG-coated with 2 panes, was chosen to be the new baseline, and the other more costly window options were then compared. Figure 3 displays the results of analyzing these incremental comparisons.

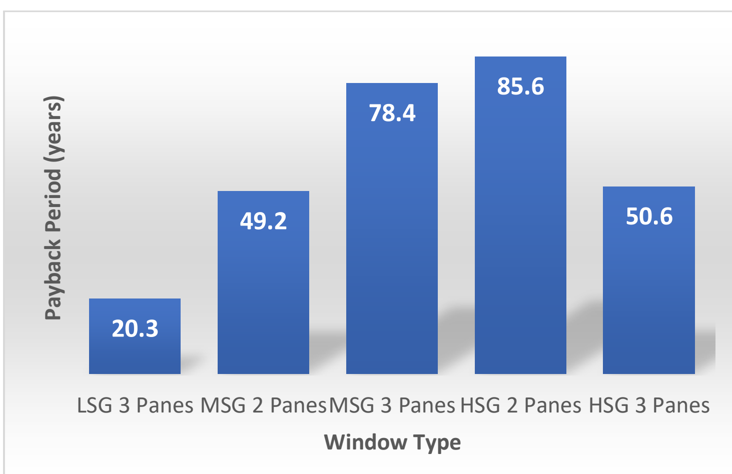

Figure 3: Payback period compared to LSG 2 panes (new baseline).

As can be seen from the figure, only the low solar gain-coated, triple-glazed window had a payback period under 25 years when compared to the new baseline. This indicates that it is the only additional window option that would be feasible economically given the development already had LSG, double-paned windows. It also economically justifies that the LSG, triple-glazed window is a better investment than the doubled-paned window with the same coating.

7. Environmental Analysis

7.1 Environmental Assessment

To evaluate the environmental sustainability aspects, the review of LCA literature as well as an EIO-LCA will be utilized. While EIO-LCA is similar to LCA, it looks at the materials and resources, energy, and environmental emissions associated with different activities in the economy (Green Design Institute - Carnegie Mellon University, 2017). In using both LCA and EIO-LCA a more comprehensive understanding of the environmental impacts associated with each window technology can be developed.

This EIO-LCA will look at the impacts of different low-e window schemes for the Sunny Hill Apartment complex. The boundaries will include window glass, frame, low-e coatings, and inert gas fill. The functional unit is all 224 windows in the model apartment complex. In order to assess a full range of environmental impacts the TRACI impact assessment method will be used.

In order to conduct the EIO-LCA additional economic data on the price of the individual components needed to be collected. Working with a sales person at Hometown Glass and Improvement in Beaver Dam, WI, estimates for the prices of window glass per square foot, glazing per square foot, and wood frame material per foot were calculated. Also, it was estimated to cost an additional $40 for argon gas fill (McNutt English, 2017). These estimates were then used to calculate the cost of each window scheme for the Sunny Hill Apartments model. The economic assumptions for each evaluated window scheme are shown in Tables 5.

Table 5: The breakdown of assumed costs of each different window scheme evaluated.

Low-e Coating	# of Panes (Glazing)	Frame Cost	Glass Cost	Coating Cost	Gas Cost
HSG	3 (triple)	$708.88	$413.91	$62.37	$80
HSG	2 (double)	$708.88	$275.94	$62.37	$40
MSG	3 (triple)	$708.88	$413.91	$41.58	$80

MSG	2 (double)	$708.88	$275.94	$41.58	$40
LSG	3 (triple)	$708.88	$413.91	$20.79	$80
LSG	2 (double)	$708.88	$275.94	$20.79	$40

In order to use the EIO-LCA tool, the costs were translated to 2002 US dollars using an assumed inflation rate of 27.1% (CoinNews Media Group LLC, 2017). These prices were then multiplied by 224 to give the impact of providing windows for the entire model apartment complex. The final values used in the EIO-LCA tool are given in Table 6, and Table 7 gives the EIO-LCA sector that was selected to model each aspect of the windows.

Table 6: The breakdown of assumed cost for the six different window schemes evaluated using EIO-LCA

Low-e Coating	# of Panes	Frame Cost	Glass Cost	Coating Cost	Gas Cost
HSG	3	$115,810.24	$45,080	$3,395.84	$13,070.40
HSG	2	$115,810.24	$67,621.12	$3,395.84	$6,534.08
MSG	3	$115,810.24	$45,080	$6,793.92	$13,070.40
MSG	2	$115,810.24	$67,621.12	$6,793.92	$6,534.08
LSG	3	$115,810.24	$45,080	$10,189.76	$13,070.40
LSG	2	$115,810.24	$67,621.12	$10,189.76	$6,534.08

Table 7: EIO-LCA Window part categories used.

Window Part	EIO-LCA Model	EIO-LCA Sector
Wood Window Frame	Wood Windows and Doors and Millwork	US 2002 (428 sectors) Producer
Glass Pane	Flat Glass Manufacturing	US 2002 (428 sectors) Producer
Low-e Coating	Paint and Coating Manufacturing	US 2002 (428 sectors) Producer

Gas Fill	Industrial Gas Manufacturing	US 2002 (428 sectors) Producer

7.2 Environmental Results

The TRACI EIO-LCA method gives results in thirteen different environmental impact categories. Included are two of each eco-toxicity, human health cancer, and human health non-cancer categories; one high estimate and one low estimate category. The numerical results for each category are shown in Table 8.

Table 8: Compiled window cost data for entire Sunny Hills apartment complex using in the EIO-LCA.

	Global Warming (kg CO2e)	Acidification Air (kg SO2e)	HH Criteria Air (kg PM10e)	Eutro-phication Air (kg Ne)	Eutro-phication Water (kg Ne)	Ozone Depletion (kg CFC-11e)	Smog Air (kg O3e)
HSG Double	209000	1501	548.1	59.43	0.07455	0.11651	31251
HSG Triple	291500	1973.9	676.3	77.98	0.0937	0.1521	41487
MSG Double	205330	1484	541.1	58.969	0.07054	0.10971	31012
MSG Triple	287830	1956.9	669.3	77.519	0.08969	0.1453	41248
LSG Double	201610	1467.1	534.15	58.509	0.06649	0.1029	30773
LSG Triple	284110	1940	662.35	77.059	0.08564	0.13849	41009

	Ecotoxicity low (kg 2,4D)	HH Cancer low (kg benzene eq)	HH Non-Cancer low (kg toluene eq)	Ecotoxicity high (kg 2,4D)	HH Cancer high (kg benzene eq)	HH Non-Cancer high (kg toluene eq)
HSG Double	7.693	36.4	18270	8.214	158.36	163240
HSG Triple	9.192	49.86	24900	9.816	187.9	195000
MSG Double	7.408	35.67	17784	7.917	153.16	156140
MSG Triple	8.907	49.13	24414	9.519	182.7	187900

LSG Double	7.124	34.947	17297	7.619	147.97	149160
LSG Triple	8.623	48.407	23927	9.221	177.51	180920

As shown in Figure 4, the window scheme with the largest impact in all categories is the triple pane high solar gain glazed window, and the scheme with the lowest impact in all categories is the double pane low solar gain glazed window. All of the categories show the same trend: triple pane windows have a greater impact than double, and the impact for the different glazes from highest to lowest impact goes HSG, MSG, and LSG. These results are different than what has been found previously with LCA window studies. However, this is likely due to the fact that the EIO-LCA doesn't take into account the energy offsets from window efficiency, which is where the LCA studies saw the greatest benefits.

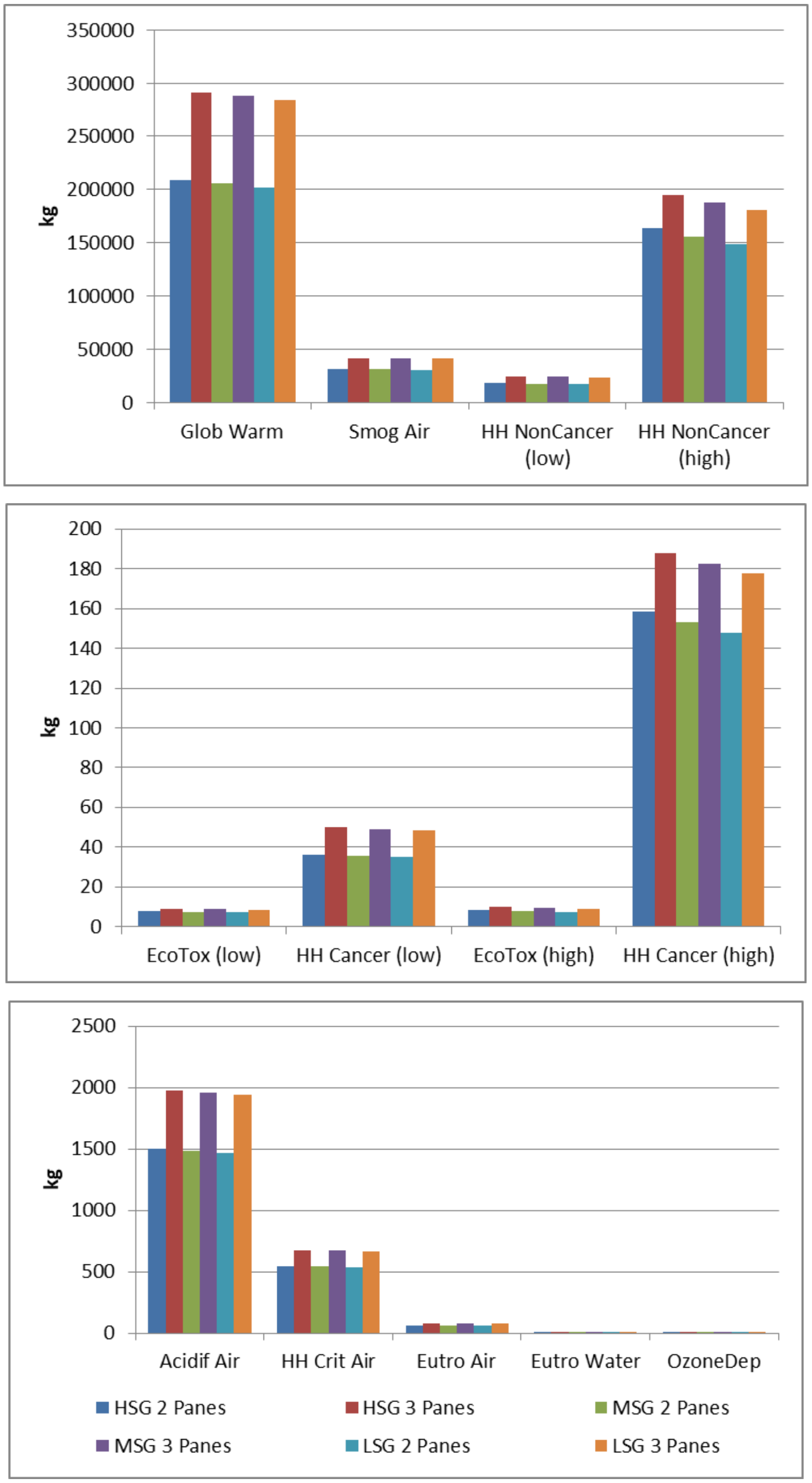

Figure 4 Comparison of all window schemes for all 13 TRACI impact categories.

The EIO-LCA show which areas of window production are of the greatest concern. Four categories: global warming, smog air, human health non-cancer low estimate (HHNCLE), and human health non-cancer high estimate (HHNCHE), have significantly higher impacts than the other nine categories. Flat glass production has the largest impact in the global warming, HHNCLE, and smog air categories, but wood frame production is the main contributor in the HHNCHE category. This shows an environmental advantage to using less panes of glass or possibly a different frame material. However, wood frames and more panes of glass would result in better insulation, so the LCA study results would argue that they will end up having greater offsets during their use phase.

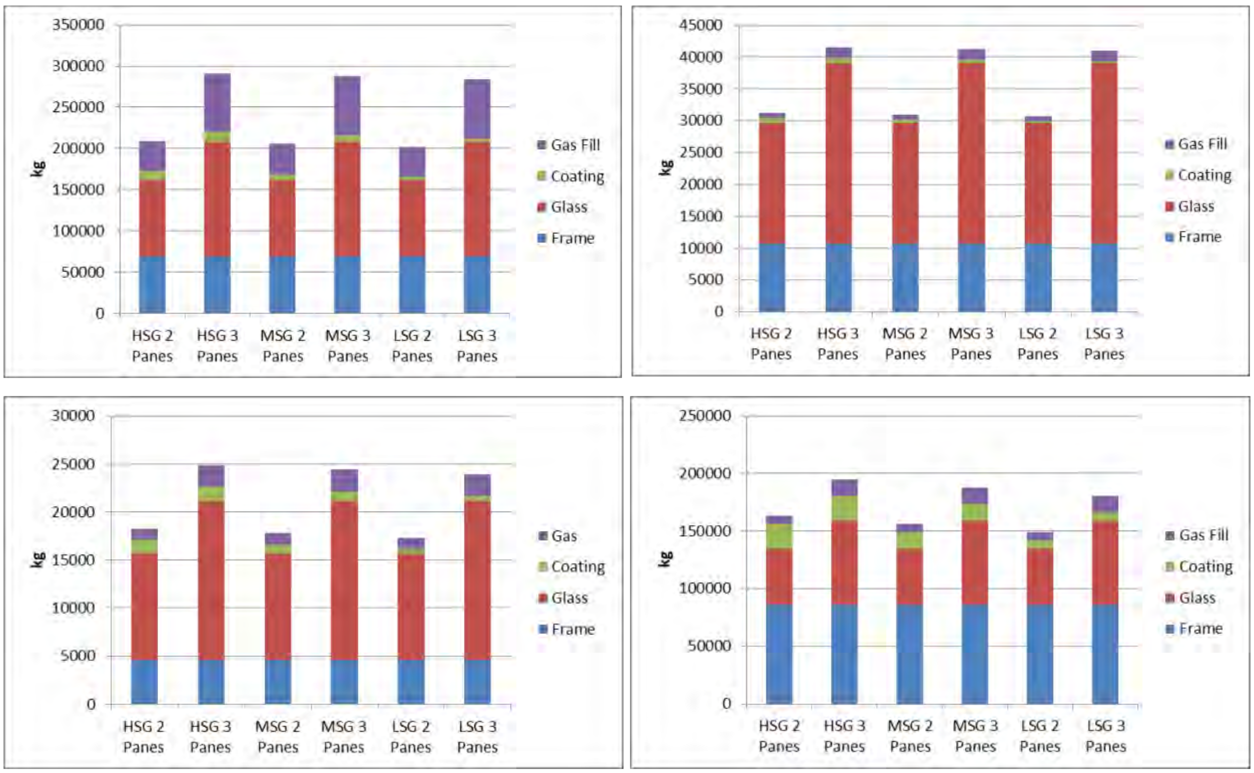

Figure 5: Breakdown of impact by window part for a) global warming, b) smog air, c) human health non-cancer low estimate, and d) human health non-cancer high estimate.

8. Social Analysis

8.1 Social Assessment

The social impacts from the implementation of low-e windows were determined using multiple pieces of current literature. It has been found that by choosing to incorporate a single energy saving measure in a space, such as low-e windows, often primes the individual to consider other energy efficient measures which can create a positive multiplier effect (Bates et. al, 2012). Multiple window panes containing a vacuum or gas filler tend to be stronger and also minimize the amount of noise that travels into a space, making homes safer and quieter (Diez, 2017). Strategically placing windows for maximum natural light exposure, a concept known as daylighting, can offer a major light source that can cut down the use of artificial lighting. The extra exposure to sunlight can also generate vitamin D, stimulate the human visual system, and overall enhance positive mood (Ruya, 2017). Finally, the use of low-e windows reduces carbon emissions through the amount of energy saved from heating and cooling (Bates et. al, 2012).

Low-e windows are not a perfect solution, however. First and foremost, they are more expensive that traditional windows, which can be problematic for upfront costs. Generally, low-e windows cost about twice as much as a traditional window (Home Advisor Inc., 2017). The windows also have the option to be vacuum-sealed or argon filled (McNutt English, 2017). The type of framing material can also have effects on the insulation properties and total cost of the windows. While wood frames offer the greatest insulative value, they are more expensive. If they aren't maintained properly in certain climates, like humid or rainy climates, they can mold and rot, which adds on replacement costs and adverse health effects. While aluminum frames don't insulate as well, they cost about 50 percent less to install per window (ImproveNet Inc., 2017; Perritt, 2017; McNutt English, 2017). Another factor to consider is personal design preference. This can sometimes corner homeowners and developers into having to choose one design over another. Another problematic area is the installation of the windows. In order to offset the upfront cost of more expensive low-e windows, developers and homebuyers frequently try to find window installers that offer their services for the cheapest amount. If the windows aren't installed properly though, all efforts to reduce energy usage will be negated. Therefore, it is important to find a contractor that will do the job correctly, even if it costs more (McNutt English, 2017). Finally, there have been cases where some low-e windows were so efficient at reflecting heat that they melted the vinyl siding of nearby buildings (usually involving high temperatures on south facing windows that were within 20 ft. of the next building), which adds another thing(National Association of Realtors, 2017).

7.2 Social Results

Considering the positives and negatives from all the social aspects described above, it was initially concluded that the most sustainable window option was the double-glazed MSG low-e window, with part of the decision being based on cost estimates. However, after a late quote became available, it was then determined that a triple-glazed LSG low-e window was more beneficial. The third pane not only allows less of a temperature change through the window, which can create a more energy efficient and comfortable living space, but also can increases the integrity and barrier thickness of the window, which provides an increase in safety and a decrease in noise pollution. The low solar gain (LSG) low-e coating is favorable for the type of climate found in Dane County, as it reduces the amount of solar heat that travels through the window by just enough, allowing an interior space to heat up slightly from the sun in winter months, but stay much cooler in summer months.

Overall, these qualities reduce the amount of energy needed for heating and air conditioning, which helps reduce CO2 emissions as well as energy bills. The increase in the number of window panes with the slight decrease in solar gain (as compared to the initial decision) provides an enhanced interior environment at a comparable price, making the triple-glazed LSG window the most sustainable option.

9. Discussion

In order to reduce life-cycle energy costs as much as possible while maintaining a reasonable capital cost and economic payback, glazed units using argon gas appear to be the optimal solution for the climate, economic cost, and social impact. This finding is reinforced by work by Clarke et. al, (1998).

While krypton-filled units offer higher thermal efficiency, the economic payback period is significantly longer and the environmental impact is over doubled compared to argon (94.7 kg CO2 to 207.6 kg CO2). The use of multi-glazed, argon-filled windows will also reduce carbon dioxide emissions by up to 20% compared to double-glazed air-filled windows (Menzies & Wherrett, 2005).

The economic results obtained in this study were based off of estimated values or a single manufacturer's quote for each window type. Because of this, the findings might vary with different inputted capital costs. Despite this variation though, an investment in multi-glazed, argon-filled windows in new constructions, or in redeveloping from single-glazed windows, will usually provide a positive return on investment over its life. In cold climates, this also holds true, with the additional specification of using a low solar gain coefficient for the low-e coating. This coating reduces the capital cost of the window without raising energy costs significantly, as they would in a hotter climate.

In the economic analysis section, it was found that the HSG low-e coated, triple-glazed window had the highest NPV. By looking solely at net present value over the time study, it would lead to the conclusion that this option is the best investment. However, this doesn't take into account funding constraints. Triple glazed, HSG windows have a longer payback period than the triple glazed LSG windows, and, more importantly, they have almost three times the capital cost. As an affordable housing development with significant funding constraints, the additional $100 saved over 25 years doesn't justify such an increase in upfront cost.

Additionally, the increased insulation of the triple-glazed window options would lower environmental impacts and provide greater noise control, safety, and comfort for the tenants, increasing social benefits. However, the addition of more extensive low-e coating (LSG to HSG) only serves to decrease environmental impact in cold climates where energy savings don't increase much with the higher solar gain coating. A more extensive low-e coating (LSG to HSG) would also help decrease the environmental impact through increased energy savings, but it is unclear exactly how much significance the decrease would be. Also, the energy savings economically are only marginal, and there would likely not be a very large difference in social impacts from a lower coating.

Overall, the results obtained from the EIO-LCA should be considered with some amount of skepticism due to some of the assumptions that were made. The cost estimates for each window scheme are not necessarily accurate, and could change for different window sizes, types, and manufacturers. Also, the EIO-LCA selector categories used are very broad and may not best represent the environmental impact of each window part. The discrepancy between the EIO-LCA results and the LCA results is due to the fact that EIO-LCA does not take into account offsets during the use phase of windows, which has shown to be a major factor in the environmental impact.

There are many different ways to account for the social aspects of a window, but ultimately the importance of each individual trait will vary from homeowner to homeowner. For some, the admittance of noise may be less significant than the aesthetics of the window, and for others vice versa. When selecting windows, homeowners should consider the pros and cons of each option and choose accordingly to the one that best fits their needs.

10. Conclusion

From research and analysis, it was determined that the LSG low-e coated, triple-glazed window with a non-metal frame and argon gas fill is the best option considering capital costs, net savings, and environmental and social benefits. The triple-glazed LSG window scheme has a low payback period of 3.2 years compared with the baseline window scenario (double-glazed with no low-e coating), and also has the second highest net present value of savings. Environmentally, it would have medium range environmental impact overall when considering all of the evaluated window schemes. The energy savings with three panes and a low-e coating would provide a decrease in environmental impacts compared to one or two panes and no coating; however, the environmental benefits would not be as high as with a triple glazed HSG low-e coated window. Additionally, the triple-glazed LSG window would have social benefits of increased noise control, safety, and comfort as compared to windows with fewer panes and no low-e coating.

It is recommended that the Dane County Board of Supervisors and their partners use the online Window Selection Tool used in the analysis here to additionally explore potential window options, and to help in identifying window manufactures for specific window schemes. Socially, the most important piece will be for the county to consider the ability to finance the capital costs, and how certain building decisions will impact the affordability of the housings units. Generally, the more window insulation, or higher specifications the county can afford initially, the greater benefits they will see overall.

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Introducing Wind Power to Workforce Housing

The world is currently facing an energy crisis, and the leaders of the world are actively trying to figure out how to reduce CO_2 emissions. While this is a global issue, it is also very much a local issue. Greg Mankiw, a conservative economist from the University of Harvard, believes that there is an external cost of carbon dioxide emissions. He is pushing for a forty dollar per ton carbon tax that will escalate significantly in the following years (Mankiw, 2017). The health-related impacts are an estimates to the damages of poor air quality and how much the government has to spend to aid these conditions. The question then has to be asked, how much energy does a typical American consume?

The U.S. Energy Information Administration estimates the average American used nearly 11,000-kilowatt hours (kWh) total in 2015 (EIA, How Much Electricity Does an American Home Use?, 2016). Madison Gas and Electric estimates that a typical family uses 8,300 kWh annually. Apply this data to a sixty-unit apartment housing approximately 2.5 residents per unit. The electricity annually consumed by the apartment building would be approximately 700,000 kWh annually. In a report by Katherine Tweed, the estimate used for a building with five plus units, the complex uses 40 million-BTU per unit annually. For the apartment in this analysis then, that would be 2400 million-BTU. Converting this to kWh one would get a value of approximately 700,000 kWh annually (Tweed, 2013). Additionally, one must also factor in transmission losses and the efficiency of the energy source to get the total electricity used. This electricity is typically produced through methods that result in significant amounts of carbon dioxide emissions. The world needs to find innovative ways to generate carbon emission-free energy. One of these solutions is wind energy.

The Dane County Housing Gap

Dane County is currently in a period of rapid growth. According to the U.S. Census Bureau, Dane County is growing at a rate that is five times faster than the overall state of Wisconsin (QuickFacts: Population, 2016). As more individuals have moved to the area, the housing demand and pricing has increased. Unfortunately, wages have not. The wage issue has created an inconsistency in the number of housing units available at an affordable price and the number of units that are needed to meet the demand (Project Team, 2017). This inconsistency is known as the housing gap. When the housing gap is large, people are forced to live in overcrowded, substandard homes. In more extreme cases they are even left homeless.

The Dane County government has worked hard over the last several years to minimize the housing gap. Currently, over 20,000 low -income households qualify. The government has invested 8 million dollars throughout the last four years in the Affordable Housing Fund (Project Team, 2017). The eight million dollar budget is used to create and upgrade buildings that can provide comfortable housing units for low-income residents. This market is called workforce, or affordable, housing. The Dane County Board is working to find solutions to increase the availability of workforce housing. While juggling social issues like population needs and demographic projections, the team also works to incorporate sustainable development and performance in these housing units.

Sustainability in Workforce Housing

The U.S. Environmental Protection Agency defines sustainability as, "The ability to maintain or improve standards of living without damaging or depleting natural resources" (U.S. Environmental Protection Agency, 2017). Dane County follows four different principles to incorporate sustainability into government decisions (Dane County's Guiding Sustainability Principles, 2012). These principles are:

1. Reduce and eventually eliminate Dane County government's contribution to fossil fuel dependence and to wasteful use of scarce metals and minerals.
2. Reduce and eventually eliminate Dane County government's contribution to dependence upon persistent chemicals and wasteful use of synthetic substances.
3. Reduce and eventually eliminate Dane County government's contribution to encroachment upon nature and harm to life-sustaining ecosystems.
4. Reduce and eventually eliminate Dane County government's contribution to conditions that undermine people's ability to meet their basic human needs.

Each of these principles can be incorporated into the development of workforce housing; from the materials used in construction, to the heating and cooling systems. There is a significant opportunity to reduce the environmental impact of housing while simultaneously reducing the housing gap. The Dane County Sustainability Principle that will be focused on most in this report is reducing dependence on fossil fuels. One step that can be taken to satisfy this principle is moving the dependence to wind energy.

Existing Wind Energy Research

Dane County has many large bodies of water, and this allows for the wind speeds to pick up. With less obstructions the wind speed will increase, despite this Dane County only has a 21.25 kilowatt capacity with regards to wind energy with not a single commercial wind turbine (Wisconsin, 2016). Madison's wind resource at 80 meters is 6.5 m/s (National Renewable Energy Laboratory, 2017). Large Scale wind turbines have been deployed in the United States and currently account for around 6 % of total U.S. energy generation (EIA, Electricity in the United States - Energy Explained, Your Guide to Understanding Energy, 2017). The United States currently has one offshore commercial wind farm. The areas with the greatest wind capacity in the United States are on the Northeast and Northwest coasts as well as "Tornado Alley". Areas with the worst wind resource tend to be in the southeast region. The wind turbine generates its energy by taking the mechanical energy of turning the blades and turning it into electrical. A well placed wind turbine can have a capacity factor between 30 and 45 percent. This means that if the nameplate capacity of the farm was 100 Megawatts, it could generate 30 to 45-megawatt hours (MWh).

There are two types of wind turbines; the first and more common is the Horizontal Axis Wind Turbine (HAWT). These tend to be the ones that are used in big wind farms because they have a much higher efficiency and are easier to scale. The second type of wind turbine is the Vertical Axis Wind Turbine (VAWT). This type tends to be smaller and less efficient; however, this system requires far less maintenance because it does not have a pitch and yaw system. This is the apparatus that controls for wind direction in the horizontal axis. Therefore, the VAWT generates its energy independent of the direction that the wind is blowing.

FIGURE 1: HORIZONTAL AXIS WIND TURBINE (LEFT). VERTICAL AXIS WIND TURBINE (RIGHT).

Project Scope

This report will look to prove if it is feasible to incorporate wind-powered energy in workforce housing design in Dane County. To do this, a comparison of electricity generated from a small-scale vertical axis wind turbine and a horizontal axis wind turbine to electricity purchased from Madison Gas and Electric will be conducted. These generation methods will be applied to a typical workforce housing building: a 60-unit apartment building located in Middleton, Wisconsin. Middleton is on the public bus route and is in biking distance from downtown Madison. The Dane County Board of Supervisors specifies that access to public transportation is important in choosing locations for workforce housing.

Wind speeds collected from the Dane County Regional Airport will be used for analysis. This will provide a good average for the area from an unbiased and trusted source. This data will be applied to both turbine options.

Energy Source Options

Madison Gas and Electric

The first and simplest way to gain electricity is for sure buying it from Madison Gas and Electric grid. Of course, the total cost is highly dependent on time and quantity of use as well as the number of people who live in the house. However, the standard charges are public and they are synthesized in the table below:

TABLE 1: MADISON GAS AND ELECTRIC'S STANDARD CHARGES (MADISON GAS AND ELECTRIC, 2017).

Service	Summer ($/kWh)	Winter ($/kWh)
Grid connection and customer service charge	0.62466	0.62466
Distribution service	0.03356	0.03356
Electricity service	0.10807	0.09669

Vertical Axis Wind Turbines (VAWT)

A VAWT is a type of wind turbine where the main rotor shaft is set transverse to the wind while the main components are located at the base of the turbine. They are designed to be economical and practical as well as quiet and efficient. Typically, a VAWT has two or three blades with a vertically operating main rotor shaft. The more blades per the unit, the more wind energy it will receive. Using a Vertical Axis Wind Turbine is becoming more popular as a source of renewable energy in people's homes. The main advantage is that it does not need to be pointed towards the wind to be effective. For this reason, it can be used on sites where the wind direction is highly variable. Buildings' rooftop is an excellent location for this kind of wind turbines. The electric power generation is close to the user and because they allow to take advantages of faster winds. This kind of installation exploits the acceleration of the airflow at the upper corners and the sides of the facade of the buildings. There are existing examples of the VAWTs, such as the Eagle Stadium in Philadelphia (Figure 2). These examples will be analyzed to determine if they are applicable for Dane County Affordable Housing.

FIGURE 2: VERTICAL AXIS TURBINES LOCATED ON PHILADELPHIA STADIUM (BONDSTK, 2013).

Horizontal Axis Wind Turbines (HAWT)

The second wind turbine that will be analyzed for implementation in workforce housing is a small scale turbine with a horizontal axis. This is similar to the typical, large wind turbine most first imagine when thinking about wind energy. However, it will be ideally installed on an apartment building roof, so it is much smaller. The concept is that many smaller versions of the traditional horizontal turbines could have the same impact as a large one. New York City has been working on a similar project over the past few years. They have been creating "green" housing throughout the city (Figure 3). This data, as well as other similar case studies, will be applied to the hypothetical Dane County Workforce Housing apartment building.

FIGURE 3: SMALL SCALE HORIZONTAL AXIS WIND TURBINES LOCATED ON ROOFTOP OF A BUILDING (MCDERMOTT, 2009).

Methods for Evaluation

There are three separate paradigms of sustainability: economical, environmental, and social. To determine the best-suited energy source for workforce housing, energy provided by the vertical axis turbine, horizontal axis turbine, and Madison Gas and Electric will be analyzed based on these three parameters.

Economical Paradigm

To compare the costs of the three options, a Net Present Value Analysis will be conducted. This will compare financial outflows and inflows of each option. A standard discount rate will be used in these computations. Initial costs and maintenance costs of each of the options will also be considered. This is especially important because Dane County has a strict budget. The housing authorities and partners that develop the housing also have tight budgets. Different sources will be explored in hopes of discovering applicable subsidies and grants that will decrease the price. Turbines will most likely be more expensive than buying from the grid, so any aid would help.

Environmental Paradigm

To compare the environmental impacts of a turbine it is first necessary to conduct a life cycle assessment for the turbine. In other words, one must look into all the inputs of the turbine and where they come from as well as what happens to the wind turbine at the end of its life. A wind turbine built for an affordable housing complex would have to be small. The smaller the size of the turbine, the larger the number of turbines will be needed to produce sufficient energy for the building. Wind turbines will also lose energy if the air flow has been impacted by other turbines, so it is necessary to position them in a way that they are not impacted. To gain this data, case studies from similar turbines will be assessed. This data will then be analyzed using a Life Cycle Assessment (LCA). It is also important to address the availability of the resources in the Madison area. These resources include wind and access to the grid.

Social Paradigm

Incorporating wind turbine in a housing environment can create both benefits and burdens. One important thing to consider the fact that different people have different values as well as different levels of sensitivity.

VISUAL IMPACTS

Aesthetics is often a primary reason for expressed concern about wind-energy projects. In general, it is impossible to predict how any one individual will react to a wind-energy project. It is, however, possible to evaluate the relationship of the proposed project to the scenic landscape features of the site and its surrounding context. A few buildings, especially in big cities such as New York or London, attempted to incorporate wind turbines but so far none have achieved it with any conviction (Rose, 2015). Aesthetic aspects are especially important in residential areas.

Wind turbines can create a constant humming noise. These can be considered to be an annoyance and also produce vibrations that can ruin the integrity of a roof over time. This has hindered the popularity of consumers wanting to have wind turbines mounted to their roof. Vibrations are difficult to prevent, but there are mounting system that can disperse the vibration before it reaches the structure of the house.

ECOLOGICAL IMPACTS

It is estimated that hundreds of thousands of birds and bats die every year when they accidentally collide with turbine blades (Hutchins, 2017). Furthermore, wind energy development can also contribute to habitat loss and the risks are, of course, much greater when wind turbines are placed in areas attracting large concentrations of birds and bats. However, there are many kinds of retrofits that people are testing to make wind turbines better for birds.

Economical Paradigm Analysis

An analysis done for a potential wind site in Arlington, Wisconsin, which is approximately 20 miles north of Madison, has very similar wind resource to the south and eastern portions of Dane County. The study, conducted by Totally into Wind, Inc. prepared for Professor Tinjum at the University of Wisconsin-Madison, states that at 25 meters the wind speed was 4.58 m/s on average (INC., 2011). Thus for an optimistic estimate, the average wind resource in the best areas of Dane County is roughly 5 m/s. Utilizing this measure and the assumption that the low-income structure is 25 meters high to determine which turbine to use. The analysis will consist of two horizontal axis wind turbine designs and one vertical axis wind turbine.

Horizontal Axis Wind Turbines

BERGEY'S EXCEL 10 TURBINE

A horizontal wind turbine manufacturer for residential systems called Bergey has a 10 kW turbine called the Excel 10. The cut in speed of this turbine is 2.5m/s, and this is important because if the cut in speed is higher than the wind resource, there will be no electricity generated. The company is in Oklahoma and is one of the few small wind producers within the United States. The company has a distributor in Platteville Wisconsin. This turbine, however, cannot be attached to a roof due to weight and stability reasons. Given the wind speed for the ideal Dane county areas, each turbine could generate 9,850 kWh annually. The kWh generation is assuming the wind direction is not overly variant. The average cost to set up one of their 10 kW turbines is $48000 to $65,000 for financial purposes, the value used is an average of the cost range, $56,500 per turbine. (Bergey)

Assuming the above turbine characteristics, and that the total energy usage for the housing complex is around 700,000 kWh annually, the housing unit would require eighteen wind turbines to match 25 percent of the complexes energy usage. The cost of this project is $1,017,000. These wind turbines should last for 20 years on average but have a degradation factor of about 1% per year. Bergey has a 10-year warranty on their turbines so that will be the duration of the Net Present Value Calculation. These turbines are also dependable and require minimal to no maintenance over the 20 years. Thus the degradation rate should be neglected in the net present value calculation. Over the last 20 years, electricity rates have grown at a 0.36% rate (Service, 2017). An average of summer and winter pricing is utilized to level the costs for the year (Table 1). The $0.14163/kWh estimate reflects the grid connection and customer service charge, the distribution and the electricity service, but this rate will increase over time at the same rate as it has from 1997 to 2017. For this governmental plan, a discount rate of 3% is used. The discount rate selected is a standard value for government assessments. To get the values for the net present value, the monthly savings and costs were compared. The annual energy usage is 58333.33 per month. The cost per kWh is $.14163 so the reduction of 25% of the monthly electric bill provides a monthly savings of $2065.44 per month (see Appendix, Equation 2).

For this calculation, the summation of 20 years was used. The project's Net Present Value is negative so it will not have a payback period. However, this number does not reflect the ability for incentives. Multifamily residential projects focus on energy provides 3.5 million dollars a year to renewable energy systems. The wind farms size is higher than 20 km, so it is not eligible for net metering, and it is subject to $300,000 in insurance coverage per occurrence (Energy). The land property would also have to be expanded several acres to accommodate the eighteen turbines. Since this project is a government project, it does not qualify for any federal tax credits offered. The amount of land required would not be ideal for low-income housing units placed in urban areas. A total of $547,909.64 is benefit of the project over 20 years accounting for an increasing trend in the price of $/kWh. The perpetuity calculation shows this investment would never pay for itself without an incentive from a third party. Therefore, it is not relevant to calculate the net present value for the twenty-year lifetime.

QINGDAO HENGFENG WIND POWER GENERATOR

Given the limit on land availability and the potential difficulty in obtaining incentives, another option may be to install smaller turbines on the roof. There are wind turbines that can be attached to the roofs of building from across the world. The manufacturers in the United States are limited. Through the use of Alibaba.com, were able to find a Qingdao Hengfeng Wind power generator. This turbine has a 1 kW capacity and has a cut in speed of 2.5 meters per second. (Hengfeng) With the Dane county wind resource, one of these turbines would produce 215.5 kWh annually at the cost of approximately $1,200. To reach a quarter of the apartments buildings demands, 175,000 kWh, the project would require 813 wind turbines. Each turbine is costing $1,200 and assume it costs $100 per turbine assembled. The total system cost would then be $1,056,900. And the system would produce 315,200 kWh annually.

One caveat to this option is that the company can only produce 500 wind turbines a month, so it will take several months to receive the product when factoring in their other orders and such. This can increase construction time and provide delays in the time that the contracted companies can work. It is evident that the Net Present Value of this system is not any better than the other system and that the financial incentives would remain the same between the turbines (see Appendix, Equation 3).

Vertical Axis Wind Turbine

The Vertical Axis Systems tend to be less efficient estimates between 15 to 25 % less energy production gave the same area. The efficiency difference is due to the design of the turbine, and while the wind is pushing the turbine, its vertical design also has resistance. The costs of the wind turbines are also significantly higher. The best estimate found was $31,000 for a 4kW turbine. The set up would then need to be constructed at the housing unit so it can be estimated that the cost would be $1,000 per turbine. (Conduit, 2017). The 4kW vertical wind turbine at a wind resource of 5.5 m/s will produce 3600 kWh annually. As a rough estimate, the turbine would produce 3000kWh annually. To match the 175,000 kWh from the horizontal system, 59 Vertical axis turbines. The costs of the system would be $1,888,000 for the same energy production. Unless the wind direction was abnormally variant the Vertical Axis technology is not adequate for this project and the horizontal design would be the ideal system between the two.

Environmental Paradigm Analysis

Resource Availability

Resource availability assesses how easily accessible the energy source generating the electricity is. For the Horizontal and Vertical Axis Wind Turbines, this would be the wind speed. The Madison area has sufficient wind resource dependent upon the elevation of the turbine. Since the turbines are small-scaled, the average height is predicted to be nearest to the 30-m wind data (Figure 4). This shows that the average wind speeds range between 4 m/s and 5.5 m/s. This is enough to generate electricity through the turbines. This is only an average however. There will be days less windy than others. Therefore, wind as resource is not consistent. Because of this, both of the turbine options receive a ranking of 3 out of 5.

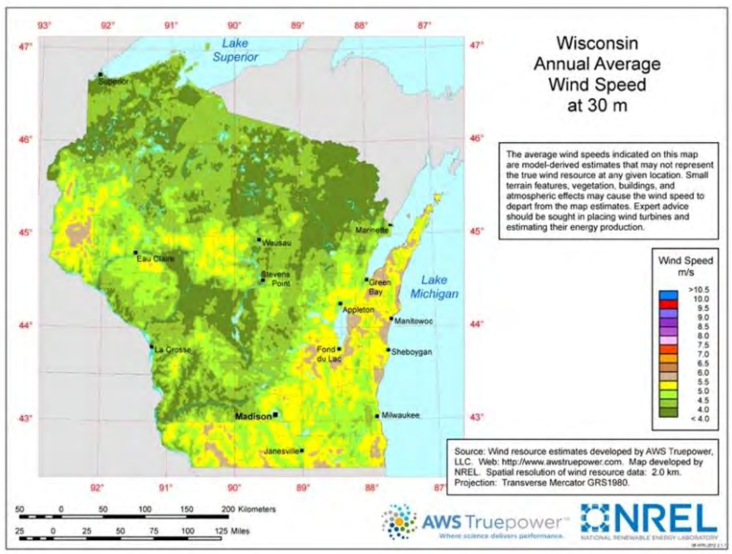

FIGURE 4: WISCONSIN ANNUAL AVERAGE WIND SPEED AT 30 METERS (NATIONAL RENEWABLE ENERGY LABORATORY, 2017)

Madison Gas and Electric is a consistent and reliable power source for electricity. Natural gas, petroleum, and coal are the major sources used (Madison Gas and Electric Company, 2017). Since it is dependent upon sources that currently are available around-the-clock, availability is not a concern. However, these sources are not renewable and will eventually run out. Therefore, it receives a 4 out 5 ranking.

Life Cycle Assessment

A Life Cycle Assessment is a great way to quantifiably assess the environmental impact of a service or good through all points in its life cycle. A study published in the *Journal of a Cleaner Production* conducted a Life Cycle Assessment for a small scale Horizontal Axis Wind Turbine (Wei-ChengWanga, 2016). In this assessment they determined the amount of greenhouse gas emissions generated during the manufacturing and implementation of a 600 W HAWT. Figure 5 illustrates the different inputs, outputs, and boundaries used in the assessment. As discussed earlier, several small-scale horizontal turbines would be needed to generate the electricity demand of the apartment building. The article concluded that 100 years would be needed to counter-balance the greenhouse gas emissions generated during the production and disposal of each turbine (Wei-ChengWanga, 2016). This would exceed the expected lifespan of the turbines. It is assumed that the vertical axis turbine is of the same scale due to similar size and material. The renewable energy source is not drawing upon fuels that release greenhouse gas emissions during it use phase, but its production is still a contributor. For this reason, the turbines are given a 3 out of 5.

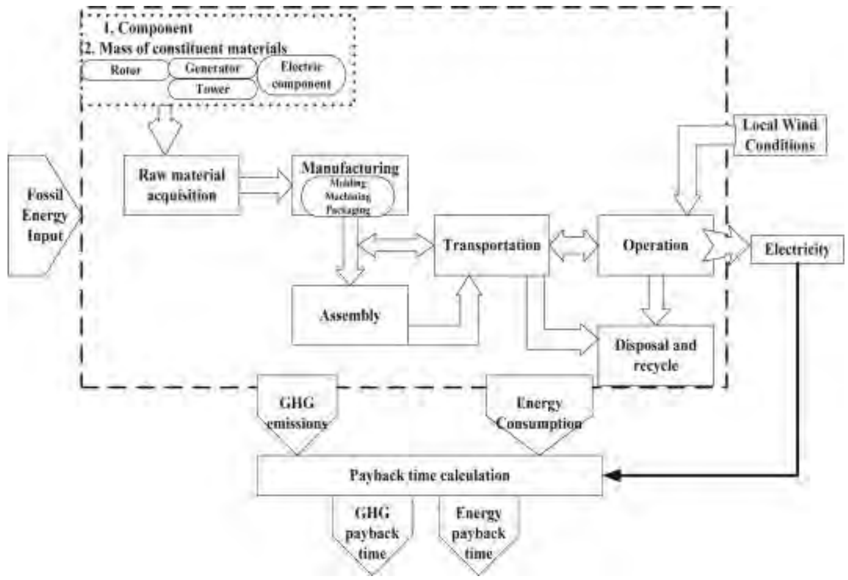

FIGURE 5: LIFE CYCLE FLOW USED IN STUDY OF HAWT LIFE CYCLE ASSESSMENT (WEI-CHENGWANGA, 2016).

Although Madison Gas and Electric are putting effort into reducing their environmental footprint, renewable energy sources only account for 12% of their electricity sources. Coal, natural gas, and oil account for about 67% of their electricity sources (Madison Gas and Electric Company, 2017). The National Renewable Energy Laboratory conducted a Life Cycle Assessment of coal-fired power production. The study concluded that carbon dioxide emissions account for almost all of the emissions that result from the mining, transportation, and burning of coal to create electricity (Spath, Mann, & Kerr). Since coal accounts for the majority of MGE's electricity source, it receives a ranking of 2 out of 5.

Social Paradigm Analysis

Madison Gas & Electric

Madison Gas and Electric is the socially accepted electricity source within Dane County. There are small ecological impacts on the birds and bats of the area. There aren't any visual or noise impacts correlated with Madison Gas & Electric. The electrical installations are part of the urban environment; people are simply used to see power pole because they are essential for the transmission of electric energy. For this reason, the score associated is 5 out of 5 for both social categories.

Vertical Axis Wind Turbine

The tip speed ratio of the Vertical Axis Wind Turbine is usually 1.5 to 2, which is much lower than that of the Horizontal model. Such low rotating speed basically can't produce aerodynamic noise, and completely mute the noise. They also have blades that are located closer together and travel at the same linear and angular velocities, making every blade section more similarly apparent for birds to see (Aelosol). Because of this, a fair score for Ecological Impacts of VAWT is a 4 out of 5.

VAWTs rotate at comparatively lower revolutions per minute than HAWT, thus producing less vibration and noise. Most VAWT manufacturers quote noise levels of less than 20 dB at a distance of less than 20 ft. /6m (Gardiner, 2015). Regarding the visual aspect, there is room for improvement. It is easier for VAWT to have more appealing design that would eliminate the "not in my backyard" phenomenon. A fair score, in this case, is 2 out of 5.

Horizontal Axis Wind Turbine

The tip speed ratio of the Horizontal Axis Wind Turbine is generally about 5 to 7. At such a high speed, many birds and bats find it difficult to escape (Aelosol). Site characteristics may influence the risk of fatality for birds, including location relative to key habitat resources or concentration areas during migration. Relatively little is known about many of these relationships, but evidence for the importance of some of these variables is becoming clearer (Council., 2007). A better understanding of these relationships will likely be helpful in siting decisions for future wind-facility development. Given this consideration, it seems fair to give a score of 2 out of 5 for ecological impact of HAWT.

The blades of a HAWT cut the air flow producing loud aerodynamic noise because of the typical high-speed rotation. Typically, HAWT builders quote noise level of 50 to 60 or more at a distance that is way bigger than 30ft. As far as it concerns the visual impact, even if we are talking about small scale HAWT they still affect the overall visual design of the building. Future residents could be happy about the green aspect of having wind turbines in their rooftop, but most of the time people tend to follow the “not in my backyard” principle. In other words, they can love the idea of having green wind energy, but still not willing to have the visual interruptions. HAWTs are noisy and visible, moreover it’s really difficult to change the shape of the blades in order to make them more beautiful. For this reason, a fair score is 2 out of 5.

Final Recommendation

The analysis based on the three paradigms of sustainability are summarized below, in Table 2. The weighted values show that purchasing electricity from Madison Gas and Electric outranks the small-scale turbine options. This is mainly due to the economic infeasibility. With the strict budget restrictions, the analysis does not recommend installing Horizontal Axis Wind Turbines nor Vertical Axis Turbines. The beneficial environmental impact does not outweigh the economical sacrifice that would have to be made.

TABLE 2: DECISION MATRIX USED FOR DETERMINING THE BEST-SUITED ENERGY SOURCE.

Standards	Weighted Value	HAWT	VAWT	MGE
Net Present Value	1.5	2	1	3
Resource Availability	1	4	4	5
LCA Analysis	1	3	3	2
Ecological Impacts	0.5	2	4	5
Visual Impact	0.5	2	2	5
Total		12	11.5	**16.5**

There are other options to incorporate sustainable choices into the housing. Architectural and material decisions can be made to aid in energy conservation within the building, to decrease the electricity demand of the building. Madison Gas and Electric also offers a Green Power Tomorrow option when using their services. It allows customers to purchase more of their electricity generated from renewable sources. This is a more sustainable, but slightly more expensive, option. Regardless there are endless avenues to be explored to create affordable housing that is beneficial for the county and the environment.

Appendix

Equation 1

Net Present Value = ∑ (Annualized Savings)/(1+r)^n-Net Present Costs

Equation 2

Bergey Wind Turbine:

$$Net\ Present\ Value = (\sum((175{,}843\ kWh)\left(\frac{\$.14163(1+.0036)^n}{(1kWh)(1.03)^n}\right)) - \$1{,}017{,}000$$

$$Net\ Present\ Value = \$547{,}909.64 - \$1{,}017{,}000$$

$$Net\ Present\ Value = -\$469{,}090.46$$

$$Payback\ Period: NPV\ Costs = NPV\ Benefits$$

$$\$1{,}017{,}000 = \frac{\$547{,}909.64}{20}\left(\frac{1.03^n - 1}{.03 * 1.03^n}\right)$$

$$Perpetuity = \frac{\$547{,}909.64}{(20).03}$$

$$Perpetuity = \$913{,}182.73$$

Equation 3

Qingdao HengFeng Wind Power

$$Net\ Present\ Value\ = (\sum(Annualized\ Savings)/(1+r)^n - Net\ Present\ Cost$$

$$Net\ Present\ Value = (\sum((175201.5\ kWh)\left(\frac{\$.14163(1+.0036)^n}{(1kWh)(1.03)^n}\right)) - \$1{,}056{,}900$$

$$Net\ Present\ Value = \$545{,}910.79 - \$1{,}056{,}900$$

$$Net\ Present\ Value = -510{,}989.21$$

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About UniverCity Year

UniverCity Year is a three-year partnership between UW-Madison and one community in Wisconsin. The community partner identifies sustainability and livability projects that would benefit from UW-Madison expertise. Faculty from across the university incorporate these projects into their courses with graduate students and upper-level undergraduate students. UniverCity Year staff provide administrative support to faculty, students and the partner community to ensure the collaboration's success. The result is on-the-ground impact and momentum for a community working toward a more sustainable and livable future.

UniverCity Alliance

univercityalliance@wisc.edu

608-890-0330

univercity.wisc.edu

COUNTY of DANE 1839 WISCONSIN

UniverCity Alliance
UNIVERSITY OF WISCONSIN–MADISON