

Worcester Polytechnic Institute

Project Number LDA-0905

Green Engineering: A Life-Cycle Cost Analysis

A Major Qualifying Project Report:

Submitted to the Faculty of the WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment of the requirements

For the Degree of Bachelor of Science by

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Date:

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Abstract

This project shows the implications of adding green technology to a structure. In order to accomplish this, a structure was designed according to the IBC building code, and a lifecycle cost was completed. Then the structure was raised to meet L.E.E.D. silver status and, another cost analysis was completed to determine the economic impact and feasibility of the changes.

Acknowledgements

A special thanks to all of the people here mentioned for their efforts in helping to make this project a success.

Thank you Professors L.R. Ram-Mohan and Fredrick Hutson for your help on the solar cell portion of this project.

Most importantly, I would like to thank my advisors Leonard Albano and Thomas Keil for all of their assistance, direction and input without which this project could not have been a success.

Capstone Design

This look into green technology will analyze five constraints that are elements of capstone design. These constraints are first and most extensively *Economic, as well as Sustainability, Constructability, Health and Safety, and Social.*

Economic Constraints

This project will focus on a total cost analysis of a structure before and after the application of Green Technologies. In order to accomplish this, a variety of structural configurations will be considered. These configurations will be compared by the following criteria: lowest initial cost, allowance for open space, and flexibility of open space. Impacts of adding Green Technology will also be considered. Items such as changes in initial costs, energy costs, and lifecycle costs will all be considered in order to determine whether the addition of these technologies is advantageous to the owner from a fiscal standpoint.

Sustainability

The addition of Green Technologies is important to the sustainability of society as a whole. Therefore this project will focus on the implications of trying to create a sustainable environment in and around a structure.

Constructability

Constructability although not a major issue in this project is an important issue when designing any structure. This is due to the fact that the materials chosen should be standard materials of standard sizes in order to reduce the cost of the members. It is also due to the fact that there is a difference in rigid frame analysis and braced frame analysis. This project will consider a braced frame only as it leads to slightly more members at a substantially smaller size.

Health and Safety

The health and safety of a building's occupants is highly important. The aspect of this project that will focus on health and safety will be designing the structure using all appropriate IBC codes as well as bringing the structure to L.E.E.D. silver status as some of the points being considered will ensure a safe environment for all inhabitants of the structure. This means that the structure must be safe, have clean air, and pollute the environment as little as possible.

Social Constraints

This structure will contain limited parking areas in order to promote carpooling, as well as various bike racks to allow individuals who wish to commute via bicycle to do so. Social constraints of this structure will focus on the ability of this structure to influence the society surrounding it as little as possible.

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Green Structures

In today's society the number one concern is sustainability. Currently the planet is heating up due to greenhouse gasses, and the human population is running out of its most used power source, oil. These problems are forcing society to alter the way that it uses energy, and even to find new ways to produce it. This fact has caused many building companies to look into "green" structures. These are structures that attempt to limit their effects on the environment as much as possible. Civil engineering firms all over the country are looking into this issue and are looking for engineers competent and willing to design such structures.

In addition to civil engineering firms, the United States government is also providing an incentive system for people who pursue adding green technology in their homes as well as new structures. The federal government offers a variety of incentives for various types of buildings, be they corporate or residential. This information is easily located at the Database of State Incentives for Renewable Energy, DSIRE (DSIRE). Although this database states that it contains state incentives, the federal incentives are included as well. In the United States, the federal government allows tax refunds up to \$1.80 per square foot for all buildings that meet ASHRAE standards (DSIRE). This credit can vary from \$.30 to \$1.80 depending on how much renewable energy is produced.

Various states are implementing credits as well including, but not limited to, New York, Massachusetts, Maryland, Oregon, and Pennsylvania (Lubell p.1). These incentives include seven to eight percent of the costs of green technology over five years with a maximum of \$150.00 per square foot of a base structure and \$75.00 per square foot for tenant space. New York for example allows for up to \$2,000,000.00 for any commercial or residential building using the following systems: Passive Solar Space Heat, Solar Water Heat, Solar Space Heat, Photovoltaics, Fuel Cells, and Daylighting (DSIRE NY incentives). In Massachusetts there is a tax incentive named the Excise Tax Deduction for Solar- or Wind-Powered systems. This incentive allows 100% of the cost of any solar or wind powered system that is installed in Massachusetts on a commercial or industrial structure to be deducted from the owner of the structure's income tax for (DSIRE MA Incentives).

Looking into Green Technology is extremely important if one looks at the exorbitant amount of energy that buildings utilize. The U.S. Green Building Council (USGBC), which was formed in 1993, has produced a list of energy consumption values for buildings in the United States. In this list it explicitly states that:

“In the United States alone, buildings account for:

- 72% of electricity consumption,
- 39% of energy use,
- 38% of all carbon dioxide (CO₂) emissions,
- 40% of raw materials use,

- 30% of waste output (136 million tons annually), and
- 14% of potable water consumption. (Council p.1)”

These figures are astounding. Buildings are one of the largest consumers of energy and only in the past 20 to 30 years have people been trying to remedy the energy crisis through altering building and site design. Therefore, there have been various standards composed for making a building “Green”. Of all of the standards, there is one that is accepted as a nationwide standard for creating a Green Structure.

This Standard is L.E.E.D. Certification. There are multiple levels of certification that one can obtain. These levels of certification are Certified, Silver, Gold, and Platinum. In order to achieve these one must attain enough credits, as specified in the L.E.E.D. for New Construction and Major Renovations Manual. This project will bring a structure up to Silver Certification. To achieve Silver Certification anywhere from 33 to 38 of the 69 possible credits must be earned. In the next section each of the credits will be discussed in detail.

L.E.E.D Green Building Rating System

The system of accepted standards for green buildings is Leadership in Energy and Environmental Design (L.E.E.D.). L.E.E.D. judges a building on whether it is green or not on only 5 categories: site design, indoor environmental qualities, and the efficient use of energy, materials and water. Based on these five categories there are a possible 69 points that may be awarded to a building certifying that it is an environmentally friendly and sustainable structure. These standards, although they are not perfect, have been giving builders an incentive to make buildings more sustainable. Between 2002 and 2003 the number of projects that applied for L.E.E.D. certification doubled showing that this is an issue that is being pursued avidly by the population (Council p.3).

Although these points do develop a standard for determining if a building is eco friendly, the points system does not definitively convey that all equal points rated buildings are equally environmentally friendly or sustainable. Whether or not these are equal standards can only be determined by looking at the actual way in which L.E.E.D. gives out points and seeing if equal points are given for equal environmental impacts. Each of these possible credits will be discussed in the following sections.

Sustainable Sites

When designing a building one must first decide on location. This section in the L.E.E.D. manual deals with this decision and provides a variety of points that should be considered when making this choice. In order to apply for L.E.E.D. certification one must first comply with the Environmental Protection Agency (EPA) Document No. EPA 832/R-92-005 by developing a plan to limit erosion of the soil, reduce sedimentation into storm or sewer water, and prevent air pollution from particulate matter.

The first four points of the fourteen possible in this section all pertain to the location of the site. The first point defines what sites should not be built upon including prime farmland, land lower than the elevation of the 100 year flood, areas where threatened or endangered species reside, land within 100 feet of wetlands, or land that was once public parkland. Credit 2 in the sustainable site section expresses the importance of building in urban areas to conserve undeveloped areas by promoting structures to be developed in a region with an existing minimum development density of 60,000 square feet per acre.

There is another point awarded for repairing brownfields and developing on them. By doing this one can reduce potential contaminants already contained in the site from further disrupting the environment. This is the most influential point in the sustainable site section of the

manual because it is the only credit in the manual that discusses repairing damages to the environment that the new owner of the structure may not have caused. Brownfields are extremely costly to repair in most cases and often have widespread impacts. In addition to the economic and environmental impacts of this point, the fact that this point encourages fixing land that would otherwise not be considered is a very proactive approach to fixing tarnished areas of the environment.

The final point awarded for appropriate site selection is to place the structure within a half mile of a commuter rail or subway station, or within a quarter mile of public bus lines. This is the second most environmentally friendly point in this section. It allows for many of the buildings inhabitants to commute via public transportation, limiting the amount of carbon dioxide emissions produced by those inhabitants.

The next three points in this section are concerned with commuters not using public transportation. The first point Sustainable Site (SS) Credit 4.2 calls for bicycle racks and changing rooms to be placed near or on the facility for at least 5% of the building's occupants. The second point is to provide alternative fuel vehicles for at least 3% of the building's occupants and provide preferred parking for these occupants. The third and final point of this section places restrictions on the parking areas available for the structure. It mandates that the amount of parking spaces must

meet and not exceed minimum zoning requirements. This point also mandates that there is preferred parking spaces for vehicles involved in carpooling.

The first and third of these points seem to be beneficial to the environment, but the environmental impacts of using hybrid or fully electric cars are not clear. For instance the 2009 Ford Escape Hybrid SUV gets 34 miles per gallon city and 31 miles per gallon highway, but the 2009 Volkswagen Jetta S Turbo Diesel Injection can maintain 34 miles per gallon city and 40 miles per gallon highway (Volkswagen). This statistic alone nullifies the point that hybrid cars are inherently better for the environment. Therefore at least one point in this group should be reformed to be definitively better for the environment.

Credit 5 is two points in the L.E.E.D. manual and promotes open space and protects the existing environment on Greenfield sites. The first of these points specifies limits on how far away from a structure the owner can disrupt the landscape when building on a Greenfield, and the second requires that one must increase the open space on the land by 25% of the minimum zoning requirement. This requirement promotes biodiversity within the ecosystem and allows for areas where both plants and animals can live. This is a point that needs to be addressed as urban sprawl is happening at an alarming rate in today's society. It is important to remember that during this change one must still provide room for an area to maintain biodiversity.

Two points of this section are also dedicated to the management of stormwater. These points are aimed at controlling both quantity and quality of stormwater on the site. The intent of the stormwater quantity credit is to limit the effects on natural water flow by creating a management plan to reduce the amount of runoff stormwater. Runoff stormwater often carries with it various pollutants and eventually flows into nearby water sources, and therefore should be limited to protect wildlife both in and out of the water. The second point addresses the issue of stormwater quality. It requires that a system is implemented to reduce the suspended solids in the water by 80% and to remove 40% of the post-development phosphorus. Reducing these contaminants will insure that the runoff water that does reach nearby water sources will be cleaner and affect the wildlife to a lesser extent.

The final two sections in the SS section pertain to Heat Island Effect and light pollution. The first two of the three credits in this section are concerned with the heat island effect both on and off the roof. In order to gain both of these points one must either provide shaded areas within five years of construction or use open grid pavement for at least 30% of the non-roof surfaces and the building must use Energy Star compliant roofing for a minimum of 75% of the structure. Implementing these changes the structure it will reduce the heat absorption of the building as well as lower the temperature in certain essential areas of the site, providing a cooler climate for both humans and wildlife. Aside from the thermal impacts on the structure, such as decreasing the rise

in internal temperature due to UV radiation, there is no real environmental benefit to these credits. Granted during the summer months there will be a reduction in air conditioning costs, but these points produce a much less substantial environmental impact than many of the other credits listed in this section and they are weighted equally.

The credit available for light pollution reduction stipulates that the lighting from the structure should be placed in such a way as to not shed light on the property of others or to have internal light shine on external areas. Again the environmental impacts of this issue are far inferior to other points in this section. This is not a stipulation on how much energy one uses in lighting but rather where lighting can shine. Although there is increasing light pollution, especially in urban areas this pollution does not disrupt the environment nearly as much as many of the other issues presented in the guidelines in this section. Each of these three points should be included in a plan for green construction but the points given for each portion should be representative of their environmental impact. This will be a difficult task because light pollution's effects, unlike most other types of pollution, is difficult to calculate. Before one can assess this issue there must be a definitive way to determine what effects, if any, light pollution has on the environment.

Water Efficiency

The section on water efficiency contains a total of 5 possible points and can be divided into three distinct sections: water efficient landscaping, innovative technologies, and water use reduction. The first two points in this section are to reduce potable water consumption by fifty percent and to input landscaping that does not require a permanent irrigation system. Each of these points has an important environmental and economical impact. In order to produce potable water, the water must be passed through a multitude of processes to ensure that the water is not harmful to drink. This water standard does not need to be maintained while irrigating plants and therefore it is wasteful to do so. By limiting or eliminating the use of this water for irrigation more potable water can be conserved for consumption.

The next point in this section has to do with using innovative technologies to limit waste water in the structure by fifty percent. In an institutional/commercial building such as the one considered in this project this is a cost effective point to gain. By inputting aerators in all of the faucets and using water efficient toiletries one can reduce the water consumption of the structure by over fifty percent and the costs will be covered for the change in less than ten years. There is no detriment to obtaining this L.E.E.D. point and limiting waste water is extremely beneficial to the environment. The next three points are additions onto this point. The following point discusses

only limiting waste water whereas the last two points in this section are concerned with limiting total water used in the structure. The same techniques can be used to limit the water use and gain each of the two points. One point is awarded for 20% reduction in water use, and another is added for a 30% reduction.

Energy and Atmosphere

This section has three stipulations that are required if one is to be considered for L.E.E.D. Certification. These requirements are that the building must be subject to a fundamental commissioning ensuring all of the buildings energy systems are performing as specified, the building must meet minimum energy performance standards, and the third requirement is that the building must not use any CFC-based refrigerants. Upon completion of these requirements one can attain up to 17 additional points.

The first ten of these 17 points are given for optimizing the energy performance of the building. One point is awarded for increased efficiency of each of the following percentages 10.5, 14, 17.5, 21, 24.5, 28, 31.5, 35, 38.5, and 42. There are many ways to optimize the efficiency including but not limited to optimizing any mechanical system (Heating, Air Conditioning, and Water Heating Systems), increasing insulation rating, and optimizing office and other miscellaneous equipment.

The next three points of this section are given for using renewable energy on-site. Like the points for optimizing energy efficiency points, are given for each of the following percentages 2.5, 7.5, and 12.5. These may be the most environmentally friendly points in the manual. Renewable energy does not harm the environment in any way to produce. It also limits the carbon dioxide emissions from the structure. These points are obviously extremely beneficial to the environment and its possible three point value shows its importance.

The next point in this section is for enhanced commissioning of the structure. This point is to make sure that a Commissioning Authority is hired to oversee the completion of all commissioning process activities. This credit is important to ensure that all processes that are supposed to be completed are in fact completed. It is unclear however why this is not a prerequisite. Why would it not be mandated that the commissioning of the building must be done by a professional in an independent company? It does not make sense to not require that this happens. If one is to be certified each of the credit's specifications should be completed and the systems used should be commissioned and checked by a Commissioning Authority to show that the commissioning was indeed done properly.

The next credit Energy and Atmosphere credit 4 mandates that either the structure does not use any refrigerants or one must choose a system that minimizes or eliminates the emission of compounds that contribute to ozone depletion. In a world where global warming is already

occurring the environmental impacts of not producing any ozone depleting compounds is obviously beneficial to the environment. The next point, Measurement and Verification is important as well. This credit ensures that all systems in the building maintain the level of efficiency that the system is supposed to perform by, L.E.E.D. standards, one year after the building's construction.

The final credit in this section is awarded for producing 35% of the building's electricity from renewable energy. This credit is only one point in the standards manual. It is unclear as to why almost tripling the amount of renewable energy used by the building from the previous credit is only worth one additional point. Using renewable energy for 12.5% of the total energy used by the structure is worth three credits but increasing the renewable energy use by almost three times that is only one point. This seems like an extremely undervalued point compared to many of the other points.

Materials and Resources

This section has 13 possible points, but many of these points can only be awarded if the project is a renovation. Because this project is a new construction project there are only 6 possible points that may be obtained. There is also a requirement for certification in this section that states there must be a collection system for recyclable materials.

The first two points that can be earned in this section is materials and resources credit 2.1 and 2.2. These credits state that one must divert 50% and 75% of construction wastes from landfills and incinerators. Essentially these credits promote recycling of all materials that are able to be recycled. It is difficult to attain these points because all of construction debris must be sorted and separated, but the environmental impacts of recycling construction material for another project are undeniable and absolutely beneficial. The next two points available in this section are for using recycled content in the building. The first credit is awarded for using 10% recycled material and the second is for using 20%. Again recycling and using recycled material is always beneficial to the environment because it saves non-renewable natural resources.

Credits MR5.1 and 5.2 promote the usage of materials manufactured near the structure. This point does not seem to have as great of an environmental impact as recycling and using recycled materials. The only benefit to the environment from purchasing locally is the reduction in pollutants from shipping the material. These points are more concerned with maintaining the economy of the nearby area. These points although good for economy do not need to be included in a green structure manual. The manual should be more concerned with environmental issues if it is to be the standard for Green Building.

Indoor Environmental Quality

The indoor environmental quality section is the second largest section of the manual and can award a possible 15 points and two requirements. The two requirements are that the building must meet minimum indoor air quality standards as specified by sections 4–7 of ASHRAE 62.1, and there must be no smoking allowed within the confines of the building.

The first potential credit in this section is to input a system to monitor the ventilation system in order to sustain comfort and well being inside of the building. This credit requires placing carbon monoxide detectors, and one must provide direct outdoor airflow around each mechanical ventilation system. The indoor air quality of a structure is very important to the occupants of the building. It is because of this that these specifications must be made in any structure attempting to go Green. Another credit in the manual pertaining to air quality is EQ credit 2.0, and it mandates that the structure increases outdoor air ventilation by 30% above the minimum rates required by ASHRAE Standard 62.1. Increasing ventilation is important in any structure because it transfers stagnant air out and allows for the flow of cleaner air to enter.

The next seven credits all regulate indoor air quality. These credits place restrictions on the adhesives, sealants, paints, coatings, carpets, and wood used in the structure. To receive these seven credits none of these materials are allowed to be highly toxic. Each of the adhesives and

sealants used must comply with the South Coast Air Quality Management District Rule 1168.

Paints and coatings used on the structure must comply with Green Seal Standard GS-11 ensuring that all paints and sealants will not affect the health of the building occupants. Any and all carpeting used in the structure must comply with the Carpet and Rug Institute's Green Label Plus program, and in addition to this all sealants and adhesives used when installing the carpeting must comply with South Coast Air Quality Management District Rule 1168. All wood in the structure must not contain any added urea-formaldehyde resins.

The next four credits are concerned with the controllability of both the lighting systems and the heating systems. In order to receive the first two credits one must provide individual lighting controls for 90% of the structure's occupants as well as provide individual heating controls for 50% of the occupants. The next two credits EQ credit 7.0 and 7.1 requires that one complies with ASHRAE standard 55-2004 and that the building owner provides an assessment of the building's thermal comfort over time. The final two credits in the Indoor Environmental Quality section require that one provides daylight to 75% and 90% of the areas in the structure. These credits can be achieved through one of three ways: calculation, simulation, or measurement. In order to achieve these credits in this project the glazing factor was calculated using the following formula found in the manual:

Glazing Factor	-	$\frac{\text{Window Area [SF]}}{\text{Floor Area [SF]}}$	x	Window Geometry Factor	x	$\frac{\text{Actual Tvis}}{\text{Minimum Tvis}}$	x	Window Height Factor
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Innovation and Design Process

The final section in the L.E.E.D. manual is worth a possible five points and is could be the most innovative section in the entire manual. In order to obtain one or all of the first four points the structure in question must implement some innovative design, not previously stated in the manual that is for the benefit of the environment. There is one point awarded for each innovative process implemented. The final credit in the manual is awarded for having at least one L.E.E.D. accredited professional involved in the project team.

Conclusions

The L.E.E.D. Specifications mentioned above are definitely a progressive attempt at creating environmentally friendly and sustainable structures. However, there is room for refinement in the points system. Not every point has equal environmental or sustainability impacts, and as such each of the credits awarded should reflect this. As this program modifies its methods for determining environmental impacts and adjusts its point values it may provide a much more accurate assessment for how well a structure is interacting with its environment and how sustainable it is.

The Structure

This project will design a three story 160' by 60' steel and reinforced concrete structure.

The structure has been designed with a few key elements in mind. These elements are as follows:

long building lifespan, maximum diversity for the interior design, minimum cost, both lifecycle and initial with lifecycle costs governing, and maximum L.E.E.D points. Because these are the governing elements of the design, we must look into what each of these stipulations changes in the way that the structure is designed.

Materials

This structure must have a long lifespan. The main way in which this influences the structure is in the types of materials chosen for construction. In a structure which is intended to last for fifty years or more the most durable materials must be considered. The options considered for this project are reinforced concrete and steel. In this structure both concrete and steel were used for different portions of the building. The floor is comprised of a reinforced concrete slab, and the rest of the structure comprised of beams, columns, girders, and bracing members. These members were created using W-type steel members.

Interior Diversity

The next consideration to be taken into account is the ability to provide maximum diversity for the interior of the structure. This aspect of the building only becomes truly important because of the usage of a braced frame. In a braced frame structure there are members placed on an angle in between columns in both directions. This can cause the areas where these braces are placed to be permanent fixtures in the structure which limits the ability to change the interior of the structure easily by limiting the walls that entry points may be input. **Configurations of**

Members

Once the materials have been designed, the issue of designing a low cost option must be looked at. The only way to truly test that the members being used are the most cost efficient is to examine multiple configurations of spacing in its members. Therefore, for this project there will be an analysis done for beams spaced at three different increments. These three increments are five feet, ten feet, and twenty feet. With these different spacings there also needs to be designed three different reinforced concrete slabs to account for the increased load capacity of the slab due to its higher tributary area. These values as well as their implications will be discussed in the section on lifecycle costs.

Member Design

In order to design this building the International Building Code (IBC) will be used. It will provide a basis for how to design the steel structure of the building as well as the concrete slabs by providing appropriate loading conditions for the structure.

The code does this using various steps. First one must find the gravity loads imposed on the structure. These loads are comprised of the weight of the building, the snow load of the building, and the live load for the specific type of occupancy used in the structure. There are also points, such as around the elevator shaft in this structure, where concentrated gravity loads must be placed. These loads are also found near the stairs and wherever any unit is permanently affixed to the structure. The dead load is difficult to calculate at the start of the design as it must be assumed based on educated guesses of the sizes of each of the members. To begin with one assumes columns to be the largest members followed by girders and beams respectively. These values may be approximated by using values for the loads that will be applied to each member and approximating member size due to the moment imposed on them. For instance each beam will have a concrete slab on top of it and will be supported by a girder on each end. Therefore the beam must only hold the weight of any live loads as well as the weight of both the slab and itself. The girders then have to carry the above loads as well as the weight of themselves etc. These

members are then input into one of many computer software programs as the base structure. Once the dead loads are found one must calculate the snow loads and the live loads for the structure which can be found in the Minimum Design Loads for Buildings. Because the building is to be designed for maximum versatility the live loads chosen were for that of an office building lobby as they exceed the loads of a classroom and are equivalent to those of stairways/entry ways and the load is 100 psf. The snow load is found using another table in the book and for Worcester, MA is 32 psf.

Next, one must calculate the lateral loading applied to the building. These lateral loads are the wind load and the earthquake load. The wind load like the snow load is found using the Minimum Design Loads for Buildings. Its value is determined to be 13 psf on the windward side, – 1.1 psf on the leeward side, and 11 psf on the other two sides of the building. The earthquake load however is more complex to calculate and must be recalculated before doing each of the iterations in the computer program as it is dependent on the dead load.

Member Sizes

Once these loads have been figured for each of the iterations they are placed on the building in the computer simulation. There are then various load combinations considered in order to see which the governing load combination for each member is. This was also done using the Risa-3D software and found that the member sizes for each of the beams were as follows:

20' spacing:	Standard Beams:	w33x118
	Standard Columns:	w14x283
	Standard Girders:	w33x130
	V-Bracing:	w10x49
	Elevator Beam:	w27x161
	Elevator Columns:	w14x283
	20' Concrete Slab:	15" w/ 5 #7 reinforcement @ 8"
10' spacing:	Standard Beams:	w21x101
	Standard Columns:	w33x118
	Standard Girders:	w30x90
	Elevator Beams:	w12x30
	Elevator Columns:	w12x45
	V-Bracing:	w8x30
	10' Concrete Slab:	12" w/ 4 #6 reinforcement @ 8"
5' spacing:	Standard Beams:	w8x35
	Standard Columns:	w12x53
	Standard Girders:	w10x39
	Elevator Beams:	w8x21
	Elevator Columns:	w8x31
	V-Bracing:	w5x19
	5' Concrete Slab:	4" w/ 4 #4 reinforcement @ 12"

All standard members were found using the maximum size beam for each of the members in an area where there were no concentrated loads. Because entry ways and office lobbies have the same live loads and dead loads there is no distinction between beams around stairwells and beams elsewhere.

Points for L.E.E.D Silver Certification

In order to attain L.E.E.D. Silver Certification one must accumulate a minimum of 33 L.E.E.D. credits. All of the potential credits for this project has been explained in detail in the section titled L.E.E.D Green Building Rating System above so below is a list of the 33 credits considered for this project.

Sustainable Site Credits

SS 1.0	Site Selection	1pt
SS 2.0	Development Density	1pt
SS 4.1	Alternative Transportation: Structure within ½ mile of subway or Com. rail	1pt
SS 4.2	Alternative Transportation: Bicycle storage and changing rooms	1pt
SS 4.4	Alternative Transportation: Limited Parking Capacity	1pt
SS 5.1	Reduce Site Disturbance: Protect or Restore Open Space	1pt

Water Efficiency Credits

WE 2.0	Innovative Wastewater Technologies	1pt
WE 3.1	Water Use Reduction 20%	1pt
WE 3.2	Water Use Reduction 30%	1pt

Energy and Atmosphere Credits

EA 1.0	Optimize Energy Performance	8pts
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EA 2.1	Renewable Energy 2.5%	1pt
EA 3.1	Additional Commissioning	1pt
EA 4.0	Ozone Depletion	1pt
EA 5.0	Measurement and Verification	1pt

Indoor Environmental Quality

EQ 1.0	Carbon Dioxide Monitoring	1pt
EQ 4.1	Low-Emitting Materials, Adhesives and Sealants	1pt
EQ 4.2	Low-Emitting Materials, Paints	1pt
EQ 4.3	Low-Emitting Materials, Carpet	1pt
EQ 4.4	Low-Emitting Materials, Composite Wood	1pt
EQ 6.1	Controllability of Systems, Perimeter	1pt
EQ 6.2	Controllability of Systems, Non-Perimeter	1pt
EQ 7.1	Thermal Comfort, Comply with ASHRAE 55-1992	1pt
EQ 7.2	Thermal Comfort, Permanent Monitoring System	1pt
EQ 8.1	Daylight and Views, Daylight 75% of Spaces	1pt
EQ 8.2	Daylight and Views, Daylight 90% of Spaces	1pt

Innovative Design Process

ID 2.0	L.E.E.D. Accredited Professional	1pt
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TOTAL **33pts**

Lifecycle Costs

Base Structure Analysis

The main concern of this project is to determine the lowest cost for the structure in question. In order to determine the lowest cost, this project will not only be focusing on the lowest cost of the building in the sense that it is looking for the lowest initial cost of the building. This project will be looking for the lowest lifecycle cost which involves various other components and attempts to find maximum economic efficiency. In order to do this a cost analysis including: standard heating systems, lighting systems, air conditioning units, bathroom fixtures, security and communication systems, initial and construction costs and roofing materials.

Because the scope of the project did not encompass designing each of these systems the cost of each of the systems had to be estimated. The cost of each of the systems above were all determined by using RS Means square foot cost estimates. This book gives estimates, based on occupancy of the structure, for each of the systems above. By taking this approximation for each of the systems and multiplying that value by the square footage of the structure one can obtain the total cost of each system. Once these values were computed the replacement fees and amount of replacements for each system had to be calculated. The replacement fees were assumed to be a complete reinstallation of the system, and the amount of replacements throughout the total life of

the building were estimated using the National Association of Home Builders' approximations (Component Life Expectancy). In order to find out what the total in replacement costs would be the number of replacements for each component was multiplied by the cost of the system. To find out the initial cost of the structure this data was added to the cost of the structural components. This was done by using the current cost of steel and concrete in the market today. These values were taken from RS Means building cost estimates and were estimated to be \$518 per ton and \$2.78 per cubic feet respectively. These values were multiplied by how many tons/cubic feet of each was used in the structure, and then this cost was increased by 15% in order to account for contractor's profit and all other fees incurred in building a structure (Waier). Each of the costs above were added together to produce a lifecycle cost of a structure's components.

Once this value was calculated a lifecycle cost analysis was done for the energy and water costs of the structure. In order to obtain values for these costs, estimate energy costs for institutional buildings were taken from the Massachusetts Department of Energy Resources (Mass. Department of Energy and Resources). Once these values were obtained the total energy cost of the structure per year was calculated.

With all of the values found, a graph could be completed for the entire lifecycle cost of the structure. This was done adding the calculated energy costs per year to the initial energy costs. However, this would not give an accurate interpretation of how the time value of money increases

or decreases. The energy costs had to be adjusted using the present value formula. This formula is given by the equation:

$$R_n \frac{(1+i)^n - 1}{(1+i)^n} = PWV$$

Where: R_n is the net value of money in or out of the system

i is the interest rate per year

n is the number of years passed

PWV is the present worth value (Dellisola p.24)

There were various interest rates considered. These interest rates were 0, 2, 4, 6, 8, and 10 percent. This value was then added each year that passes to the previous year's cost. The replacement fees for each of the structure's components also had to be considered. The same formula was applied to the replacement costs at their respective time of replacement. These values were taken over the fifty year lifecycle of the structure resulting in the total lifecycle cost of the structure.

Structure with L.E.E.D. Silver Certification

This analysis was almost the same as the analysis above except the values for initial cost and energy cost were modified. The initial cost changed because in order to attain Silver Certification many modifications to the structure must be added. Each of the components added to this section are stated above in the L.E.E.D Silver Certification section. Because some of the modifications the

energy costs had to be adjusted. For instance more efficient bathroom fixtures decrease the water costs by over 50% of the initial cost, and the addition of more efficient mechanical systems and solar cells decreased energy costs by over 35%. The same formula and interest values were used for this analysis.

Results

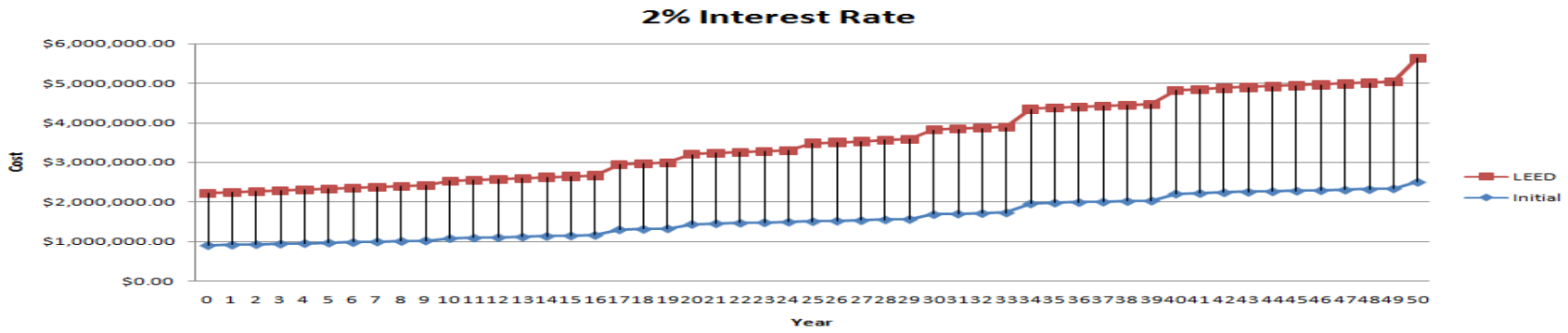


Figure 1: Lifecycle Cost Base Structure vs. LEED Silver Certification 2%

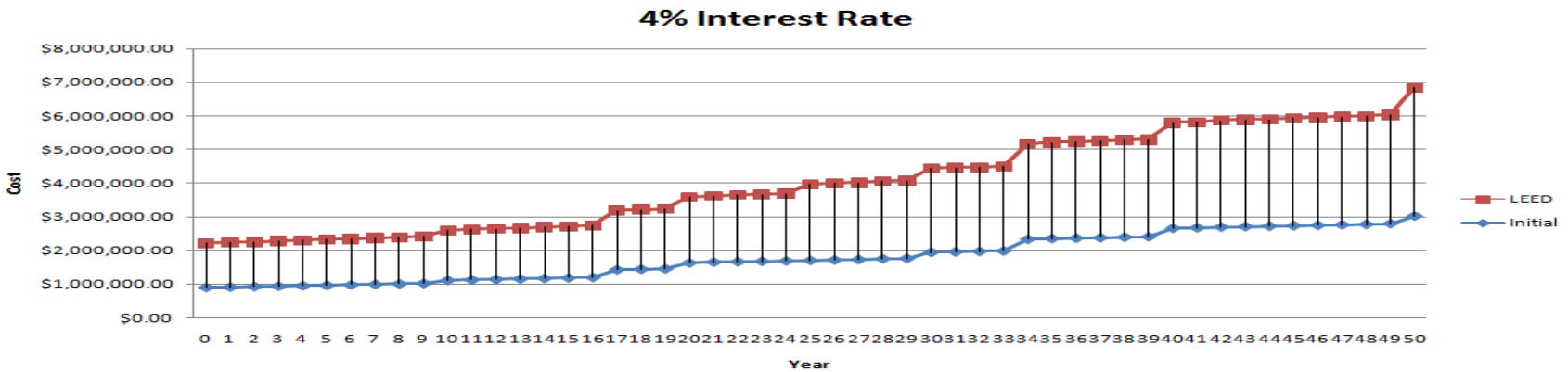


Figure 2: Lifecycle Cost Base Structure vs. LEED Silver Certification 4%

6% Interest Rate

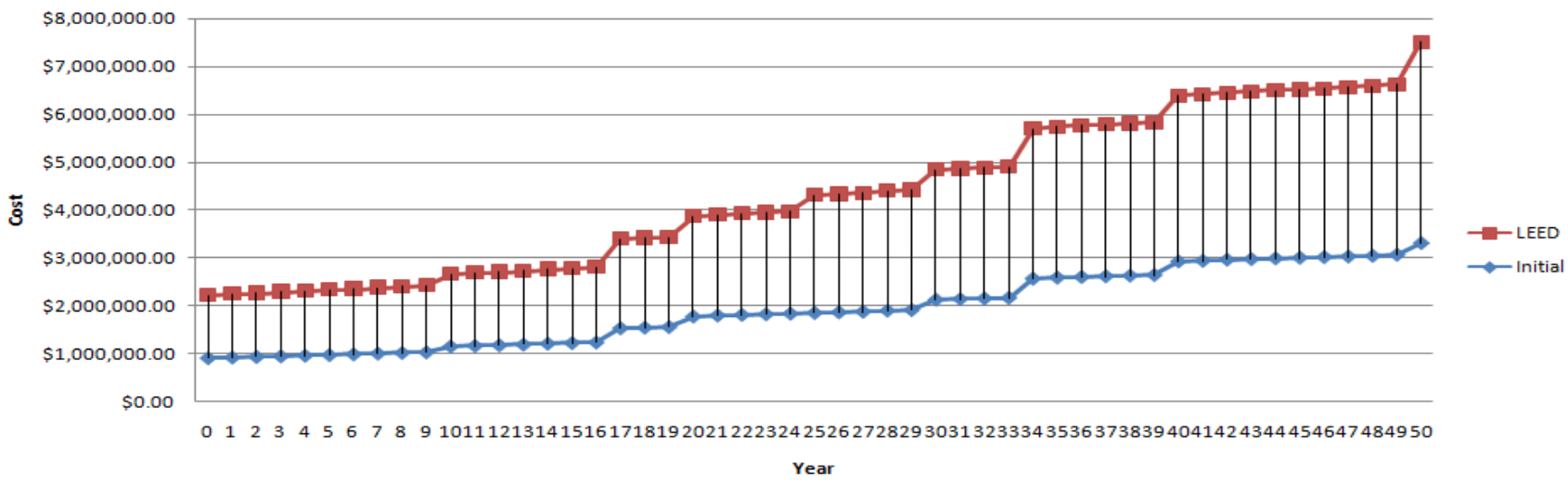


Figure 3: Lifecycle Cost Base Structure vs. LEED Silver Certification 6

8% Interest Rate

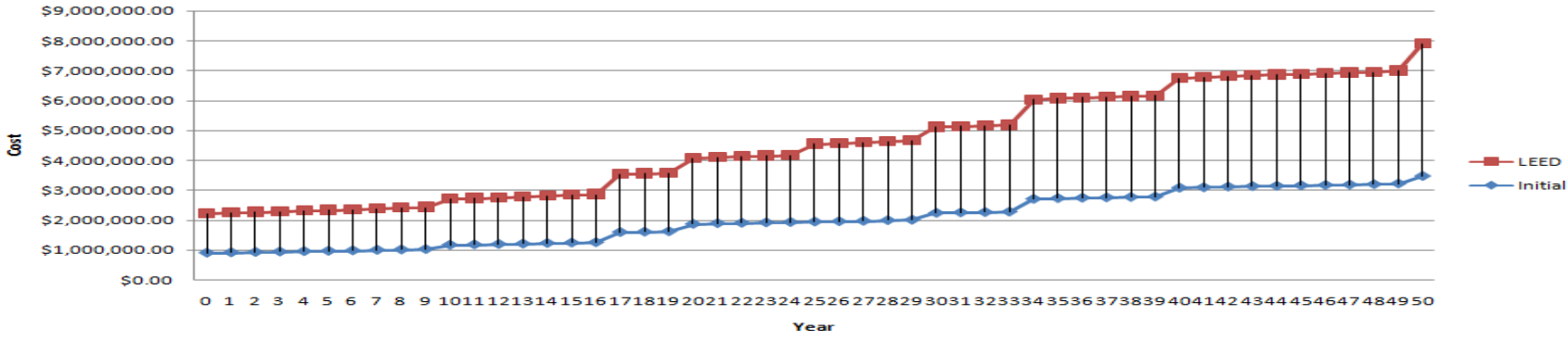


Figure 4: Lifecycle Cost Base Structure vs. LEED Silver Certification 8%

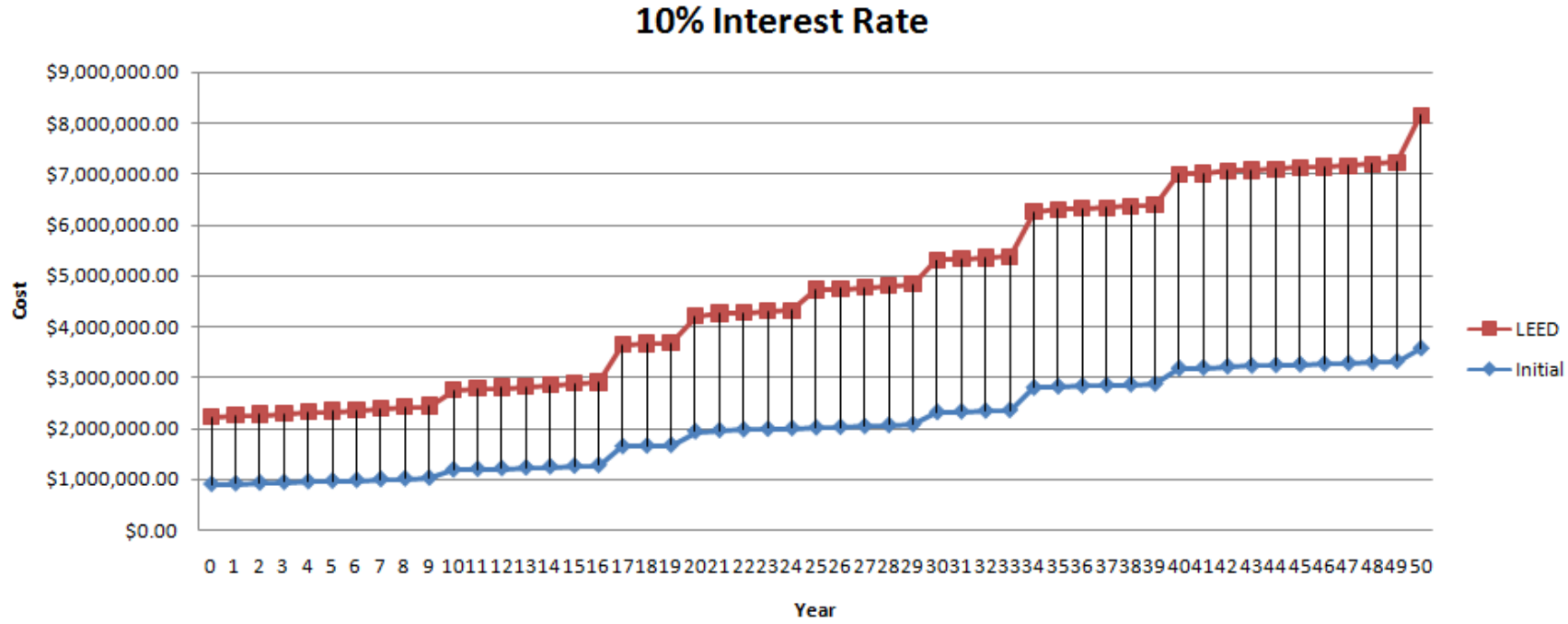


Figure 5: Lifecycle Cost of Base Structure vs. LEED Silver Certification 10% interest rate

Discussion

Upon completion of the cost analysis multiple issues come to light. In the structure this size with the modifications chosen L.E.E.D. Silver Certification is not a wise economical investment. The cost differences between a structure without L.E.E.D. modifications vs. one with the modifications shows that L.E.E.D. will cost the structure's owner a minimum of \$500,000 dollars extra and can vary up to \$750,000. However, if we look at these differences from a yearly standpoint this cost is an extra \$10,000–\$15,000 per year. This is a substantial increase in cost.

This being said, it begs the question, how much money is an acceptable amount to spend to help the environment? With the modifications made to the structure it now uses 35% less energy and over 50% less water. If every structure in the country was optimized as much as this structure the energy consumption of buildings in the United States would drop from 75% of all energy consumed to 49.8% of all energy consumed. This is an exorbitant change in energy usage. The savings in potable water would be large as well, although not nearly as much as energy usage. domestic and commercial water usage only accounts for 12% of all water used in the United States (P. Torcellini p.13). Still to save 6% of the total potable water is a considerable amount especially with the limited amount of potable water.

Although the final decision lies with the owner of the structure, when considering whether or not to upgrade a structure to the specifications of L.E.E.D. Silver Certification this decision should not be made from a purely economical standpoint. There are important environmental implications to “Going Green”. In a world where global warming is a definite problem it is more important now than ever to include the environment in one’s decisions.

Although reaching L.E.E.D. Silver Certification is very expensive in this structure one can change their building to a lesser extent. Any and all changes to help the environment would be beneficial. Also, this project is being created for institutional purposes so it is exempt from the tax breaks offered both by the state and federal government. If these tax breaks were able to be implemented the difference in price between the base structure and the modified structure would have been decreased. The data suggests that this certification is impractical for this structure, but another building, used for a different occupancy, may find that achieving L.E.E.D. Certification to be a more economically sound investment.

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Appendix A: An Introduction to Photovoltaic Cells

Photovoltaic Cells

One of the various technologies that can be applied to a building in order to increase the use of renewable energy is a photovoltaic, or solar, cell. The use of these cells is increasing at a rapid rate in today's society. These systems are highly complex systems and require many disciplines of science to understand. The reason for this is that photoconductivity, the process of turning photons emitted from the sun into a usable DC current, is a process that requires various components of many fields including electromagnetic and solid state physics to understand.

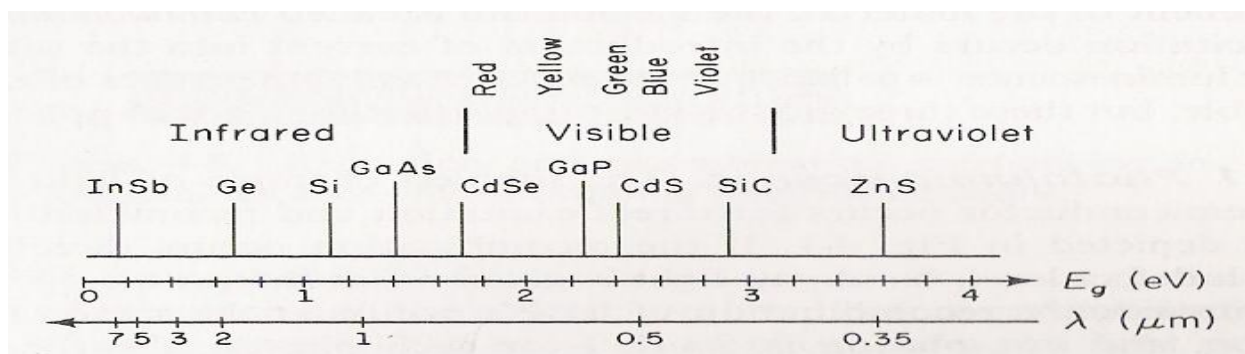
In order to begin talking about solar cells one must first look at the design and then from that one can show how all of the parts of the cell work in order to form a cohesive mechanism able to convert the energy of incident photons into a usable energy source. The common cell is can vary in size from around 3' by 1.5' to a 3' by 5' and is always comprised of a multitude of smaller cells encapsulated in a metal frame with a glass covering over the top to protect the cell's integrity. These cells are connected via a semiconducting lattice, which carries the current produced from the cells themselves into an inverter placed on the inside of the building. This current then does one of three things. It can either go directly into the building if there is a need for it, it can be sent back into the energy grid and the owner will be paid for the energy supplied to the grid, or it can be stored in a battery in order to prepare for a failure of the utility systems (Solar p.1).

Photoconductivity and the p-n junction:

In order to understand solar cells completely one must understand each one of its processes individually and then look at how the system functions as a whole. The first process and possibly the most important is the process of photoconductivity. This process is extremely well known, however it is the basis of all solar energy. Photoconductivity is defined as the process by which photons excite electrons out of their valence shell to create a current.

Photovoltaic cells make use two different sheets of amorphous silicon in order to create a material that can perform this process. In order to understand this process one must look into the field of chemistry and define what a valence shell is. A valence shell is the outer shell of the electron configuration of an atom. In a silicon atom which contains 14 electrons, the valence shell contains four electrons, two in the 3s shell and two in the 3p valence shell. This leaves silicon open to bond with other substances. In photovoltaic cells the most common material to bond with silicon are boron and phosphorous. The reason for this is that these two atoms, when bonded with silicon atoms, create materials that contain completely different properties.

Another quantity that must be defined is taken from the field of solid state physics. This quantity is called the band gap energy, and it is defined as the amount of energy that is required for an electron from the valence shell of a material to be excited into the conduction band of that material. In a photovoltaic cell the photons that are either equal to or greater than this energy that are absorbed into the cell. This band gap is highly dependent on the material used, and a graph of how much this energy can vary is given below.



(Streetman p.99)

In silicon photovoltaic cells the most common materials that are doped with silicon are boron and phosphorous atoms, as stated before. This is because these two atoms also have various properties pertaining to their valence electrons which make them highly valuable when creating a photovoltaic cell. The boron atom contains five electrons total and therefore has three electrons available in its valence shell. These electrons completely fill the 2s shell and also partially fill the 2p shell with two of its six possible electrons. When doped with a silicon atom this creates a p type material, which is a material that is missing one electron for each doped molecule. This creates a hole in the valence band of the material. Phosphorous though has fifteen electrons total which fills the 3s shell completely with two electrons and fills the 3p orbital of the atom partially with three electrons. Because of this, when the phosphorous atom is bonded with silicon atoms it creates a material called n type which contains an extra electron in its valence shell. When the n type and the p type materials are placed in close proximity to one another they form what is known as a p-n junction.

The p-n junction is responsible for all of the energy that is created in the solar cell.

Now that the basic properties of a solar cell are defined we can begin to define the processes that these independent systems perform. To begin with one must examine the process of photoconductivity. This process is fairly straightforward if we develop it starting from the formation of the p-n junctions that govern the output. A p-n junction in the most common photovoltaic cells is created by doping, or inserting elements/abnormalities into a substance, to separate sheets of amorphous silicon with two different types of materials. The first sheet is doped with boron atoms, and is called p type silicon, and the second sheet is doped with phosphorous atoms and is called n type silicon. When the n type silicon is created it creates a material in which each of the atoms are missing an electron in their outer valence shell. The n type silicon forms another type of material which has an extra electron in its valence shell. When these two doped silicon sheets are combined together the n type silicon shares its electron with the p type junction and they form the p-n junction.

It is at this point that we must introduce a concept called the band gap energy. This is the energy that is required to enter the p-n junction in order to excite the electron from the valance shells of the material into the conduction shell of the material. In order to correctly explain this process we must first look into the field of solid state physics. In this field there is a quantity, band gap, defined as the amount of energy that an electron in the valance band of a semiconducting material requires in order to be excited into the conduction band. It is photons that are either equal to or very near to this band gap energy that are absorbed effectively. It is, in general, these photons with an energy that is either equal to or exceeds this band gap energy

which are absorbed by the solar panels and used to create energy, because photons with much greater energy than that of the band energy are usually absorbed at the surface and are not very important when we consider the conductivity and photons with an energy lower than this value are unable to excite the electron enough (Streetman p.96). This band gap is highly dependent on the material used, and a graph of how much this energy can vary is given below.

(Streetman p.99). When this photon is absorbed and the electron is excited into the conduction band there is what is called an electron hole pair of EHP formed. It is the electrons from these EHPs that are carried to the semiconducting lattice, via an electric field, and create the current which powers the system. The amount of band gap energy photons that will be absorbed depends on the material and the photon's intensity, I , in the form:

$$I_{\text{total}} = I_{\text{original}} * e^{(-\alpha L)} \quad (\text{Eq. 1})$$

Where α is the absorption constant of a material, and L is the thickness of the material (Streetman p.98). As materials with better absorption constants are created more photons will be able to be absorbed, and therefore increase the conductivity of the materials.

Generally, when considering semiconductors one must consider the rate at which direct recombination occurs. Direct recombination is the process of the free electrons filling the holes in the valance band in order to create a state of equilibrium. If direct recombination is able to create a state of equilibrium there will be no induced current, so it essential to the solar cell to extract the electrons before they are able to re-enter the valance band. The rate at which this occurs is given by the equation

$$- (dn(t)/dt) = \alpha_r n(t) p(t) - \alpha_r n_i^2 \quad (\text{Eq. 2})$$

Where: α_r is the proportionality constant for recombination

$n(t)$ is the excess electron population as a function of time

$p(t)$ is the excess hole population as a function of time

This equation is essential to the solar cell and can be considered as one of the governing equations of the solar cell (Streetman p.106).

The p-n junctions are also important because they provide a way to measure the current density during the entire process. When one takes the density of holes in relation to the density of electrons and how it changes with time in a non-equilibrium state, an equation for the total current density moving through an area of the cell can be derived. The current density if an electric field is present, as in a solar cell, is defined as the drift component of the current (due to the electric field) added to the diffusion component (due to random thermal motion among atoms). These two quantities are defined by J_{en} and J_{dn} respectively for the relationship of electrons in the valence shell, and as J_{ep} and J_{dp} for the holes where:

$$J_{en} = q\mu_n n(x) E(x) \quad (\text{Eq. 3})$$

$$J_{ep} = q\mu_p p(x) E(x) \quad (\text{Eq.4})$$

$$J_{dn} = qD_n (Dn(x)/dx) \quad (\text{Eq.5})$$

$$J_{dp} = -qD_p (Dp(x)/dx) \quad (\text{Eq. 6})$$

And μ is the electron mobility coefficient, D is the diffusion coefficient defined as $dl/2dt$, and $n(x)$ and $p(x)$ are the functions as units of length of both the hole and electron densities (Streetman p.122).

$$f(E) = 1 / (1 + e^{((E-E_F)/kT)}) \quad (\text{Eq. 7})$$

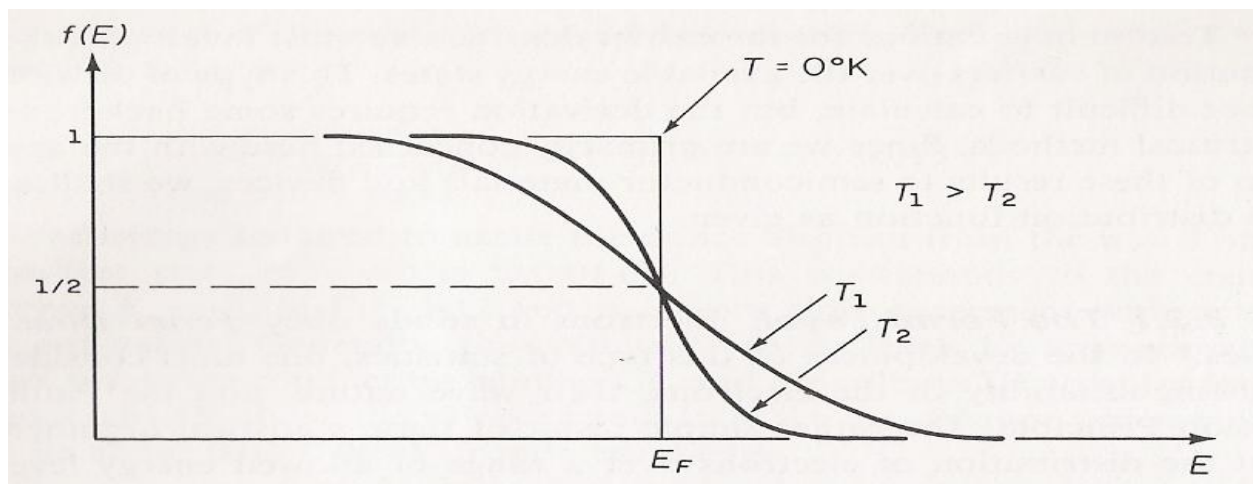
Where: k is the Boltzmann constant 8.62×10^{-5} eV/degrees K

T is the absolute temperature

E_F is the Fermi energy level

(Streetman p.71)

Using this equation we define the energy E to be equal to the Fermi energy we find that the Fermi state has a fifty percent chance of being occupied by an electron. When $T=0$ it can be shown that the probability of the valence shell being filled is 1 when the exponent is negative, and it is 0 when it is positive. Thus proving that at $T=0$ every energy state up to E_F is full and every energy state above that level is empty. Choosing this value for the Fermi energy ensures that all points, above and below the Fermi level, are symmetrical. This energy level happens to end up being exactly half way between the valance shell and the conducting shell (Streetman p.71). In the graph below there is a picture of the Fermi-Dirac function and its distribution for three separate temperatures. It shows the symmetry with respect to all points above and below the Fermi Level defined as half way between the Fermi-Dirac function.



(Streetman P.71)

Using this property and defining Quasi-Fermi levels we are able to rewrite the current density in terms of the carrier density equation, the charge, the Quasi-Fermi levels, and the electron mobility coefficient in the form

$$J_p(x) = q\mu_p p(x) \frac{d(F_p/q)}{dx} = \sigma_p(x) \frac{d(F_p/q)}{dx} \quad (\text{Eq. 8})$$

Where F_p is the Quasi-Fermi Level for holes

And

$$J_n(x) = q\mu_n n(x) \frac{d(F_n/q)}{dx} = \sigma_n(x) \frac{d(F_n/q)}{dx} \quad (\text{Eq. 9})$$

Where F_n is the Quasi-Fermi Level for electrons (reference 4P. 125)

This formula shows that the current produced by any drift or diffusion is proportional to the gradient of the Quasi-Fermi Levels (For the explicit derivation and explanation of this refer to Appendix I). If the current density is then multiplied by the cross sectional area that the current is flowing through we can calculate the current flowing through the wire as current density is defined as the amount of current flowing through a unit area (Griffiths p.213). Knowing the amount of current that is flowing through the system is important because the total usable energy is directly related to the current exiting the system.

One other property of p-n junctions must be mentioned. By the formation of these junctions alone there is a diode created. This diode can take many different forms depending on the configuration of the junction and with each of these different forms different properties of the junction can be obtained. For solar cells, the diode that must be created is a photodiode which is simply any single junction device that is designed to respond to photon absorption (Streetman p.223).

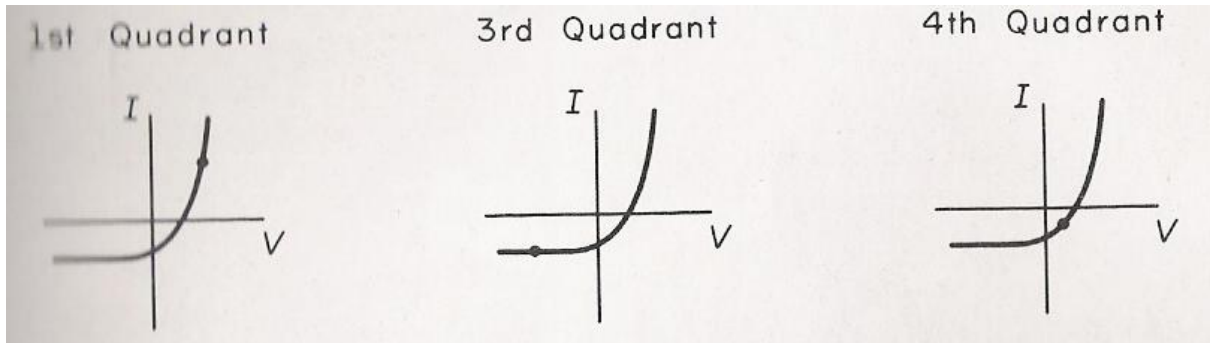
It is this specific photodiode that is solely responsible for the photovoltaic cell's ability to create energy out of radiation emitted from the sun. In order to create a photodiode one must create a reverse bias p-n junction, creating a rectifier. This means that the p type atom is now

negative relative to the n type which causes the current to flow in one direction (Streetman p.222).

The solar cells photodiodes must have specifications in the silicon in order for it to facilitate its function. The main characteristic that governs whether a photodiode will perform is that the p-n junction must be smaller than the diffusion length of holes in the p region, and electrons in the n region. This conclusion is obvious if one considers the system. If this property is not true then the EHPs will be able to complete the process of direct recombination. When initially designing the solar cell the engineers discovered a problem. Using a typical photodiode the contact voltage V_0 of the p-n junction needed to be high, as high contact potential leads to high photovoltage. This was a serious problem because the contact potential is directly proportional to the amount of doping in the silicon, and the lifespan of the cell is inversely proportional to the doping of the system. This meant that making a cost effective system would be extremely difficult.

However, to rectify this problem we can input a photodetector. In its simplest terms the photodetector is a mechanism used to change varying optical signals into an electrical current (Streetman p.238). The photodetector has a property that is invaluable to a solar cell. When a photodetector is functioning in the third quadrant of its graph of current vs. voltage (See graph

Below) the current is essentially independent of the voltage.



(Streetman p.235)

If the current is no longer affected by the contact potential, then what is it affected by?

In the case of the photodetector we know that the current I is then directly proportional to the optical generation rate which is defined as

$$g_{OP} = \alpha_r(n_0 + p_0)\delta n = \frac{\delta n}{\tau_n} \quad (\text{Eq. 10})$$

Where α_r is the recombination coefficient

n_0 is the equilibrium coefficient for free electrons

p_0 is the equilibrium coefficient for holes

and δn is the excess electron density (Streetman p.114).

The relationship of the optical current to the optical generation rate is given by

$$I_{\text{optical}} = q \cdot A \cdot g_{\text{optical}} \cdot (L_p + L_n) \quad (\text{Eq. 11})$$

Where: q is the charge

A is the cross sectional area that the current is flowing through

g_{optical} is the generation current due to minority carriers

L_p and L_n are the diffusion lengths for the hole and electrons respectively (Streetman p.232)

By substituting this equation into the total current equation of a carrier which is derived in Appendix II we find that the equation for the total current in the photodiode is

$$I = qA \left(\frac{L_p}{\tau_p} p_n + \frac{L_n}{\tau_n} n_p \right) (e^{qV/kT} - 1) - qAg_{op}(L_p + L_n) \quad (\text{Eq. 12})$$

(Streetman p.223)

When actually calculating this current for a single photodetector this current is in the milli-ampere range, but when there are many of these junctions combined the result can be a significant amount of current. It is this current that is transferred to the inverter and used as energy in a given solar cell application.

Inverters

An inverter is an essential component of a solar energy unit. Without it the DC current created by the photodiode would be useless in our current electrical systems. However this component of a solar cell has the shortest life span in the range of 5-10 years depending on size and quality, and most manufacturers are only offering replacement warranties in the 3-5 year range. This shows that the manufacturer does not truly know the lifespan of the inverter.

The inverter itself is a highly complex circuit. It involves multiple capacitors, transistors, and inductors. The type of inverter that is typically used in a solar cell is the saturated core inverter. This is an inverter in which the transistors diodes, which are npn diodes are forward bias. This property of saturation creates various complexities in the function of the inverter related to the short lifetimes.

The reason that the lifetime of the inverter is so limited is due to the fact that the inverter contains transistors that are subject to transient waves as one transistor shuts off and the other begins to turn on. Although this transient wave over a short period of time can be neglected, but if this process is repeated indefinitely as in a solar cell this process begins to degrade the transistor (Gottlieb p.44-45). These transient waves although they do not increase the temperature of the transistor significantly it is proven that the efficiency of the transistor due to these waves is drastically decreased over time.

These spikes are due to two factors, one of which is called leakage inductance, and the other is that there is an induced EMF when the current is shut off. This EMF however is countered by the alternated transistor creating a "clamping" force which greatly limits the electro motive force (EMF). The leakage inductance, which is a property of an electrical

transformer that causes a winding to appear to have inductance in series with the mutually coupled transformer windings due to imperfect coupling of the windings and the creation of leakage flux, is a much more complicated process to understand, and modern science has only been able to analyze this problem empirically (Gottlieb p.46). The only correlation that can be deduced is that as the leakage inductance of a system is increased the amplitude of the spikes is increased. This process is also amplified but the fact that saturable-core inverters, like the ones used in most solar applications, require feedback to maintain the transistors in saturation during their "on" periods (Gottlieb p.46). This process is shown to increase with the base drive of the system. It is because of this fact that research is currently being done in this area in order to further understand this problem (Gottlieb p.46).

There are various formations of the circuit inside of the transistor that are being researched in order to rectify this problem, but with each alteration there is a compromise made in another part of the inverter, and all configurations of the circuit that are progressive are still too costly to put into production.

Lifecycle Cost

In an institutional building the owner plans on owning the building for an extended period of time, usually in the range of 40-50 years. In this period of time there are various maintenance costs on a solar system that cannot be overlooked. For instance due to the Satebler- Wronski Effect, which states that the tendency of the sunlight to alter the composition of the silicon wafer will decrease the efficiency of the system given by the relation

$$N_d(t) = \text{const } G^{2/3} t^{1/3} \quad (\text{Eq. 13})$$

Where: N_d is the defect density induced by the sunlight at a given time

G is the illumination density

t is time

(Kolodziej p.22).

This effect causes the photovoltaic cell to be replaced every 15-20 years, and it also causes the amount of energy that is produced by the cell to decrease as time passes.

There are other elements that contribute to the lifecycle cost as well. The inverter, that must be used in order to change the energy gathered by the panel into a usable energy source, tends to fail every 5-10 years. The battery that generates the electric field inside of the solar cell also must be replaced. This occurs every 2-3 years on average.

So with all of these factors included one can see that considering the initial cost of the system is not enough when factoring whether the system would be an effective addition to the building. A cost breakdown per decade must be applied in order to see if the institution should implement this design.

Adding all of the factors included in maintenance fees for a fifty year cycle we find that the solar cells themselves must be replaced approximately three times, the inverter would need to be replaced at least five times, and the battery will need to be replaced approximately fifteen to twenty times. On top of this the installation fees must be incorporated as each time the system requires maintenance removal of the old product and installation of the new product.

Appendix B: Structural Layouts

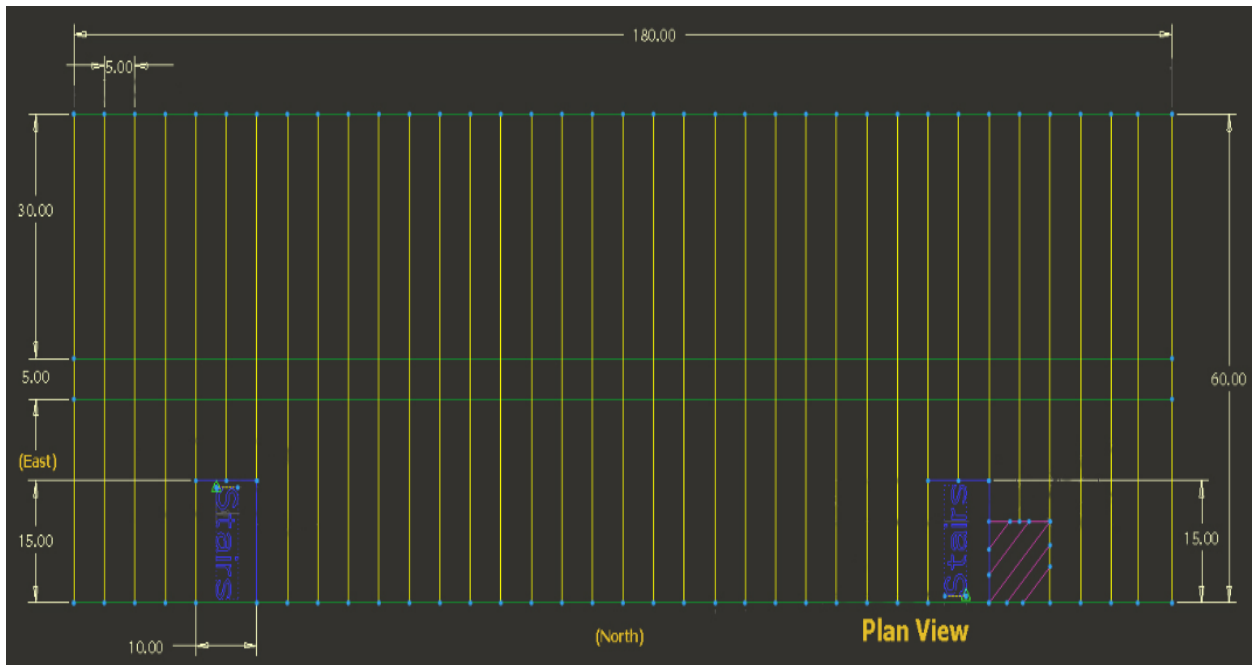


Figure 6: Plan View 5' beam spacing

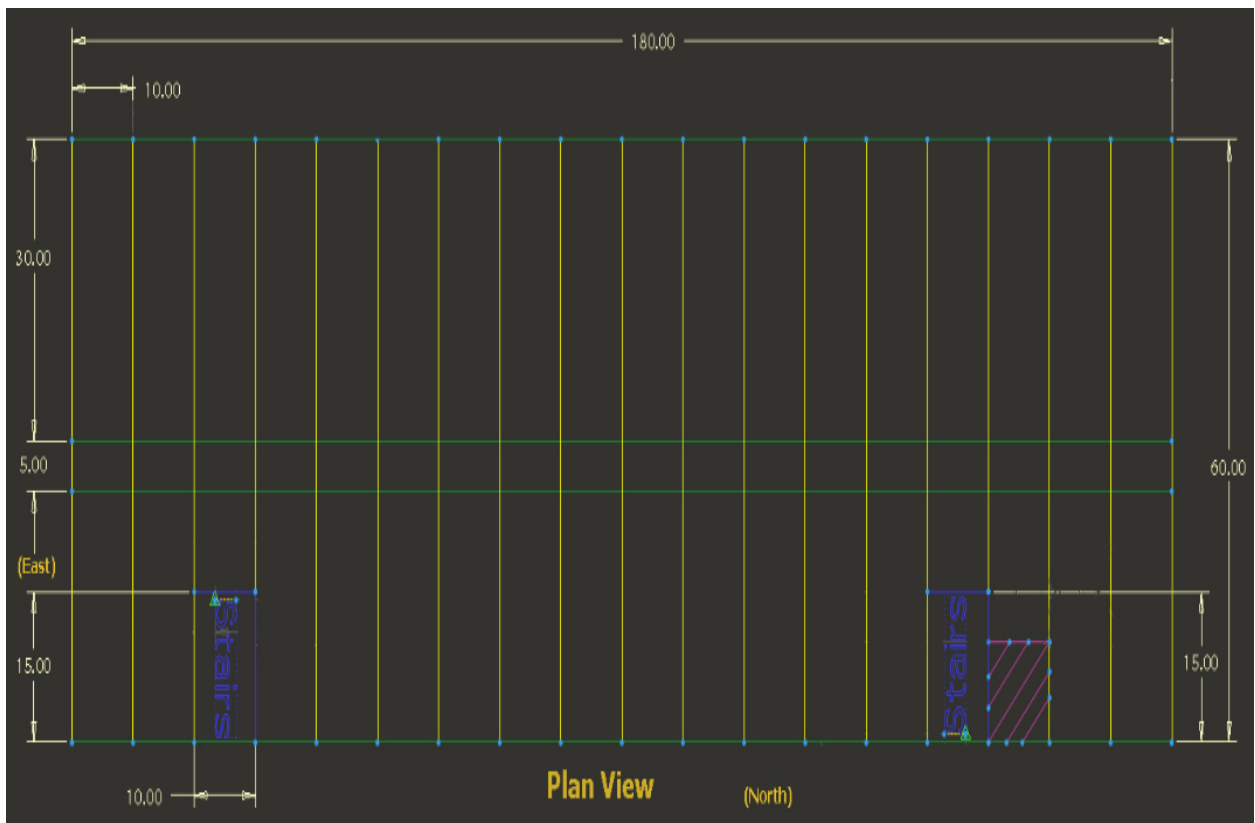


Figure 7: Plan view 10' beam spacing

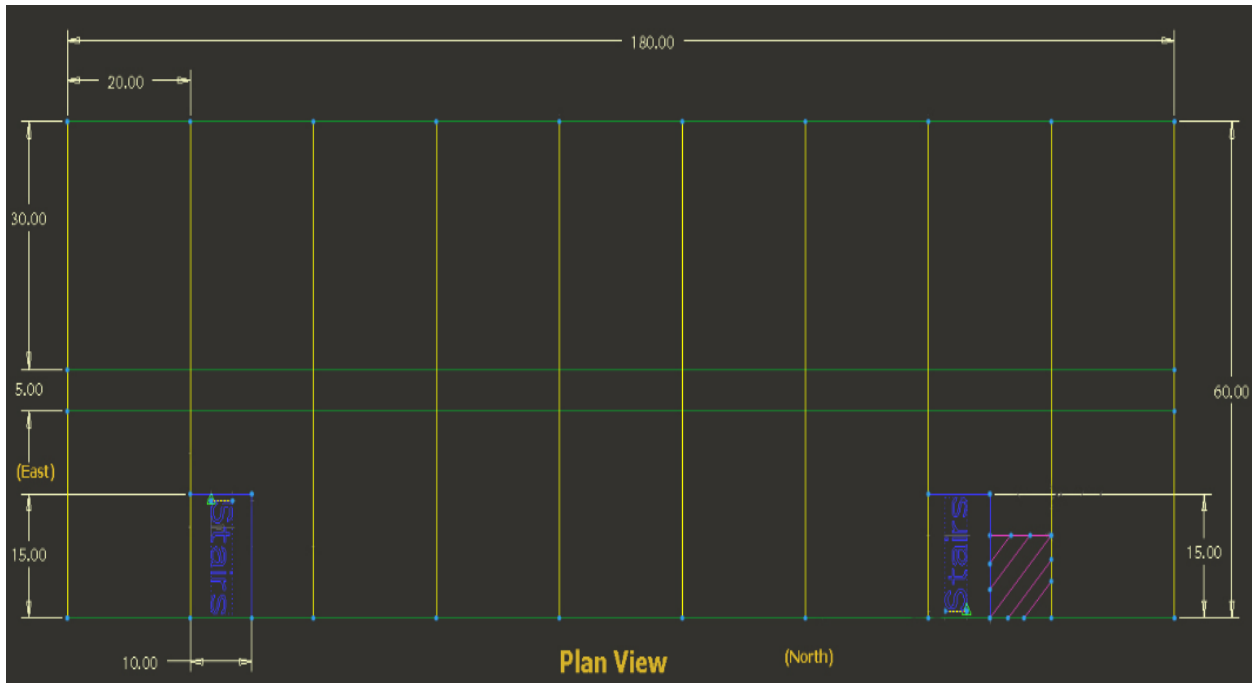


Figure 8: Plan View 20' beam spacing

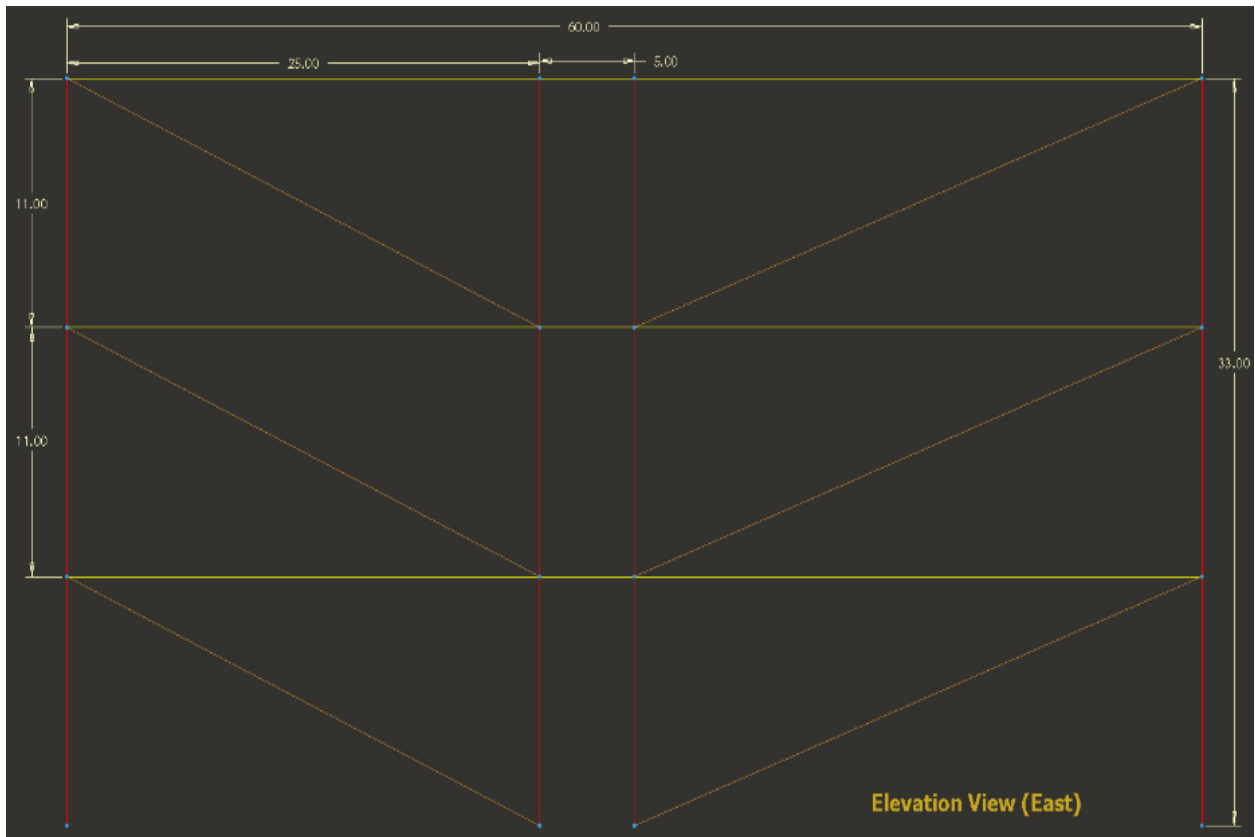


Figure 9: Elevation view East side

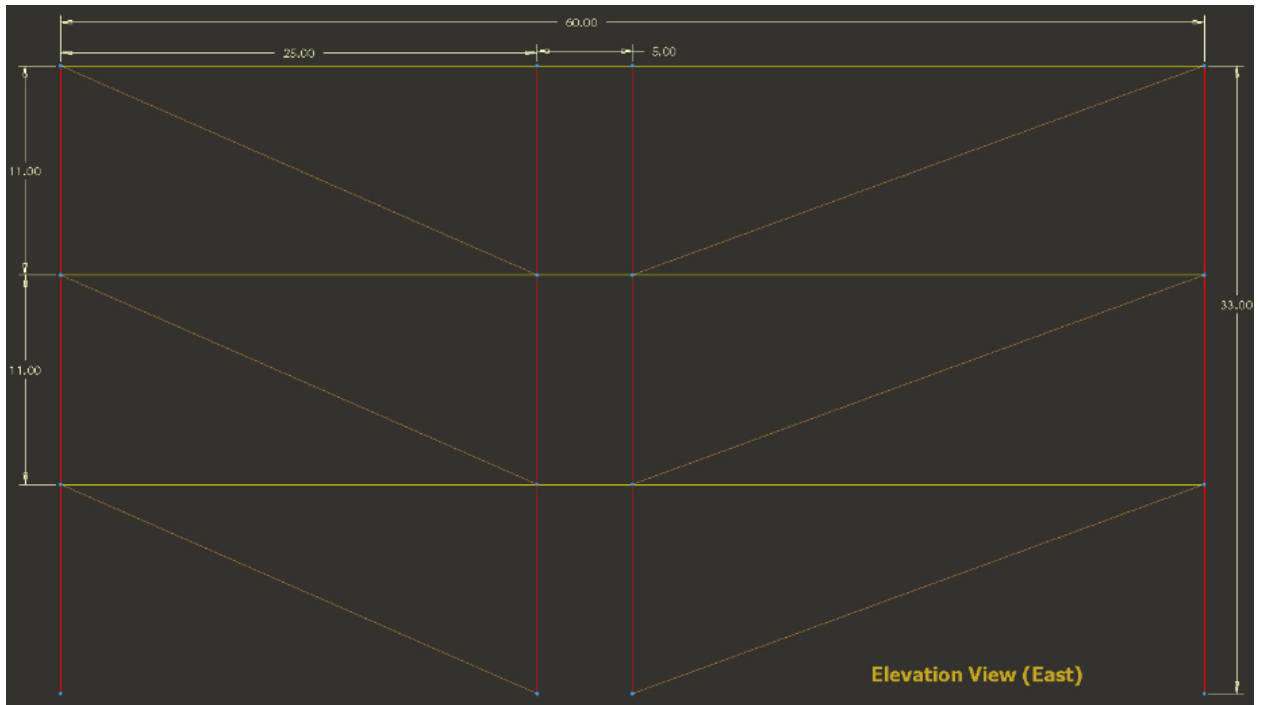


Figure 10: Elevation View North side

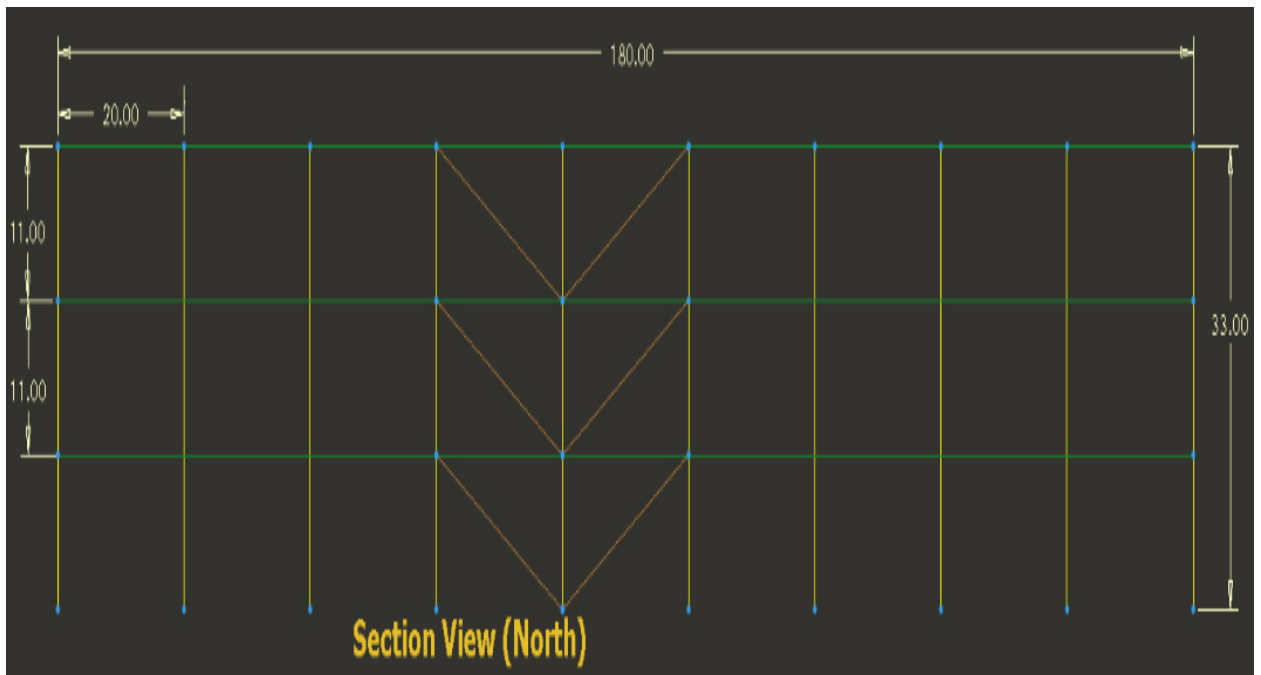


Figure 11: Section View Facing North

Appendix C: MQP Proposal

Introduction

One of the most important considerations one must make when designing a building is determining what members should be used in order to provide the lowest construction costs. The cost of materials is usually the majority of the cost of any construction project. Therefore any modifications to the structure that can reduce building materials and consequently building cost are desirable. Another trait that is highlighted for building design is building green structures. This project will also focus on creating a green structure using the L.E.E.D. guidelines.

This Major Qualifying Project will accomplish this task while maintaining a dual girder system slightly off center in the building. Because the majority of the internal walls in this structure will have to be changed throughout the life cycle of the structure to compensate for the various special needs that may be required, there are only certain degrees of freedom that can be taken into account in the design process. For this building these degrees of freedom are the spacings between beams and/or columns, the types of footings or foundations used, and the type of flooring material to be used. So for the purposes of this structure it is these elements of the structure that will be analyzed. Each of the structure layouts that will be presented will contain a cost analysis

breakdown including material cost, approximate labor costs, maintenance costs, and demolition/removal costs.

In order to determine beam/column/footing sizes and spacings one must look at the loads on a system and compile them into the total force acting on the members. For the building in question these loads will be calculated using the International Building Code (IBC), and they are the wind load or the earthquake load (whichever is greater), snow loads, loads on the building due to building materials and other structures (Dead Loads), loads incurred on the system due to the building being used (Live Loads), incurred on the building by photovoltaic cells placed on the roof, and loads due to utilities i.e. HVAC, electric, plumbing, lighting etc. These loads when compiled will be the total load on the system and will govern the types and sizes of the material.

In addition to determining the cost effects of each of the modifications and determine the layout that is the least expensive, this project will also calculate lifecycle costs for the entire site. This includes not only the initial cost and maintenance costs of the building but also potential tax rebates given by government offices for satisfying certain building/ green energy criteria, and the operating cost of the entire structure as a whole. One of the criteria of tax rebates is to modify the building/site in order to bring it to L.E.E.D silver status or higher. Another includes providing renewable, sustainable energy sources. These tax reductions will be calculated using the DSIRE

Massachusetts Incentives for Renewables and Efficiency and the Federal Incentives for Renewables and Efficiency.

This Major Qualifying Project will design a 160' X 60' building that is for business use. The building is then characterized as a group B building by the IBC code and will follow all specifications stated in the code manual. This building will have a, near central, dual girder system which, with the help of the exterior walls will support all loadings on each of the three floors individually. The building will also have handicapped accessible egresses as well as meeting all design code requirements for handicapped persons. The structure will also have many arrays of photovoltaic cells on the roof of the building in order to provide an alternate source of renewable energy.

In addition to meeting capstone design requirements for a Bachelor of Science Degree in Civil and Environmental Engineering, this project will also satisfy the capstone requirement for Physics. To accomplish this it will explain how a photovoltaic cell works in order to create a usable renewable energy source. The analysis of the photovoltaic cell was chosen due to its rapid increase in use over the last ten years, and especially in the last three years due to increasing oil cost. Also the photovoltaic cell or solar cell as it is commonly known is a complex system that relies on multiple fields of physics in order to function.

Each of these systems will be examined in detail, and an overall description of the system and how its processes work to provide a usable renewable energy source will also be included. This will involve the use of several fields of physics including electromagnetic theory, quantum mechanics, and solid state physics. These fields allow one to analyze physical makeup of the cell down to an atomic level, as well as define the chemical properties of the substance that all for the main process used in a solar cell, photoconductivity. Quantum mechanics provides a way to understand how the materials used in a solar cell bond with each other and create what is known as a p-n junction. Solid State Physics allows one to understand how a material as a whole is able to transfer small amounts of charge from one point in a system to another point. And, Electromagnetic theory gives one the ability to calculate how charge is accumulated in the system and also explains how much current is delivered to the structure in the form of DC current. In order to completely explain how the system functions another process must be explained briefly as it converts the DC current that a photovoltaic cell creates into an AC current which is what almost all modern structures depend on. This process is accomplished via the use of an inverter, and its circuitry must be discussed briefly in order to fully understand how one can extract power from the sun's energy. The inverter is of special interest when considering the lifecycle costs of the photovoltaic cell system because its lifespan is the shortest of any of the other components.

Typically the inverter must be replaced every five to seven years due to its failure, and because this is an expensive component, replacement costs over a fifty year cycle can become expensive.

As well as defining the process and how they work a brief look at new advancements in the field will also be provided, with projected cost analysis for each of the new technologies that are feasible to use on a building. Various modifications are being considered in solar cell systems because the efficiency achieved in modern solar cells is half of what the optimum photovoltaic unit could produce. These modifications usually consist in changing the materials used in the solar cell. However, there are also other research areas looking to decrease the cost of these systems. These other areas are including but not limited to the creation of thin film solar cells, modifications in antireflective coating, and efficiency increases in the inverters by modifying its circuitry. Although most of these advancements are not in full production yet many of these systems provide a much more efficient gathering of photo electricity.

Objectives

This project has various objectives that must be completed at various stages. These include:

1. Applying undergraduate coursework understanding to a real world application
2. Designing a structure using multiple layouts
3. Provide a complete understanding of photovoltaic cells and their applications
4. Create a Green Building using L.E.E.D. guidelines
5. Provide a cost analysis of life cycle costs of the entire structure including installation, maintenance, and removal costs.

Scope

This project can be broken into a small set of individual parts. These parts are the design of the base structure and its modifications with respect to beam/column/girder size and span, design of the structure incorporating photovoltaic technology, mechanisms of photovoltaic technology, current research in photovoltaic technology, L.E.E.D modifications, and cost analysis of each system and the system as a whole.

Design of Base Structure

The first task of this project will be to provide multiple design options for a 160' X 60' building with near center dual girder design. This will be accomplished by first by spacing columns at twenty foot increments and adjusting the beam spacing. The loads will be calculated by using beams that are spaced five foot apart up to twenty feet apart increasing at five foot increments. This will be repeated for each of the column spacings which will begin at forty foot spacing, one quarter of the length of the building, and will be decreased by ten feet in each of the iterations. Each of the floors will be analyzed by this method in order to determine the most cost effective situation. The loads that must be considered when analyzing the system are:

- I. Gravity Loads i.e. weight of slabs, beams, columns, and girders
- II. Lateral Loading i.e. earthquake loads, wind loads

Design Incorporating Photovoltaic Technology

This process is similar to the previously stated process with the slight modification that the loads on the structure will be different. A large array of photovoltaic cells will be placed on the roof of the structure, which will increase the dead loads on the building. Each of the designs in the previous portion of the project will be reanalyzed for the photovoltaic cells and beam/column/girder sizes will be adjusted accordingly.

Mechanisms of Photovoltaic Cells

Each of the various processes of the photovoltaic cell will be defined and explained in this section. This incorporates how p-n junctions are formed and operate. This includes the use of the Pauli Exclusion Principle and an explanation of orbitals and how silicon is altered through the process of doping. Some topics that will be discussed from the field of solid state physics are the definition of a conduction band, valance band, and band gap energy. Also in this section the process of photoconductivity will be discussed and explained in detail. A derivation of how current flows through the system will also be incorporated.

Current Research

This section will introduce areas that are currently being improved upon in the photovoltaic cell industry. Topics that will be discussed are new materials being used in the field, thin film solar cells, orientations of arrays of photovoltaic cells, and a brief explanation of why these are the fields being researched will be included.

L.E.E.D Modifications

Once the design of the structure is complete there are various minor and some non minor alterations that can be made in order to allow the structure to obtain a silver rating by L.E.E.D. standards. These will include alterations to the entire site not just the structure itself. Also a brief analysis of the points system will be analyzed including its flaws, and its strengths.

Cost Analysis

When all modifications and iterations have been completed one must determine whether the addition of these modifications is a feasible option. In order to determine whether this option is feasible a lifecycle cost analysis must be determined. This will be done over a fifty year period and will include all costs during this period. This section will also describe the cost flow as a function of time as well as a totaling of all costs as an initial cost for the system.

Appendix D: Additional Calculations

In order to calculate the energy and water costs for the structure energy and water costs per square foot were taken from the Massachusetts Department of Energy website. These values were found to be 18 cents per square foot per year and 8 cents per square foot per year respectively.

Then, in order to calculate the total cost for this structure these values were multiplied by the total square footage of the structure. The formula is as follows

$$A * B * C = \text{total yearly cost}$$

Where: A is the cost per square foot of the structure per year

B is the square footage of each story, and

C is the number of floors

These yearly values were found to be \$5177.98 per year and \$2208.82 per year respectively.

Then when the green technology was added there were additional savings in water and energy costs. The water costs were reduced to half because of the instillation of eco-friendly urinals and toilets as well as aerators in each of the faucets. Using Lowes and Home Depot's websites the average toilet was found to consume an average of 3.5 gallons per flush for toilets and 1.9 gallons per flush for urinals. However, the eco-friendly fixtures only consumed 1.6 and .9 gallons per flush respectively. This in addition to the aerators that were installed and improve water efficiency by fifty percent allowed for the savings of over half of the water costs for the structure.

The electricity savings were more difficult to approximate as the building's electrical system cost was estimated. So, using the L.E.E.D. modifications and values found for a breakdown of a structure's total energy consumption percentages were deducted from the total energy cost of the structure (Energy). This was done by the following formula:

$$D * E * F = \text{Total cost of system being analyzed}$$

Where: D is the total energy cost of the structure

E is the percentage of the energy cost that is designated to the system i.e. electrical or mechanical

F is the percentage reduction in the system's cost due to green modifications

Also, in order to fully compensate the cost of each of the changes the components to each of the systems, such as dimmer switches, aerators, thermostats etc., had to be figured into the cost. Each of these components were priced using Lowe's and Home Depot's website and their costs were added into the total cost of each of the systems and their replacement costs were added into the cost analysis.