WORCESTER NORTH HIGH SCHOOL

FINAL THESIS REPORT :: **ADAM TRUMBOUR** :: CONSTRUCTION MANAGEMENT

ADVISOR: JIM FAUST :: **APRIL 7, 2010**

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ACKNOWLEDGEMENTS

Special thanks go to the following people for helping me through thesis:

Gilbane Building Company:
Joe McCoy
Melissa Hinton
Tony Iaccarino
Justin MacEachern

Mintz Levin Cohn Ferris Glovsky & Popeo PC:
Will Hill
Lisa Glahn

Rhodeside & Harwell, Inc.:
Aaron Feldman

Earth Our Only Home, LLC:
Karen Weber

Many Penn State faculty for their help and understanding,

My fellow AE students for their technical help and moral support,

My family and friends for their moral support,

And to anyone I may have forgotten,

Thank You.

EXECUTIVE SUMMARY

This is the final report on a construction management study of the Worcester North High School project. It aims to reflect a year's worth of analysis tied with a semester's worth of research. There are four analyses that were conducted for the body of this thesis, detailed below.

Demonstrating proficiency in construction management is the depth analysis on sustainability rating systems—primarily CHPS compared with LEED. This analysis takes a review of the current CHPS and LEED systems to define each one's strengths and weaknesses. Furthermore, surveys were sent out to industry professionals in Massachusetts to glean their opinion of the two methods of certification. Based on this data, it is apparent that CHPS is a better system for school in Massachusetts, but that it lacks the robust education and knowledge base that LEED provides.

Next, an electrical breadth analysis on implementing a grid-tied solar photovoltaic system was conducted. This aimed at providing two design alternatives: one that met the $250,000 allowance in the project budget and one that fit in the space allotted on the roof by the design engineers. A 38.6 kilowatt system and a 7.59 kilowatt system are designed and compared; both systems provide energy savings over time.

For a structural breadth study, the design and installation of a green roof was examined. Included in the study is a review of available green roof assemblies, costs, and structural implications. A typical bay of the roof structure was analyzed to ensure its suitability for a green roof assembly. According to these calculations, a 23 psf roof landscape will work fine.

Finally, as a lighting/electrical breadth, LED luminaires were considered for use on North High School. Research shows that LEDs are not suitable yet for general illumination but do have a niche in down lighting and accent lighting. As an alternative, an LED recessed downlight was looked at to determine if it could be used on North High School. Initial procurement costs made this option unfeasible, despite significant energy savings over time.

PROJECT OVERVIEW

HISTORY OF PROJECT

Situated in central Massachusetts, Worcester is a small city of 183,000 people spread over 38.6 square miles. The Worcester Public School System operates fifty-two schools in the area, of which seven are considered High Schools. One of these seven, North High School, is an existing facility located at 150 Harrington Way, as shown in Figure 1A. This one-story building, approximately 75,000 square feet (SF), was built in 1970. Currently, it serves over 1,200 students and as it is forty years old, North High is showing its age. Horizontal expansion is not efficient given the site constraints, and the primarily masonry construction does not allow for vertical expansion. Furthermore, the forty years of use has rendered the existing facility in need of a total renovation. Upon exploring these project constraints and the costs involved with renovation, the City of Worcester deemed an entirely new structure was necessary.

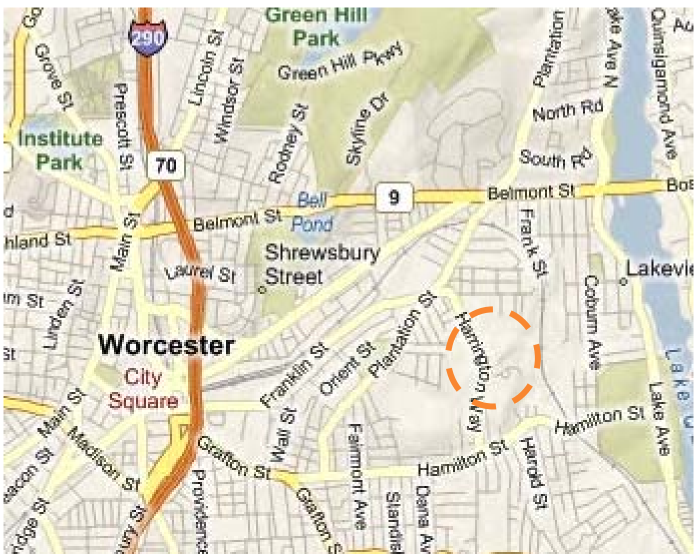

Figure 1A Map of site vicinity.

The existing building is located on a 14-acre parcel of land owned by the City of Worcester; sufficient space was available on this site for the construction of the new building. Plans for a new North High School have been purportedly in the works since the year 2000, though the current project did not materialize until April 2008. Massachusetts adopted the Collaborative for High Performance Schools (CHPS) rating system, a sustainability rating system pioneered by the state of California. The CHPS program dictates the need for early project integration, which is why a construction manager was brought onto the development team early on.

Gilbane Building Company was retained as Construction Manager At-Risk, under a Guaranteed Maximum Price contract. The original contract value (as of April 2009) is $54 Million. Due to the CM At-Risk agreement, Gilbane provided input during the preconstruction phase and is now acting as General Contractor (GC) for the duration of construction. As mentioned above, early input is required under the CHPS program; this aims to curtail budget overruns and schedule extensions due to lack of coordination and constructability.

DESIGN

A new North High School was designed by in-house architecture services for the City of Worcester. The Department of Public Works and Parks has a team of registered architects which works to redevelop Worcester in accordance with its Master Plan; the Architect of Record is Eric G. Twickler. Four floors distribute 195,000 SF of space, which increases the current space by 2.6 times. As the facility will hold a rating by the Massachusetts chapter of CHPS, the design must be innovative, environment and energy conscious. These goals drove the design of the school.

Space is allocated to five general needs of the school: academics, administration, food-service, recreation and the performing arts. There are: a total of 75 classrooms, computer labs and science labs; a 12,500 SF gymnasium with athletic training support spaces; a 1,200 SF library; a 360-seat auditorium; a 2,800 SF cafeteria/food prep space and numerous administration offices.

The exterior aesthetic is composed of brick veneer, metal panels and curtain wall. The brick pays homage to both local architectural styles and the previous school, which was entirely brick and concrete-masonry-unit. Employing metal panels is an injection of modern design and sustainability, as they are fully recyclable. Curtain wall is used, especially in the library, main entrance and gymnasium loggia as a daylighting feature (tying back to CHPS) and to further the overall modern “innovative” style of the new North High school.

STRUCTURAL

A skeleton of structural steel supports the four above-grade levels of North High school. Composite decks (concrete tied to metal decking) rest on typical steel shapes, ranging in size from W8 to W30 in size; the smallest steel member (by weight) is W12x14 while the largest is W30x99. Hollow Structural Sections (HSS) and L-shapes are employed in the gymnasium for the lateral bracing and roof truss systems. Typical floor structural characteristics are 6 ½" concrete slabs on 2" 20-gauge metal deck, reinforced with 6x6 W2.9 W2.9 Welded Wire Fabric (wwf).

MECHANICAL

Heating is generated with two gas-fired boilers capable of outputs from 200,000 – 3,000,000 BTUs/hr. Cooling is available via chilled water furnished by a Trane RTHD series helical rotary chiller, capable of 175-400 tons of cooling load. Classroom spaces are conditioned individually via room Fan Coil Units (FCUs), while support spaces are serviced via Variable Air Volume (VAV) boxes. There is a 15 degree HVAC dead zone where no heating or cooling is provided to improve economy. It is crucial that the chiller and boilers arrive on-site at an early enough point where they can be easily installed. This is an aspect where having a CM on the project early can help with long-lead items and large equipment that requires special logistics planning.

ELECTRICAL

Servicing North High School's electricity demands is a 3-phase, 4-wye utility tie in, rated 4000 Amps at 480/277 Volts. This connection is made at a utility company pad-mounted transformer and switch, located at the southwest corner of the building. Emergency power is provided by a 400 kilowatt (kW) diesel generator, also located at the southeast corner of the building. As designed, fluorescent fixtures dominate the lighting system, with lamps ranging from compact fluorescents (CFL) to—primarily—T8 specifications. Fluorescent hi-bay fixtures are used in the gymnasium for sports lighting.

FIRE PROTECTION

In compliance with the National Fire Protection Association (NFPA) code, state and local code, North High School is fully sprinkled. Every space is served by the appropriate number of heads. Water is supplied to the wet-pipe sprinkler system via 8" fire service connection to the local water utility, backed by a 4" fire department street connection. The quick-action, pendant-type sprinkler heads located throughout the building ensure the safety of its occupants. This system is monitored by an electric fire detection system, which is monitored by the local authorities.

SPECIALTY SYSTEMS

There are several specialty systems involved on this project, meaning that these systems must be planned by a specialty contractor and bid out as specialty items. These include the theatre lighting for the auditorium, the CCTV system (as part of the robust Ethernet network), auditorium seating and athletic flooring. These are reflected in the project scope and schedule as separate bid packages.

PROJECT MANAGEMENT CONSIDERATIONS

CONTRACTING

Worcester Public Schools does not have staff with the qualifications to oversee a major construction project such as North High School. To facilitate project delivery in the interests of the City of Worcester a project management firm, McGuire Group, was retained. Tony DiLuzio is the project manager for the job. The use of a third-party for project management is important, especially on high-performance buildings, since integration of design, engineering and construction management occurs at an early stage; the owner is behooved to have an experienced person retained to monitor the entire process.

As mentioned previously, Gilbane Building Company is working as Construction Manager At-Risk under a Guaranteed Maximum Price of $54 Million. Gilbane contracted in April of 2009, resulting in a 28-month job duration (the total project duration, however, from conception to completion is 3 years, 4 months). Scheduling for project management is handled via Critical Path Method on Primavera software. Short Interval Production Schedules were not employed on the project, though this project may have held the potential for their use.

Subcontractors are retained through the use of lump-sum bidding, where Gilbane issues the bid documents and winning bidders must complete the scope of their work within the agreed upon contract value (the lowest bid price). While this method may be criticized, the integrated building process warrants this type of sub contracting since the scope is presumably complete before the package is sent to bid.

SITE

Located on a 14 acre site, the new North High School must be built in close proximity to the existing North High School. Fortunately for the construction team, the placement of the building worked so that ample space was provided for the construction process. A site plan is located in Appendix I. As shown in Figure 1B, special care was taken not to disturb the structure of the school as the gymnasium was built.

Figure 2A Gymnasium built in close proximity to existing building.

Careful planning is required throughout the project to ensure student safety. This includes overhead protection near adjacent buildings and a secure site fence to keep people out. This is compounded by the close proximity to the existing school, where curious student s may be tempted to break into the site. For this reason, CCTV has been used to monitor the site 24/7.

CRITERIA FOR THESIS STUDY

BACKGROUND

In February 2009, the U.S. government passed the American Recovery and Reinvestment Act of 2009. This plan includes an investment of $61.3 billion in the energy sector, including the weatherization of current buildings, the development of renewable energy, and energy efficiency projects for buildings (United States 2009). With rising energy costs and an increased awareness of society's impact on the planet, the importance of designing an energy efficient building has never been greater. At the PACE 2009 Roundtable, Energy and The Building Industry was one of three topics of discussion, further indicating the relevance and importance of energy efficiency in buildings. Currently, the construction industry is faced with meeting the physical needs motivating design as well as the building's impact on the environment. To that end, the focus of my research was energy and sustainability's role on the North High School project. This investigation was performed within the mindset of a construction manager, taking into consideration business (management) decisions, cost, schedule and construction logistics.

STUDIES

Massachusetts set the bar for their schools with the selection of the CHPS program; new schools must meet the rigorous criteria set forth by this code. Designing and building a 195,000 school within the confines of those regulations presents many questions: why was the CHPS program was chosen over other rating systems, such as LEED? Is there any value-added by creating a CHPS certified building? How can the CHPS program be applied in the best manner for WNHS? Drawing from these questions, areas of CHPS that could be improved are identified.

An allowance of $250,000 was included in the original estimate for the construction of a roof-mounted solar photo-voltaic (PV) system. This system is not being actively designed or pursued, and the allowance may go unused. My proposal is to design a solar PV system for WNHS. The design must meet the $250,000 budget. Furthermore, I will conduct a constructability study on the system. Areas to discuss include the trades that would be involved (would a new subcontract be required?), effects to the current project schedule, and the consequences for implementing a PV system during this stage of construction.

Continuing with sustainability, green roofs will be investigated, as they are commonplace on today's high-performance, certified building. The buzz is that they have good aesthetic value with significant structural impacts. This investigation scope includes assembly choices, structural impacts, cost and approximate schedule impact. This is done knowing that the green roof most likely presents added costs to the owner, which may or may not be paid back over time.

The advent of new technology provides new equipment that can be used to reduce energy consumption in buildings. LED (Light Emitting Diode) lamped luminaires are one such advancement that claims to compete with existing technology for efficient illumination. There is a lot of hype in the industry about LEDs but there is not a clear definition of their ideal purpose or efficacy. The lighting system will be looked at to determine areas where LEDs can be effectively implemented.

In summary, the role of construction management is present in each analysis. While the studies involve different aspects of sustainability, they are related back to their impact on areas including budget and schedule. Every analysis does not intend to individually and explicitly address time and money. The investigation areas of thesis are intended to portray a general affect on the project as a whole.

ANALYSIS I: MASSACHUSETTS CHPS STUDY (DEPTH ANALYSIS)

INTRODUCTION

Society's impact on the natural word is of increasing importance, as evidenced by the recent spike in green culture. Sociologist Daniel Bell identifies the increase importance of environmentalism with the shift in the United States to a post-industrial society (Bell 1973). The most evident change is in the world of architecture, where sustainability is now an integral part of the construction vernacular. To provide a design metric, several programs exist, with LEED being the most prominent. There are other programs, too, that were created to cater to specific building types and locations. The Massachusetts Collaborative for High Performance Schools (MA CHPS) is a program designed to increase the efficiency and sustainability of school buildings and is part of a larger CHPS program that governs several state members. It is "committed to building a new generation of healthy, efficient, environmentally responsive schools for all school children" (CHPS 2009). CHPS also aims to have a more region relevant rating system, as the United States contains diverse climate and social deviations.

PROBLEM STATEMENT

Sustainability extends deep into all aspects of a project, affecting every level of project development from concept to completion. It is a mindset rather than a method of design and an experienced professional will tell you that the key to success is implementing it early. It will, and should, control every decision made throughout a project's inception. Since this 14 letter word has such gravity in the construction world, it is an important area of modern Construction Management. The question becomes "how do sustainability rating systems affect the construction management process?" The research is forthcoming on how a program like CHPS affects a project or what can be done to improve the certification process. These issues are what drive the following analysis.

GOALS

The main goal is to answer two broad questions: how do CHPS and/or LEED affect the process of building construction and what can be done to improve the quality and efficiency of the rating system? These will be integrated other related questions, such as how has CHPS affected the overall project schedule. Ultimately, this research aims to improve how projects are executed under CHPS in order to save time, money and headaches.

RESEARCH

METHODS

To provide a mixed perspective, personal review of the CHPS standards will be combined with data retrieved through surveys. These surveys consist of 5 questions sent to professionals in Massachusetts. LEED v3 is discussed, juxtaposed with MA-CHPS to expose their differences, strengths and weaknesses.

REVIEW OF CHPS SYSTEM

The Collaborative for High Performance Schools began in California in November of 1999, when the state of California teamed up with utility companies to render their schools more efficient. They created a Best Practices Manual, released in 2001, which sparked the interest of many other states. CHPS incorporated in 2002 as a non-profit organization that oversees the entire CHPS program, which now has several regional adaptations (one of which is Massachusetts).

Massachusetts is on its second version of the “MA-CHPS” rating system. The first version, 1.0, was adopted in 2006. After 3 years of pilot schools, the MACHPS board revisited lessons learned to create version 2009. This is now the standard for all new schools built in Massachusetts. Among other things, it requires a 20% improved energy efficiency over the national baseline. There are 125 possible points, plus 23 prerequisites; a minimum of 40 points must be met to be verified (the baseline certification). In order to be a “verified leader,” the highest (and only other) rating, a building must meet the prerequisites and earn 50 additional points. Finally, to obtain this certification, MA-CHPS does not collect a fee. The following (Table I.1) are the prerequisites that all projects must meet:

Category	ID	Title
STRATEGY		Integration and Innovation
	II.P1	Integrated Design
	II.P2	Educational Display
DESIGN		Indoor Environmental Quality
	EQ.P1	HVAC Design - ASHRAE 62.1
	EQ.P2	Construction IAQ Management
	EQ.P3	Pollutant and Chemical Source Control
	EQ.P4	Moisture Management
	EQ.P5	Minimum Filtration
	EQ.P6	Thermal Comfort - ASHRAE 55
	EQ.P7	View Windows, 70%
	EQ.P8	Eliminate Glare
	EQ.P9	Minimum Acoustical Performance
	EQ.P10	Minimum Low Emitting Materials
		Energy
	EE.P1	Minimum Energy Performance, 20%
	EE.P2	Commissioning
	EE.P3	Facility Staff & Occupant Training
		Water
	WE.P1	Irrigation System Performance on Recreational Fields
	WE.P2	Indoor Water Use Reduction, 20%
		Site
	SS.P1	Joint Use of Facilities and Parks
		Materials & Waste Management
	MW.P1	Storage and Collection of Recyclables
	MW.P2	Minimum Construction Site Waste Management, 75%
PERFORMANCE		Operations and Maintenance
	OM.P1	Maintenance Plan
	OM.P2	Anti-Idling Measures
	OM.P3	Green Cleaning

Table I.1 Prerequisites of a CHPS certification.

It is evident upon looking at the table that CHPS stresses Indoor Environmental Quality (IEQ). CHPS has a priority of prescribing a high-quality environment for teaching and learning; weighting the prerequisites ensures that every certified building will meet that objective. Upon inspecting the available credits (see Appendix I.1), however, it is apparent that there are more opportunities and higher rewards for improvements in the energy category. There are 36 available credits in energy while there are 23 available in IEQ and about 10-15 each in the other

5 categories. This reflects the program's dedication to providing "environmentally sustainable and healthy places of learning" (CHPS 2009).

IMPLEMENTATION ON NORTH HIGH SCHOOL

North High School is slated to receive a CHPS verified certification upon completion. This means that it will adhere to all 23 prerequisites and has identified 40 applicable credits. The decision to pursue CHPS was made due to legislation; LEED was not considered since the Commonwealth of Massachusetts requires a CHPS certification. This dictated the project's delivery method, as Integrated Design is obligatory under Prerequisite I. As a side note, this implication will drive a trend in Massachusetts school projects: they will all be executed under Integrated Design. The City of Worcester employed in-house Architects to work with the design engineers as part of an integrated design that began in April 2008 and ran until April 2009 (duration 1 year).

Conversations with the Gilbane construction management team reveal that while there are indeed specific details that the management team must address while executing the job, they have not presented any significant issues. Details like capping HVAC ductwork (shown in Figure IA) or documentation of compliance during the submittal process are easily implemented on the job. The team is not versed on CHPS, however; attempting to discuss certain aspects of the program yielded very little input aside from "I don't really know…" This could mean a lack of understanding, proper education or unwillingness to share details; the interpretation is subjective and will not be used as a basis for judgment here. Construction waste recycling is mandatory with CHPS, which may actually save money, according to King County Washington's Recycling Economics website (Washington 2010).

Figure IA Capped ductwork as CHPS requirement.

SURVEY AND RESULTS

The following questions were disseminated to industry professionals in the Massachusetts area (see Appendix I.3 for compiled survey results):

1. How many projects (roughly) have you worked on where a sustainability rating system was used (i.e. LEED, Energy Star, CHPS, etc.)?

2. Have you worked on projects aiming for a CHPS certification? If yes, please answer questions A, B, C

    A. What are the pitfalls of the CHPS system?
    B. What are the benefits of CHPS, both independently and vis-à-vis LEED?
    C. What suggestions do you have for a new project aiming for a CHPS certification?

3. How have sustainability rating systems affected the industry, specifically the construction management process, in your opinion?

4. What are the areas of LEED and/or CHPS that have the most influence on the construction management process, and what is done to control these (i.e. certification paperwork headaches; paperwork is managed by one person throughout the entire project)?

It was important to get subjective answers in order to provide material to investigate further. For this reason, the questions were rather broad. Returned surveys answers showed the following trends:

- Rating systems have created a level of panic within the industry, for various reasons.
- There is a need to communicate lessons learned from professionals with experience.
- Certification becomes a means by which companies can green wash themselves.
- Using a rating system may be out of reach for limited budgets.
- There are a lot of young LEED accredited prof'ls but they lack experience.
- Sustainability in building has forced CM's and design prof'ls closer together.
- CHPS is not as robust an organization as LEED; communication with them needs improvement.
- The industry is seeing a definite increase in interest by owners to have their buildings sustainable, regardless of a certification.

CURRENT TRENDS

Evident throughout the responses collected, there are various reasons why an owner would choose to have their new building certified. It is imperative that these be identified early in project delivery so that the building design and construction can meet those needs effectively.

The professional input pointed in a lot of different directions. Some feel that this is simply the current craze, just as skyscrapers were what the best companies used symbolically in the early 20th century. Others see this as merely the edification of the way things have always been; owners don't purposely build energy inefficient buildings. Still more believe that the evidence is in the numbers, where since "5 years ago the percentage of projects using LEED or some other sustainability rating system has gone from 25% to 75%. And the percentage of projects that are committed to sustainable design but not seeking the accreditation is probably 100%," opined one survey participant.

Regardless of the reasons why the industry is currently focusing on sustainability, changes in energy code and the increase in popularity of rating systems shows that it is here to stay. Furthermore, CHPS is mandatory for all new schools in Massachusetts; this will not go away as a fad would.

CHPS V. LEED

Perhaps the most popular rating system in the construction industry today is LEED, or Leadership in Energy and Environmental Design. The current version is LEED v3 which was released in April of 2009. For the sake of relevance, this version is compared with CHPS 2009, though they both were published after the building's design was complete. Refer to Appendix I.2 for a copy of the LEED 2009 scorecard.

LEED, developed by the United States Green Building Council (USGBC), aims at "providing third-party verification that a building or community was designed and built using strategies aimed at improving performance across all the metrics that matter most: energy savings, water efficiency, CO_2 emissions reduction, improved indoor environmental quality, and stewardship of resources and sensitivity to their impacts" (USGBC 2010). This is a significantly broader goal than CHPS, which is further reflected in the distribution of LEED credits.

LEED provides more flexibility in the range of credits a building can achieve. The number of prerequisites is smaller than in CHPS; the remaining required credits for certification are distributed however the owner/designer sees fit. This is good from a design standpoint since it creates a more omnipotent system. Since this is an evaluation for use in schools in Massachusetts, it may be better to have rigid guidelines. CHPS accomplishes this by having only two certification levels and both have a majority of the credits prescribed.

CHPS is a non-profit organization, while LEED is a for-profit organization. This is embodied in LEED's notorious fees for certification, costing close to $100,000 according to one survey participant. This is unacceptable for schools. $100,000 is better invested in the students, not on a plaque touting certification. Indeed, this was a common thread in responses to the surveys.

MA-CHPS was developed by Massachusetts engineers and designers with the climate, design standards, building code, culture and environment in mind. As such it is a program that is tailored *specifically* for the region, its stakeholders and their needs. This has a significant advantage over LEED, which has merely 7 "regional" credits that can be sought, for a maximum of 4 used. They include brownfield redevelopment, stormwater design, and heat island effects.

LEED requires an accredited professional to have worked on the project in order to gain certification. This is a good thing from a management prospective, since it ensures that there will always be a professional that is knowledgeable and experienced in LEED on the project. As mentioned in the surveys, however, it is common for young professionals to hide behind the guise of LEED AP who may have certification but lack the necessary experience. This does not happen with CHPS.

Finally, CHPS does not have a formal education process for professionals. Mentioned above, this is a negative aspect since there is no way to create knowledgeable employees without solely relying on experience.

ISSUES TO ADDRESS

Based on the research, I reflect the following for the MA-CHPS system:

1. The CHPS program is a strong choice for schools in Massachusetts, since it is designed around the specific constraints of the region.
2. Establishing training for school boards and construction professionals alike will facilitate smoother project execution and CHPS adoption.
3. Create a lessons-learned database, accessible to the public, which allows everyone to learn from the process.
4. Increase capabilities of regional offices; one experienced survey respondent expressed frustration with getting straightforward answers easily.
5. Develop a guide for construction managers to inform them of their crucial role in completing a CHPS-verified building.
6. Ensure buy-in from the entire team. Mandating the CHPS program without fully informing every party leaves some reluctant to participate actively.
7. Input from students and teachers as a requirement for the design process. There is no provision for that currently, and it leaves their valuable additions unheard.

SUMMARY

CHPS and LEED both present a list of pros and cons. CHPS is more relevant to Massachusetts, while LEED is a broader system, applicable to buildings beyond schools. In the context of a sustainability rating system for North High School, however, CHPS reigns supreme. The lack of bureaucracy, the specialization of its function and the non-profit approach allow any owner to effectively employ it on their educational facility. The MA-CHPS program does exhibit some areas where it could be improved; indeed the governing board commits to reevaluating the requirements every three years for reasons such as those discussed prior. The construction management process is ultimately little changed by the use of CHPS on North High School. It may be of interest for CM firms to investigate the complexity of CHPS schools vs. traditional schools and determine if there is any correlation to schedule delays and change orders.

ANALYSIS II: SOLAR PV SYSTEM DESIGN (ELECTRICAL BREADTH)

INTRODUCTION

Alternative energy sourcing is important to sustainable architecture and society. The use of alternative energy decreases dependence on limited resources, such as oil and natural gas. Furthermore, alternative energy significantly reduces a building's CO_2 emissions, creating a more responsible building. This is increasingly important in modern building design as energy conservation drives *******. Several options exist for the generation of electrical or thermal energy without the use of fossil fuels; Geothermal, solar thermal, biomass, biodiesel and solar photovoltaic are just a few. These systems require additional upfront costs but, if designed properly, they have the ability to offset or reduce the building's energy consumption to net zero.

Included in the CHPS rating system are specific credits for alternative energy. A total of 5 points are available solely for the employment of "electricity-producing renewables". This analysis intends on investigating the fulfillment of the requirements for such credits, specifically through the use of a solar phot0voltaic (PV) system.

PROBLEM STATEMENT

The WNHS building is situated on an east-west orientation, as seen in figure IIA. This means that there is significant southern exposure along the roof, enough possibly for a solar PV system. The original budget estimate included a $250,000 allowance for the procurement and installation of such a system, size and schematics to be determined. While this was indeed an initial plan, it was scrapped due to budget re-structuring. The owners of WNHS have the potential to benefit from a PV system through

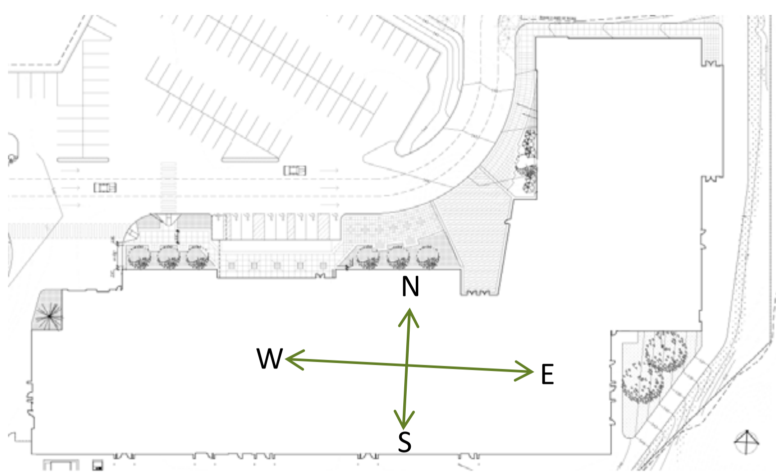

Figure IIA Building orientation.

the payback it may present. Investigating the situation will reveal what the budget can yield in terms of system size, how long the payback period is and ultimately whether or not the system is feasible.

GOALS

The intent of this analysis is to evaluate the feasibility of a roof-mounted, solar PV system, given a budget of $250,000. In order to accomplish this study, research was devoted to study the concept of solar PV systems, schematic designs, costs and case studies. The ultimate objective is to provide the owner with a research-backed proposal for the implementation of a PV system on the school. It was the intent that the design would present a cost-savings over the duration of the building's operation.

RESEARCH

ESSENTIALS OF SOLAR

Current solar panels are capable of producing approximately 13 watts of power per square foot. Buildings use power on the magnitude of 1000 watts (kilowatts); therefore the space required for a system to meet these energy demands would take acres. As such, PV systems are often used to supplement a portion of a building's energy usage. North High School is a large consumer of electricity (80-100 MWh per month) so the size of an array that could handle 100% of its demand is not feasible. A smaller solar array that could fit on the roof is more appropriate and cost-effective. This system could serve as both energy producer and teaching tool, all the while adding to the CHPS rating with anywhere from 1 to 5 credits (depending on energy produced).

Bearing the aforementioned constraints in mind, a grid-tied system was chosen. This PV system converts energy from the sun into a usable form (electricity) that is matched to the power provided by an electric utility. As North High School is on an established grid with little downtime, the need for the PV system to be grid-tied is not an issue.

COST AND SCHEDULE

Four types of sources were used to collect cost data on PV systems: RS Means, newspaper articles, supplier estimation software and communication with contractors. A summary of collected cost data is shown in Table II.1. The RS Means data was highest and determined an outlier since the data is a yearly publication and prices can fluctuate from month to month, as well as by location. The newspaper articles and online estimates were all close. These are considered the most accurate since the estimates are quite precise and they come from actual projects. The cold call gave a range of $7-$10 per watt, which is quoted as a "rough order of magnitude" and does not reflect an actual project estimate. A per watt cost of $5.98 was used for the system design in this thesis; the averages for each source type are shown in Table II.2. Schedule estimates were more difficult to procure. Articles viewed online and cold calls reveal that a 20kW – 40kW system would take less than 6 weeks to install.

Source	Cost per Watt
Estimation Cost Data	
RSMeans 2009 Cost Data	$11.70
Newspaper Articles	
Alteris Renewables	$5.87
Ostrow Electric	$5.39
Fall River Electrical Associates	$4.72
Waterline Industries, Corp.	$5.86
Online Estimation Tools	
BP Solar Estimator:	$6.00
Solar-Estimate.org:	$6.03
Cold Calls	
Zapotec Solar	$8.00

Table II.1 Cost estimates

Source	Average Cost per Watt
Newspaper Articles	$5.46
Online Estimates	$6.02
Cold Call	$8.00
Total Average:	**$5.98**

Table II.2 Average cost per installed watt.

Two designs were considered: the first used the $250,000 budget allowance as a parameter for total PV system cost; the second took the allotted roof space (as seen in Figure IIB) and established the maximum power-producing system for that area. This was done so that the owner would have the best system to meet costs (ie a higher electricity production) as well as a system that met the limits of the structure as designed. The steps of the design process (which can be found in Appendix II.1) are as follows:

1. Establish approximate production capacity of system, in kW
2. Find panels that will meet the capacity economically
3. Establish controlling specifications of panels (max voltage, current)
4. Select inverter and check for capacity
5. Configure panels, check voltage and current ratings
6. Select combiner box

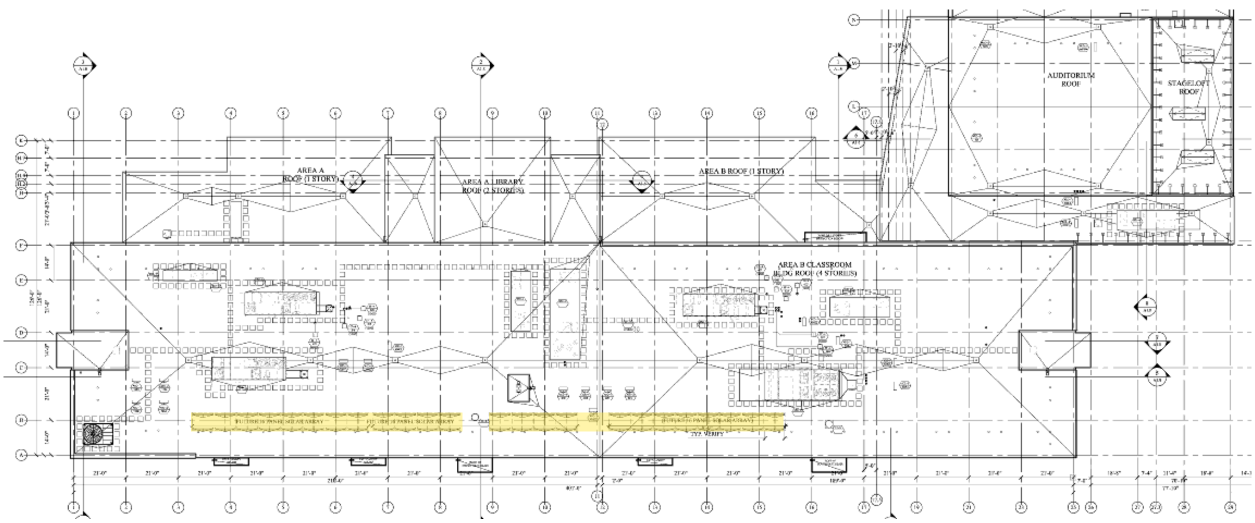

Figure IIB Space allotment for PV array, as designed by Architect, shown in yellow.

SYSTEM DESIGN 1: MEETING A $250,000 BUDGET

Specifications

Maximum power rating: 38,640 Watts (38.64 kW)

Three of the following 12.88kW systems comprise the entire 38.64 kW system:

Solar Panels:	(56) BP Solar 3230T, rated 230W each
Inverter:	(1) Fronius IG Plus 12.0-3 WYE 277, rated 10.2 – 13.8 kW
Combiner Box:	(1) SMA SBCB-6
Wiring Configuration:	(4) Strings in Parallel, one string = 14 panels wired in series
Schematic: (see Figure IIC)	

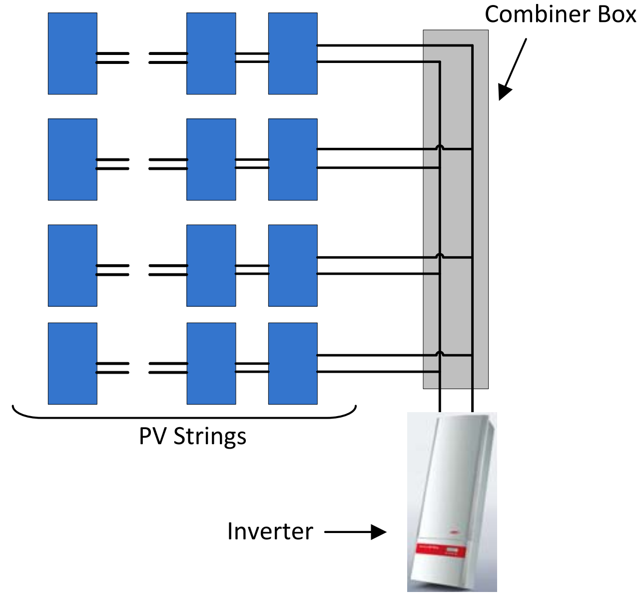

Figure IIC 12.88 kW System Schematic. Three of these will be wired in parallel to supply 38.64 kW of power.

SYSTEM DESIGN 2: MEETING 113.5' LF REQUIREMENT

Specifications

Maximum power rating:	7,590 Watts (7.59 kW)
Solar Panels:	(33) BP Solar 3230T, rated 230W each
Inverter:	(1) SMA Sunny Boy SB7000US, rated 8.75 kW
Combiner Box:	(1) SMA SBCB-6
Wiring Configuration:	(3) Strings in Parallel, one string = 11 panels wired in series

Schematic: (see Figure IID)

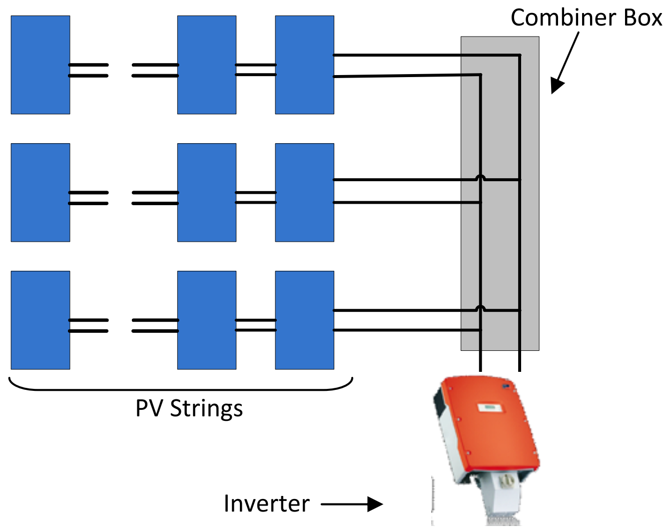

Figure IID 7.59 kW System Schematic

FINAL COST ANALYSIS

The two system designs present two different approaches to meeting constraints. The larger system produces more electricity, at 38.64 kW. This configuration also costs the most, at $230,000, and takes up the most space (6,000SF). Looking at the 7.59 kW system, it produces less energy but costs less, at $45,200, and fits on the allotted roof space. It is necessary to look at cost analyses to truly make an informed decision.

Using NREL's PV Watts program, a 38.64 kW array would offset $8237.60 per year and a 7.59 kW system would offset $1618 per year. If both systems are paid for with cash, the payback would take thirty years (assuming a panel derating of 0.6 % per year). After 50 years, the larger system has a value of $121,000 while the smaller system has a value of $23,800. This does not include the source of financing, nor does it include inflation, so it may not be accurate for the application of a public project.

According to the BP Solar online estimator, a system rated at 40 kW has a net present value (NPV) of $60,000; a system of 7.59 kW has an NPV of $15,830. The larger system presents the larger valued investment, assuming that much financing could be secured. Both systems qualify for state rebates through Commonwealth Solar and federal/state tax credits; the larger receiving $124,500 and the smaller receiving $33,000. Detailed cost data can be found in Appendix II.2

RECOMMENDATION

Installing a 38.64 kilowatt grid-tied PV system is the best option since it offsets the most carbon and earns the most CHPS credits, while staying within the allotted budget. Furthermore, since the inverter in this system provides electricity in a 3-phase, 4-wye configuration, power can be delivered directly back to the main electricity tie-in. Installing the smaller configuration delivers single-phase power at 277 volts, which could only be tied into the lighting system without the use of a step-down transformer.

The larger system is only feasible, however, if the roof can handle the load of such a system; the structure needs to be evaluated to ensure its stability. Using the smaller 7.58 kilowatt system is a smart option if significant costs would be incurred to support the larger system. As the roof structure has already been designed to support a smaller system of this size, the installation would not incur additional costs due to structural reinforcement. Both systems do not require any additional conduit runs to the mechanical rooms. The electrical contractor is running 4" conduit from the mechanical room to the roof so that wiring may be run for a PV system.

The size requirement of a 38.64 kW system is a limiting factor, as it requires just over 3000 SF of roof space. This is twice the feasible roof space on the main building (shown in Figure IIB). To execute this system, it is possible to mount the system on the gymnasium roof. This would again require the analysis of the structure to ensure it could support the loads induced by the PV system.

Either of these installations would require less than 2 months installation time. It is worth noting, though, that significant time is required in the planning phase for permitting. This task will be assumed by the construction manager, assuming the solar contractor has submitted construction drawings and schematics for approval. The actual installation merely requires access to the finished roof and a crane pick to hoist the equipment onto the roof.

Since the installation of the PV system does not have any successors in terms of scheduling, the activity will not lie on the critical path. In fact, the installation could even take place well after the building is complete, since the conduit has been run already. This is important because it allows the owner and CM to decide on the system's implementation at a late stage in the construction process, such as now.

ANALYSIS III: GREEN ROOF DESIGN (STRUCTURAL BREADTH)

INTRODUCTION

There are numerous features of a building that affect its energy consumption, aside from systems that use energy explicitly (HVAC equipment, lighting, etc.). The building envelope and roof assemblies directly affect how thermal energy is transferred to and from the outdoor environment. A popular design choice as of late is a green roof, where the roof structure supports a landscape assembly. These range in weight and complexity. Benefits of using a green roof relate to its aesthetic, sociological and energy efficient properties. Indeed a green roof has benefits, but there are drawbacks, including cost increases due to needed structural changes to support the weight of a green roof. The implementation of a green roof on any project requires prior investigation to determine its feasibility.

PROBLEM STATEMENT

The common thread of sustainability is reducing the impact of the built world on the natural environment. The task is to lessen this impact. One such way is to reduce direct environmental impacts such as storm water runoff and heat island effects. To that end, North High School is attempting a CHPS sustainability certification and there are various ways to fulfill the qualifying point requirements. The addition of a green roof will add to the “Sites” category with the addition of 2 extra points. Adding a green roof will be an added structural load, and this must be considered. Furthermore, an added system means an increase in the project’s overall cost.

GOALS

This investigation intends to evaluate the existing roof’s ability to support a green roof and how much the addition of a green roof would cost. Additional considerations include the benefits of implementation and its effects on the overall building’s presence. Research must be accumulated from literature, case studies and communication with contractors. An analysis on structural impact, cost, storm water retention and schedule impact will be conducted.

GREEN ROOF SYSTEMS

Two types of green roof exist: intensive and extensive. An extensive roof is shallow, meaning the growth medium is 2" – 6" deep. Intensive roofs are much deeper and consequently very heavy; the structure must be designed around an intensive green roof. Given the ongoing nature of the construction, the use of an extensive green roof is appropriate for North High School.

Manufacturers develop and market their own proprietary green roof assemblies, so there are innumerous extensive roof systems available. These can be divided into three broad categories: built-in-place, mat-type and unitary. The first type, built-in-place is the least expensive but requires the most installation time. As with most landscaping, a built-in-place green roof is comprised of several layers. Shown in Figure IIIA, a root barrier is placed over the roof membrane, followed by a drainage layer. 2" – 6" of planting medium is then spread over the roof. Finally, sprigs, seeds or vegetated mats are installed on the medium. It is important to water the roof for a period of 2 weeks after it is installed to ensure the plants take root. According to a landscape contractor, the optimal time to install a green roof in New England is in the fall. This is an important aspect to consider when scheduling the installation, as it can help determine the success of the green roof installation. Considered with the solar array study above, a green roof can be planted under it—even providing excess anchoring for the panels (according to contractors interviewed).

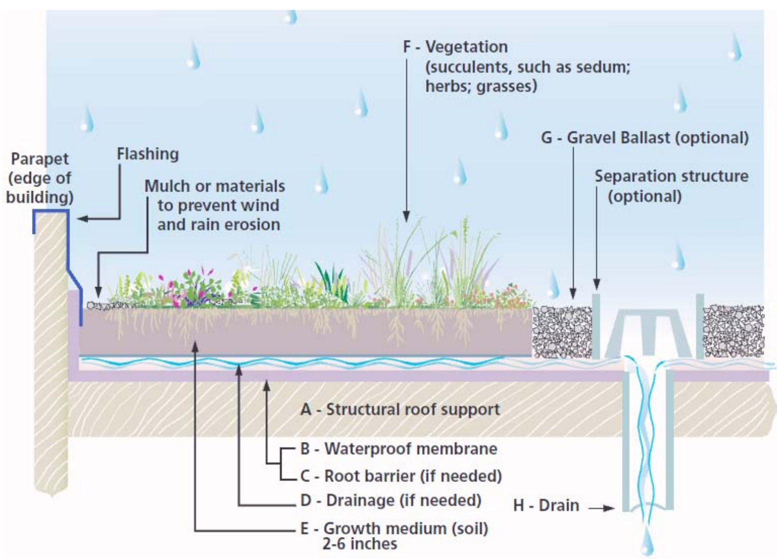

Figure IIIA Typical extensive green roof assembly. (Image courtesy Portland Ecoroof Program)

BENEFITS OF GREEN ROOFS

The benefits of a green roof are numerous, but they are known primarily to offer the following not available via conventional roofing materials (City of Portland 2008):

- Mitigate storm water runoff by 10-100% through absorption and evaporation
- Lower temperature of runoff, beneficial to streams and watersheds
- Decrease summer roof temperatures which decreases building cooling loads
- Increase life of roof up to twice its normal life

The direct, measurable benefits are experienced over the life of the roof. There are other benefits that are not quantifiable; the space can be used as an outdoor classroom for science experiments and observations for example. A green roof can also be considered aesthetically pleasing. The US Department of Energy is aware of the benefits, evidenced by their release of a Federal Technology Alert as part of the Federal Energy Management Program. Generally, they "help to minimize the environmental footprint of buildings and mitigate the impacts of urban runoff and urban heat islands" (US DOE 2004).

COSTS AND SCHEDULE

In order to create an accurate estimate of costs for a green roof on North High School, cost data was collected from contractors and suppliers. Parametric cost data is not yet available through RS Means or other sources, since the technology is new and varies from project to project. Shown in Table III.1, the average cost of a built-up system is $10 per square foot installed. The price increases as the system's modularity increases; an easy-to-install prefabricated green roof tray system costs on average 2.5 times a built-in-place system. For this reason, a built-in-place system is chosen as the economic option for North High School.

Rates of install and total install times were more difficult to procure than cost data. The built-in-place system takes longer to install than modular systems. This is not a controlling factor, though, since a green roof installation would not be on the critical path of the schedule. Contractors quoted a time frame of several weeks for installation. The installation can occur independent of other activities, assuming the roof membrane is fully installed; only a crane pick is needed to deliver materials onto the roof. It is shrewd to coordinate the green roof installation after the installation of major mechanical equipment on the roof is complete, so as to not disturb a newly planted roof. As mentioned previously, the installation is not on the critical path, so exact schedule information is not pertinent to this thesis (as long as it can be guaranteed not to cause schedule delays).

Manufacturer	Min Cost/SF	Max Cost/SF	Roof Size	Min Cost	Max Cost	Avg Cost
Built-In-Place						
Roofscapes	$10	$12	51000	$510,000	$612,000	$561,000
Furbish Co.	$8	$11	51000	$408,000	$561,000	$484,500
Mat	**Average:**	**$10**			**Avg Cost:**	$522,750
Furbish Co.	$12	$14	51000	$612,000	$714,000	$663,000
	Average:	**$13**				
Trays						
Furbish Co.	$18	$24	51000	$918,000	$1,224,000	$1,071,000
Gilbane Estimating	$20	$30	51000	$1,020,000	$1,530,000	$1,275,000
Green Roof Blocks	$19	$36	51000	$969,000	$1,836,000	$1,402,500
	Average:	**$25**				

Table III.1 Cost data for various green roof systems.

STRUCTURAL ANALYSIS

In order to receive CHPS credits for the green roof, it must be equal to 25% of the site's proposed impervious surfaces. After calculating the impervious surface of the site, it was determined that the minimum green roof size is 31,000 SF. Next, the total "greenable" roof area was determined:

Main Building		**Side Buildings**	
Gross Roof Area: 403'-4" x 86'-4":	= 34,821 ft^2	Gross Roof Area:	= 22,090 ft^2
Less 1'-2" parapet: 401' x 84':	= 33,684 ft^2	Less 1'-2" parapet:	= 20,826 ft^2
Less Service/Mech. Areas:	(3,280 ft^2)	Less Service/Mech. Areas:	(479.25 ft^2)
Total "Greenable" Roof Area:	**= 30,404 ft^2**	**Total "Greenable" Area:**	**= 20,347 ft^2**

The main building does not have enough roof space to cover the 31,000 SF minimum requirement. Greening the entire roof, however, will satisfy the requirement and provide a uniform look. For this reason, the size being evaluated is 51,000 SF, the approximate sum of all roof space. The installation will take place on the roof areas shown in Figure IIIB (note that mechanical equipment will not have green roof. Image is shown for concept only).

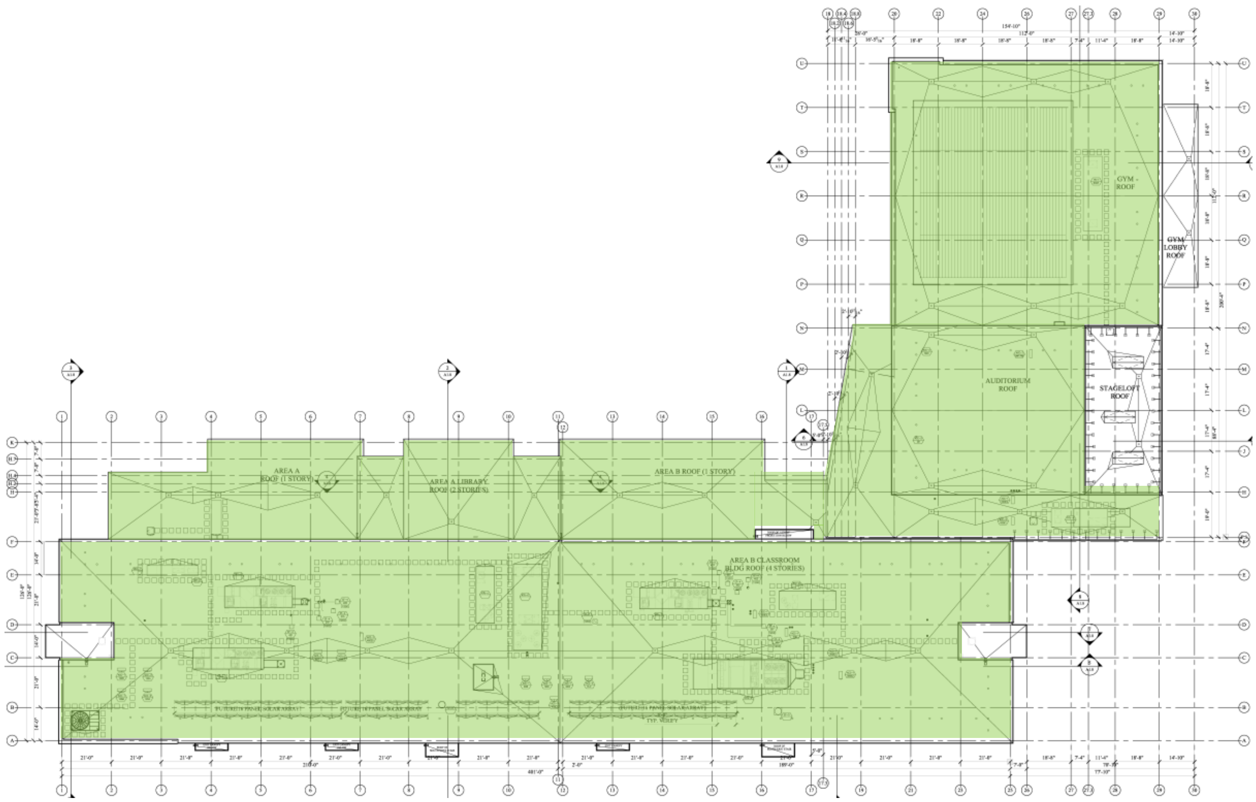

Figure IIIB Proposed green roof area.

An extensive roof was identified as an economical candidate due to its lightweight nature, posing the smallest structural effects. The characteristics of different systems are shown in Table III.2.

Manufacturer	Size	Soil Depth	Saturated Weight
Roofscapes Roofmeadow	No module size (mat-type)	3" – 5"	20 – 34 PSF
ZinCo	No module size (mat-type)	4.5"	22 PSF
Hydrotech USA	No module size (mat-type)	2" – 6"	17 – 41 PSF
GreenGrid	2' x 2', 2' x 4', 1.5' x 2'	4"	18 – 25 PSF
LiveRoof	1' x 2'	4" – 4.25"	15 – 29 PSF
Barrett Company	No module size (mat-type)		21 PSF

Table III.2 Size and weight characteristics of various proprietary systems.

The following steps outline the evaluation of the roof structure:

1. Choose green roof assembly, note unit weight in PSF
2. Determine roof assembly weight, in PSF
3. Calculate Roof Snow Load (IBC 2006)
4. Calculate load combinations
5. Determine ultimate moment, M_u
6. Find required cross-section, Z_x, compare with Z_x of roof members
7. Calculate maximum deflection, compare with allowable deflection

(A detailed analysis can be found in Appendix III.1)

The roof structure was evaluated at a typical bay, shown in Figure IIIC, which includes W12x14 beams connected to W24x68 and W21x44 girders. These are then tied into the columns which are part of a moment frame. Only roof members were analyzed due to the sophistication of the column splices and moment frame, which are beyond the scope of this thesis. Note that effects from rain and seismic loading were not considered in this analysis.

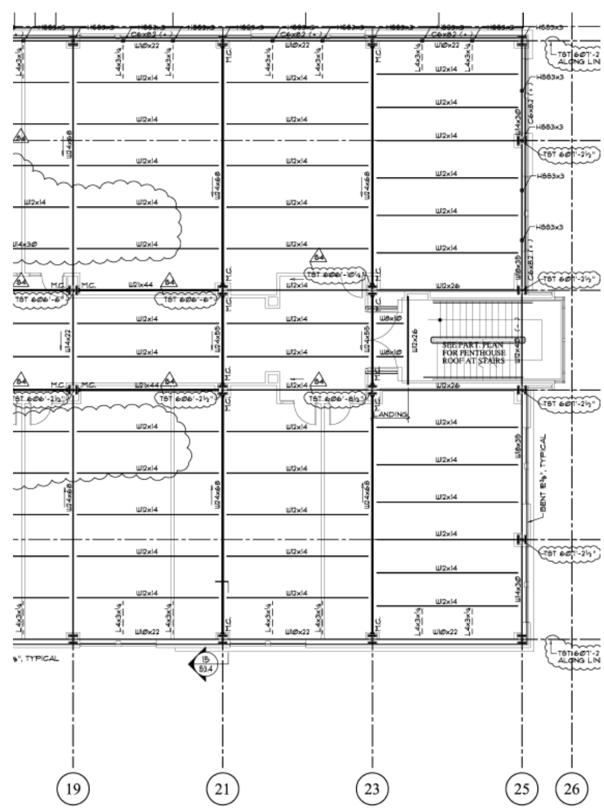

Figure IIIC Bay of interest for structural analysis.

Installing a green roof means the imposition of 23 PSF over the area it is located. According to the calculations, the members can support this as designed. This assumes that the roof is designed for a maximum deflection of $\Delta_{\text{MAX}} = \frac{\text{L}}{240}$ which is the serviceability requirement set forth in the Massachusetts Building Code CMR 780 (Commonwealth of Massachusetts 2008). According to manufacturer websites and contractors, a concrete roof deck is not required, so there is no increased cost involved with a deck assembly upgrade; the current roof assembly was evaluated to ensure it could handle the increased load from a green roof. These calculations were made in an effort to roughly determine the structural feasibility of the existing roof structure. As the entire design intent is unknown without the complete input of the structural engineer, the full impacts of the green roof cannot be determined. There is a possibility that the loads included were larger or smaller than those used by the design engineer. What were used here are the minimum values set forth by the Massachusetts Building Code CMR 780, which references IBC 2006.

FINAL COST ANALYSIS

Installing a 51,000 square-foot green roof is estimated to cost $522,750. This is a significant addition to the overall project cost, raising the budget 9.6% from $54 Million to $54.5 Million. Green roofs purportedly increase the life of a roof membrane by 2 times, however (City of Portland 2008). After 40 years (the warranty of the roofing system) a non-green roof would need re-roofing. The original roof estimate is $1.5 Million. If the replacement costs were 50% ($750,000) that cost alone justifies the installation of a green roof. Worcester Public Schools is the owner and operator of this North High School and has a long term investment in the property. This means that significant costs over a 50 year life cycle are of importance to them. Saving a projected $750,000 means that money can be reinvested into the school for teaching materials, building refurbishments and other student needs.

The initial cost may also be offset by the ability to reduce storm water catchment systems. The Massachusetts Storm water Handbook states that green roofs may be used as an effective means of reducing impervious runoff: “research indicates that peak flow rates are reduced by 50% to 90% compared to conventional roofs … peak discharge rates are delayed by an hour or more” (Mass. Stormwater 2008). Furthermore, “if sized to retain the required water quality volume, the area of the green roof may be deducted from the impervious surfaces used to calculate the required water quality volume for sizing other structural treatment practices” (Mass. Stormwater 2008). This equates to a reduction in cost for the systems designed to process storm water and catch total suspended solids. The cost reduction is beyond the scope of this thesis, but its impact should be considered.

The final cost consideration is the effect a green roof has on cooling loads. According to a study by the Lawrence Berkley National Research Laboratory, “the total air-conditioning energy use was reduced by 11 percent and peak air-conditioning demand fell by 14 percent" (Konopacki & Akbari 2001). A reduction in air-conditioning use will also present a value-added by a green roof. This is only calculable via whole-building energy modeling, which is beyond the scope of this thesis. The study did calculate that $65,000 would be saved over the life of the roof, a savings that should be considered as part of the life-cycle cost of the roof.

As mentioned above, the complete structure must be evaluated by the design engineer to properly determine its suitability for a green roof. If the structure needs reinforcing, a cost of $5 - $8 must be added to the cost of the steel structure. This could effectively double the cost of adding roof landscaping, since the selected system costs $6 per square foot.

RECOMMENDATION

Installing a green roof presents a simple addition of 23 pounds per-square-foot roof load. The effects of this load are induced from the roof to the foundation. A thorough analysis of these impacts is required by the design engineer in order to ensure that the structure can handle the increase. This preliminary study indicates that no further structural reinforcing is required in order to support the landscaping. The roof structure deflections and ultimate moments are within the limits of the design requirements, as outlined in Appendix III.1.

The final cost of procuring and installing a green roof is roughly $530,000. This cost may be mitigated over the life of the roof by the aforementioned values-added, including decreased cooling load, smaller storm water catchment systems, and an increased life of the actual roof membrane.

It is recommended to pursue the installation of a green roof if the structure is indeed suitable for the loads. This would enhance the overall school in terms of energy consumption and the environmental statement it makes. While the green roof is not intended for occupant access, it will be suitable for use as a living example to students of sustainability.

ANALYSIS IV: BUILDING ILLUMINATION (LIGHTING/ELECTRICAL BREADTH)

INTRODUCTION

Lighting systems in buildings are an obvious area of energy consumption. When designing the lighting scheme in any building, the design engineer is faced with many options in terms of layout and component selection. Both of these have a drastic impact on the performance of the system, but there is a balance that must be achieved in order to create an efficient, user-friendly, cost-effective design. There are a wide variety of products available (at varying costs) to improve certain aspects of a lighting scheme. LED fixtures are an increasing presence in the marketplace and provide high energy output per watt consumed.

The lighting system is a component of a building's electrical system. Each major system in a building plays a role in the timeliness of project completion; that is to say they are usually on the schedule's critical path. Any delay or acceleration in a system's construction can cause direct consequences to the project schedule.

PROBLEM STATEMENT

As with the other focus areas of this study, energy consumption is an area of extreme interest. The lighting system is not currently using LED fixtures or high performance T8 fixtures. Not all spaces have occupancy sensors or photo sensors. Also, there is a seemingly small amount of windows in most non-corner classrooms. The CHPS program incorporates analysis points pertaining to all of these topics, so any improvements may result in a higher score.

GOALS

This analysis aims to investigate the optimization of the lighting system to include LED fixtures. The intended outcome is an option for the owner to choose a more efficient luminaire that will cut utility costs and outperform the standard CFL fixture in the long-run.

RESEARCH

LED FIXTURES

LED lighting is the "hot topic" in the lighting industry today. LED stands for Light Emitting Diode, which describes the electrical apparatus that produces light. Technically, they are known as solid state lighting, which encompasses the three types of LEDs available today: semiconductor-, organic- and polymer light-emitting diodes. The technology in general purpose lighting is still very new, so the amount of manufacturers that produce LED fixtures is small. The Next Generation Luminaries™ Design Competition named numerous manufacturers and designs as recognized winners. Further research indicates that LED luminaires are (currently) best-suited for down lighting, outdoor and track lighting (Taub 2008). Since classrooms require direct/indirect lighting, it is not appropriate to evaluate LED luminaires for these areas. LEDs will be analyzed in direct lighting applications for the corridors and support spaces of North High School.

The research also pointed out that the technology on LEDs is not up to standards for general lighting purposes. This was apparent in both luminaire research and literature review. In a February 2010 edition of *snap* magazine, Clara Powell of Mundo Illumination and the Illuminating Engineering Society's New York Chapter reflected that "larger LED fixtures, including downlights and cans, are still lacking performance wise" (Taraska 2010). This does not bode well for the implementation of LED fixtures on North High School.

COSTS OF LEDS

Luminaires driven by LEDs are significantly more expensive than fluorescents and are one of the main reasons they are not readily installed. The reason for this may be due to their sophisticated design and manufacturing process; as it is so new, the cost is still relatively high. Some predict that the purchase price will come down as their popularity increases, competition stiffens and the manufacturing process improves. Analyzing the total cost of ownership for LEDs tends to be its selling point, as the procurement cost of an LED luminaire is much higher than an incandescent or fluorescent fixture. When the energy savings are calculated over the life of the lamp, however, an LED is the more economical choice.

An example is given here:

Lamp Type	Initial Cost	Lamp Life	# Lamps per 30,000 Hrs	Watts	Cost/kWh	Total Cost for 30,000 Hours	Cost Savings Over Life of Lamp
LED	$50	30000	1	12	$0.17	$111	22%
CFL	$12	8000	3.75	19	$0.17	$141.90	

Table IV.1 Cost analysis of LED v. CFL over life of lamp.

Looking at the costs of a replacement downlight, on average, LED downlights cost $400 - $500 per luminaire, for a fixture with the technology to replace a CFL. The downlight specified on North High School costs $175 - $250 per luminaire, according to contractors. The cost is effectively doubled. This must be considered when making a recommendation.

SCHEDULE ACCELERATION

Schedule acceleration occurs for a number of reasons in the Construction Management world, but there are 5 common situations (Mubarak 2005):

1. The finish date in a contractor's schedule is later than the contract date.
2. During construction, a contractor falls behind schedule and cannot complete on-time.
3. There is a reward for finishing ahead of schedule

4. Finish early to move on to another job, if there are other projects in the pipeline
5. Finishing early means excess profit for the contractor

These common occurrences have one thing in common: it is in the contractor's financial interests to finish ahead of schedule. Acceleration (compression) of the schedule will only occur when it is financially beneficial for the contractor to do so. In the first and second cases mentioned above, there are almost always penalty charges for delaying a project finish date, so there is financial incentive to finish early there as well.

The Construction Industry Institute, in their 1988 publication "Concepts and Methods of Schedule Compression," provides more than 90 methods for accelerating a project schedule. Eight techniques recommended by Mubarak are:

1. Examine the schedule for constraint logic inaccuracies
2. Use the fast-track method of project execution
3. Investigate areas that show constructability issues or value engineering
4. Employ/increase labor shifts, including overtime
5. Use incentives to increase labor productivity
6. Use special equipment or materials (admixtures for concrete or prefabrication)
7. Improve supervision
8. Improve communication

Each of these is effective at different areas of production that need improvement, as well as different incurred costs. Additionally, the above methods come with their own set of caveats, which should be considered if they are used on a job.

ANALYSES

LUMINAIRE SELECTION

Luminaires were sought from the prospective of a construction manager; that is a similar product that performs the same function to the same degree. It is beyond the efforts here (as it would be for a true Construction Manager) to redesign the entire effect of the lighting scheme, where a variety of lighting options could be explored.

To evaluate the use of a new luminaire on North High School, the following process was used:

1. Determine required illumination for space
2. Determine the type of illumination required (direct, indirect, etc.)
3. Search for luminaires that are similar in function to the existing
4. Model the selected fixture
5. Determine the number of fixtures required to meet minimum illumination
6. Compare watts per square foot of new versus existing luminaire
7. Make recommendation on use

Significant research was devoted to choosing a luminaire that fit the needs of North High School. For a basis of design the luminous efficacy of the specified downlight for corridors was calculated. The 8" CFL produced 2400 lumens per lamp with 36 watts of input power, which equates to 66 lumens per watt. In order for any LED to be feasible, it must outperform this value. After searching over the databases of manufacturers, there were only two fixtures that produced 66 lumens per watt or more.

The first is a Gallium 6” square downlight, producing 1350 lumens. At a color temperature of 5000K, the Gallium model does not meet the design requirement of 3500K. Indeed color temperature is a problem with LED fixtures, which tend to be cool blue in hue (Taraska 2010). The second, by Cree Lighting, is a 6"round downlight, with an output of 1020 lumens. This fixture only produces 1020 lumens, half of what the specified fixture produces. This means that more luminaires are required per space in order to achieve the design illumination of 15 foot candles. The cut sheet is provided in Appendix IV.

A Cree LR6-DR1000 was analyzed in AGI32 for average illumination in a corridor. The results show that in order to maintain 15 foot candles, 14 luminaires must be used. Summing the wattage for 14 luminaires at 12 watts yields 168 watts to illuminate the space. This is compared next to the specified luminaire, which requires 288 watts to achieve similar illumination. Switching to LED equates to a 41.7% savings in energy costs. As shown in Figure IVA, using the LED luminaire results in a more uniform distribution of light (less “scalloping” on walls), as well as its sufficient illumination.

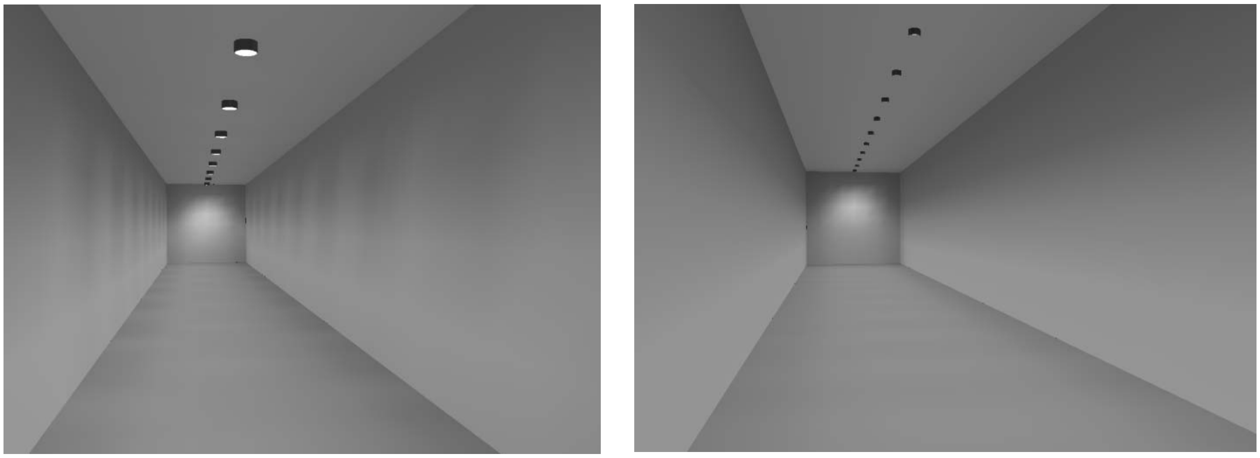

Figure IVA Rendering of specified CFL luminaire (left) and proposed LED luminaire (right).

The life cycle cost analysis, shown in Table IV.2, indicates that at current market prices, choosing this LED luminaire is not an economical choice. The sole reason is the purchase cost. If prices do indeed fall, this luminaire will be a suitable replacement.

Luminaire	Lamp Type	Watts	Cost	Design Life Hrs	Cost per kWh	Cost for 50k Hours	Cost for 15 fc over 50k hours	
AF 1/32TRT 277	CFL	32	$200	12000	0.172	$525.20	**$4,726.80**	(Req's 9 Luminaires)
LR6-DR1000 277V	LED	12.5	$450	50000	0.172	$557.50	**$7,805.00**	(Req's 14 Luminaires)

	# Lamps required for 50k hours	Min # Lamps for 50k hours	Cost per Lamp	Relamp Cost Over 50k Hours
	4.166667	5	$10	$50

Table IV.2 Life cycle cost analysis of LED v. CFL over life of lamp.

This analysis was by far the most fickle. After completing research and preliminary analyses, it was evident that LEDs cannot be implemented on a large scale. The opportunity did come into play when considering the corridors, as they are using downlights and LEDs are a good fit for that application. Replacing all 125 CFL luminaires will require 186 LED luminaires. This will reduce the energy use by 41% in that area, from 3968 watts to 2325 watts. If used 10 hours per day, 5 days per week, this equates to $3696 in annual energy savings. While this is a significant savings in energy, over the life of the lamp (assuming 50,000 hours) the initial procurement costs will not be recovered. It is not recommended that North High School use the LED fixture unless the unit price comes down or there are other ways to curb cots (rebates, tax cuts, etc.). Finally, because these fixtures are in a corridor, the use of daylight sensors would be impractical, as little light penetrates from the stairwells at each corridor end.

Finally, relating this to scheduling, using this LED fixture will increase the time needed for installation. This could add to a delay in the project which is not advisable; construction managers aim to compress the schedule, not accelerate it. The increased labor required will also lead to an increase in labor costs, affecting the installed price of the luminaire. Again, using the Cree LED luminaire is not advisable on this project.

As a note on this electrical breadth, a lot was learned in terms of lighting technology. It was assumed that the hype about LEDs was true and that they would be an economical choice over their life cycle. The research here proves otherwise, as the purchase price is still too high to justify their use. Additionally, the technology must improve in general lighting applications since it does not provide any substitute for a T5 or T8 lamped luminaire for direct/indirect lighting purposes.

CONCLUSIONS

A common thread of energy improvement underlies each of the four analyses conducted in this thesis. While every option considered does not present immediate cost savings, they demonstrate the ability to save the owner money in the long run.

In reviewing the CHPS rating system, it was found that its implementation may have defined the project duration clearer but it did not add time to the project schedule or complicate the construction management process. Using CHPS forced the design, engineering and construction teams to cooperate earlier on so that future problems could be avoided. This may have indirectly saved money in change orders and schedule delays.

Implementing a solar array on North High School presents an excellent opportunity to demonstrate the viability of alternative energy. Seeking out the government rebates and tax cuts will help cut the initial cost of the system, which will pay itself back in less than 30 years. Since there is already a budget allowance, it makes sense to pursue this.

A green roof costs about $550,000 and the energy savings over time are elusive. In order to properly evaluate the feasibility of this option, the building must be modeled with energy software. The preliminary structural analysis did show that the roof structure could support a lightweight system, such as the Roofscape system.

Finally, the lighting/electrical analysis found that LED luminaires still need improvement to compete with energy efficient CFL luminaires. Used in downlighting, they present energy savings over time, but the initial cost is too great to justify their implementation at this time.

Each of the analyses presented a challenge in their respective field. It was necessary to research, compare, analyze and decide on which systems to implement and how they would impact the North High School project. If implemented, the first three systems wouldn't present a delay in scheduling since they would not be on the critical path. Installing LED luminaires, however, would most likely increase that activity's duration, which is not desirable. The systems analyzed represent higher up-front costs but provide cost savings in the long run. It is important for the owner to consider this when deciding whether or not to implement those systems.

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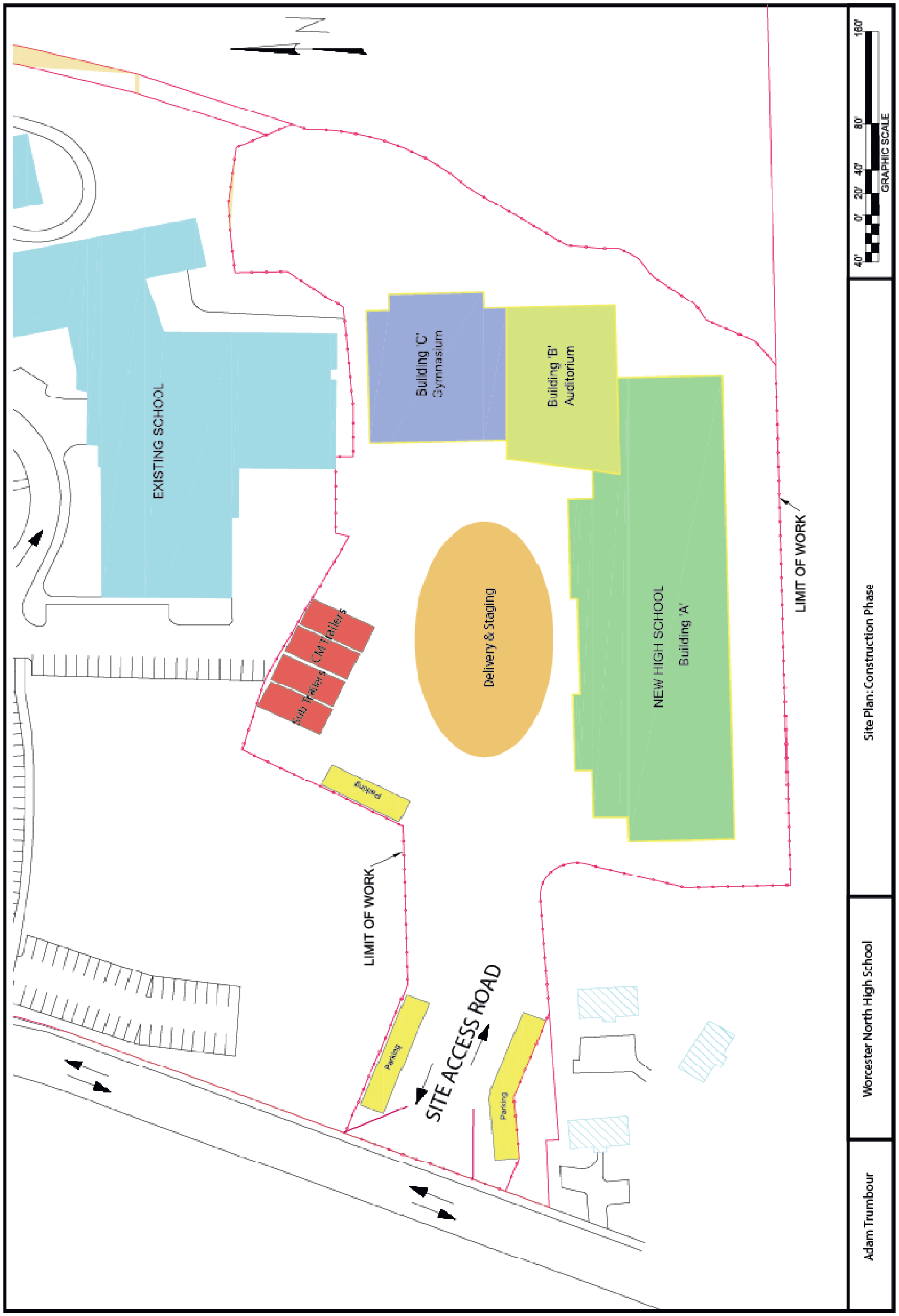
APPENDICES

APPENDIX 0: SITE PLAN



Criteria Summary

CATGORY	ID	TITLE	TOTAL POSSIBLE POINTS	POINTS TARGETED
STRATEGY	**INTEGRATION & INNOVATION**		**11**	
	II.P1	Integrated Design	P	
	II.P2	Educational Display	P	
	II.C1	Demonstration Areas	1	
	II.C2	Innovation	1-4	
	II.C3	Life Cycle Cost Analysis	3	
	II.C4	School Garden	1	
	II.C5	School Master Plan	1	
DESIGN	**INDOOR ENVIRONMENTAL QUALITY**		**23**	
	EQ.P1	HVAC Design - ASHRAE 62.1	P	
	EQ.P2	Construction IAQ Management	P	
	EQ.P3	Pollutant and Chemical Source Control	P	
	EQ.P4	Moisture Management	P	
	EQ.P5	Minimum Filtration	P	
	EQ.P6	Thermal Comfort - ASHRAE 55	P	
	EQ.P7	View Windows, 70%	P	
	EQ.P8	Eliminate Glare	P	
	EQ.P9	Minimum Acoustical Performance	P	
	EQ.P10	Minimum Low Emitting Materials	P	
	EQ.C1	View Windows, 80 – 90%	1-2	
	EQ.C2	Daylighting in Classrooms	1-6	
	EQ.C3	Low-Emitting Materials	1-4	
	EQ.C4	Ducted Returns	1	
	EQ.C5	Enhanced Filtration	1	
	EQ.C6	Post-Construction IAQ	1	
	EQ.C7	Enhanced Acoustical Performance	1-4	
	EQ.C8	Controllability of Systems	1-2	
	EQ.C9	Duct Access & Cleaning	1	
	EQ.C10	Electric Lighting	1	

DESIGN	**ENERGY**		**36**	
	EE.P1	Minimum Energy Performance, 20%	P	
	EE.P2	Commissioning	P	
	EE.P3	Facility Staff & Occupant Training	P	
	EE.C1(A)	Superior Energy Performance (Performance Approach)	2-15	
	EE.C1(B)	Superior Energy Performance (Prescriptive Approach)	1-2	
	EE.C2	Minimize Air Conditioning	1-3	
	EE.C3	Renewable Energy	1-12	
	EE/C4	Plug Load Reduction & Energy STAR Equipment	1	
	EE.C5	Energy Management System and Sub Metering	1-3	
	EE.C6	Flex Energy	1-2	
DESIGN	**WATER**		**16**	
	WE.P1	Irrigation System Performance on Recreational Fields	P	
	WE.P2	Indoor Water Use Reduction, 20%	P	
	WE.C1	Indoor Water Use Reduction, 30-40%	2-3	
	WE.C2	Reduce Potable Water Use for Sewage Conveyance	4	
	WE.C3	No Potable Water Use for Non-Recreational Landscaping Areas	3	
	WE.C4	Reduce Potable Water Use for Recreation Landscaping Areas	2	
	WE.C5	Irrigation System Commissioning	1	
	WE.C6	Water Management System	1-3	
DESIGN	**SITE**		**16**	
	SS.P1	Joint Use of Facilities and Parks	P	
	SS.C1	Sustainable Site Selection	1-5	
	SS.C2	Central Location / SMART Growth	1	
	SS/C3	Reduced Building Footprint	1	
	SS.C4	Building Layout & Microclimates	1	
	SS/C5	Public Transportation	1	
	SS.C6	Pedestrian/Bike/Human Powered Transportation	2	
	SS.C7	Parking Minimization	1	
	SS.C8	Post-Construction Stormwater Management	1	
	SS.C9	Reduce Heat Islands – Landscaping	1	
	SS.C10	Heat Islands – Cool Roofs	1	
	SS.C11	Light Pollution Reduction	1	

DESIGN	**MATERIALS & WASTE MANAGEMENT**		**14**	
	MW.P1	Storage and Collection of Recyclables	P	
	MW.P2	Minimum Construction Site Waste Management, 75%	P	
	MW.C1	Minimum Construction Site Waste Management, 90%	1	
	MW.C2	Single Attribute - Recycled Content Materials	1-2	
	MW.C3	Single Attribute - Rapidly Renewable Materials	1	
	MW.C4	Single Attribute - Certified Wood	1	
	MW.C5	Single Attribute - Regional Materials	1-2	
	MW.C6	Material Re-Use	1	
	MW.C7	Durable and Low Maintenance Flooring	1	
	MW.C8	Building Reuse – Exterior	1-4	
	MW.C9	Building Reduce – Interior	1	
PERFORMANCE	**OPERATIONS & MAINTENANCE**		**9**	
	OM.P1	Maintenance Plan	P	
	OM.P2	Anti-Idling Measures	P	
	OM.P3	Green Cleaning	P	
	OM.C1	Work Order and Maintenance Management System	1	
	OM.C2	Indoor Environmental Management	1-3	
	OM.C3	Green Power	1	
	OM.C4	Climate Change Action: Diesel Bus Retrofit	1	
	OM.C5	Carbon Footprint Reporting	1	
	OM.C6	Energy Benchmarking	3	

TOTAL POINTS POSSIBLE **125**

APPENDIX I.2: LEED SCORECARD

Yes	?	No			
0	0	0	**SUSTAINABLE SITES**		**24 Points**
Y			Prereq 1	Construction Activity Pollution Prevention	Required
Y			Prereq 2	Environmental Site Assessment	Required
			Credit 1	Site Selection	1
			Credit 2	Development Density and Community Connectivity	4
			Credit 3	Brownfield Redevelopment	1
			Credit 4.1	Alternative Transportation - Public Transportation Access	4
			Credit 4.2	Alternative Transportation - Bicycle Storage and Changing Rooms	1
			Credit 4.3	Alternative Transportation - Low-Emitting and Fuel-Efficient Vehicle:	2
			Credit 4.4	Alternative Transportation - Parking Capacity	2
			Credit 5.1	Site Development - Protect or Restore Habitat	1
			Credit 5.2	Site Development - Maximize Open Space	1
			Credit 6.1	Stormwater Design - Quantity Control	1
			Credit 6.2	Stormwater Design - Quality Control	1
			Credit 7.1	Heat Island Effect - Nonroof	1
			Credit 7.2	Heat Island Effect - Roof	1
			Credit 8	Light Pollution Reduction	1
			Credit 9	Site Master Plan	1
			Credit 10	Joint Use of Facilities	1

Yes	?	No			
0	0	0	**WATER EFFICIENCY**		**11 Points**
Y			Prereq 1	Water Use Reduction	Required
			Credit 1	Water Efficient Landscaping	2 to 4
			Credit 2	Innovative Wastewater Technologies	2
			Credit 3	Water Use Reduction	2 to 4
			Credit 4	Process Water Use Reduction	1

Yes	?	No			
0	0	0	**ENERGY & ATMOSPHERE**		**33 Points**
Y			Prereq 1	Fundamental Commissioning of Building Energy Systems	Required
Y			Prereq 2	Minimum Energy Performance	Required
Y			Prereq 3	Fundamental Refrigerant Management	Required
			Credit 1	Optimize Energy Performance	1 to 19
			Credit 2	On-Site Renewable Energy	1 to 7
			Credit 3	Enhanced Commissioning	2
			Credit 4	Enhanced Refrigerant Management	1
			Credit 5	Measurement and Verification	2
			Credit 6	Green Power	2

Yes	?	No	Category		Points
0	0	0	**MATERIALS & RESOURCES**		**13 Points**

Y	?	No	Credit		Points
Y			Prereq 1	Storage and Collection of Recyclables	Required
			Credit 1.1	Building Reuse - Maintain Existing Walls, Floors and Roof	1 to 2
			Credit 1.2	Building Reuse - Maintain Interior Non-Structural Elements	1
			Credit 2	Construction Waste Management	1 to 2
			Credit 3	Materials Reuse	1 to 2
			Credit 4	Recycled Content	1 to 2
			Credit 5	Regional Materials	1 to 2
			Credit 6	Rapidly Renewable Materials	1
			Credit 7	Certified Wood	1

Yes	?	No	Category		Points
0	0	0	**INDOOR ENVIROMENTAL QUALITY**		**19 Points**

Y	?	No	Credit		Points
Y			Prereq 1	Minimum Indoor Air Quality Performance	Required
Y			Prereq 2	Environmental Tobacco Smoke (ETS) Control	Required
Y			Prereq 3	Minimum Acoustical Performance	Required
			Credit 1	Outdoor Air Delivery Monitoring	1
			Credit 2	Increased Ventilation	1
			Credit 3.1	Construction Indoor Air Quality Management Plan - During Construc	1
			Credit 3.2	Construction Indoor Air Quality Management Plan - Before Occupan	1
			Credit 4	Low-Emitting Materials	Up to 4
			Credit 5	Indoor Chemical and Pollutant Source Control	1
			Credit 6.1	Controllability of Systems - Lighting	1
			Credit 6.2	Controllability of Systems - Thermal Comfort	1
			Credit 7.1	Thermal Comfort - Design	1
			Credit 7.2	Thermal Comfort - Verification	1
			Credit 8.1	Daylight and Views	1 to 3
			Credit 8.2	Daylight and Views - Views	1
			Credit 9	Enhanced Acoustical Performance	1
			Credit 10	Mold Prevention	1

Yes	?	No	Category		Points
0	0	0	**INNOVATION IN DESIGN**		**6 Points**

Y	?	No	Credit		Points
			Credit 1	Innovation in Design	1 to 4
			Credit 2	LEED® Accredited Professional	1
			Credit 3	School as a Teaching Tool	1

Yes	?	No	Category		Points
0	0	0	**REGIONAL PRIORITY**		**4 Points**

Y	?	No	Credit		Points
			Credit 1	Regional Priority	1 to 4

Yes	?	No	Category		Points
0	0	0	**PROJECT TOTALS (Certification Estimates)**		**110 Points**

Certified: 40-49 points Silver: 50-59 points Gold: 60-79 points Platinum: 80+ points

1. How many projects (roughly) have you worked on where a sustainability rating system was used (i.e. LEED, Energy Star, CHPS, etc.)?

- 2, 4, 3, 4, 1, 2
- Gilbane as a company has over 190 projects that are going for, or has achieved LEED, CHPS or Energy Star Labeling. We also have at least one Green Globes project. I personally have been the AP for one project and provided assistance on 15 others, but this is mainly because my role with Gilbane is one of a more national support than a regional or project assignment.
- It's difficult to say since as someone involved on the Preconstruction End I work on so many projects – since I became a Leed Accredited Professional 5 years ago the percentage of Projects using Leed or some other Sustainability Rating System has gone from 25% to 75%. And the percentage of projects that are committed to sustainable design but not seeking the accreditation is probably 100%; some owners recognize the inherent benefits but just don't want to pay for the plaque.

2. Have you worked on projects aiming for a CHPS certification? If yes, please answer questions A, B, C

A. What are the pitfalls of the CHPS system?

B. What are the benefits of CHPS, both independently and vis-à-vis LEED?

C. What suggestions do you have for a new project aiming for a CHPS certification?

- CHPs is good because it is free of the hype that comes with LEED. I like that it is more accessible, and when you call their offices, you get a real person. The regional CHPS, however, can be a bit confusing as not all of them offer the third party verification that California CHPS can have, and because regional offices are usually part of another organization, answers can be difficult. The regional websites are not as developed as the USGBC's and information can be hard to navigate.
- I would say to make sure you have a good contact with the regional CHPS and understand what the client wants out of the process. Many times they themselves don't understand what is available. Also know why the client wants CHPS or LEED; is it for additional funding? Is it a law?
- (0) Yes – Every new Public School Project is required to be MaChps (the Massachusetts version of CHPS)
- (A) Potential Pitfalls can be the mad scramble at the end if things are not well coordinated. The design needs to match the established CHPs goals, and the execution by the team in the field needs to be seamless and not impact the budget or schedule. A good example of a pitfall could be the Indoor Air Quality Plan. If the plan dictates that Building Flush out is required but that activity, which could take two weeks, is not built

into the schedule, then there could be some serious schedule challenges – not a good thing for any project but especially a school.

- (B) Life Cycle Costs Savings (energy, maintenance, operations), a more productive user (Staff, Students), a marketing tool, a community beacon of pride – some of the benefits are obvious and tangible while others are inherent and more subtle.
- (C) The goals need to be established early in the Design Phase, and Monitored throughout Design and Construction. A separate series of meetings dedicated to this is a good idea.

3. How have sustainability rating systems affected the industry, specifically the construction management process, in your opinion?

- A lot of clients ask if it costs more to obtain LEED certification, for a Certified and Silver project we would say no, it is easy to obtain the appropriate credits without incurring additional costs. When you start talking Gold or Platinum, there tends to me more money involved from buying green energy, signing longer leases etc…
- On the construction management end it just involves more paperwork and an understanding on what is going to be required upfront. Submittals need to be reviewed with LEED in mind. Then during closeout more time will be taken organizing and submitting for the certification.
- Third party rating systems have created a level of panic and lots of paperwork. Many people don't understand the LEED or other processes, which causes confusion and fear. While it has subsided some, and therefore the cost of getting the paperwork has decreased, it is one of those things where you want at least a resource or a person onsite who knows what they are doing. The concepts that LEED pushes with charrettes and integrated design has made the CM process more CM and not just glorified GC's, by pulling the CM into Precon more and more. In the long term, this early involvement can help to minimize costs during construction.
- Young LEED compliance consultants have little or no knowledge of construction means and methods, which limits their ability to lead the process.
- Generally positive. I think the process causes the need for a greater focus and diligence during the entire construction process on sustainability issues to ensure they are being met. In general I think LEED, which I have the most experience with, is getting better as it starts to focus more on weighting points based on their impact and their relative magnitude of complexity. For example previously you got the same 1 point from USGBC if you put in a bike rack and shower as if you put in a wind turbine. Obviously these things are very different in their sustainable impact as well as their upfront investment. LEED is beginning to acknowledge this difference a bit more in the v3.0.
- There is a lot more focus and attention given to issues beyond first cost. Budget is important, but owners recognize there is return on the investment. Any CM or Design firm not on board has already been left behind. We do have to remain vigilant about the technical aspects and the sometimes conflicting results of Green…for example, the use of water based low VOC (volatile organic compound) adhesives has caused many

resilient flooring failures due to the normal vapor emissive of concrete slabs. Hospitals especially have been impacted by this, since they utilize welded seam sheet goods (rubber) for many of their program spaces. The water content in the slabs causes the flooring to bubble because the glue while healthier to breath just doesn't stick as good as the old stuff. Potential solutions include allowing more time in the schedule to dry out the slabs and / or put down a "coaster" system – a fluid applied waterproofing system – prior to the flooring product. Both add time and money.

- LEED has been instrumental in moving the construction industry toward more consideration of sustainable design, more choices in materials with recycled materials, and more sustainable construction techniques such as with waste management and air quality.
- In my opinion, sustainability rating systems, specifically LEED, would not be needed if the government would establish proper energy efficiency standards. LEED is a for profit organization that is governed by no rules, regulations, other than its bottom line. To be honest, in today's environment, nobody intentionally builds a non-energy efficient building. Seeking a LEED certification could push a developer to gain an extra 5 percent efficiency, maybe, and only if it is cost effective. If a developer/owner is willing to pay the extra to get those extra points to go from a silver to platinum certification, my guess is they were going to do it anyway, with or without a LEED Certificate that will cost $100,000 in LEED fees. I will encourage clients to keep track of the LEED points, but not necessarily seek the actual certification. If they meet all the criteria, they can claim "LEED Certifiable" without having to pay LEED the large fee to certify.
- More inquiries from Owners and Clients about pursuing certification. More time and costs involved in using the rating systems and then going after certification.

4. What are the areas of LEED and/or CHPS that have the most influence on the construction management process, and what is done to control these (i.e. certification paperwork headaches; paperwork is managed by one person throughout the entire project)?

- Paperwork management. This is handled by having LEED sheets filled out and returned with all submittals, making it so the person on our end only needs to perform data entry tasks. This means the project engineer on the job can do 90% of the extra work that LEED requires and at the end the PM or other LEED professional reviews.
- The best thing a company can do is to create standard tracking documents and a have to manual beyond the Reference Guides that gives practical tips to supporting the process for each credit. Also having someone available who has gone through the complete certification process previously is also helpful.
- Cost of implementing LEED compatible systems in restricted budgets is difficult. Projects are built with capital budgets and operated with operating budgets. It is often a hard sell for the savings, which is realized in the operations of the building, to be borne by the capital budget.
- As an A/E Professional I can't really speak to the CM process from a 1st. hand experience. From our perspective it has the most influence on the CM process in the

need for additional tracking and certification measures. From the A/E end we try to have one person manage the entire process that is involved in the construction administration so they are familiar with the goals and necessary requirements and work closely with the CM to obtain the necessary information. It certainly adds a layer of administrative effort to the process for both CM and Architect.

- For us and many Construction Managers it is not that much different than it has always been done – we help facilitate solutions to problems. Before LEED there were plenty of other opportunities, just different areas of focus. Architectural and Engineering trends are always changing and evolving, but each new era brings another set of challenges. I think that the most important thing at least in Preconstruction is to draw upon the ever accruing lessons Learned Database. As far as paperwork it is just another task in the field – the key is to understand the roles and responsibilities within the GBCo team as well as between the CM and Design Team. Also very important is to make sure the project is purchased in a way such that the subs understand their responsibilities as well. The industry is well versed in it these days as most everyone has been through one or two Sustainable projects.
- Waste management, materials documentation, and construction IAQ plan. Teams that embrace sustainable construction and have some level of experience seem to have no trouble dealing with the requirements. Teams that only give it lip service are less effective in their work and seem to make the requirements more difficult than they need to be.
- In my opinion, the largest influence is the "green wash" - the good will that a company which plunders the third world for natural resources can produce by saving a few pennies of energy here at home - is an excellent investment for a big pharmaceutical firm or software company seeking to "green up" their image. If these firms are willing to pay the fees and administration costs to meet the requirements, the certifications will continue to be used.
- Certification is the most difficult piece. The cost involved can often be prohibitive for smaller projects or clients with limited funding. Often times, Owners are willing to implement sustainable strategies outlined in the rating systems without pursuing certification. Many of these strategies are part of good architectural/engineering design anyways Working with contractors that are new to the ratings systems poses challenges both in execution of the work and in the required submittal process; making them understand that both are important.

Checking Module Voltages: 230 Watt BP Solar BP3230T

MPP-voltage V_{MPP} (at 25°C) = 29.1 V
MPP-current I_{MPP} (at 25°C) = 7.90 A
Open circuit voltage V_{OC} (at 25°C) = 36.7 V
Short circuit current I_{SC} (at 25°C) = 8.40 A
Voltage temperature difference coefficient T_C (V_{OC}) = -0.36%/°C
Current temperature difference coefficient T_C (I_{SC}) = 0.065%/°C
Power coefficient T_C (P_{MAX}) = -0.5%/°C

V_{OC} (at -10°C) = 36.7 V x (1+ (35 x 0.0036)) = 41.32 V = V_{Max}
V_{MPP} (at -10°C) = 29.1 V x (1+ (35 x 0.0036)) = 32.77 V = V_{AVG}
V_{MPP} (at +70°C) = 29.1 V x (1- (45 x 0.0036)) = 24.39 V = V_{MIN}

System: 39.79 kW – (173) 230-Watt Modules

Inverter Selection
Power range: 0.90 … 0.95 x PV array peak power: 35.81 kW – 37.80 kW
Fronius 12.0-3 wye 277 Inverter, 10.2 – 13.8 kW Peak Power

- Recommended PV Power: 10.2 – 13.8 kW
- V_{MPP} Range: 230 V – 500 V
- V_{MAX} Input: 600 V
- I_{MP} Nominal: 33.1 A
- I_{MP} Maximum Input: 56.1 A

Panel Configuration (Strings, Series v. Parallel)

Using 3 Inverters, 57 panels per inverter (171 panels total):

- Using 4 strings wired in parallel, of 14 panels wired in series: 56 panels/inverter
- 56 panels x 230 W/panel = 12.88 kW < 13.8 kW = PV power max of inverter
- 14 panels x V_{Max} = 14 x 41.32 = 578.48 V < 600 V = V_{MAX} inverter input
- 14 panels x V_{MIN} = 14 x 24.39 = 341.46 V > 230 V = V_{MIN} inverter input for tracking
- 4 strings x 8.4 A per string = 33.6 A < 56.1 A = I_{MP} maximum input of inverter

System design is okay.

Combiner Box Selection

SMA SBCB-6
Maximum 6 string attachment
15A fuses, 600 VDC rating
8.4 A x 1.45 safety factor = 13.1 Amp fuse requirement < 15 Amp fuse in system → ok
14 panels x V_{MAX} = 578.48 V < 600 V maximum → ok
4 strings < 6 string max → ok

System: 7.59 kW – (33) 230W Panels

Module Voltages as above.

Inverter Selection
Power range: 0.9 … 0.95 x PV array peak power: 7.245 – 7.6475 kW

(1) SMA Sunny Boy SB 7000US Inverter, 8.75 kW Peak Power

Recommended Max PV Power:	8.75 kW
V_{MPP} Range (DC):	250 – 480 V
V_{MAX} Input (DC):	600 V
I_{MP} Maximum Input:	30 A

Panel configuration (Strings, Series v. Parallel)

Using (1) inverter, 33 panels:

Using 3 strings wired in parallel, of 11 panels wired in series
33 panels x 230W/panel = 7.59 kW < 8.75 kW = PV power max of inverter
11 panels x V_{MAX} = 11 x 41.32 = 454.52 V < 600 V = V_{MAX} inverter input
11 panels x V_{MIN} = 11 x 24.39 = 268.29 > 250 V = V_{MIN} inverter input for tracking
3 strings x 7.9 A/string = 23.7 A < 30 A maximum input of inverter

System design is okay.

Combiner box selection

SMA SBCB-6
Maximum 6 string attachment
15A fuses, 600 VDC rating
8.4 A x 1.45 safety factor = 13.1 Amp fuse requirement < 15 Amp fuse in system → ok
11 panels x V_{MAX} = 268.29 V < 600 V maximum → ok
3 strings < 6 string max → ok

PVWatts ***** AC Energy & Cost Savings *****

Station Identification	
Cell ID:	0272366
State:	Massachusetts
Latitude:	42.2 ° N
Longitude:	71.9 ° W
PV System Specifications	
DC Rating:	7.59 kW
DC to AC Derate Factor:	0.821
AC Rating:	6.23 kW
Array Type:	Fixed Tilt
Array Tilt:	42.2 °
Array Azimuth:	180.0 °
Energy Specifications	
Cost of Electricity:	17.2 ¢/kWh

Results			
Month	Solar Radiation (kWh/m²/day)	AC Energy (kWh)	Energy Value ($)
1	3.03	612	105.26
2	3.90	711	122.29
3	4.81	931	160.13
4	4.78	866	148.95
5	5.06	910	156.52
6	5.16	866	148.95
7	5.24	897	154.28
8	5.19	891	153.25
9	4.83	826	142.07
10	4.27	796	136.91
11	3.00	561	96.49
12	2.72	539	92.71
Year	4.33	9408	1618.18

PVWatts ***** AC Energy & Cost Savings *****

Station Identification	
Cell ID:	0272366
State:	Massachusetts
Latitude:	42.2 ° N
Longitude:	71.9 ° W
PV System Specifications	
DC Rating:	38.6 kW
DC to AC Derate Factor:	0.821
AC Rating:	31.7 kW
Array Type:	Fixed Tilt
Array Tilt:	42.2 °
Array Azimuth:	180.0 °
Energy Specifications	
Cost of Electricity:	17.2 ¢/kWh

Results			
Month	Solar Radiation (kWh/m²/day)	AC Energy (kWh)	Energy Value ($)
1	3.03	3115	535.78
2	3.90	3622	622.98
3	4.81	4739	815.11
4	4.78	4409	758.35
5	5.06	4634	797.05
6	5.16	4409	758.35
7	5.24	4567	785.52
8	5.19	4537	780.36
9	4.83	4207	723.60
10	4.27	4053	697.12
11	3.00	2858	491.58
12	2.72	2743	471.80
Year	4.33	47893	8237.60

Clean Power Estimator

Location and Usage

City, State
Worcester MA

Utility
National Grid USA
(Massachusetts Electric)

Rate
Net
Metered
General
Service

Monthly Electric Bill
$9,000 per month

Annual Bill Escalation
5.0% per year

PV System

Adjust your system size to offset a higher percentage of your electricity bill with solar:

Size (dc)
10 kW

Cost
$6.00 per Watt-dc

Click here for detailed inputs

Financing

Loan Type
Loan

Click here for detailed inputs

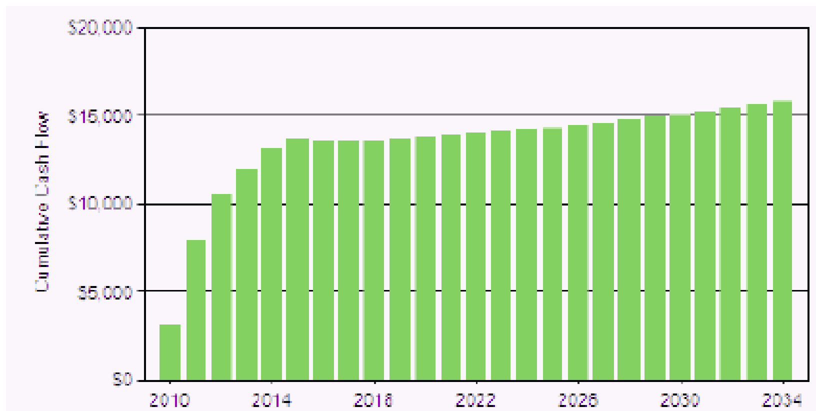
Benefits of your BP Solar system

Estimated System Cost	$60,000
Federal / State Tax Credit	$18,000
State / Utility Rebate	$15,000
Net Cost	$27,000
Cumulative Lifetime Savings	$108,376 over 25 years
Investment Return	17.8%

Net Cost - Year 1 **Annual Cash Flow** **Cum Disc Cash Flow** **Monthly Electric Bill**
Monthly PV Output **Daily PV Production** **Daily Electricity Use** **Pollution Prevention**

Net Present Value of $15,830 on your BP Solar system

Cumulative Discounted Net Cash Flow



	Net Cash Flow	Discount Factor	Discounted Net Cash Flow	Cumulative Discounted Net Cash Flow
2010	$3,263	0.9580	$3,126	$3,126
2011	$5,397	0.8846	$4,774	$7,900
2012	$3,233	0.8168	$2,641	$10,541
2013	$1,738	0.7542	$1,311	$11,852
2014	$1,798	0.6964	$1,252	$13,104
2015	$862	0.6430	$554	$13,658
2016	$-72	0.5937	$-43	$13,615
2017	$-4	0.5482	$-2	$13,613
2018	$66	0.5062	$33	$13,646
2019	$139	0.4674	$65	$13,711
2020	$214	0.4316	$92	$13,804
2021	$293	0.3985	$117	$13,920
2022	$154	0.3680	$57	$13,977
2023	$239	0.3398	$81	$14,058
2024	$326	0.3137	$102	$14,160
2025	$416	0.2897	$120	$14,281
2026	$509	0.2675	$136	$14,417
2027	$605	0.2470	$150	$14,567
2028	$705	0.2281	$161	$14,727
2029	$807	0.2106	$170	$14,897
2030	$913	0.1944	$177	$15,075
2031	$1,021	0.1795	$183	$15,258
2032	$1,133	0.1658	$188	$15,446
2033	$1,248	0.1531	$191	$15,637
2034	$1,366	0.1413	$193	$15,830

Clean Power Estimator

Location and Usage

City, State
Worcester MA

Utility
National Grid USA (Massachusetts Electric)

Rate
Net Metered General Service Rate

Monthly Electric Bill
$9,000 per month

Annual Bill Escalation
5.0% per year

PV System

Adjust your system size to offset a higher percentage of your electricity bill with solar:

Size (dc)
40 kW

Cost
$6.00 per Watt-dc

Click here for detailed inputs

Financing

Loan Type
Loan

Click here for detailed inputs

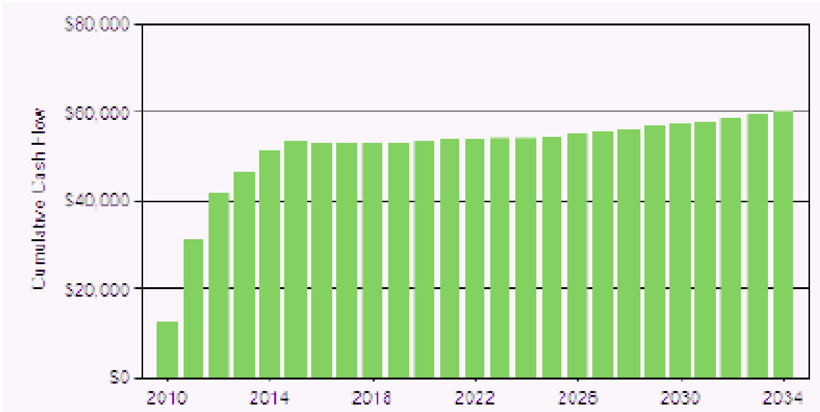
Benefits of your BP Solar system

Estimated System Cost	$240,000
Federal / State Tax Credit	$72,000
State / Utility Rebate	$52,500
Net Cost	$115,500
Cumulative Lifetime Savings	$433,505 over 25 years
Investment Return	17.0%

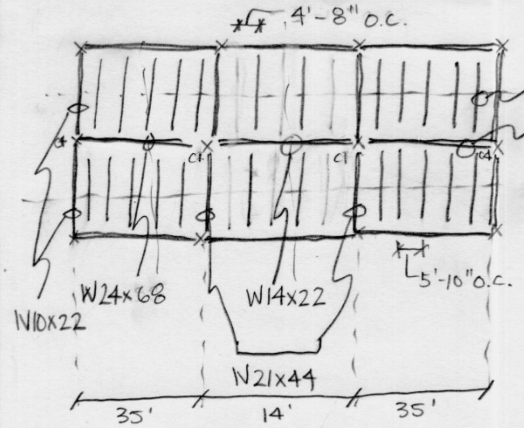
Net Cost - Year 1 | **Annual Cash Flow** | **Cum Disc Cash Flow** | **Monthly Electric Bill**
Monthly PV Output | **Daily PV Production** | **Daily Electricity Use** | **Pollution Prevention**

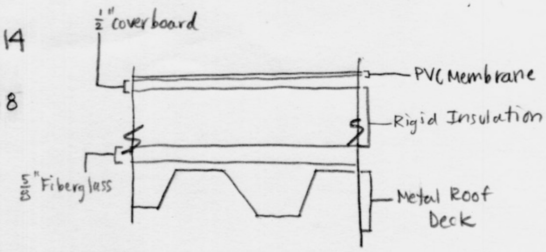
Net Present Value of $60,079 on your BP Solar system

Cumulative Discounted Net Cash Flow



	Net Cash Flow	Discount Factor	Discounted Net Cash Flow	Cumulative Discounted Net Cash Flow
2010	$12,780	0.9580	$12,243	$12,243
2011	$21,315	0.8846	$18,855	$31,098
2012	$12,657	0.8168	$10,338	$41,436
2013	$6,674	0.7542	$5,034	$46,470
2014	$6,912	0.6964	$4,814	$51,283
2015	$3,165	0.6430	$2,035	$53,318
2016	$-573	0.5937	$-340	$52,978
2017	$-306	0.5482	$-168	$52,810
2018	$-29	0.5062	$-15	$52,795
2019	$259	0.4674	$121	$52,916
2020	$557	0.4316	$240	$53,157
2021	$866	0.3985	$345	$53,502
2022	$309	0.3680	$114	$53,615
2023	$640	0.3398	$217	$53,833
2024	$983	0.3137	$308	$54,141
2025	$1,338	0.2897	$387	$54,529
2026	$1,704	0.2675	$456	$54,985
2027	$2,082	0.2470	$514	$55,499
2028	$2,472	0.2281	$564	$56,062
2029	$2,873	0.2106	$605	$56,667
2030	$3,287	0.1944	$639	$57,306
2031	$3,712	0.1795	$666	$57,973
2032	$4,149	0.1658	$688	$58,661
2033	$4,597	0.1531	$704	$59,364
2034	$5,056	0.1413	$715	$60,079





ROOF ASS'Y

$D = 15\,psf$

$L_r = 20\,psf$ — per IBC 1607.11

SNOW LOAD CALCULATION:

$P_g = 55\,psf$ — per CMR 1604.10

$C_e = 0.9$

$C_t = 1.0$

$I = 1.1$

$P_f = 0.7\,C_e \cdot C_t \cdot I \cdot P_g$

$P_f = 0.7(0.9)(1.0)(1.1)(55)$

$P_f = 38.115\,psf \Rightarrow$ say $\boxed{P_f = 39\,psf}$

LOAD COMBINATIONS, LRFD: (No green roof)

excluding effects of wind load

examining typical bay with no mechanical equipment

$W_u = 5.83'(1.2D + 1.6(L_r \text{ or } S))$

$W_{u_1} = 5.83'(1.2(15) + 1.6(20))$

$W_{u_1} = 291.67\,plf$

$W_{u_2} = 5.83'(1.2(15) + 1.6(39))$

$W_{u_2} = 469\,plf = 0.469\,klf$

$$M_u = \frac{0.469(21)^2}{8} = 25.85\,k\cdot ft$$

$$w = \overset{S}{39} + \overset{L}{20} + \overset{D}{15} = 74\,psf$$

$74(5.83) = 431.7\,plf$

$= 0.432\,klf$

$M_a \le \phi M_n = \phi F_y Z$

W12x14: $I_x = 88.6\,in^4$

$Z_x = 12.6\,in^3$

$$Z_{req} = \frac{M_u}{\phi F_y} = \frac{25.85(12)}{0.9(50)} = 6.89\,in^3 \ll 12.6\,in^3 = Z_x$$

$$21' \times 12\,in/ft = \frac{252''}{240} = \Delta_{max} = 1.05''$$

$$\Delta = \frac{0.432(5)(21)^4(12)^3}{384(29{,}000)(88.6)} = 0.736'' < 1.05''$$

P. 1

Load Combinations, LRFD: w/23 psf GreenRoof

$W_u = 5.83'(1.2(15+23) + 1.6(39)) = 630\text{plf}$

$w = 39+20+15+23 = 97$
$\times 5.83$
$= 565.83\text{plf}$
$= 0.566\text{ klf}$

$M_u = \dfrac{0.63(21)^2}{8} = 34.73\text{ kip.ft}$

$Z_{req} = \dfrac{34.73(12)}{0.9(50)} = 9.26\text{ in}^3 < Z_{xW12\times14} = 12.6\text{ in}^3 \therefore \text{ok}$

$\Delta = \dfrac{5wL^4}{384EI} = \dfrac{5(0.566)(21^4)(12)^3}{384(29{,}000)(88.6)} = 0.96'' < 1.05'' = \dfrac{L}{240} \therefore \text{OK}$

*MA Building Code Req $\frac{L}{240}$ *

$\dfrac{L}{240} = 1.05''$ $\dfrac{L}{360} = 0.7''$

Mu, Including Member self Weight

$M_{uSW} = 1.2\left(\dfrac{0.014(21)^2}{8}\right) = 0.926\text{ kip.ft}$

* Assume member is braced laterally by roof system *

$M_u = 34.73 + 0.926 = 35.66\text{ kip.ft}$

$Z_{req} = \dfrac{35.66(12)}{0.9(50)} = 9.51\text{ in}^3 < 12.6\text{ in}^3 \therefore \text{OK}$

W14x22 Analysis

MSW ⟶ $22\text{plf} \times 14' / (21' \times 14') = 1\text{ psf}$

$D = 15+23+4 = 42\text{ psf}$

$\quad$ └ $W12\times14\text{ wt} = \dfrac{14\text{plf} \times 21\text{ft} \times 4}{14' \times 21'} = 4\text{psf}$

$w = 39+20+15+23+4+1 = 102$
$\times 14$
$= 1428/1000$
$= 1.428\text{klf}$

$W_u = \dfrac{14'(1.2(42)+1.6(39))}{1000} = 1.58\text{klf}$

$M_u = \dfrac{1.58(14)^2}{8} = 38.71\text{ kip.ft} + \underbrace{1.2\left(\dfrac{0.022(14)^2}{8}\right)}_{\text{member self wt}} = 39.36\text{ kip-ft}$

$Z_{req} = \dfrac{39.36(12''/ft)}{0.9(50)} = 10.5\text{ in}^3 < Z_{xW14\times22} = 33.2\text{ in}^3 \therefore \text{oK}$

$\Delta = \dfrac{5(1.428)(14^4)(12)^3}{384(29{,}000)(199)} = 0.213'' < 0.7'' = \dfrac{L}{240} \therefore \text{OK}$

$\dfrac{L}{240} = \dfrac{14(12)}{240} = 0.7''$

p.2

W24x68 Analysis

$$\frac{14\text{ plf} \times 21' \times 10}{14 \times 35} = 6 = \text{Member wt of W12x14's in Trib Area}$$

$$D = 15 + 23 + 6 = 44\text{ psf}$$

$$w = 39 + 20 + 15 + 23 + 6 = 103$$
$$\times\ 35$$
$$= 3.605\text{ klf}$$

$$W_u = \frac{35(1.2(44) + 1.6(39))}{1000} = 4.032\text{ klf}$$

$$M_u = \frac{4.032(35)^2}{8} = 617.4\text{ kip-ft}$$

$$Z_{req} = \frac{617.4(12)}{0.9(50)} = 164.64\text{ in}^3 < 177\text{ in}^3 = Z_{x\ W24x68} \therefore ok$$

$$\Delta = \frac{5(3.605)(14^4)(12^3)}{384(29{,}000)(1830)} = 0.059'' < 1.75'' = \frac{L}{240} \therefore ok$$

$$\frac{L}{240} = \frac{35(12)}{240} = 1.75''$$

LR6-DR1000 -277V 6" Recessed Downlight

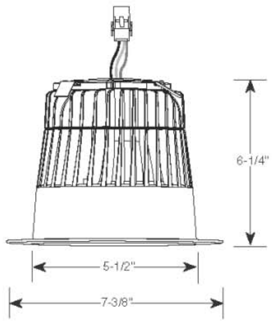
Product Description

The LR6-DR1000 -277V is a recessed architectural downlight that utilizes Cree TrueWhite™ Technology to deliver 1,000 lumens of high quality light, with an unprecedented efficacy of 80 lumens per watt. Its exceptional CRI of 90 brings out the true beauty of applications ranging from offices, schools, hospitals, restaurants, airports, hotels, and homes. US Patent #7,213,940. Numerous patents pending.

LR6C-DR1000 -277V

Performance Summary

- Utilizes Cree TrueWhite™ technology
- Delivered light output = 1,000 lumens
- Input power = 12.5 Watts
- CRI = 90
- CCT = 2700K or 3500K
- Not Dimmable
- Three Year Warranty



Ordering Information

Must be used with Cree H6-277V Housing

Housing

H6--277V- Recessed Housing, 277V

Light Engine

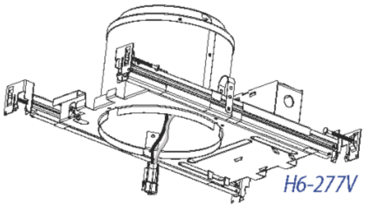
LR6-DR1000 -277V - 277V Incandescent Color (2700K)

LR6C-DR1000 -277V -277V, Neutral Color (3500K)

Accessories - Reference accessory spec sheets

Accessory Trims

- **LT6A-DR** - Diffuse anodized trim
- **LT6AW-DR** - Wheat diffuse anodized trim
- **LT6AP-DR** - Pewter diffuse anodized trim
- **LT6BB-DR** - Flat black trim
- **LT6WH-DR** - Smooth white trim



H6-277V

CREE LED Lighting

CREE TRUE WHITE TECHNOLOGY

LR6-DR1000-277V 6" Recessed Downlight

Product Information

Cree TrueWhite™ Technology

- A better way to generate white light that utilizes a patented mixture of unsaturated yellow and saturated red LEDs.
- Tuned to optimal color point before shipment.
- Color management system maintains color consistency over time and temperature.
- Designed to last 50,000 hours and maintain at least 70% of initial lumen output in IC and non-IC installations.

Construction

- Durable die-cast aluminum upper housing, lower housing, and upper cover.
- Integrated thermal management system conducts heat away from LEDs and transfers it to the surrounding environment. LED junction temperatures stay below specified maximums.
- Must be used with Cree H6-277V, recessed architectural housing with rugged, integral, extruded aluminum bar hangers (h = 7")

Optical System

- Proprietary optical system utilizes a unique combination of reflective and refractive optical components to achieve a uniform, comfortable appearance. Pixelation and direct view of unshielded LEDs is eliminated.
- White Lower Reflector balances brightness of refractor with the ceiling to create comfortable high-angle appearance. Works with refractor to deliver an optimized distribution that illuminates walls and vertical surfaces increasing the perception of spaciousness.

Electrical System

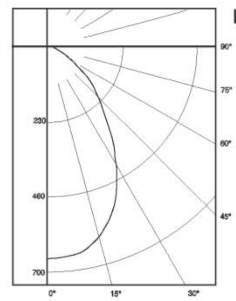
- Integral, high efficiency driver and power supply. Power factor > 0.9 Input voltage = 277V, 60Hz

Regulatory and Voluntary Qualifications

- Tested and certified to UL standards. Suitable for damp locations.

Photometry

LR6-DR1000-277V
Based on OnSpex 30012426-F



Intensity (Candlepower) Summary

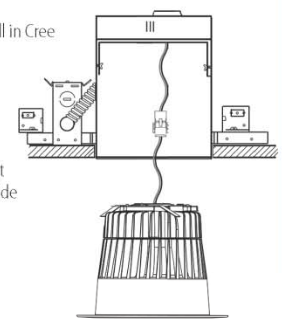
ANGLE	MEAN CP
0°	597
5°	593
15°	559
25°	463
35°	329
45°	207
55°	120
65°	61
75°	32
85°	7
90°	0

Zonal Lumen Summary

ZONE	LUMENS	%LAMP	%FIX
0° - 30°	424	42.42	42.42
0° - 40°	629	62.89	62.89
0° - 60°	897	89.71	89.71
0° - 90°	1000	100.00	100.00

Installation

- Designed to easily install in Cree H6-277V housing.
- Quick install system utilizes a unique retention feature. Simply attach socket to LR6-DR1000. Move light to ready position and slide into housing.



CREE LED Lighting

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