2015 ASHRAE ISBD Competition Report
Portland State University

Portland State University
Student Chapter

Portland State UNIVERSITY

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Executive Summary

Our goals for this project are aligned with those set forth by ASHRAE for the 2015 Integrated Sustainable Building Design Competition. A team of mechanical engineering and architecture students was assembled to collaborate on the design of a high-performance building, taking into account both energy efficient design and considerations unique to the locality of Doha, Qatar. The team worked to integrate site location, building orientation, envelope components, and mechanical systems to achieve a building approaching net-zero energy. The final design has been checked against the OPR, LEED standards, ASHRAE Standards 90.1 and 189.1, and a budget cap of $200 per square foot.

The project team was divided into project sub-groups, defined by various aspects of the project. Members were assigned to solar analysis, mechanical systems, site selection, energy modeling, and building envelope. The earliest deliverables included site selection and climate analysis. Analysis of the desert climate was performed using Climate Consultant software, which guided site selection and narrowed the options of low-energy mechanical systems. The building site was chosen on the basis of wind-direction, public transportation, and proximity to the Persian Gulf to take advantage of any naturally cooled air available in the region. Once site and climate were established, work began on energy modeling in eQuest and load calculations in Trace 700. Several mechanical systems were selected and discussed amongst the entire team, selections favoring technologies that did not rely on free-cooling by outside air given the consistently high outdoor air temperatures of the region. Low flow plumbing was selected to reduce the building's reliance on the energy intensive desalinated water available in Doha. Shading and orientation were an important point of discussion throughout the design process due to the inevitably high solar gain in the region, and solar generation became the obvious choice for a source of renewable energy.

The building was rotated 205° CCW to maximize self-shading and utilize the prevailing wind direction to complement thermal mass cooling strategies. Shaded low SHGC windows were selected for the east and west walls to reduce solar gain while still providing adequate daylighting to the space. Autoclaved Aerated Concrete walls were selected for their high thermal mass, low construction cost, and recyclable material composition. The selected mechanical system is a combination of radiant beams with a dedicated outdoor air system, energy recovery ventilators, and thermal storage. This system was systematically compared against the baseline model as well as high-performance options, and chosen on the bases of low energy demand, initial cost, and life-cycle reliability.

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Overview

The goal of the Integrated Sustainable Building Design (ISBD) project was to design a renovation for the given building that approaches "zero energy". The multidisciplinary team worked to design the building for Doha, Qatar's environment while meeting the owner's project requirements. The building is a three story combined classroom and office building for a local university. Additionally there will be an attached welding and woodworking studio.

Design goals

The project has numerous parameters to follow and objectives to achieve. To approach a "zero energy" building, numerous standards must be met in almost every design area. The following is a summary of some of the major design considerations and limitations that must be fulfilled in order to meet the objectives of this project:

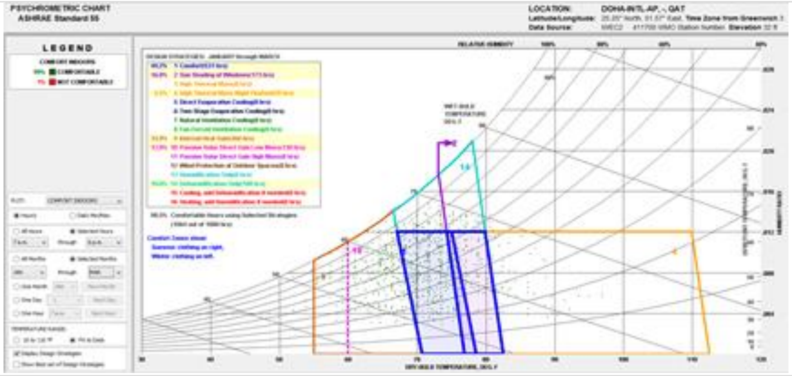
- Meet or exceed ASHRAE standard 189.1 for energy performance
- Meet or exceed ASHRAE standards 55 and 62.1
- Meet or exceed local building codes
- Provide a reliable and easily maintained system(s)
- Provide an exceptional indoor environmental quality including thermal comfort, acoustical performance as well as air quality
- Maintain a budget less than $\$200/ft^2$
- Provide the lowest feasible life cycle cost for the project
- Size and design a solar photovoltaic system for a minimum 5% of the overall building load

Climate study

The overall climate can be classified as very hot and dry (Climate zone 1B). Although Doha has very low annual rainfall humidity levels can vary widely throughout much of the year.

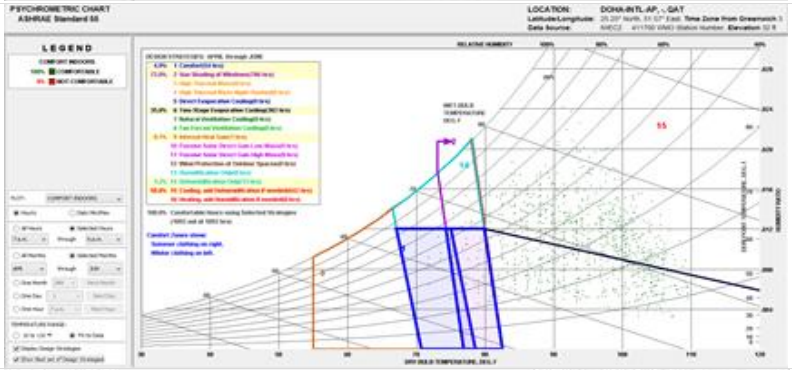
Climate consultant

Climate Consultant 5.5 was used to analyze the dry bulb and wet bulb temperatures, solar radiation characteristics, and psychrometric data points during operational hours for each month. Overall, the climate is very hot and dry for the majority of the year. Figure 1 on the following page shows a large difference between dry bulb and wet bulb temperatures for several months, indicating a low relative humidity. Winter months (December - March) have much cooler average temperature and are within the comfort zone.



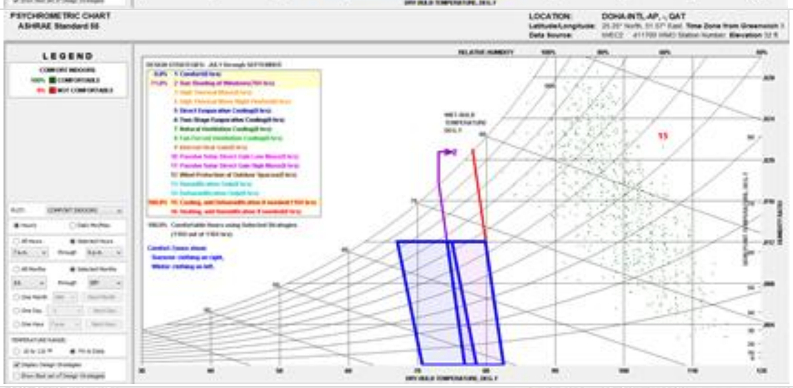
January – March
(7am – 6pm)

Temperatures stay within or close to the comfort zone. Relative humidity is higher during these months.



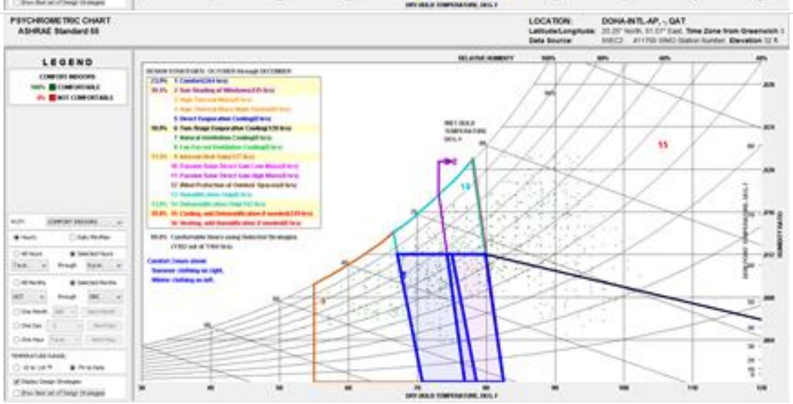
April – June
(7am – 6pm)

Temperatures are beyond the comfort zone (80°F – 110°Fand most hours are relatively dry.



July – September
(7am – 6pm)

Temperatures are very hot (90°F – 115°F) and humidity levels vary widely.



October – December
(7am – 6pm)

Temperatures range from 60°F – 95°F and air is more humid during these months.

Figure 1 - Seasonal outdoor air condition

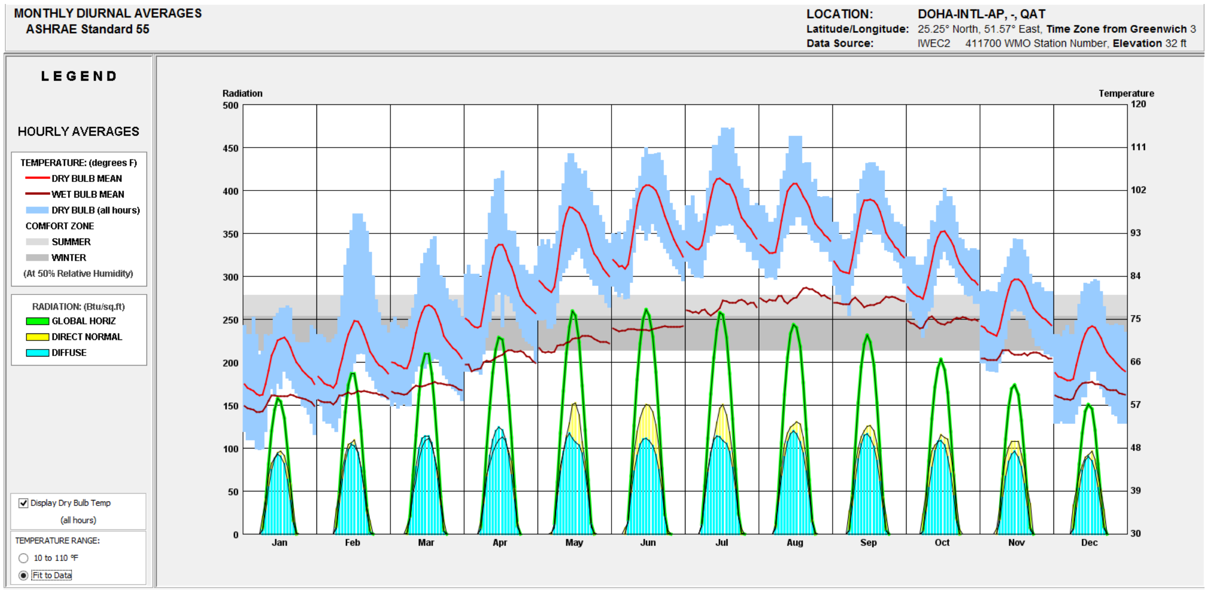


Figure 2 - Monthly average diurnal conditions

Shown above is the average diurnal distribution of dry and wet bulb temperature with respect to the standard 55 thermal comfort band. This figure shows that much of the year the diurnal temperature is entirely out of the thermal comfort range.

Other design conditions of interest are the average annual cloud cover which is just under 20% with more cloud cover during the winter. The annual ground temperature average is just above 80 °F.

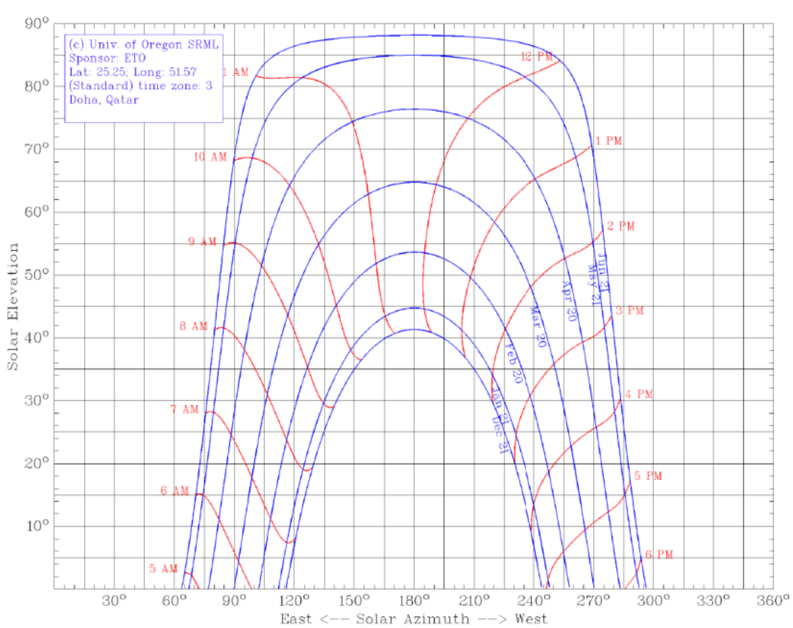


Figure 3 - Solar angle diagram

This solar diagram shows that the majority of solar radiation is from a steep angle especially during the middle of the day. This indicates that the majority of solar radiation will be incident upon the roof while low angle solar radiation will be limited to the east and west aspects.

Windfinder

Wind patterns were investigated using windfinder.com with measurements located at the Doha International Airport. The most prominent wind originates from the NW, which helped inform the building orientation.

Statistics based on observations taken between 05/2005 - 02/2015 daily from 7am to 7pm local time. You can order the raw wind and weather data in Excel format from our historical weather data request page.

Month of year	Jan 01	Feb 02	Mar 03	Apr 04	May 05	Jun 06	Jul 07	Aug 08	Sep 09	Oct 10	Nov 11	Dec 12	Year 1-12
Dominant Wind dir.													
Wind probability >= 4 Beaufort (%)	23	35	39	33	40	51	37	24	25	16	24	17	30
Average Wind speed (mph)	9	12	12	10	12	14	12	10	10	9	10	9	10
Average air temp. (°F)	68	71	78	86	96	102	104	102	98	91	80	71	86

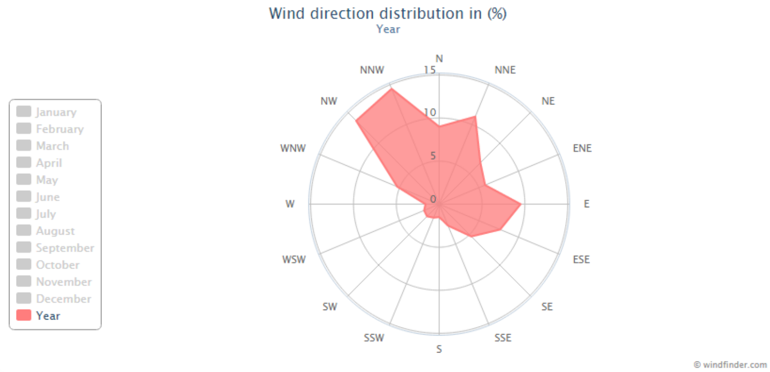


Figure 4 - Wind rose

Site selection and layout

The chosen site for the project is located just 3 miles from the center of the city. No information is available detailing the density of developments nearby, but the location meets greenfield criteria under Section 5.3.1.1 (f). The site is located adjacent to Omar Al Mukhtar St., which is served by Route 77 of Doha's Mowasalat bus service. Along this route, bus service is provided to the public daily from 6:00 AM to midnight.

The site is approximately 5 acres and allows for the building footprint as well as a parking lot. Additionally, basic services are provided within ½ mile of the site, but there is a lack of available data about the nature and service of each business.

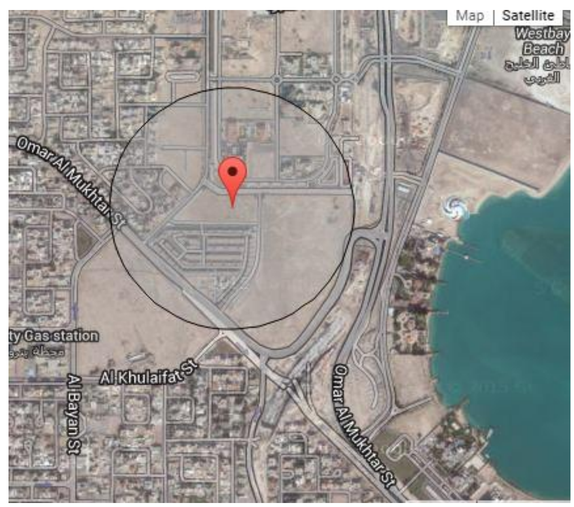


Figure 5 - Site location

Building orientation and layout

For very hot climates, the building's orientation is crucial to reducing solar heat gain loads. It can be effectively reduced by minimizing exposure on the east and west facades. Since the building's plan is rectangular, the optimal orientation would be close to an east-west orientation.

The original plan placed the workshop on the east side of the building. After analyzing the baseline load for this space and the scheduled occupancy, we decided that it would be beneficial to place the workshop on the west side. The two reasons for this change was that it shields the space from direct solar heat gain during the first part of the day and by the time the sun's intensity increases on the west façade, the workshop will not be in use (Monday – Friday 3pm). Massing will also delay the elevated solar heat gain until unoccupied hours.

The entire building was rotated 205° CCW. The offset from the east-west orientation provides some self-shading during the day. The offset also aligns closer with the prominent northwest winds to enhance the thermal mass cooling at night during part of the year.

Integrated design process

A multidisciplinary team of architecture, mechanical, and civil engineering students collaborated from the earliest stages of the project. This was a key step in ensuring a synergistic relationship between individual design components. Project sub-groups were formed on the basis of expertise and interest. These groups then proposed design solutions to the entire team to evaluate on the bases of budget and original design intent. Passive strategies were sought through site selection and envelope considerations, eventually guiding the selection of mechanical systems. Finally, all selections were validated through energy modeling and life-cycle cost analysis. The design solutions presented were guided by a fully collaborative process.

Baseline Model

The baseline model was developed using eQuest and adhered to the requirements listed in ASHRAE Standard 90.1-2013 Appendix G. Default occupancies and lighting power densities were defined using the space-by-space method. WWR ratio was set at 22% from TABLE G3.1.1-1 for School (secondary and university). Minimum values for the building envelope were used for Climate Zone 1. Miscellaneous loads for each space were calculated and estimated based on equipment listed in the owner's requirements and/or typical equipment for the space. Baseline HVAC systems was defined per TABLE G3.1.1-3 as System 6—Packaged rooftop VAV with parallel fan power boxes and reheat. Each floor was modeled with a separate HVAC system without outdoor air economizers. Outdoor air requirements were specified from ASHRAE Standard 62.1-2013.

Baseline equipment capacity was determined using TRACE 700 and the 2% cooling design temperature condition. It was clear that even in a very hot climate, the building was very internally loaded. Apart from ventilation, the majority of sensible and latent loads came from people, lighting, and equipment.

Architectural design

The architectural design of the building is the first part of reducing the loads of the building. Additionally, it is the part of the building which the building occupant will have direct interaction with and is therefore important for both energy performance as well as occupant satisfaction.

Building envelope

General building envelope constructions were specified in the owner's project requirements. Detailed specifications are listed below.

Walls

Autoclaved aerated concrete (AAC) was chosen for the exterior mass walls. It provides high thermal mass with insulating properties and can contain recycled materials, such as fly ash and rebar. It is a lighter material, with low initial construction costs and low maintenance costs. The material is very good for minimizing infiltration, good fire rating and soundproofing qualities, insect resistant, and contains lower embodied energy than conventional cement. Thermal mass is defined as any concrete or masonry wall with a heat capacity exceeding 7 Btu/ft^2·°F or a heat capacity greater than 5 Btu/ ft^2·°F for lightweight materials with a density less than 120 lb/ft^3.

Thermal mass is especially important in the very hot climate since it helps dampen the peak temperature and produces a time lag so that the interior space does not "see" the peak until unoccupied hours. It also performs best having the thermal mass located on the interior side and any additional insulation on the exterior side. Unfortunately, summer temperature lows typically do not fall below 80°F and nighttime flushing would not be effective for this region.

Density	40 lb/ft^3
Conductivity	0.0844 Btu/h-ft°F
Heat Capacity	0.263 Btu/lb°F
Sound Transmission Class (STC) with Insulation	55

Table 1 - Autoclaved aerated concrete physical properties

Fenestration

Fenestration	Assembly Maximum U-Factor	Assembly Max SHGC	Assembly Min VT/SHGC	Assembly Min VT
	Vertical Fenestration, 0%-40% of Wall			
ASHRAE 90.1/189.1 Metal framing, fixed window	0.5	0.25	1.1	0.28

Table 2 - ASHRAE fenestration requirements

Window to Wall Ratios [WWR] comply with ASHRAE 189.1 Section 7.4.2 based on equation 1:

$$(1) \qquad A_W \leq (A_N + A_S)/4 \; and \; A_E \leq (A_N + A_S)/4$$

It was important to minimize SHGC as much as possible on the east and west facades since the direct solar radiation is the most intense on these sides during operational hours. High visible transmittance values are preferred to allow the maximum amount of daylight during operating hours. High performance glass should be used to include bronze tinting and low-e coating to reduce the SHGC while maintaining a high VT.

Glazing	WWR	U-Factor	SHGC	VT	Exterior Shading Strategy
North	40%	0.30	0.25	0.47	No external shading
South	30%	0.30	0.25	0.47	Floor 1-2: 4.5 ft overhangs Floor 3: Roof overhang
East	15%	0.20	0.18	0.33	Vertical fins
West	10%	0.20	0.18	0.33	Vertical fins

Table 3 - Glazing properties

Roof

The roof is comprised of 3" extruded polystyrene insulation over a concrete deck. It is covered with high solar reflectance paint with a SRI greater than 78. Photovoltaic installations will provide additional shading. Skylights were not selected since it was decided to be more beneficial to have a greater amount of surface area for PV modules.

The roof design includes a 15 foot overhang, which will provide shading for the 3rd floor and allow a greater roof surface area for the PV installation. Conservatively, the overhang results in 5,000 ft^2 of added surface area to the ~15,000 ft^2 main building footprint.

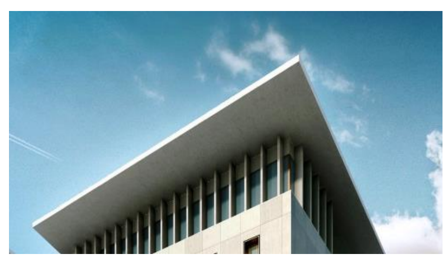


Figure 6 - Overhang examples

Floor

Floors shall be poured in place concrete featuring a light limestone color. The added thermal mass will help even out temperature swings throughout the day. Since we are not using this mass to store passive solar gain, the mass can be a light color to help diffuse light throughout building spaces.

Figure 7 - Flooring example

Indoor environmental quality

Achieving good indoor environmental quality is a priority for this building and it is how the majority of occupants will determine whether a building is well designed. As such, the following criteria were considered during design: acoustics, daylighting, shading as well as thermal comfort.

Acoustics & Interiors

One of the more important design aspects of the interior spaces is the acoustic separation between classroom and shop spaces. Most classrooms are located along the perimeter of the building and within the same position from floor to floor. 4" AAC thermal mass partition walls are to be used, containing additional sound dampening materials to reach an STC value of >55 between classroom walls and >50 STC for walls separating the classroom and hallways. The wall separating the hallway and workshop shall have an STC >60.

Opaque interior wall surfaces shall have visible light reflectance greater than 60% and all ceiling reflectance will be greater than 80% to allow for maximum diffusion of light throughout the building.

Shading

Shading is a crucial strategy to reduce the need for air conditioning during the hottest summer months. We prioritized exterior shading devices in order to minimize direct solar radiation from entering and heating the interior perimeter spaces.

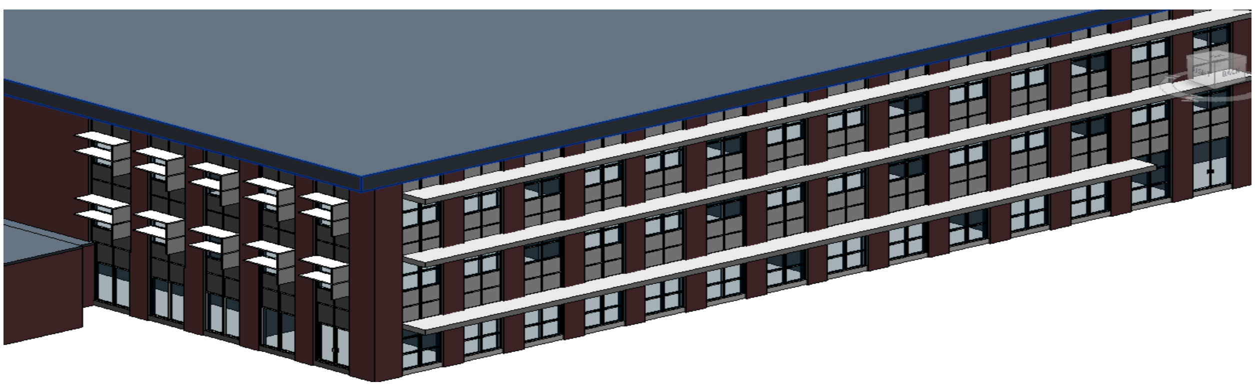


Figure 8 - Visualization of west & south façade

Peak cooling load occurs on August 18th at 4pm. Sun position at this time was used to size overhangs and fins. 4' 6" and 2' wide overhangs were placed on the South and East face respectively. On the West side, 3' wide overhangs and fins were designed to reduce the rapid heat gain from the direct sun in the summer and avoid glare from low angle sun in the winter as shown in figure 8.

Daylighting

Utilizing natural light is an important strategy to reduce building energy usage. Daylighting is especially effective in the summer when the cloud coverage is typically between 3-10%. Also, the building layout allows for most of the classrooms and other occupied spaces to be on the perimeter with access to both daylighting and outdoor views.

The daylighting study was done using the Lighting Analysis add-in in Revit 2015. This add-in was designed to help architects achieve LEED 2009 IEQc8.1 credit. LEED requires the analysis on a clear day within 14 days of Sept 21 and Mar 21. The software uses actual weather data and automatically chooses the closest date to Sep 21 that has a clear sky measurement at 9am and 3pm, and has the highest global horizontal value.

We studied what the level of illuminance would be with the optimal orientation. Actual glazing, ceiling, interior wall, and floor properties were set up to generate the most accurate result. The following page shows pre and post design results for the first floor. Similar results were obtained for second and third floors. Blue represents the optimal range of illuminance level that is recommended for classroom activities, about 20-40 footcandles (fc). Most of the rooms at the perimeter have enough daylight level and penetration. An area near the exterior wall on the South and East would need shading and glare control. Internal light shelves were considered to give minimal improvement but were not found to be a worthwhile improvement.

On the North façade, approximately 50% of spandrel glass wall of the welding workshop were replaced by double pane glazing to bring in horizontal diffuse light and provide a view to the outside environment.

Analysis on the final design indicates that 64% of the space at 9 am, Sept. 17 and 70% at 3PM, Sep 16 have illuminance level between 10-500 footcandles (fc). It did not pass 75% mark to claim the LEED credit, but we can use the result to estimate the LPD reduction. Also, less high illuminance level regions mean that shading devices block the direct sunlight as expected.

The minimum illuminance of 10 fc in the analysis was low compared to the recommended value of 20-40 fc for classroom activity. The minimum was changed to 25 fc to comply with standard 189.1. From our estimate, an average of 48.5% of the regularly occupied area would get 25 fc or more.

The building operates 11 hours (7am-6pm) whereas the software analyzed just 6 hours (9am-3pm). We assumed the other 5 hours would run on 100% LED lights without daylight support. Out of 6 hours of available daylight, 48.5% are useful, in equivalence to 2.91 hours. So another 3.09 hours will need LED lights, bring up the total to 8.09 hours, which is 74% of initial 11 hours, or 26% reduction.

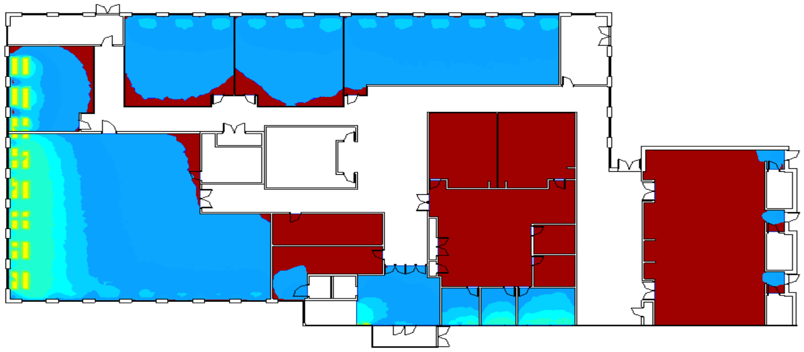


Figure 10 – Initial daylight analysis on 9/17 at 9 am

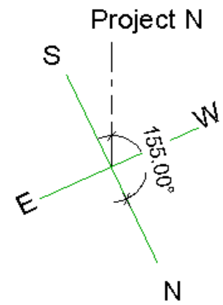


Figure 9 - Project orientation

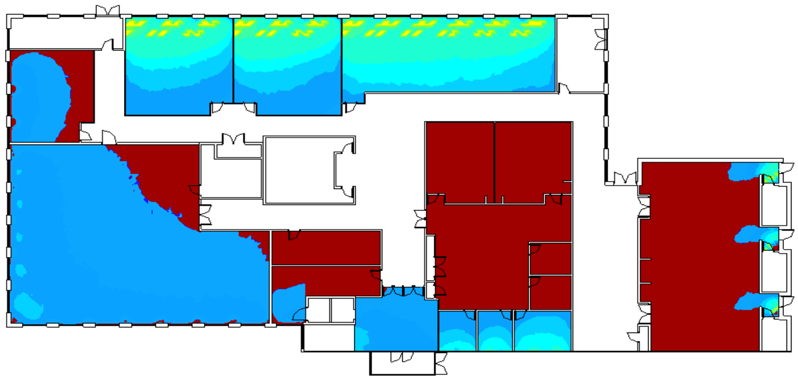


Figure 11 – Initial daylight analysis on 9/17 at 3 pm

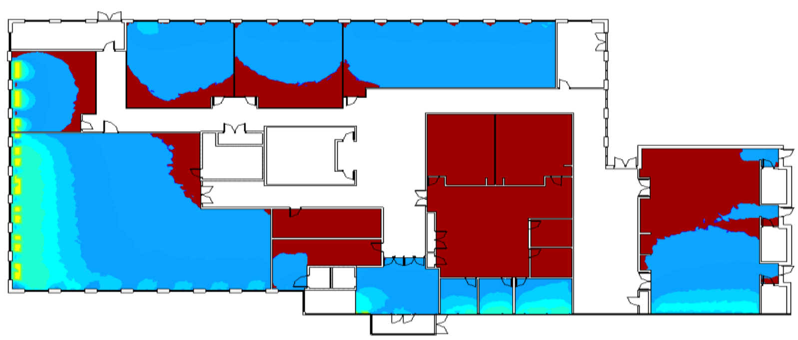


Figure 13 - Final design daylight analysis on 9/17 at 9 am

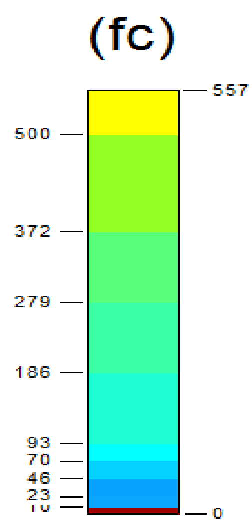


Figure 12 - Legend

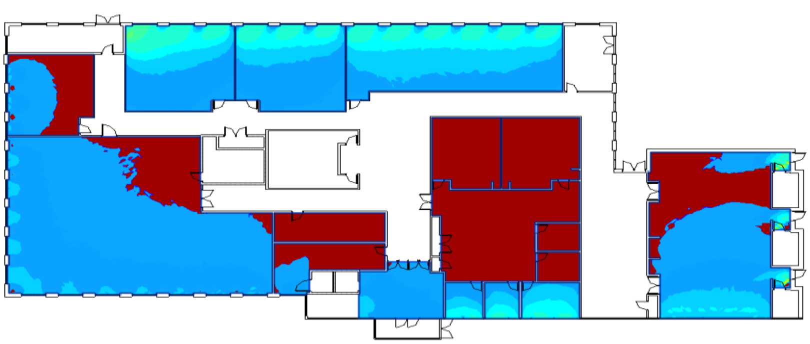


Figure 14 - Final design daylight analysis on 9/17 at 3 pm

Environmental impacts

The project is designed to minimize the adverse effects which the building has on its local environment. The major goals are to reduce urban heat island and light pollution

Urban heat island mitigation

This project will utilize multiple strategies to reduce urban heat island effect. Shading exterior walls will be done with the roof façade as well as additional horizontal overhangs. Some additional shading will be provided by site landscaping. The roof material selected has an SRI greater than 79. Finally, semi-permeable surfaces will be used for adjacent walkways and parking lots. This will also aid in storm water control in the event of a rainstorm.

Light pollution

To avoid creating light pollution, exterior lighting systems will be designed to meet requirements of the International Dark Sky Association (IDSA). All selected fixtures will have the Fixture Seal of Approval (FSA) from the IDSA, and will be selected appropriately for their individual uses. Fixtures meeting the FSA emit no light above 90 degrees, and thus are below the maximum allowable backlight, uplight, and glare requirements detailed in sections 5.3.6.2 and 5.3.6.3.

Shown here is an example of a fixture from the Promenade series of lights from Architectural Area Lighting. This series meets the IDSA requirements and range from 70 to 400 watts, have IES full cutoff reflector systems, and optical grade acrylic lenses. It contains lights appropriate for egress lighting, pathways, parking lots, and other exterior settings.

Figure 15 - Fixture example

Mechanical systems design

The major mechanical systems comprise the energy recover ventilators (ERV), air handling units (AHU), chiller and the thermal storage systems. These are combined with a radiant beam system in order to serve the sensible load in the space. Ventilation is served by a separate dedicated outdoor air system (DOAS).

Ventilation

The ventilation loads which must be met by the DOAS were calculated from ASHRAE 62.1 to be approximately 13,200 cfm for the main building. For the woodshop/welding studio area the requirements of 62.1 are overshadowed by the exhaust requirements of the welding studio which is expected to exhaust a maximum of 5,600 cfm through the welding exhaust hoods.

2% Dry condition			2% Humid condition		
DB temp °F	MCWB temp. °F	Enthalpy (Btu/lb)	WB temp. °F	MCDB temp. °F	Enthalpy (Btu/lb)
106.4	73.2	36.5	86.2	94.3	50.7

Table 4 - Design outdoor air conditions

These ASHRAE design conditions were used for cooling and dehumidification loads for the ventilation air. Due to the condition of the air it is observed that the humid condition must be the design condition for calculation purposes. Also, this illustrates how much of the overall building cooling load is simply to supply ventilation air.

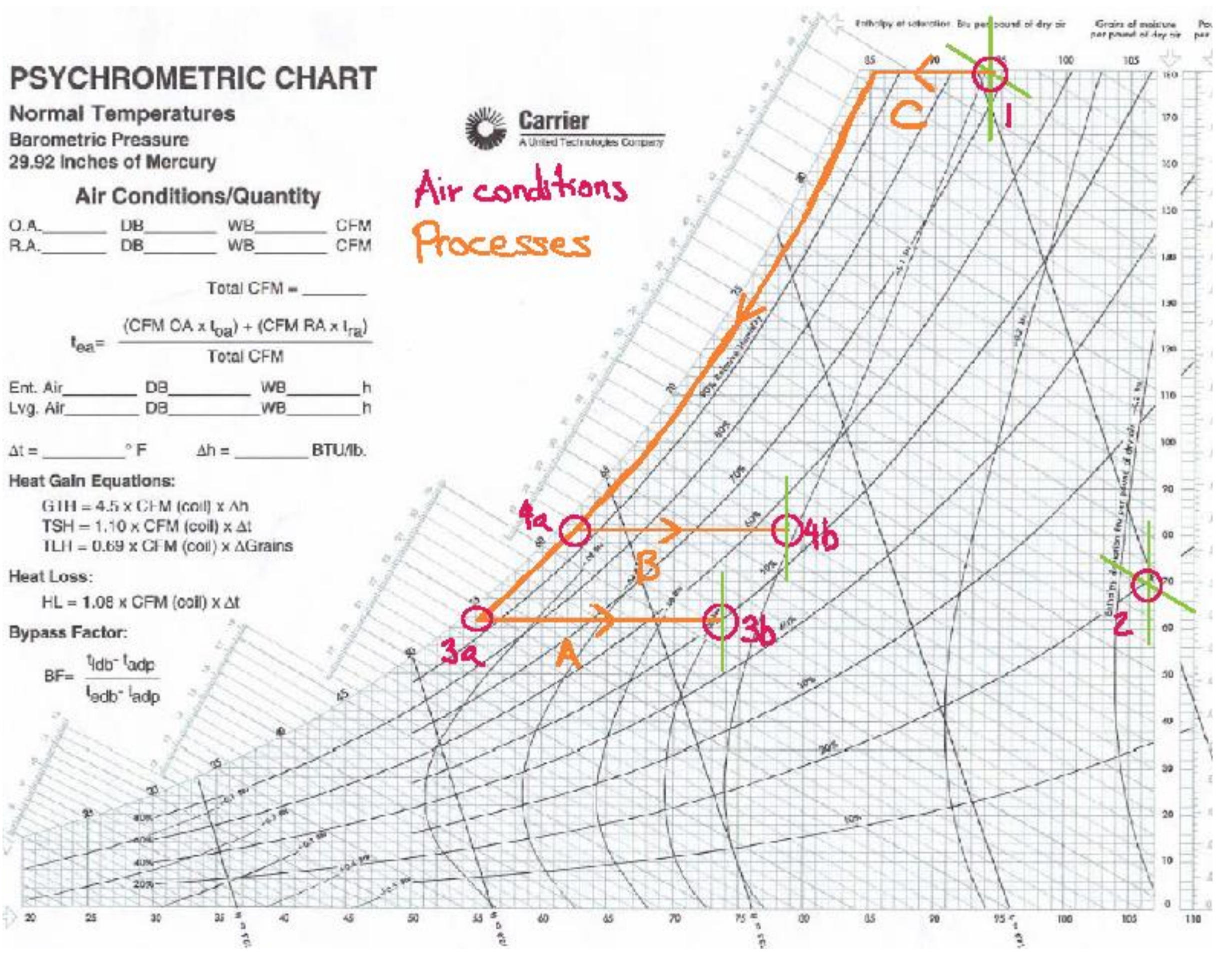


Figure 16 - Psychrometric calculations

Loads

When plotting these points on the psychrometric chart along with the design points. The calculations show the maximum Δh required for cooling and dehumidification of the ventilation air. The Δh required is 28.4 btu/lb for the main building and 22.9 btu/lb for the woodshop and welding studio. These values result in a total cooling load of approximately 140 tons for the main building and 48 tons for the woodshop and welding studio.

Energy recovery ventilator

Due to the large difference in both temperature and humidity between the exhaust air and the outdoor air an ERV will reduce the ventilation cooling load by approximately 40 tons during peak load. Shown below is a calculation from Renewaire's ERVcalc sizing program applied to both the 98% dry condition (winter) and the 98% humid condition (summer).

	Sensible		Total	
	Winter	Summer	Winter	Summer
Exchanger Effectiveness (Info)	63 %	63 %	60 %	37 %

	Room Exhaust		Outside Air		Supply Air	
	Winter	Summer	Winter	Summer	Winter	Summer
Dry Bulb (F)	75.0	75.0	106.4	94.3	86.5	82.1
Wet Bulb (F)	65.3	65.3	73.2	86.2	68.0	79.6
Relative Humidity (%)	60	60	21	73	39	90
Absolute Humidity (lbH20/dryair)	0.0111	0.0111	0.0099	0.0254	0.0104	0.0213
Enthalpy (BTU/lb)	30.2	30.2	36.5	50.7	32.2	43.0

	Sensible		Latent		Total	
(Info on Loads)	Winter	Summer	Winter	Summer	Winter	Summer
Original Load (BTU/h)	447638	275141	70164	943871	517803	1219012
Original Load (Tons)		22.9		78.7		101.6
Load with RenewAire (BTU/h)	164222	100939	45086	663464	209308	764403
Load with RenewAire (Tons)		8.4		55.3		63.7
Savings (BTU/h)	283417	174202	25078	280407	308495	454609
Savings (Tons)		14.5		23.4		37.9
Load Savings Ratio (Info)					60 %	37 %

Figure 17 - ERV Calc output

Using this ERV the Δh for the main building is reduced to 20.5 Btu/lb which results in the main building design cooling load being reduced to approximately 102 tons. In addition to reducing the design cooling load the ERV will reduce the cooling load during the non-peak conditions by up to 22 tons. This reflects the drier design condition which is point 1 on the psychrometric chart on the preceding page.

The ERV allows for the chiller to be downsized as well as reducing the operating cost of the ventilation system. Due to this savings ERV's are being used for the main building. However, due to the exhaust requirements of the welding studios and woodshop there is no ERV for those spaces.

Air handling unit

The main building will be served by 3 of Renewaire's RD4XRT combined ERV/AHU system. These have a capacity of 4400 CFM each, and will be supplied with chilled water from the air cooled chiller. The shop spaces will be supplied by a separate AHU which will provide the 5600 CFM ventilation and makeup air.

Cooling load

Following the design iterations performed in eQuest the total envelope and internal gain cooling load was reduced to 108 tons. Combined with the main building ventilation load of 100 tons and a 48 ton ventilation load for the woodshop and welding studio. Finally, there is 32 tons of 'free' cooling available from the ventilation air which must be cooled to below space temperatures for dehumidification. Thus, the total load seen by the chiller is 224 tons.

Chiller

The selection process for choosing the chiller for this project was dominated by the local climate. Due to the scarcity of potable water in the region water intensive options such as water cooled chillers with cooling towers were not considered. Additionally, due to the high local ground temperature and the severely unbalanced annual heating and cooling load ground source heat pumps were also rejected.

Three systems were chosen for further consideration. The ASHRAE 90.1 baseline system, packaged VAV rooftop units was chosen as it was already a necessary benchmark for comparison. Second was an air cooled chiller with an ice storage system. The third option was an absorption chiller with concentrated solar collectors.

Option 1: ASHRAE 90.1 baseline system

This option is anticipated to have the lowest initial cost and is simple to design and implement. However, it would also have the worst performance for ongoing cost and efficiency due to the on-peak electrical demand.

Option 2: Air cooled chillers with variable refrigerant volume system and ice storage

The thermal storage system in this system allows for lower on-peak electrical demand which will result in lower operating costs. Additionally, it allows for a smaller chiller to be installed which will reduce the initial capital cost. Finally it will reduce the frequency of the chiller cycling on and off. The thermal storage system is not expected to significantly alter the overall energy use of the building.

Option 3: Absorption chiller with concentrated solar collectors

The solar absorption chiller has the lowest operating cost of the systems being considered. This is due to the majority of the energy supplied being from the concentrated solar collectors. Additionally, as the remaining energy is drawn from a gas boiler this system is expected to have very low on peak demand charges, even when the backup gas boiler is in operation.

However, this option is also expected to be substantially more expensive than the other two as well as having increased maintenance cost and complexity. Also, the solar array required by this system is limited by the size of the available rooftop. Finally, due to the high initial cost of the chillers themselves it is costly to provide a system with much redundancy.

Selection

A decision matrix was created in order to compare the different systems and how they performed with respect to certain criteria. The important criteria were energy usage, initial cost as well as reliability.

		Raw score (1-10)			Weighted score		
Criteria	Weight	1	2	3	1	2	3
Initial cost	5	8	7	2	40	35	10
Energy use	8	2	7	10	16	56	80
Reliability	6	7	7	4	42	42	24
Maintenance	4	7	7	4	28	28	16
Ease of use	2	6	5	5	12	10	10
				Total:	138	171	140

Figure 18 - Decision matrix

As shown above, option 2 has shown to have the highest combined performance and was chosen as a compromise between initial cost, ongoing energy costs as well as providing some degree of redundancy in the event of equipment failure or maintenance.

System description

The air cooled chillers sized for this project were each sized for sixty percent of the overall 224 ton load in order to allow for redundancy for maintenance, emergency downtime, extreme weather and to protect critical zones such as the server room. This results in a 135 ton chiller size. In order to further reduce this the thermal storage system is sized such the load can met by two 100 ton chillers.

Using the same methodology, chillers are appropriately sized for a 167 ton load. Thus, the ice storage system must be able to make up 57 ton difference in capacity. It was assumed that the ice storage system must be able to store enough cooling capacity for eight hours of peak load. Thus the system must be able to store 456 ton-hours of capacity. In order to maintain reliability, two 324 ton-hour ice storage tanks were chosen.

In addition to serving peak capacity this storage system is intended to take advantage of off peak electrical rates. Due to the lack of an off peak demand charge and the lower off peak energy rate the system is capable of using off peak rates for much of the year.

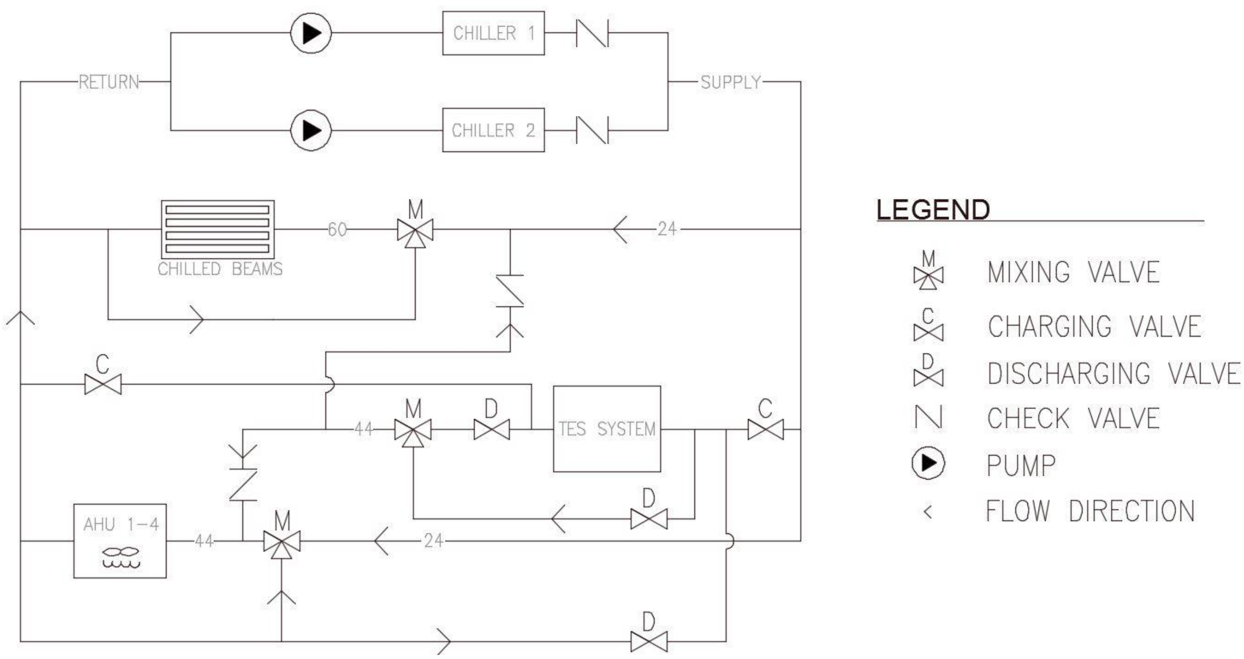


Figure 19 - Control diagram

This simplified process and instrumentation diagram shows how the chiller, thermal storage system, AHU and chilled beams systems are connected. This shows how the system is providing 44 °F water glycol solution to the AHU coils as well as 60 °F to the chilled beams. When the system is charging mode overnight the charging valves are open, allowing some of the 24 °F chilled water glycol solution through the ice storage. During discharging the charging valves are closed and warm return solution is brought across the ice storage tanks. This is then mixed with solution from a bypass in order to create 44 °F solution. Finally, the AHU and chilled beams have an upstream mixing valve connected to the return chilled solution in order to provide 44 °F and 60 °F respectively.

One feature of this system is the low supply temperature requirement. While this decreases the efficiency of the chillers it is a required property of an ice storage system. Also it does allow for lower pumping energy which will partially offset the lower chiller efficiency.

Special instruction space

As described in the owners project requirements the building has an attached shop containing a woodshop and welding studio. As described these spaces have their own design conditions as well as ventilation requirements. The shop has its own AHU as well as exhaust fan.

The maximum exhaust required by 62.1 for this space is approximately 1,000 cfm. However, the maximum exhaust requirements for the welding shop drives the sizing of the AHU. As such, the AHU is sized to accommodate the required make up air. The return air damper will be controlled by the building control system and will close when one or more exhaust hoods are in operation to prevent over ventilation of the space.

Woodshop

The woodshop requires sufficient dust collection capabilities for all of the equipment in the shop. These systems will collect exhaust from the equipment and filter the dust and then return the air to the space. Shown below are the exhaust requirements for the equipment.

In order to provide adequate dust collection capability there will be two 20" and one 18" cyclone dust collectors. These provide a combined 7,600 cfm of dust collection capacity.

Tool	Quantity	CFM (ea)	CFM (total)
16 in. Table Saw	2	500	1000
20 in. Rip Saw	2	400	800
Vertical Belt Sander	1	400	400
Planer (22" Knives)	1	800	800
Wood Lathe	2	400	800
6 in. Floor Sweeps	3	800	2400
		Total:	6200

Table 5 - Dust collection requirements

Welding studio

Each of seven welding stations will be exhausted at a rate of 800 cfm with cone hood flexible exhaust connections as specified by the OPR. Airflow was calculated assuming an 8 inch diameter opening and a distance of 6 inches between the exhaust inlet and work areas. Combined, the welding studio has 5,600 cfm of exhaust capacity.

Lighting

Lighting fixtures will be a combination of LED and fluorescent lights. Areas which have little or no daylighting such as the restrooms and other deep interior spaces will be provided with LED lighting. Perimeter areas which are expected to be occupied for longer periods of time as well as having more consistent daylighting will have high efficiency fluorescent lighting with dimmable electronic ballasts. This is simply a cost saving measure as these lights will be operating infrequently and for longer periods of time when they are in use.

Sensors

Rooms will be equipped with dual CO_2 and temperature sensors. These will allow the building control system to provide demand control ventilation and avoid unneeded ventilation. The sensors will connect to the building control system and monitor ventilation and cooling requirements.

Restrooms, closets, mechanical and electrical rooms will have occupancy sensors for lighting control. For the mechanical and electrical rooms the sensors will have an additional manual override for maintenance worker safety.

Water use efficiency

Measures which are being taken to reduce the overall building water use.

- Xeriscaping
- Low flow fixtures
- Leak detection system
- Condensate collection

Xeriscaping

Only native plants will be used for landscaping. These will not require permanent irrigation after being established.

Low flow fixtures

Plumbing fixtures will meet or exceed the requirements listed in table 6. Hallways will be equipped standard water fountains. Additionally there will be adjacent bottle filling stations providing chilled water.

Fixture	Water use
Dual flush toilet	1.28/0.7 per flush
Waterless urinal	0
Low flow faucet	0.5 GPM
Medium flow faucet	1.5 GPM

Table 6 - Maximum water use

According to a 2014 case study at Texas Wesleyan University the payback from implementing similar low flow water reduction strategies were found to be 5.7 years. As this project is using waterless urinals and is initially installing the fixtures versus remodeling the actual payback is expected to be lower than the case study.

Leak detection system

There shall be flow meter for each bathroom, break room, and any other water using fixtures. These flow meters will be wired into the building digital control system. The system will send out an alarm if there is either a measurable constant flow for a set period of time or any flow during times when the building is known to be unoccupied.

Condensate collection

Condensate from the AHU's and chillers will be collected in a storage tank. This will be used for flushing toilets. The tank will be connected to the city water in order to maintain a minimum level during extended dry periods.

Domestic hot water

The domestic hot water shall be provided by a small flat plate solar hot water collector. This system will be located on the roof and will comprise the collectors, an insulated hot water storage tank and a mixing valve. This will allow for a steady supply of hot water which can be controlled by the building control system. The building fixtures which can provide hot water are the sinks in the bathrooms, conference room, break room and shop area.

The combined maximum flow rate from these fixtures is 10.5 gpm. This was used to size the solar hot water system along with a utilization factor of 0.1, a design temperature of 110 °F, and an entering water temperature of 75 °F. Thus the collector must be able to provide 18 kbtu/h.

$$(2)\ P_{req} = 8.34\left(\frac{lb}{gal}\right) * 1\left(\frac{btu}{lb\ F}\right) * 35\ \Delta\ F * 0.1 * 10.5\left(\frac{gal}{\min}\right) * 60\left(\frac{min}{hr}\right) = 18\left(\frac{kbtu}{h}\right) = 5280\ W$$

From the climate consultant data shown earlier in this report a design irradiation of 200 btu/(h ft^2) or approximately 620 watts/m^2 was selected. This allows for the system to provide hot water for the majority of the year while minimizing overproduction during peak periods. This plus an assumed collector efficiency of 70% yields a maximum required collector area of 12 m^2.

Additionally this system will have a storage tank sized using the rule of thumb of 1.5 gallons per ft2 of collector area. This yields a 200 gallon tank which will be a dark colored steel tank located on the roof. Due to the high ambient outdoor temperature this tank will be uninsulated and act as a solar collector itself. Finally, there will be a mixing valve connecting the storage tank, the city water line and the hot water supply line. This will keep the hot water supply from becoming too hot.

Photovoltaic System

Due to the steep sun angles as well as the typically clear sky conditions Doha is an excellent location for PV systems. For this project solar radiation was studied with Autodesk Vasari. The highest annual solar insolation is approximately 1215 kWh/m^2 on the roof of surface. The PV system was assumed to be installed on 80% (15,000 sf) of the roof of the main building. Energy generation and saving were estimated by using the PVWatts program available from the National Renewable Energy Laboratory.

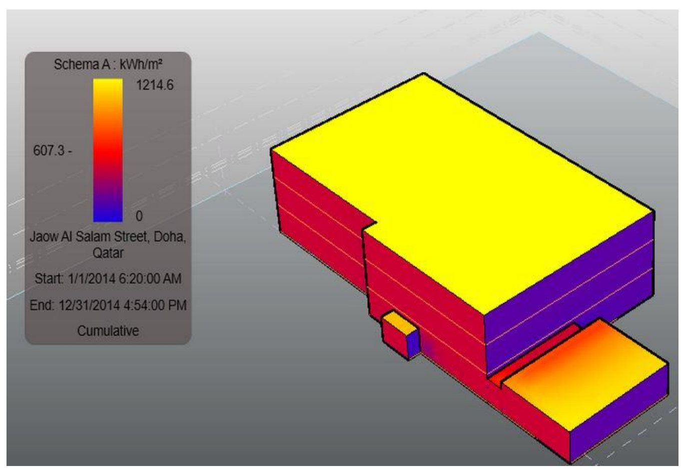


Figure 20 - Solar insolation

Table 7 & 8 below show the input used for the simulation as well as the results. Although the nearest weather file available in PVWatts is Abu Dhabi this is not expected to significantly alter the results due to the similar location and climate.

PV System Specifications (Commercial)			
Project location	Doha, Qatar	Array Tilt	0°
Weather file	Abu Dhabi, UAE	Array Azimuth	180°
DC System Size	180 kW	Inverter Efficiency	96%
Module Type	Standard	DC to AC Size Ratio	1.1
Array Type	Fixed (roof mount)		

Table 7 - PV simulation input

Month	Consumption (kWh)	Electricity Generated (kWh)	Actual Electricity Use (kWh)	Electricity Generation percentage
January	17015	17,881	-866	105%
February	16613	20,073	-3,460	121%
March	20197	23,210	-3,013	115%
April	26955	25,589	1,366	95%
May	31474	30,321	1,153	96%
June	40302	29,519	10,783	73%
July	45901	28,674	17,227	62%
August	45376	27,816	17,560	61%
September	41483	24,899	16,584	60%
October	34339	22,669	11,670	66%
November	22476	17,994	4,482	80%
December	19826	16,530	3,296	83%
Annual	**361,959**	**285,175**	**76,784**	**79%**

Table 8 - PV simulation output

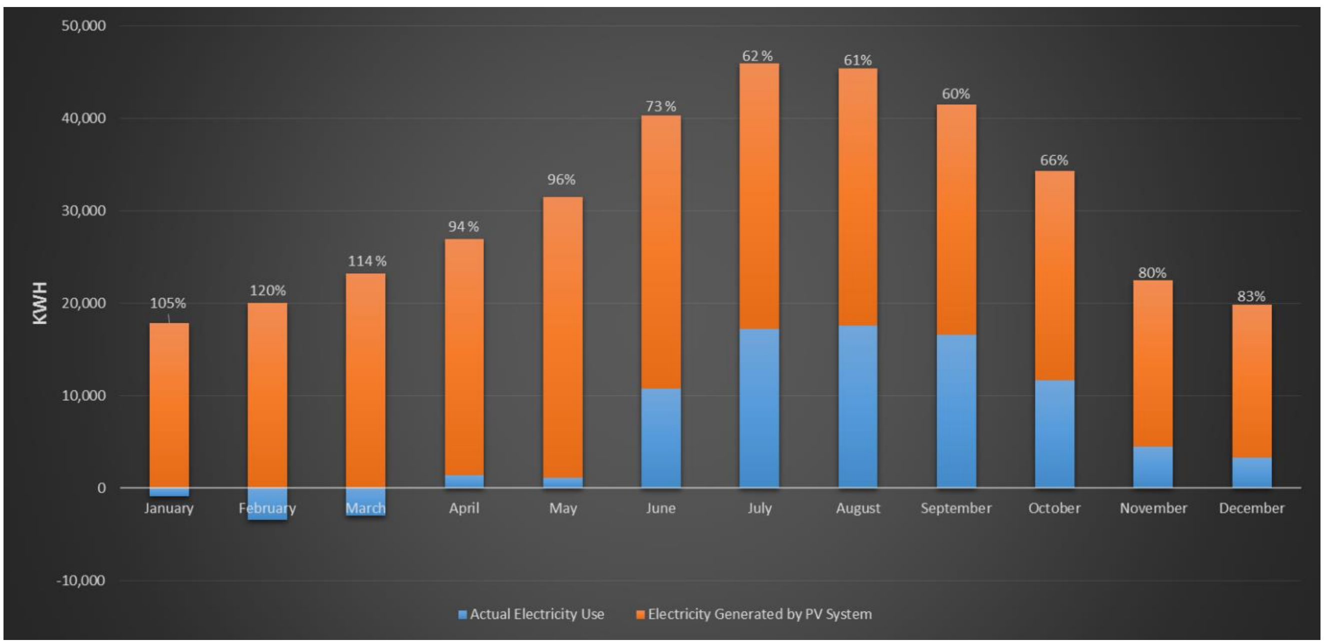


Figure 21 - Monthly electricity generation and consumption

Finally, figure 21 shows that for a sizable portion of the year the solar array can provide energy to provide or offset the building electrical use for a quarter of the year. Further future expansion of this solar array would allow for this to be a net-zero energy building.

Operations

Building operations are at least as important as the actual design of the building. Systems must be maintained adequately in order for them to function as designed.

Construction

The building shall be built by following the guidelines laid out in ASHRAE standards and local building codes which highlight using local and sustainable products. Over 50% of nonhazardous waste shall be reused in the construction project to help reduce the total amount of waste produced from the construction project. Total waste from the project will be tracked according to the requirements of ASHRAE standard 189.1 9.3.1.3 and shall not exceed 210 yd^3 or 60,000 lbs. Our design does not require the use of wood other than for concrete forming. These wood products shall be harvested in compliance with 189.1 9.3.2.

Building operation

The building will regularly operate to a high standard that follows ASHRAE standards and the standards laid out in this report. The building will have easily accessible recycling stations for common materials such as plastic, glass and metal. There will also be a central recycling station which will have bins for electronics and batteries. Any regular maintenance and replacement will be done by professional staff. HVAC equipment in our design will have a life longer then the building or need to be replaced every 25 years. Finally, no CFC or HCFC refrigerants will be used during building operation.

Measurement and verification

On-going measurement and verification will be a part of this buildings operation in order to maintain a high level of performance. As mentioned previously under the leak detection system, real-time building water usage will be measured and recorded in order to monitor building performance and troubleshoot problems. Similarly, each piece of major mechanical equipment as well as the lighting system and PV system will be connected to an electricity meter.

Although not specified in the project this could allow for a usage data to be displayed real time on a monitor to the occupants in order to increase awareness of the building’s energy use.

Building performance

Analysis of building performance was conducted using eQuest for iterative design. Additionally Revit was used for daylighting analysis and Trane Trace was used for load calculations. All of these were compared against a baseline built from the guidelines of standard 90.1 appendix G.

Design iterations & Comparison to 90.1 Baseline

The integrated design process prioritized a thorough investigation of passive architectural design strategies that would enable a large reduction of energy use from the baseline model. For this climate, it was understood that proper orientation and thoughtful strategies to reduce the solar heat transmission through the building's envelope would be crucial. The model was passed through several iterations to study the effects of increased thermal mass and U-values, different WWR and glazing properties, and shading techniques. Our final proposed architectural design described above was shown to reduce the energy usage by 27% from the baseline model. These changes resulted in a reduction in the cooling energy load, which also decreased fan energy. Proper placement of windows and the change to the building orientation increased daylighting and allowed for the reduction of LPD in most spaces, which resulted cutting the lighting energy almost in half.

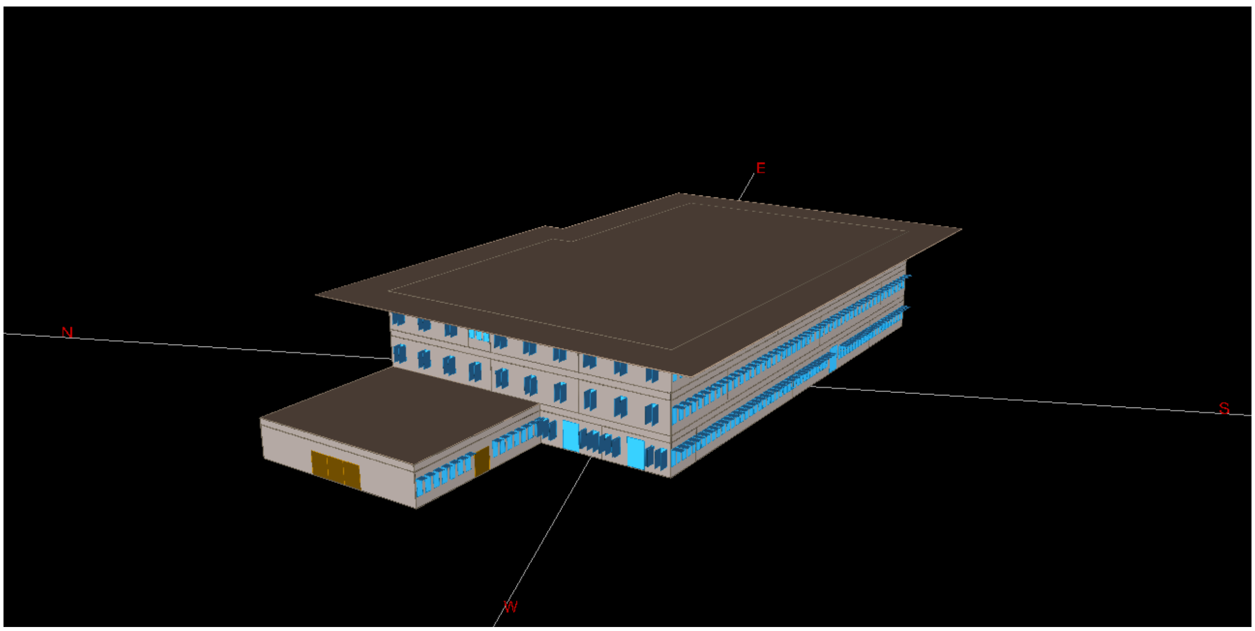
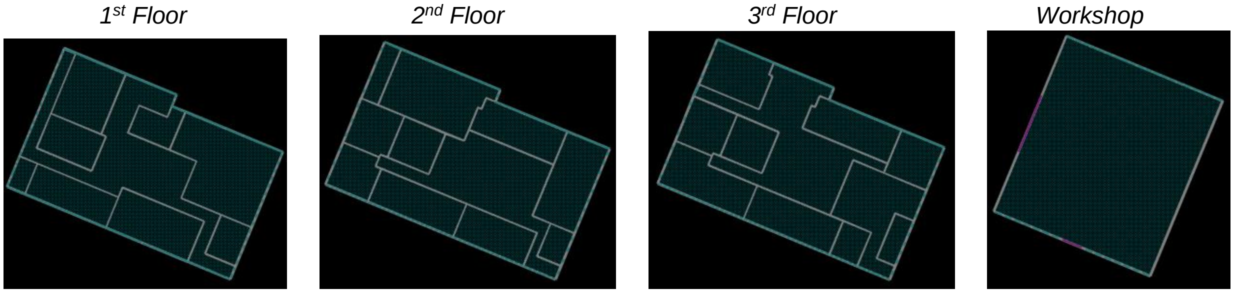


Figure 22 - Building model

Zones were selected based on the occupancy for each space. Where possible, rooms were grouped to minimize the number of zones in the building.

1st Floor *2nd Floor* *3rd Floor* *Workshop*



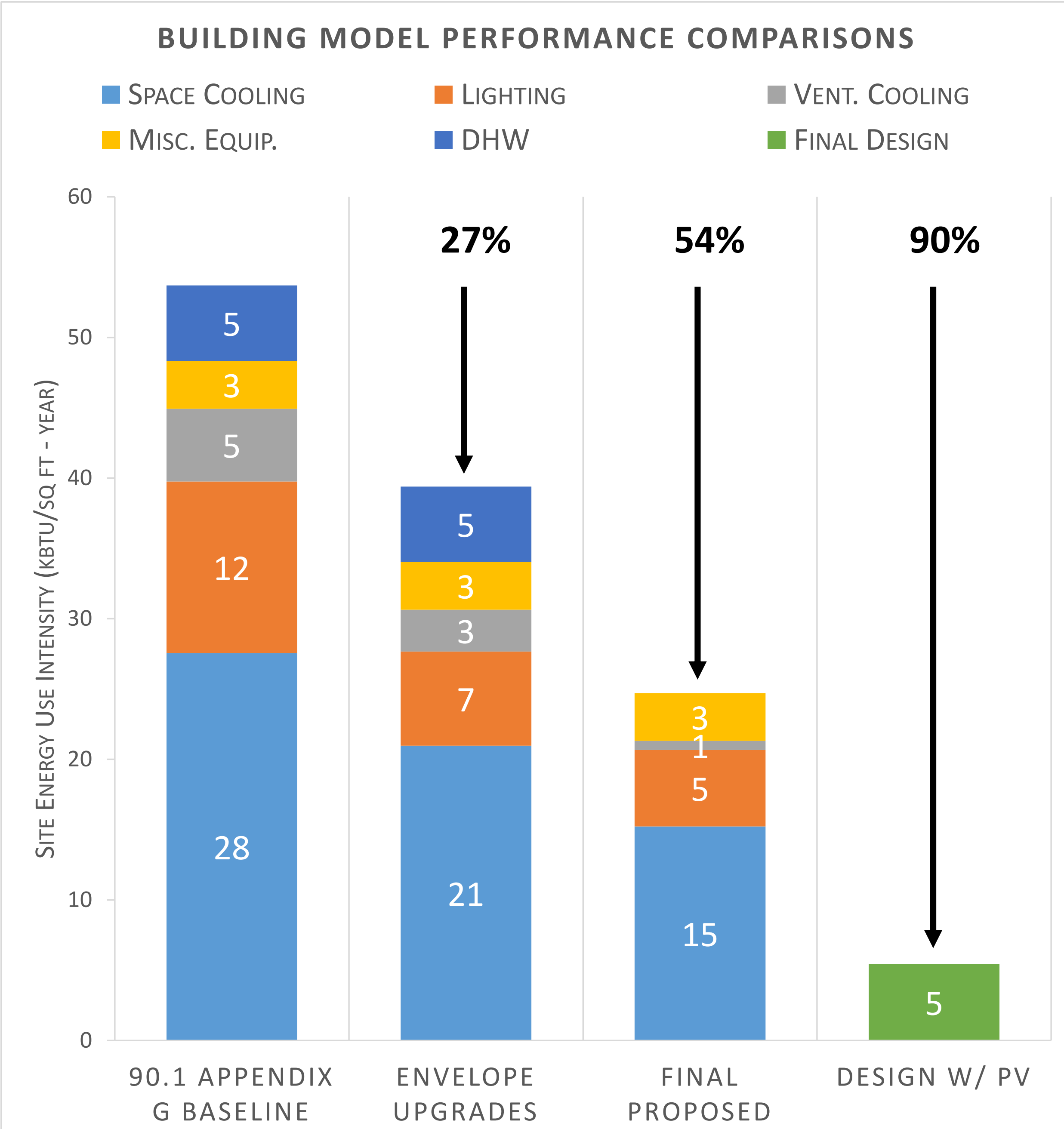


Figure 23 - Building performance comparison

Life cycle cost analysis

A life cycle cost analysis helps to determine the economic feasibility and the return on investment between systems selection. We looked at a comparison between the 90.1 baseline system of packaged RTU VAV system versus the DOAS/chilled beam system with thermal storage. In life cycle cost analysis it is the sum of initial investment, replacement, operation and maintenance cost over the life span of the building. Each value is given in present worth accounting for both the interest and escalation rates.

For each system we determined the initial investment using rules of thumb based off either area or load calculation. Tables 9 and 10 show the breakdown of each system components. Operation costs are incurred by the operation of each mechanical system. This was calculated by using our energy model to determine annual energy usage. Then cost was determined by applying the given utility costs and escalation rates.

Baseline System Design			
Equipment	Unit of Load	Rule of thumb	Total
RTU (4)	100 ton	$850/ton	$320,000
Sensor & Controls	50000 s.f	$2.5/s.f	$125,000
Piping	50001 s.f	$1.5/s.f	$75,000
Duct	48000 cfm	$5/cfm	$240,000
Insulation	$760,000	5% of HVAC	$38,000
Test and Balance	50000 s.f	$0.25/s.f	$12,500
		Total =	$810,500

Table 9 - Baseline system cost

Final System Design			
Equipment	Unit of Load	Rule of Thumb	Total
Air cooled Chillers (2x)	100 ton	$ 420/ton	$84,000
TES storage tanks (2x)	324 ton/hr	$500 ton/hr	$324,000
AHU w/ ERV (3x)	14000 cfm	$5/cfm	$70,000
Radiant passive chilled beams	50000 s.f	$12 /s.f	$600,000
Ducts (ventilation)	18000 cfm	$5/cfm	$90,000
PV system			$495,000
Solar Water			$14,000
Condensation			$10,000
Insulation	$1,687,000	5% of HVAC	$84,350
Test and Blance	50000 s.f	$0.35/s.f	$17,500
		Total =	$1,788,850

Table 10 - Final system cost

The maintenance of for the baseline system was estimated from ASHRAE operation and maintenance database at $0.22 per ft^2. The proposed system was estimated to be $0.165 per ft^2. The replacement cost depends heavily on the system and its service life of each component. Using ASHRAE equipment life expectancy a rough estimate of service life was determined.

About $200,000 is remaining in the owner's budget. This money will go to hire an independent commissioning agent (CxA) prior to the mid-point of the construction documents phase. The CxA will review the Owner's Project Requirements and design documents, review contractor submittals, and develop a systems manual for the operations staff to successfully operate the building's systems. The CxA will also train and review building operation with the staff within the first 6 months and will be available to resolve commissioning-related issues within the first two years of the building's life.

From initial cost our proposed system is twice the cost of our baseline system. This financial investment can be a challenge to most owner but due to the high performance and efficiency of our proposed system. We can cut the annual utility cost by 70% from the baseline system and within the life span of the build operation, our design has a return on investment starting in year 11. At the end of 50 year life span, our proposed system can save approximately three million dollars through maintenance and replacement cost savings.

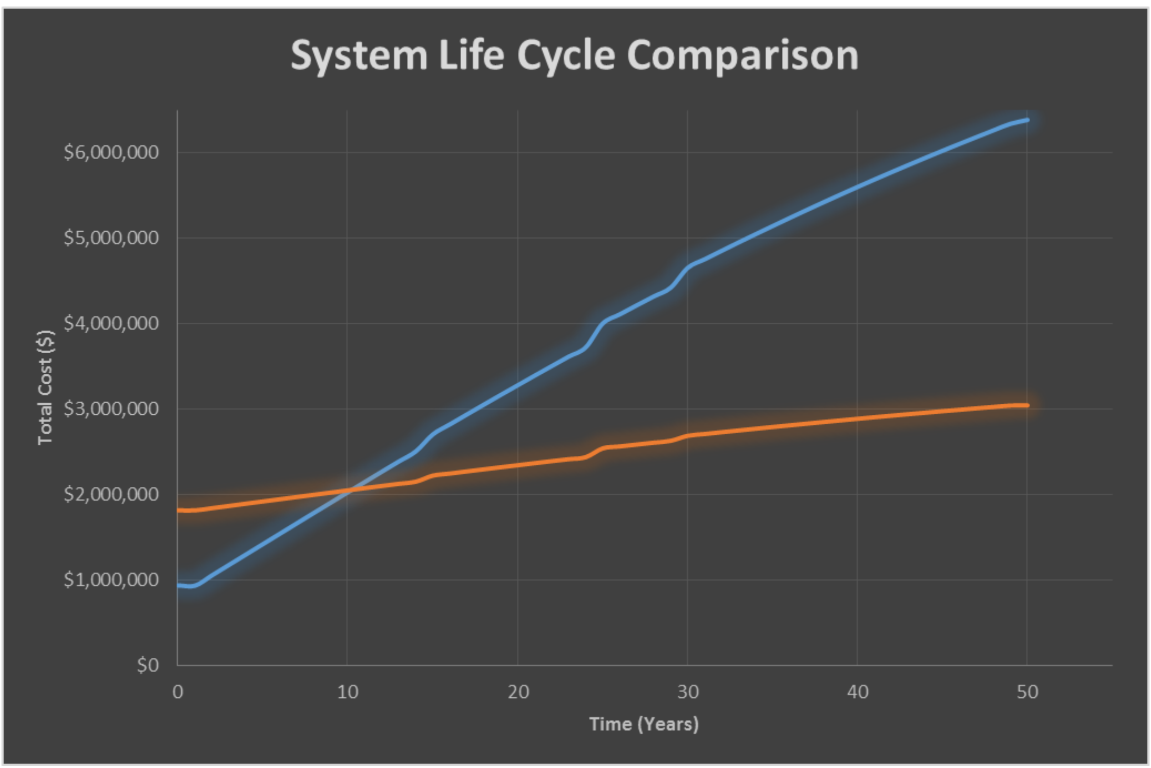


Figure 24 - Life cycle cost comparison

Compliance

As the OPR specifies one goal of the project is to comply with ASHRAE standard 189.1. The following section lists applicable requirements of the standard as well as how the project complies with each requirement.

Sustainable sites

The site related requirements require the project to address the impacts of the project on the local area. This particular project is located on a greenfield site within the Doha city limits.

Requirements	**Compliance**
5.3.1 Site selection	Project location is within 800m of Mowasalat bus line
5.3.4 Stormwater management	Permeable paving materials
5.3.5 Heat island mitigation	Permeable paving materials, roof overhang for shading walls
5.3.6 Light pollution control	IDSA approved lighting fixtures
5.3.6 Transportation impacts	Bicycle racks located by each building entrance

Table 11 - 189.1 Sustainable site requirements

Water use efficiency

This project is following the prescriptive approach for satisfying the standard's mandatory provisions.

Requirements	**Compliance**
6.3.1 Site water use	Xeriscaping with only water use during establishing period
6.3.2 Building water use	Low flow fixtures per table ()
6.3.2.3 HVAC systems	Air cooled chillers, condensate used for toilet flushing
6.3.3 Water management	Flow meters integrated with building control system

Table 12 – 189.1 Water use efficiency requirements

Energy efficiency

This project is following the prescriptive approach for energy efficiency requirements. Additionally the project is following the requirements for the standard renewables approach. However to further reduce energy use the major equipment will also meet energy star requirements.

Requirements	**Compliance**
7.3.2 On-site renewable generation	Photovoltaic array on roof with area zoned for future expansions
7.3.3 Energy consumption management	Major mechanical equipment as well as the PV array will have individual electricity meters
7.4.2 Building envelope	Opaque elements and fenestration designed to exceed minimum U-value requirements
7.4.3 HVAC	1. Major equipment will meet energy star requirements 2. CO_2 & occupancy sensors for optimized zone control
7.4.6 Lighting	26% reduction below 90.1 lighting power density

Table 13 - 189.1 Energy efficiency requirements

Indoor environmental quality

This project follows the prescriptive approach for materials and performance based for daylighting.

Requirements	Compliance
8.3.1 Indoor air quality	1. Ventilation air required per standard 62.1 2. Outdoor air provided and measured by DOAS
8.3.2 Thermal comfort	Designed in compliance with standard 55
8.3.3 Acoustical control	
8.3.5 Lighting quality	Classroom and office spaces will have daylight sensing controls
8.3.6 Moisture control	Indoor conditions will conditioned to a maximum of 60% RH
8.4.2 Materials	Adhesives, sealants & furniture shall satisfy Green Seal and California section 01350 requirements
8.4.3 Presentation lighting	Presentation surfaces shall have independently controlled dimmable lighting
8.5.1 Daylighting simulation	Design simulation exceeds 25 fc between 9:00-3:00

Table 14 - 189.1 Indoor environmental quality requirements

Environmental impacts

In addition to the mandatory provisions this project follows the prescriptive approach for reduction of environmental impacts.

Requirement	Compliance
9.3.1. Construction waste management	Over 50% of nonhazardous waste materials will be reused or donated to local organizations and total waste shall not exceed 42 yd^3 or 12,000 lbs per 10,000 ft^2
9.3.2 Raw material harvesting	Wood used during the project will conform with local requirements for sustainable harvesting
9.3.3 Refrigerants	No CFC or ozone depleting materials shall be used by this project
9.3.4 Recyclables	Recycling containers will be located throughout the building
9.3.4.3-4 Other recyclables	Fluorescent lamps will be collected by maintenance for recycling and the central recycling station will have a bin for batteries and electronics.
9.3.5 Mercury content	Lamps shall not exceed 5 mg of mercury per lamp
9.4.1 Reduced impact	1. Minimum of 10% of the building material cost will be from salvaged material 2. Minimum of 15% of the building material cost will be locally sourced material

Table 15 - 189.1 Minimizing environmental impacts

LEED Checklist

LEED v4 for BD+C: New Construction and Major Renovation

Project Checklist

Project Name

Date

Y	?	N			
Y			Credi 1	Integrative Process	1
			Location and Transportation	**Possible Points:**	**16**
		N	Credit 1	LEED for Neighborhood Development Location	16
Y			Credit 2	Sensitive Land Protection	1
		N	Credit 3	High Priority Site	2
Y			Credit 4	Surrounding Density and Diverse Uses	5
Y			Credit 5	Access to Quality Transit	5
		N	Credit 6	Bicycle Facilities	1
Y			Credit 7	Reduced Parking Footprint	1
Y			Credit 8	Green Vehicles	1
			Sustainable Sites	**Possible Points:**	**10**
Y			Prereq 1	Construction Activity Pollution Prevention	Required
Y			Credit 1	Site Assessment	1
Y			Credit 2	Site Development--Protect or Restore Habitat	2
		N	Credit 3	Open Space	1
Y			Credit 4	Rainwater Management	3
Y			Credit 5	Heat Island Reduction	2
Y			Credit 6	Light Pollution Reduction	1
			Water Efficiency	**Possible Points:**	**11**
Y			Prereq 1	Outdoor Water Use Reduction	Required
Y			Prereq 2	Indoor Water Use Reduction	Required
Y			Prereq 3	Building-Level Water Metering	Required
Y			Credit 1	Outdoor Water Use Reduction	2
Y			Credit 2	Indoor Water Use Reduction	6
		N	Credit 3	Cooling Tower Water Use	2
Y			Credit 4	Water Metering	1
			Energy and Atmosphere	**Possible Points:**	**33**
Y			Prereq 1	Fundamental Commissioning and Verification	Required
Y			Prereq 2	Minimum Energy Performance	Required
Y			Prereq 3	Building-Level Energy Metering	Required
Y			Prereq 4	Fundamental Refrigerant Management	Required
Y			Credit 1	Enhanced Commissioning	6
Y			Credit 2	Optimize Energy Performance	18
Y			Credit 3	Advanced Energy Metering	1
		N	Credit 4	Demand Response	2
Y			Credit 5	Renewable Energy Production	3
Y			Credit 6	Enhanced Refrigerant Management	1
Y			Credit 7	Green Power and Carbon Offsets	2

Figure 25 - LEED checklist

Y	?	N		Materials and Resources	Possible Points: 13
Y			Prereq 1	Storage and Collection of Recyclables	Required
Y			Prereq 2	Construction and Demolition Waste Management Planning	Required
		N	Credit 1	Building Life-Cycle Impact Reduction	5
		N	Credit 2	Building Product Disclosure and Optimization - Environmental Product Declarations	2
		N	Credit 3	Building Product Disclosure and Optimization - Sourcing of Raw Materials	2
		N	Credit 4	Building Product Disclosure and Optimization - Material Ingredients	2
Y			Credit 5	Construction and Demolition Waste Management	2
				Indoor Environmental Quality	**Possible Points: 16**
Y			Prereq 1	Minimum Indoor Air Quality Performance	Required
Y			Prereq 2	Environmental Tobacco Smoke Control	Required
Y			Credit 1	Enhanced Indoor Air Quality Strategies	2
Y			Credit 2	Low-Emitting Materials	3
Y			Credit 3	Construction Indoor Air Quality Management Plan	1
		N	Credit 4	Indoor Air Quality Assessment	2
Y			Credit 5	Thermal Comfort	1
Y			Credit 6	Interior Lighting	2
		N	Credit 7	Daylight	3
	?		Credit 8	Quality Views	1
Y			Credit 9	Acoustic Performance	1
				Innovation	**Possible Points: 6**
Y			Credit 1	Innovation	5
		N	Credit 2	LEED Accredited Professional	1
				Regional Priority	**Possible Points: 4**
Y			Credit 1	Regional Priority: Specific Credit	1
Y			Credit 2	Regional Priority: Specific Credit	1
Y			Credit 3	Regional Priority: Specific Credit	1
Y			Credit 4	Regional Priority: Specific Credit	1
				Total 84	**Possible Points: 110**

Certified 40 to 49 points Silver 50 to 59 points Gold 60 to 79 points Platinum 80 to 110

Figure 26 - LEED checklist

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