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Assessment of the Hybrid Solar Technologies for Air Conditioning in the Sustainable City of Dubai

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Sponsor: Diamond Developers of Dubai, UAE

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Disclaimer: No specific product or technology constitutes an endorsement by the researchers of this report and UC Davis.

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Executive Summary

Air conditioning is one of the major energy consumption items in Dubai and countries with the same environmental conditions. Providing the majority of the air conditioning energy demand by renewable technologies will be a major step toward sustainable and green communities. The Sustainable City (TSC) in Dubai is currently under design, construction, and development by Diamond Developers Company (DD) with the most recent and innovative sustainable standards and technologies. As part of its policy to support research and development as well as to use the state of the art technology and knowledge for projects, DD collaborated with UC Davis and has sponsored multiple research projects. The current report has been sponsored by DD and summarizes the results of research by researchers from UC Davis and American University of Beirut (AUB).

In this study, different scenarios of integrated solar technologies and air conditioning systems for providing the energy demand of the Center of Excellence (SCE) building in the Sustainable City of Dubai has been evaluated. This study includes the determination of air conditioning demand of the building based on the environmental condition, behavioral aspects of the users of the building, air conditioning modeling, and the technologies available in the building.

After comparison of various scenarios, we recommend photovoltaic (PV) technologies for supplying the electrical demand of the building. Evacuated tube solar collectors will be used to provide the thermal energy for the thermal-driven single state absorption chiller. The results show that 1764 PV panels and 4120 evacuated tube solar collectors will be required for the SCE building. Additionally, the potential advantages of the building-integrated solar technologies for the building has been calculated and discussed. The life cycle assessment of solar and air conditioning technologies for the building shows that the payback time is in the range of 4 to 8 years. The study also addresses the human factors related to system performance and acceptability, and main barrier being an anticipated temperature setting of 24°C, slightly highly than the local norm. Ensuring system performance may require changes in occupant behavior. To estimate the acceptability of such changes, a survey on thermal comfort in the workplace was conducted. Twelve recommendations addressing occupant behavior were developed based on the survey results, the theory of behavior change, the physiological and cultural aspects of thermal comfort, and international best practice on thermostatic control. The recommendations address selecting controls technology, encouraging occupant acceptance and adaption, and empowering occupants to control temperature settings, in order to promote energy conservation and reliable system operation.

List of Abbreviations

Table 1: List of abbreviations.

DD	Diamond Developers
TSC	The Sustainable City
UC Davis	University of California Davis
AUB	American University of Beirut
SCE	Sustainable Center of Excellence
GF	Ground Floor
1F	First Floor
2F	Second Floor
PV	Photovoltaic
PV/T	Photovoltaic/Thermal
BIPV/T	Building-Integrated Photovoltaic/Thermal
BAPV	Building-Applied Photovoltaic
SAPV	Stand-Alone Photovoltaic

1 Introduction

The Sustainable City (TSC) in Dubai is currently under design, construction, and development by Diamond Developers Company (DD) with the most recent and innovative sustainable standards. TSC will be the first residential community in Dubai adopting sustainable design, highest environmental standards, and eco-tourism. TSC is an outstanding model of sustainable living, work, education and entertainment. The current report has been sponsored by DD and summarizes the results of research by researchers from UC Davis and AUB.

Air conditioning is a major energy consumer in hot and humid environments. Providing the air conditioning requirement of buildings by renewable resources is a promising approach toward sustainable design of buildings or zero net energy communities, especially at the time when non-renewable resources are being harshly exhausted. The design of the Sustainable City of Dubai is among the pioneering designs in employment of state-of-the-art research and technology toward green designs.

One of the main features of TSC is its net-zero-energy design. Around 10 MW_P of solar panels on the rooftop of the buildings and parking shades will generate most of the required electricity of the city. By proper design of the architectural regions a microclimate with cleaner air and lower temperature has been provided for the residents.

In this report, the first chapter summarizes the building information, weather, and occupants of the buildings. This information has been used as the input for the following chapters.

1.1 Dubai Weather

The average monthly temperatures in Dubai are presented in Figure *1*.

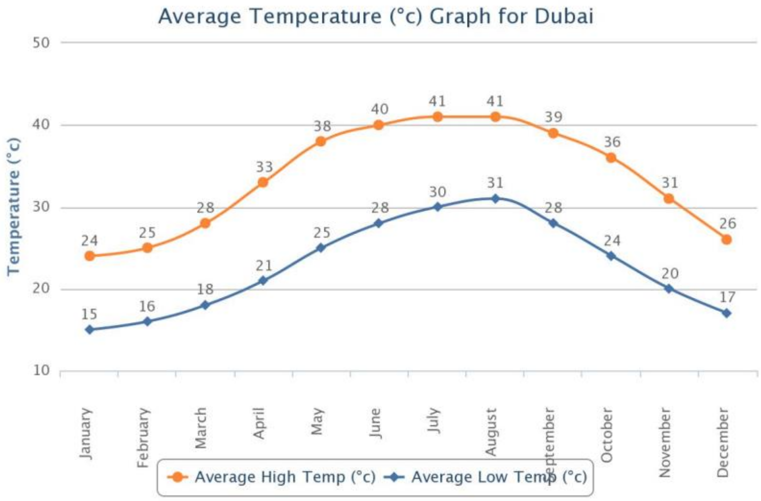

Figure 1: Average monthly high and low temperatures in Dubai. (Ref: worldweatheronline.com)

The average daily sunshine hours and humidity for each month in Dubai are summarized in Figure 2.

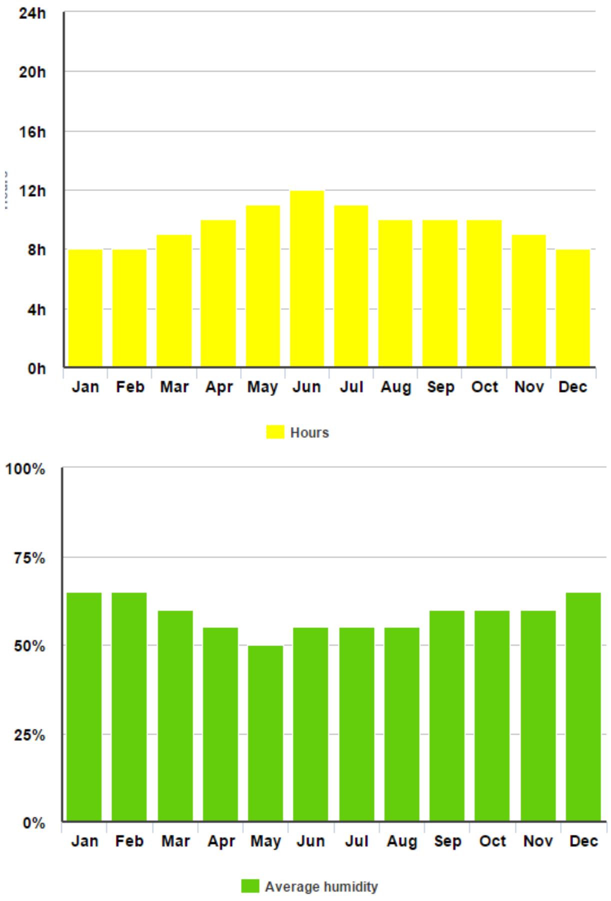

Figure 2 The average daily sunshine (up) and humidity (bottom) for each month in Dubai. (Ref: worldweatheronline.com)

1.2 Sustainable Center of Excellence: the SCE Building

TSC contains the following sections:

Table 2: Buildings in the Sustainable City of Dubai.

1- Buffer Zone	7- Eco-Resort & Spa
2- Equestrian Centre	8- Country Club
3- The Central Green Spine	9- School
4- Residential Clusters	10- Science Museum & Planetarium
5- Community Mall	11- Sustainability Centre of Excellence
6- Mosque	

The various sections are shown in the following schematic of the city (Figure *3*). The location of TSC is shown in Figure *4*. The approximate GPS location of the city is 25.029332, 55.280821.

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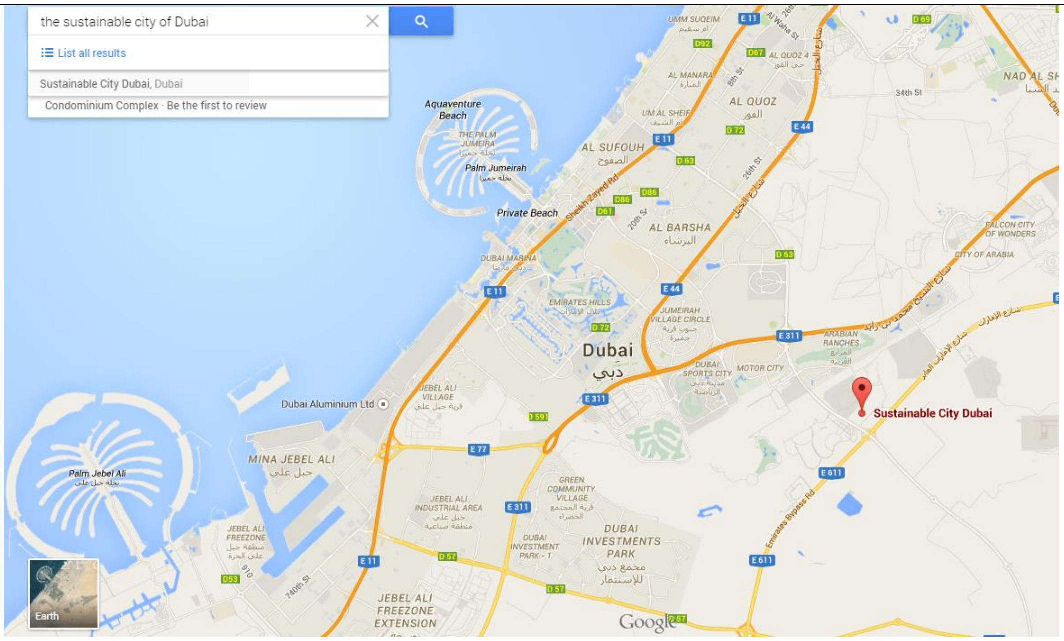
Figure 3: The general plan of TSC


the sustainable city of Dubai

List all results

Sustainable City Dubai, Dubai

Condominium Complex · Be the first to review

Figure 4: Location of TSC.

Figure 5:The location of the TSC in Dubai and the most recent satellite image of the TSC progress in construction (July 2015)

In this report we only focus on the Sustainable Center of Excellence (SCE building). The main objective of this report is the investigation of various scenarios of integrated solar technologies and air conditioning technologies for the SCE. The SCE building will offer research, training, exhibitions and conferences on sustainability and sustainability related topics.

The SCE is composed of three floors, which are named ground floor (GF), first floor (1F), and second floor (2F). The auditorium is shared between all the three floors. The GF also contains the lobby, exhibition center, and coffee shop. The detailed drawing of the GF is shown in Figure 6.

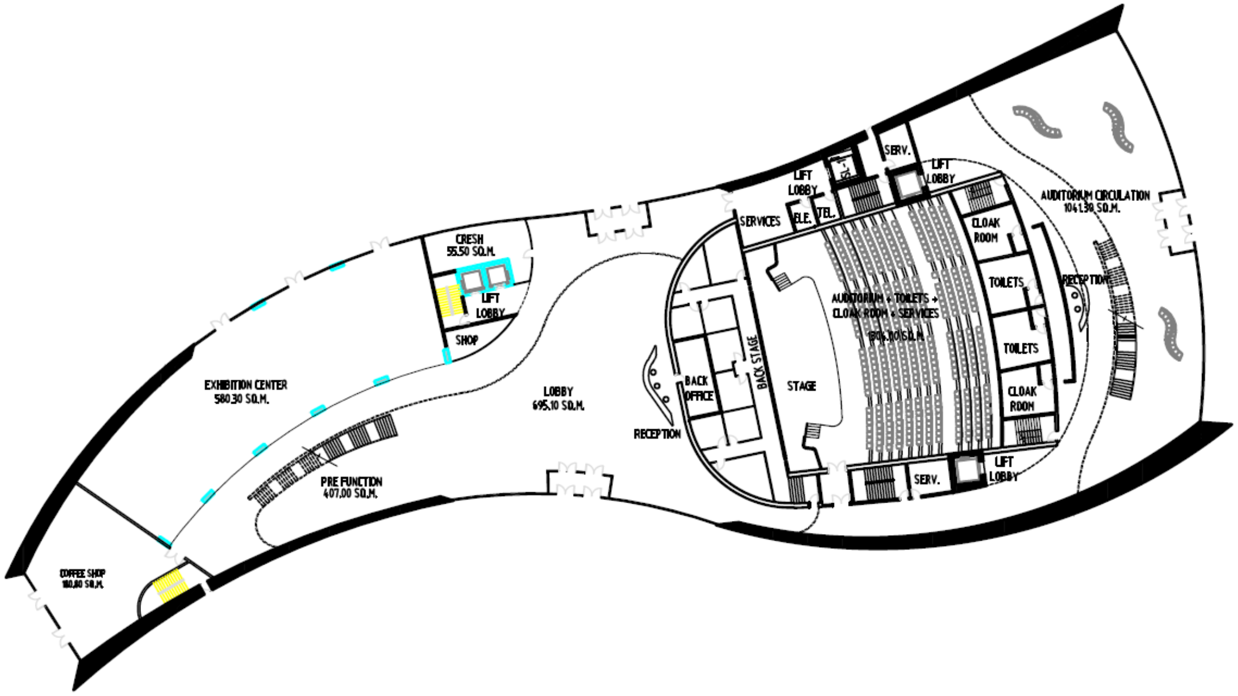


Figure 6 Ground Floor Plan

The 1F consists of conference center and kitchen. The detailed drawing of the 1F is shown in Figure 7.

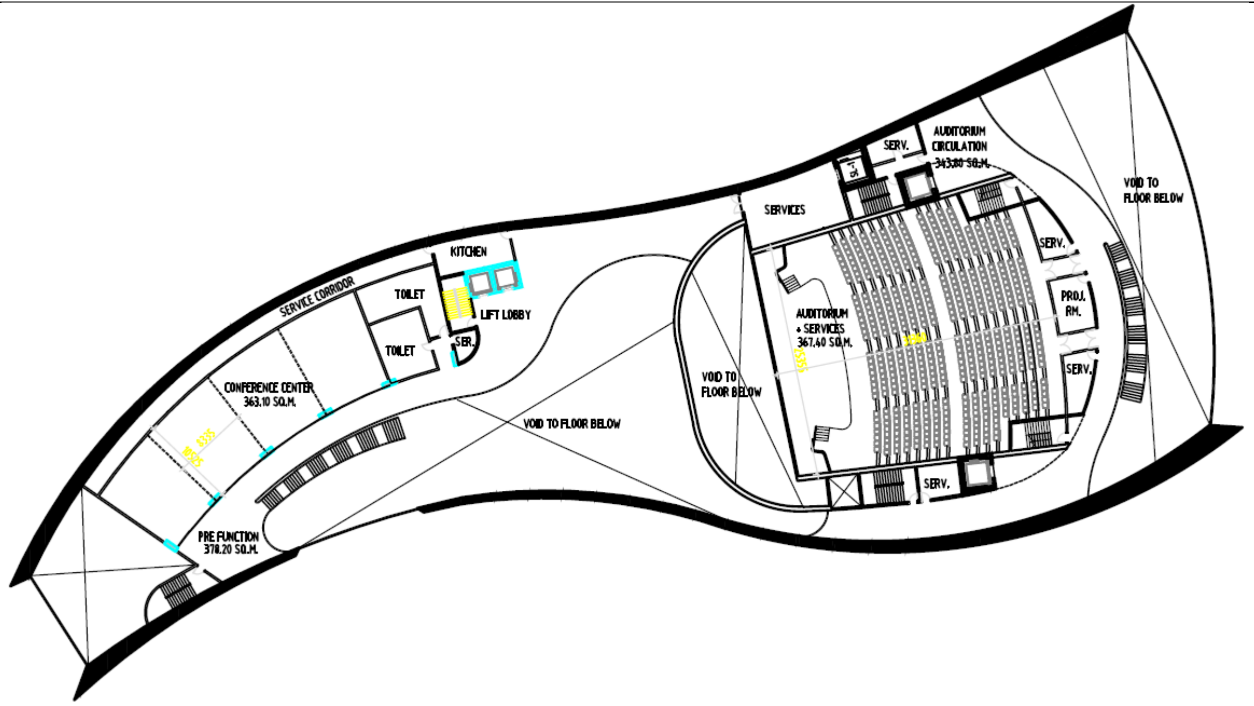


Figure 7 First Floor Plan

The 2F contains the management offices. The detailed drawing of the 1F is shown in Figure 8.

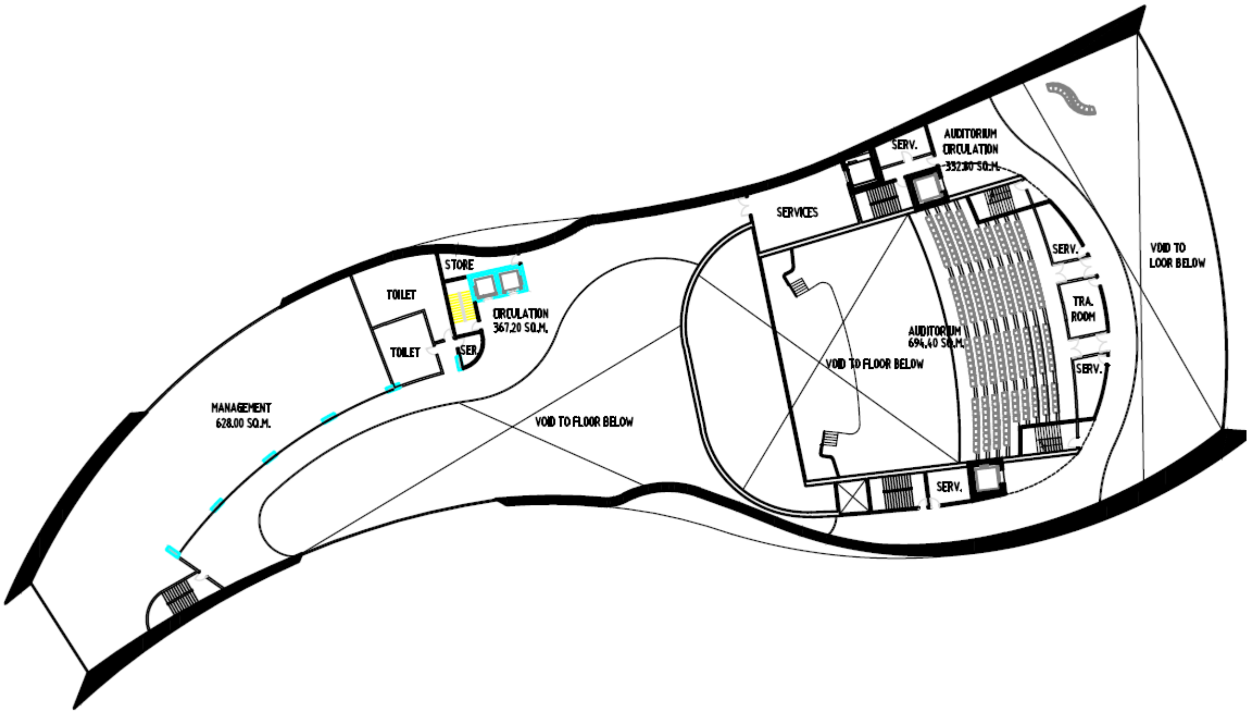
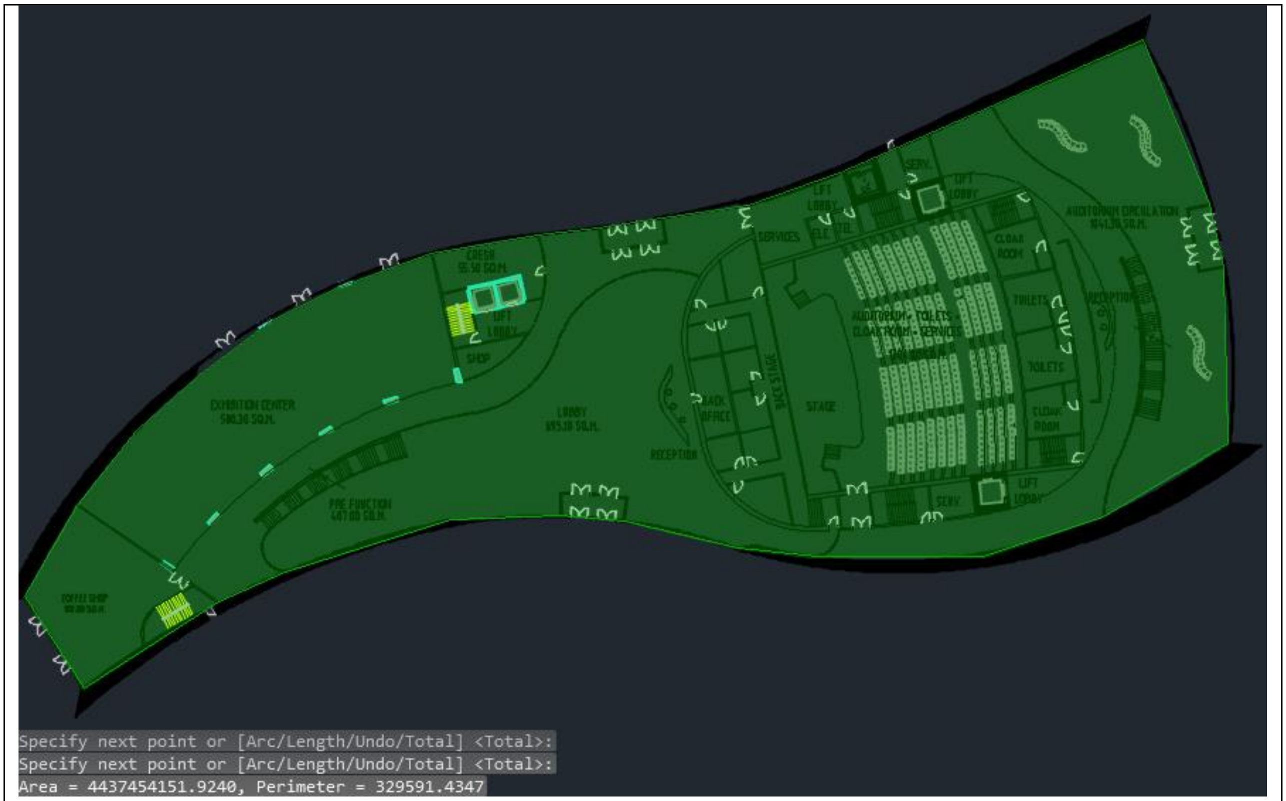


Figure 8 Second floor plan

The internal surface area of the GF was calculated using the AutoCad software, which is around 4,450 m^2. The perimeter of the building is around 330 m. (Figure 9).



```
Specify next point or [Arc/Length/Undo/Total] <Total>:
Specify next point or [Arc/Length/Undo/Total] <Total>:
Area = 4437454151.9240, Perimeter = 329591.4347
```

Figure 9 The approximate area of the inside of the building (in square millimeter) as well as the perimeter (in millimeter).

The height and other specification of each floor are summarized in Table 3

Table 3: The height of each floor in the center of excellence

Floor	Finish to Finish Height [m]	Finish to Ceiling Height (Clear Height) [m]	Window to Wall Ratio
Ground Floor	5.5	4.5	45%
First Floor	5.5	4.5	26%
Second Floor	4.5	4.0	33%

1.3 Sustainable Center of Excellence: Occupants

Based on the DD’s information, the auditorium is designed to accommodate 600 individual. The total number of staff for the building will be around 50 persons. The working hour for the staff will be 8 am to 6 pm. The capacities of each section in the building as well as the total capacity of occupants are summarized in Table 4.

Table 4 The capacity of each section in the building

Location	Capacity for People
Auditorium	600
Conference Hall (Four Halls)	4 x 30 = 120
Exhibition Hall	230
Management Offices	200
Total Occupants	**1150**

1.4 Sustainable Center of Excellence: Energy Demand

According to the sponsor's comments, the following criteria were considered for our calculations:

- ✓ **Electricity need of the building:** 90 kWh/m2 per year
- ✓ **System oversize:** 140% (The reason is to make sure that the energy balance is not only on the yearly operation but also on the life cycle of the building. The sponsor wants to account the building energy from cradle to grave of 50 years.)

The following table summarizes the surface area of each section in each floor. The required annual energy for the building was calculated based on the 90 kWh/m2. Therefore, considering 40% over design, the total annual electrical energy demand for the Center of Excellence is 975 MWh.

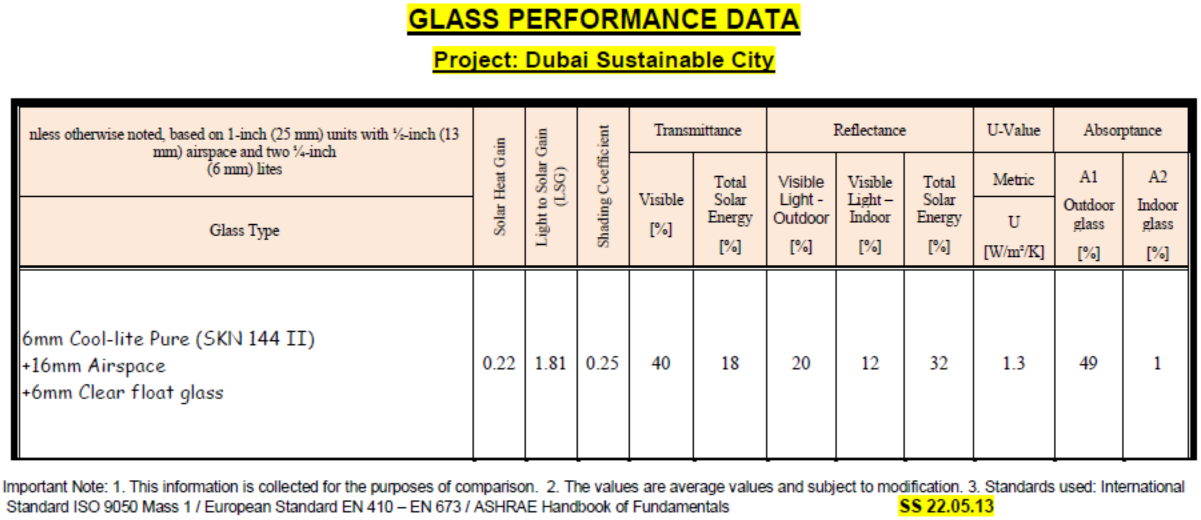
Table 5 The surface area and the electrical energy demand of each section of the SCE building.

Locations		**Surface Area (m2)**	**Annual Electricity Requirement (MWh/yr)**	**40% Over Design (MWh/yr)**
Ground Floor				
1.1	Coffee Shop	180.8	16.272	22.78
1.2	Exhibition Center	580.3	52.227	73.12
1.3	Pre Function	407	36.63	51.28
1.4	Crèche	55.5	4.995	6.99
1.5	Lobby	695.1	62.559	87.58
1.6	Auditorium + Toilets + Cloak Room + Services	1304	117.36	164.30
1.7	Auditorium Circulation	1041.3	93.717	131.20
Total GF		**4264**	383.76	537.26
First Floor				
2.1	Pre Function	378.2	34.038	47.65
2.2	Conference Center	363.1	32.679	45.75
2.3	Auditorium + Services	367.4	33.066	46.29

2.4	Auditorium Circulation	343.8	30.942	43.32
Total 1F		**1452.5**	130.725	183.02
Second Floor				
3.1	Management	628	56.52	79.13
3.2	Circulation	367.2	33.048	46.27
3.3	Auditorium	694.4	62.496	87.49
3.4	Auditorium Circulation	332.8	29.952	41.93
Total 2F		**2022.4**	182.016	254.82
Total Building		**7738.9**	**696.501**	**975.10**

1.5 Building Materials and Specifications

The sponsor has provided the following information about the building materials.

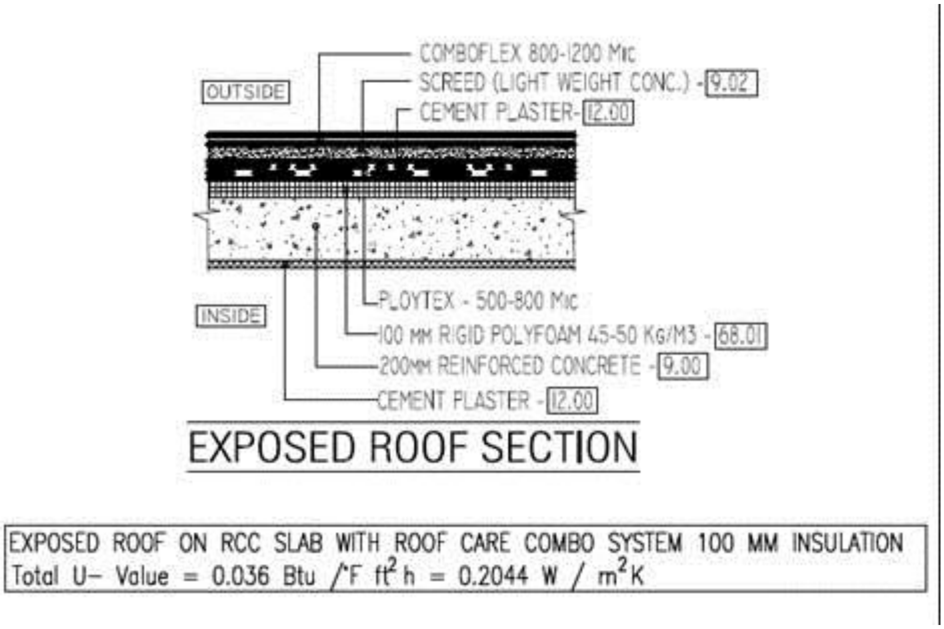


GLASS PERFORMANCE DATA

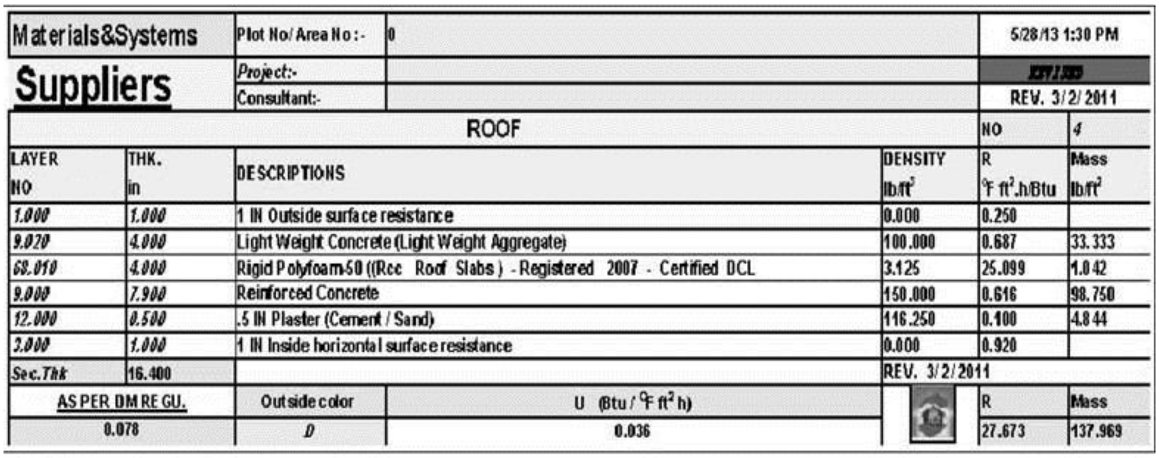
Project: Dubai Sustainable City

nless otherwise noted, based on 1-inch (25 mm) units with ½-inch (13 mm) airspace and two ¼-inch (6 mm) lites	Solar Heat Gain	Light to Solar Gain (LSG)	Shading Coefficient	Transmittance		Reflectance			U-Value	Absorptance	
Glass Type				Visible [%]	Total Solar Energy [%]	Visible Light - Outdoor [%]	Visible Light – Indoor [%]	Total Solar Energy [%]	Metric U [W/m²/K]	A1 Outdoor glass [%]	A2 Indoor glass [%]
6mm Cool-lite Pure (SKN 144 II) +16mm Airspace +6mm Clear float glass	0.22	1.81	0.25	40	18	20	12	32	1.3	49	1

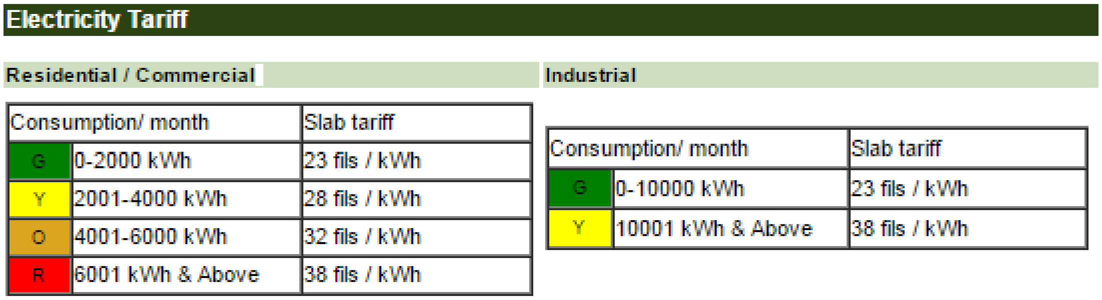
Important Note: 1. This information is collected for the purposes of comparison. 2. The values are average values and subject to modification. 3. Standards used: International Standard ISO 9050 Mass 1 / European Standard EN 410 – EN 673 / ASHRAE Handbook of Fundamentals SS 22.05.13



EXPOSED ROOF ON RCC SLAB WITH ROOF CARE COMBO SYSTEM 100 MM INSULATION
Total U– Value = 0.036 Btu /°F ft^2 h = 0.2044 W / m^{2}K



Materials&Systems	Plot No/ Area No :-	0			5/28/13 1:30 PM
Suppliers	*Project:-*				[illegible]
	Consultant:-				REV. 3/2/ 2011
		ROOF		NO	*4*
LAYER NO	THK. in	DESCRIPTIONS	DENSITY lb/ft^3	R °F ft^2.h/Btu	Mass lb/ft^2
1.000	*1.000*	1 IN Outside surface resistance	0.000	0.250	
9.020	*4.000*	Light Weight Concrete (Light Weight Aggregate)	100.000	0.687	33.333
68.010	*4.000*	Rigid Polyfoam-50 ((Rcc Roof Slabs) - Registered 2007 - Certified DCL	3.125	25.099	1.042
9.000	*7.900*	Reinforced Concrete	150.000	0.616	98.750
12.000	*0.500*	.5 IN Plaster (Cement / Sand)	116.250	0.100	4.844
3.000	*1.000*	1 IN Inside horizontal surface resistance	0.000	0.920	
Sec.Thk	16.400		REV. 3/2/2011		
AS PER DM REGU.		Outside color	U (Btu / °F ft^2 h)	R	Mass
0.078		*D*	0.036	27.673	137.969



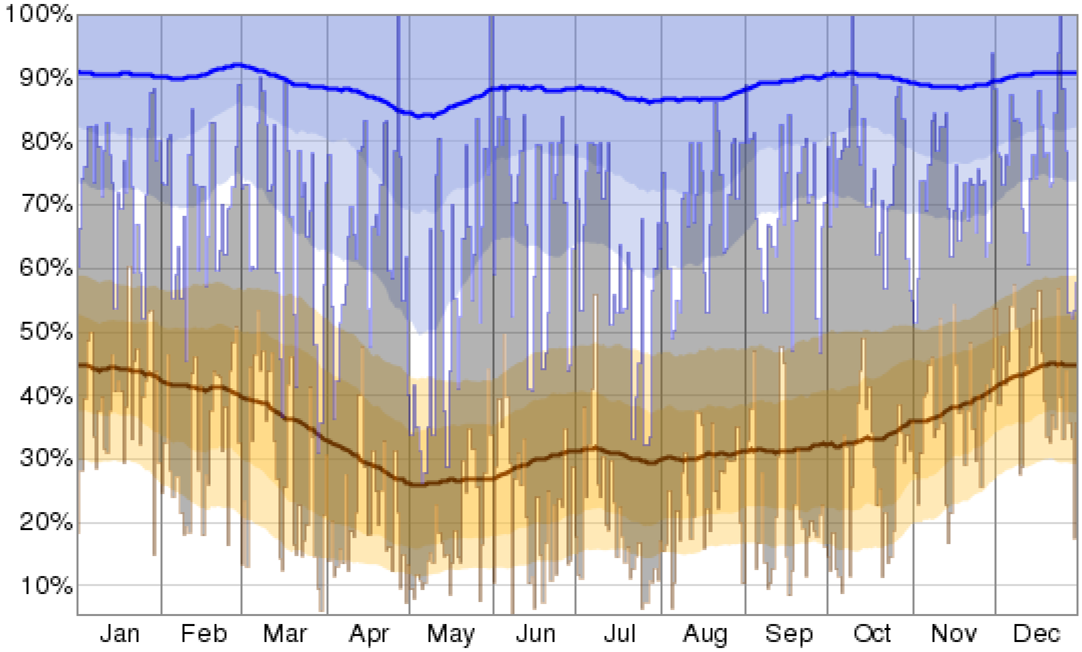
Electricity Tariff

Residential / Commercial

Consumption/ month		Slab tariff
G	0-2000 kWh	23 fils / kWh
Y	2001-4000 kWh	28 fils / kWh
O	4001-6000 kWh	32 fils / kWh
R	6001 kWh & Above	38 fils / kWh

Industrial

Consumption/ month		Slab tariff
G	0-10000 kWh	23 fils / kWh
Y	10001 kWh & Above	38 fils / kWh



Data from: https://weatherspark.com/history/32855/2012/Dubai-United-Arab-Emirates

2 Project Background

2.1 Introduction

The continuing rise in energy demand, costs as well as associated climate change and environmental problems, have increased emphasis on the design of energy efficient and renewable driven air conditioning systems for both industrial and comfort applications. Buildings are responsible for approximately 40% of the world's total annual energy consumption.[1] In hot and humid climates such as Dubai, large portion of the building energy consumption is dedicated to the air conditioning (AC). The AC increases the Dubai's energy consumption by 60% during the summer months.[2] The high solar irradiance intensity of Dubai provides the opportunity of using solar technologies for air conditioning.

When considering solar-assisted systems for small scale residential or office building applications, the area requirements for solar collectors and the capital cost associated with it render the use economically infeasible when compared with conventional air conditioning systems. This report evaluates hybrid solar powered air conditioning systems to provide the energy demand for building cooling, dehumidification and electric power. Therefore, the systems contain absorption chiller, desiccant dehumidification wheel, and hybrid photovoltaic-thermal technologies.

2.2 Thermally Driven Air Conditioning

Thermally driven cooling cycles for air conditioning can work with various sources of thermal energy such as solar thermal and waste heat. Thermally driven cooling systems are composed of an absorption chiller. In climates with high humidity, solid or liquid desiccant dehumidification systems can be integrated to the system These cycles have the advantage that they can be operated at low temperatures 5-6 °C. Ghaddar et al. (1997) reported results on a hybrid small-size absorption cooling system where for each ton of refrigeration it is required to have a minimum solar collector area of 18.2 m2 with an optimal water storage tank capacity of 1500 liter. Homoud et al. (1996) reported the installation of three 35 kW $LiBr/H_2O$ absorption chillers for an office building in Kuwait using 300 m^2 of flat plate water collectors and a vertical hot water tank of 20 m^3. Fong et al. (2011) reported energy savings of more than 35% compared with conventional air conditioning systems when using solar hybrid system coupled with chilled water from absorption refrigeration. The ventilation load (largely latent) provided by desiccant dehumidification while utilizing solar energy for driving the absorption chiller and regenerating the desiccant.

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[1] http://www.c2es.org/technology/overview/buildings

[2] http://www.thenational.ae/uae/air-conditioning-heats-up-energy-bills

Prof Ghaddar and her colleague Prof. Ghali have an extensive and impressive research in applications that improve efficiency of systems for heating, cooling and water production, human comfort, and clothing design. Some of the areas of expertise and previous experiences of Prof. Ghaddar and her team can be summarized in the following points:

1- Localized cooling devices to improve overall thermal comfort indoor and outdoor

The focus of the work is to improve the productivity and the well being of people in both indoor and outdoor environmental conditions at minimal energy cost. In indoor applications, the aim is to deliver thermal comfort and good air quality to the occupant at low energy cost (task ventilators, personalized coolers, clothing design, air cleaning systems, smart space, online HVAC control, hybrid air conditioning systems). The applications of the bioheat model and predictive models of local and global comfort enabled addressing important problems that may help approach the zero-net energy building target.

2- Hybrid renewable Energy Systems: Solar-powered air-conditioning liquid desiccant system is a hybrid system that has been researched to assess if the two needs of fresh water and air conditioning can be met by use of this system while entirely powered by solar energy in Beirut humid climate. This work focused on the feasibility of using a solar-powered liquid desiccant system to meet both needs at minimum cost. We have set up an experimental station connected with the two outdoor climatic chambers to test the concept and assess comfort conditions in the space while using the dry air stream from the liquid dehumidifier to supply fresh air to the space.

3- Development of space thermal models for heating and cooling integrated with system models and bioheat models to improve energy efficiency.

HVAC equipment running cost contributes to more than 35%-40% of the total energy consumption in buildings. Thermal comfort and indoor air quality (IAQ) for a given space can be provided by different types of HVAC systems that consume different amounts of energy. We have considered several applications for improving energy efficiency of heating and cooling systems of buildings.

2.3 PV/T Technology

There are two major challenges with the PV panels. More than 85% of the solar energy cannot be captured by the PV panels. The hot environment of the Dubai decreases the efficiency of the PV panels. In order to solve these challenges PV/T panels can be replaced by PV panels. Replacing the PV panels with PV/T panels has the advantage of simultaneous production of hot water and electricity. Additionally, the cooling system in PV/T technology decreases the temperature of PV panels and therefore, the efficiency of the electricity production is increased. The combined heat and electricity increases the efficiency of the solar technology by capturing around 80% of the solar radiation energy.

Photovoltaic thermal technology offers the advantage of providing both high-grade electrical energy and low-grade thermal energy. The increased electrical energy due to cell cooling, and the high thermal efficiency of the PV/T panel make the latter a more attractive alternative to conventional electricity, and make the panels more cost competitive since increased energy yield means a shorter payback period. PV/T applications are numerous and PV/T panels can be used in practically any application requiring low-grade thermal energy. Cooling of PV panels can be done by air or water medium. Cooling using water has higher thermal efficiencies due to higher heat transfer coefficients, but requires special design and manufacturing considerations, such as fluid tubes, and thermal expansion of the fluid.

The air-cooled panels are regular PV panels, provided with an air channel, and the various designs include: single air passage above or below the absorber, two air passages above and below the absorber in a single-pass or a double-pass. According to Hegazy (2000), numerical solutions of the energy balances show that the single air pass above the absorber has the lowest performance as compared to cooling the lower absorber side or the two sides of the absorber (above and below) in a single or double passes. Cooling the panels by air was studied also by Garg and Adhihri (Garg et al., 1999), who found that thermal and electrical outputs are directly proportional to collector length, airflow rate and packing factor, and inversely proportional to duct length. In another work, the combined effect of the airflow rate, the air channel depth, the length and the packing factor on the efficiency and outlet temperature was evaluated by Prakash (1994). The output temperature decreased with increasing the mass flow rate, while the thermal efficiency increased. To improve the performance of air-cooled PV/t panels, the addition of fins was considered in several papers. For example, Kumar and Rosen (2011) evaluated the performance of a double-pass PV/t solar air heater with and without fins. They found out that the addition of fins in their model increased the thermal and electrical efficiencies to 15.5% and 10.5%. Other studies conducted by Tonui and Tripanagnostopoulos (2007) showed that adding a suspended plate to enhance heat transfer to the air, increased the energy efficiency from 25% to 28%, while adding fins allowed the energy efficiency to reach 30%. So replacing the PV panels with PV/T panels has the advantage of simultaneous production of hot water and electricity. The combined heat and electricity increases the efficiency of the solar technology by capturing around 80% of the solar radiation energy.

The PV/T panels will be considered to minimize the seasonal energy cost (electrical and thermal) of residence in Dubai City. The project focuses on optimizing the required airflow that will enhance electrical output of the PV/T panels and minimize the thermal heating needs for regenerating the desiccant wheel during the summer cooling season. Given the limited options for getting cool air stream due to Dubai high ambient air temperature, we use exhaust return flow to cool the PV panel.

The objectives for the PVT system sizing and utilization in Dubai residential units can be summarized as follows: 1) Use a simulation model to predict the performance of the PV/T panels at different ambient conditions and cooling air flow rates for Dubai weather. 2) Integrate the PV/T model with a space model, a desiccant model and an evaporative cooler model to predict the energy performance of the combined system and 3) Size and optimize the system's operation for lowest operating cost while maintaining thermal comfort.

2.3.1.1 Use of solar powered desiccant dehumidification system to decouple humidity removal from sensible cooling in the air conditioning system

Dubai climate is known for its high relative humidity during most of the year. Extreme levels of relative humidity can irritate people's comfort [Yang et al. (2014)]. In humid climates, the humidity issues are a major contributor to energy inefficiency in HVAC devices. The high humidity of the outside air combined with ventilation requirement increases the latent load. Most conventional air-conditioning systems are not designed to independently control temperature and humidity. The conventional way of moisture removal is cooling the indoor air (using vapor compression cycle) to temperatures below its dew point temperature to condense the excess moisture followed by reheating to the adequate supply air temperature. This is an energy intensive process [Bahman et al. (2012)]. Recently, research has been oriented towards considering non-conventional, passive and less-intensive methods for controlling indoor humidity. A known sustainable dehumidification technique is the use of desiccant technology as a passive method for HVAC applications [Ghaddar et al. (2003), Audeh et al. (2011), Li et al. (2011), Wang et al. (2013), El-Deeb et al. (2009)].

Conventional desiccant dehumidification techniques utilize solid or liquid desiccant based systems. In the case when a liquid desiccant is used, dehumidification and regeneration tower beds are employed [Li et al. (2011), Audi et al. (2012)], whereas in the case of a solid desiccant, a rotary desiccant wheel is used [Wang et al. (2013)]. An attractive feature of desiccant dehumidification systems is their suitability for solar or other low-grade thermal energy applications [Ghaddar et al. (2003, Wang et al. (2011)].

A solid desiccant dehumidification system will be sized and integrated with an absorption chiller system to air condition the space. The hybrid system will be totally powered by solar energy that provided regeneration heat needed for the absorption chiller [Ghaddar et al. (1997)] and the dehumidification solid desiccant wheel as shown in Fig. 1 that integrates PV/T, desiccant dehumidification, and sensible cooling (absorption chiller) to provide space cooling needs and power needs.

2.3.2 Thermal Comfort

Thermal comfort is a subjective evaluation of one's satisfaction with the thermal environment. Comfort roughly equates to thermal neutrality, whereby occupants are neither losing nor gaining heat from their environment, but instead, are able to maintain equilibrium with the ambient conditions. In essence, with thermal neutrality, the body does not have to expend energy to stay warm or to cool off. Thermal comfort is important because it affects occupants' health, happiness, and productivity.

Providing thermal comfort to occupants is the primary objective of conditioning indoor spaces. A widely accepted guideline for doing so is provided by ASHRAE Standard 55, produced by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers. The stated purpose of ASHRAE Standard 55 is "to specify the combinations of indoor thermal environmental factors and personal factors that will produce thermal environmental conditions acceptable to a majority of the occupants within the space".(ASHRAE, 2010) Thus, many of the specific details on how thermal comfort is measured and what influences it are derived from ASHRAE Standard 55.

Delivering thermal comfort to many occupants simultaneously is difficult because thermal comfort is highly individual, and there are many factors that drive thermal comfort. They can be broadly categorized as either environmental or personal factors.

Environmental factors influencing thermal comfort include air temperature, mean radiant temperature (derived from heat transferred from a surrounding surface), air speed and humidity. In general, humans feel relatively warmer as air temperature, radiant temperature and humidity increases, and as air speed decreases.

The typical personal factors considered include individuals' metabolic rate and clothing level. The metabolic rate is a function of human physiology (which includes elements such as age, gender, body mass, metabolism, and dietary intake) and activity level. The metabolic rate is expressed in units of "met", where 1 met = 58.2 W/m^2 (or 18.4 $Btu/h\cdot ft^2$). ASHRAE provides estimates for the met value of various activity levels (e.g., 1.0 met for reading or writing while seated, 1.2 for standing relaxed, 1.7 for walking about) undertaken by an “average person”. (ASHRAE, 2013a)

The insulation humans receive from clothing also affects thermal comfort by preventing heat loss. The insulation provided by clothing is measured in a unit called a clo value, where 1 clo = 0.155 m^2•°C/W (or 0.88 ft^2•h•°F/Btu). This is equivalent to the insulation provided by trousers, a long sleeved shirt, and a jacket, according to ASHRAE Standard 55.

There is also evidence that assessments of thermal comfort have a psychological component. The human body is highly adaptable, and comfort can be measured (and interpreted) in absolute terms or in relative or conditional terms. For example, there is evidence that expectations influence one’s reporting of thermal comfort. Thus, seasonal outdoor temperature shifts often affect occupants’ expectations of indoor conditions such that thermal comfort, as they assess it, is associated with slightly higher or lower indoor temperatures throughout the year, and even throughout the day. (Mishra & Ramgopal, 2013).

Numerous studies have also demonstrated that occupants’ control (or perceived control) over indoor conditions can also affect occupants’ assessment of thermal comfort. For example, Karjalainen (2009) found a strong correlation between satisfaction with room temperature and the perceived level of control over room temperature. This finding was statistically significant in both home and office environments.

Although norms about spacing conditioning differ substantially around the world, it is generally accepted that significant cultural differences in thermal comfort do not exist. Indeed, intra-group differences typically exceed inter-group differences. However, there are cultural differences in the social norms governing factors such as clothing, body mass, and nutritional intake, which in turn affect thermal comfort. Thus, when attempting to determine or establish acceptable indoor conditions, it is important to keep cultural factors in mind. For example, a field study by Al-Rashidi et al. (2009), found that the comfortable classroom temperatures differed for boys and girls, something previous studies cited had not reported. The authors found this by properly accounting for the separation of classrooms by gender (as is the custom) and differing clo values associated with the boys’ and girls’ mandatory uniforms.

While many factors influence thermal comfort, as described above, measuring thermal comfort is fairly straightforward. Typically, at least two dimensions of thermal comfort are measured: thermal sensation and comfort. ASHRAE’s thermal sensation measure, for example, is a 7-point scale where -3 = cold, -2 = cool, -1 = slightly cool, 0 = neutral, +1 = slightly warm, +2 = warm, and +3 = hot. This scale has been used by many empirical studies of thermal comfort around the world, although it is by no means the only one.(Zhang, 2003)

Separate from thermal sensation, individuals are often asked to assess their comfort. ASHRAE’s 9-point scale ranges from −4 (intolerably cold) to +4 (intolerably hot). Other comfort scales ask about satisfaction with,(Hoyt et al, 2013) or the acceptability, comfort (Zhang, 2013) or tolerability of, the indoor temperature, without reference to the thermal sensation.

Some acceptability scales explicitly acknowledge the fact that thermal comfort can be considered in relative terms. For example, prior UC Davis research has shown that the acceptability of a given indoor temperature can depend in part on the other parameters over which an occupant is attempting to maximize utility, i.e., balancing comfort with energy cost or environmental impact of energy use. There is some evidence to suggest that individuals are willing to extend their normal boundaries of acceptability to make allowances when thermal comfort is delivered in more environmentally benign manners (e.g., natural ventilation, solar-powered air conditioning).(Outcault, et al., 2014)

To measure thermal comfort on an aggregate level, data from thermal sensation ratings are compiled across a group of occupants. Two commonly used indicators derived from thermal sensation data are:

- Predicted mean vote (PMV), defined by ASHRAE as “an index that predicts the mean value of the votes of a large group of persons on the seven-point thermal sensation scale”; and
- Predicted percentage of dissatisfied (PPD), defined by ASHRAE as “an index that establishes a quantitative prediction of the percentage of thermally dissatisfied people determined from PMV”.

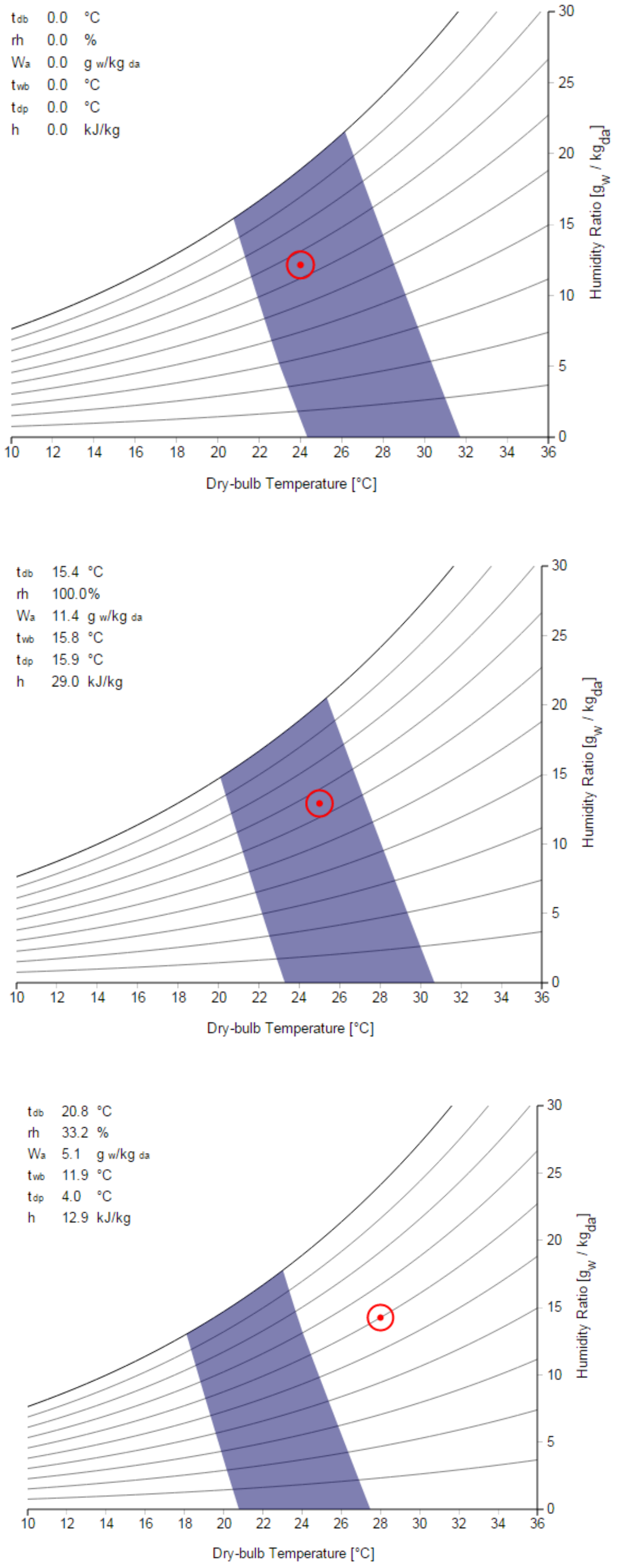
Both PMV and PPD are used to establish guidelines for space conditioning, such that thermal comfort can be optimized across many (potentially diverse) occupants.

There are numerous ways to consider the various types of data collected on occupants' thermal comfort. An example of a fairly comprehensive tool is the interactive web-based tool created by the University of California-Berkeley's Center of the Built Environment to predict thermal comfort (using ASHRAE Standard 55). The tool allows users to adjust the indoor air temperature, radiant temperature, air speed, humidity, and occupants' metabolic rate and clothing level. The model then generates an estimate of the PMV and the PPD among occupants. ASHRAE sells a software tool that has similar capabilities (ASHRAE, 2013b). Both tools are consistent with ASHRAE Standard 55-2010.

When developing new instruments to measure thermal comfort in a particular environment (e.g., thermal comfort surveys), it is important to consider local conditions and, to the extent possible, utilize established scales for measuring concepts such as thermal sensation and comfort. The latter generates data that is both valid and reliable, and facilitates comparisons with previous studies.

By using the weather data and the online thermal comfort calculator only January and February meet the requirement of thermal comfort based on the ASHRAE 55-2010 standard. The results of the thermal comfort modeling for January, February, and March are shown in the following figures. Therefore, ten months in Dubai the air conditioning is required.

Sponsor mentioned the 22 ^{o}C as a set point for temperatures. However, we will provide some guidance about the set temperature of each room at each season in our final report.



tdb 0.0 °C
rh 0.0 %
Wa 0.0 g w/kg da
twb 0.0 °C
tdp 0.0 °C
h 0.0 kJ/kg
Dry-bulb Temperature [°C]
Humidity Ratio [gw / kgda]
10 12 14 16 18 20 22 24 26 28 30 32 34 36
0 5 10 15 20 25 30
tdb 15.4 °C
rh 100.0%
Wa 11.4 g w/kg da
twb 15.8 °C
tdp 15.9 °C
h 29.0 kJ/kg
Dry-bulb Temperature [°C]
Humidity Ratio [gw / kgda]
tdb 20.8 °C
rh 33.2 %
Wa 5.1 g w/kg da
twb 11.9 °C
tdp 4.0 °C
h 12.9 kJ/kg
Dry-bulb Temperature [°C]
Humidity Ratio [gw / kgda]

Figure 10

The thermal comfort modeling for January (top), February (middle), and March (bottom) using the comfort tool and ASHRAE-55-2010 standard.

2.3.3 Solar-based Absorption Chillers

In general, a single-effect absorption chiller has a rough coefficient of performance (COP) of 0.65 and requires a heat source at a temperature of 90^{o} C. On the other hand, a double effect absorption chiller has a COP of 1.2 and a heat source at a temperature of 200 °C. Therefore in the proposed chiller system, it is recommend to use single effect absorption chiller (lower temperature heat source). Below are some comments:

- To prevent crystallization of the LiBr in the absorption chiller, a cooling tower is needed to deliver cooled water to the absorption condenser at a temperature of 34 °C and the water returning to the cooling tower at 39 °C. The design environmental conditions in Dubai are 35 DB and 30 WB. Please note that the design environmental conditions are taken for the highest WB temperature and the coincident DB temperature. The highest outdoor temperature is taken as 46 °C. Having chosen 30 ^{o}C WB and an approach temperature of 4 °C for the cooling tower, the supply cooling water coming out from the tower is chosen as 34 °C.

- The low COP of the single effect means that large quantity of heat needs to be dissipated in the cooling tower requiring large size of the tower and large quantity of water. Alternatively we can use geothermal to dissipate the absorption-wasted heat to the soil. The temperature of the desert soil is about 26 °C. However, the first cost of installing absorption condenser dissipated heat to the soil (bore holes) will be large. Another alternative is to use the rejected heat from the condenser to preheat air for the desiccant dehumidifier and thus reduce solar captured thermal energy. The sizing has to be done simultaneously for both chiller and dehumidifier.

2.3.4 Ventilation Requirements

There have been several standards for the ventilation requirements. However, the one that will be used in this project will be ASHRAE standards. ASHRAE recommends a ventilation rate of 0.7 liter/second/m2 for occupancy of 0.08 person/m^2. On the other hand, the minimum ventilation requirement should be set per person in order to provide good and proper indoor air quality. ASHRAE standards provide a range between 4 and 10 liter/second/person. For Dubai Center of Excellence, since the metabolic rate is relatively low and the occupants are not doing any hard physical actions, as well as smoking prohibition inside the building, the ventilation requirement was set to 4 liter/s/person. The minimum exhaust rate is set to 3.5 liter/s/m^2. The relative humidity of the ventilated space should be maintained between 30% and 70%. Finally, any ventilation system should remove a maximum of 40 W/m^2 of heat with a vertical temperature gradient of around 1.5 °C/m.

2.4. References

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3 System Designs and Models

The Center of Excellence has two major occupancy zones with separate schedules. One of the zones is a large auditorium with a maximum capacity of 600 persons representing more than 50% of the building maximum total occupancy of 1150 persons. Since the auditorium is not used as frequently as other zones of the building, it was proposed to design the cooling system such that it would include two absorption chillers; one that meets the building demand in normal operation and is continuously operated and the other absorption chiller to be used when the auditorium is occupied. To downsize the absorption chillers, they are designed such that they remove the sensible load of the Center of Excellence while dehumidification load (latent load mainly of people) would be removed using solar-powered solid desiccant dehumidification system. A geothermal heat sink will also be used to improve the performance of the solar driven absorption chiller system providing cooler air to the condensers. Figure 11 shows a schematic of the proposed two cooling systems and the zones they cover. The absorption chillers will be operated by using solar thermal collector system as the heat source. The solar system can be either solar concentrator system or vacuum tube collectors. In addition, a PV/T system is also used to cover all electrical energy needs of the system. Fig. 14 shows a schematic of the proposed system.

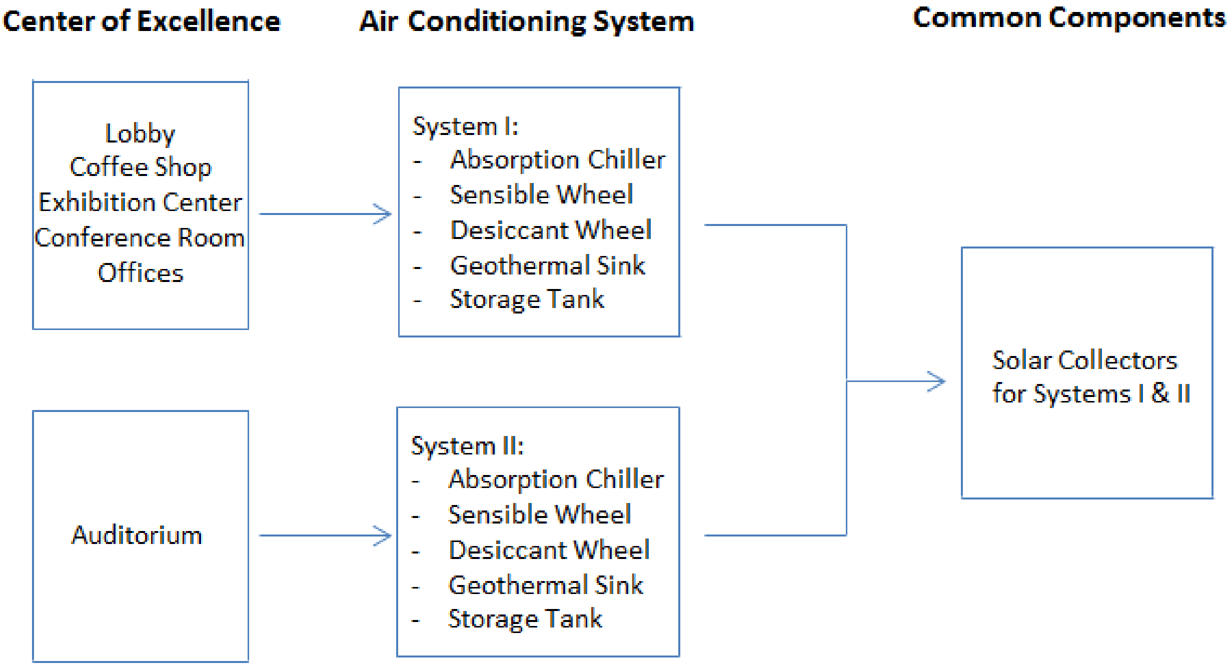

Figure 11 Schematic of zones and systems for cooling.

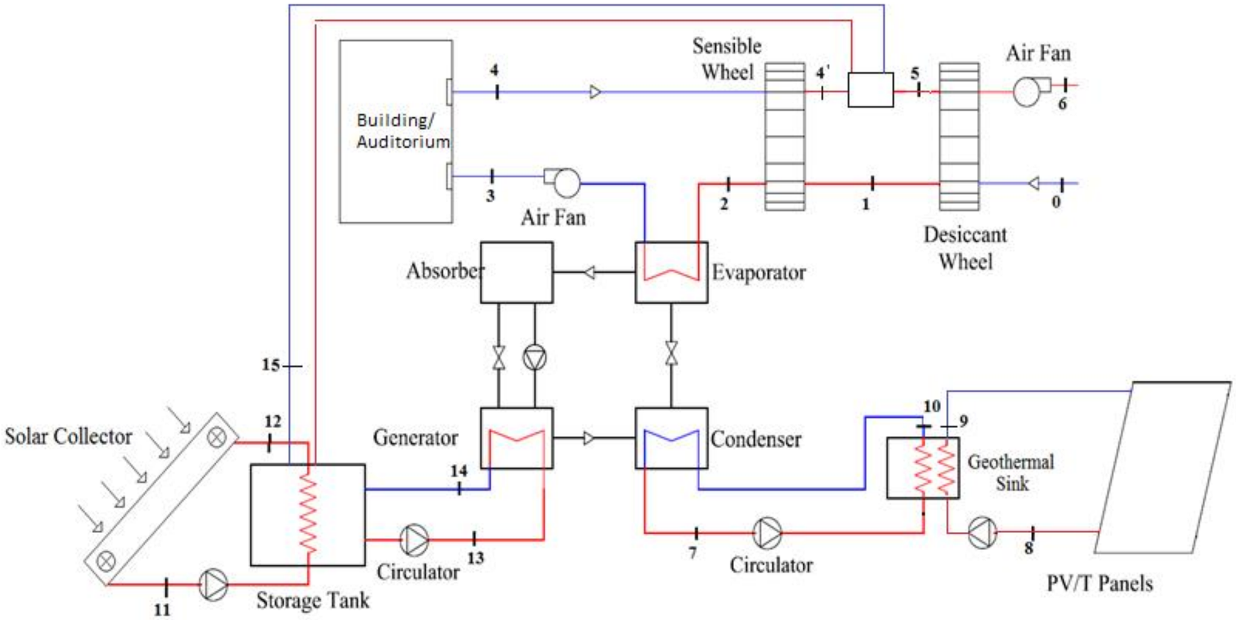

Figure 12: System Component Design with PVT Panels

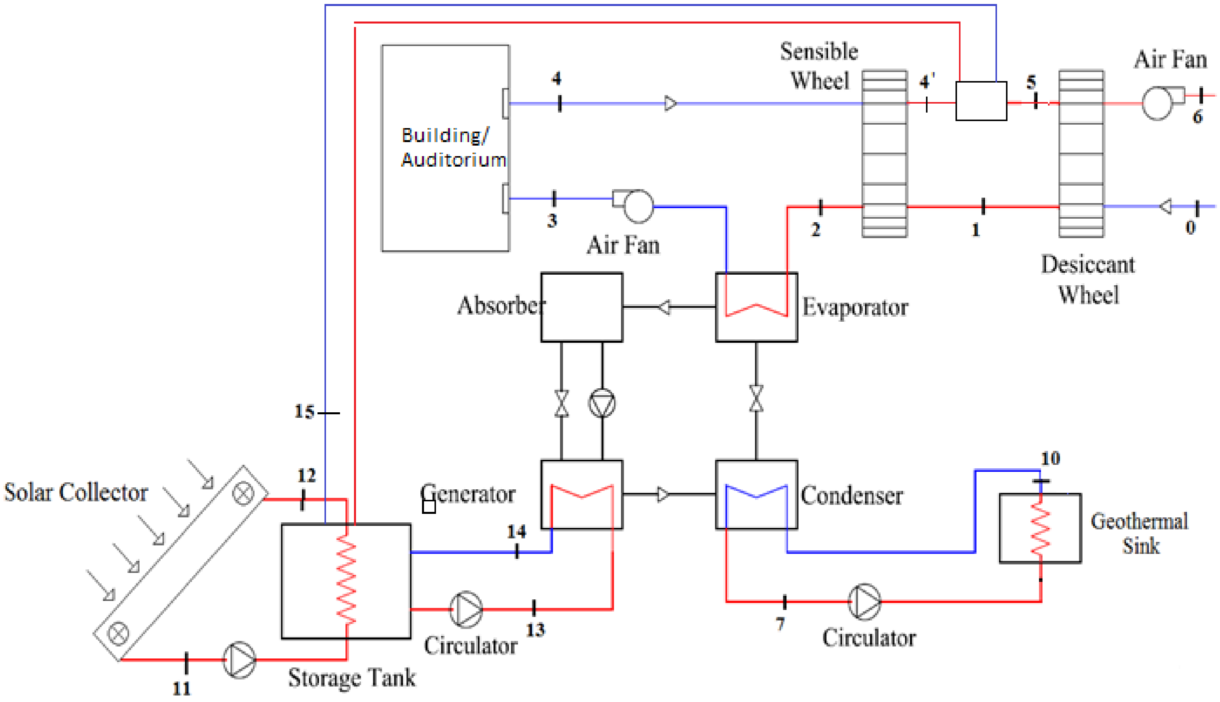

Figure 13: System Component Design without PVT Panels

Table *6* demonstrates the scenarios that were studies for the purpose of meeting thermal comfort requirements in the space. Scenario 4 is the adopted system for which the system has been designed and sized.

Table 6: Progress of systems to suit the project application.

No.	Scenario	Description
1	Personalized Cooling Air Conditioning System	One of the earliest considered scenarios; it is based on the idea of increasing the supply air temperature (in order to decrease the HVAC demand) and provide personalized cooling for the occupants. This scenario was found useful in offices rather than in large centers.
2	PV/T panels and one absorption chiller	This scenario includes the usage of PV/t panels in order to produce the needed electricity demand for the center of excellence. The absorption chiller is used to meet the sensible cooling demand of the building. A desiccant wheel for dehumidification purposes has been also added. However, due to the presence of two different cooling loads (auditorium and rest of the building) it was found to be impractical. Lastly, the condenser of the chiller needed large amounts of heat removal, which is why a new scenario had to be introduced.
3	PV/T panels with two absorption chiller and geothermal sink	It was decided to use two absorption chillers (one for the auditorium and one for the rest of the building) in order to accurately meet the cooling loads as any deviations from the calculated load will sacrifice the efficiency of the chiller. Moreover, a geothermal sink had to be introduced in order to remove large amounts of heat from the cooling water that is passing through the condensers of the chillers. However, one hurdle was faced; the hot water had to be maintained at high temperature in order to be supplied to the generators of the chiller. Once again, this scenario had to be subjected to further changes.
4	PV/T panels, two absorption chillers, geothermal sinks and evacuated tube solar collectors	This scenario is based on the last scenario but with the addition of solar collectors in order to keep the hot water at high temperatures in order to be supplied to the generators of the chillers. Evacuated tube solar collectors have been chosen because the sponsor had extensive knowledge and achievements in this field.
5	PV panels instead of PV/T, two absorption chillers, geothermal sinks and evacuated tube solar collectors	This is similar to scenario 4 but using PV instead of PV/T. The hot water stream from the PV/T is at relatively low temperature (below 45° C) which does not justify the added cost for using it in the building cooling systems that need a temperature above 70 °C.

3.1 Sizing of Building Solar-Powered Cooling Systems

The cooling season is assumed to be between March and October. The results for sensible and latent cooling load requirements at peak hours were found using HAP software for both the auditorium and the building (excluding the auditorium). As was mentioned earlier, the HVAC system of the building is done via two systems. Each of these systems is identical in components to the system schematic shown in Figure 18. The first system (System I) is composed of absorption chiller and desiccant dehumidifier which are both powered by solar energy and is sized to be continuously operated during schedule hours for removing the total building thermal load while excluding the people's load of the large auditorium. The second system (System II) includes also solar powered equipment (absorption chiller and desiccant dehumidifier) and is only operated when the auditorium is in use. The absorption chiller of System I is sized at 230 RT while the absorption chiller of System II is sized at 270 RT. Both chillers are responsible of removing sensible load during operation. The desiccant dehumidification systems are for removing the latent load from both fresh air and from the people and other latent load sources. Most of the load is sensible, and both sensible and latent loads increase from March until they reach their peak values in June and July, and then decrease back until October.

The design loads of system I which covers the building load (excluded the auditorium people's load) are summarized in Table 7a while the values of operational parameters of the components of the system at peak load, for states shown in Fig. 18, are summarized in Table 7b. Similarly, Table 8(a-b) presents (a) the design loads for the System I and (b) the operational parameters and power needed for System II. The operational parameter include temperature states, flow rates, thermal and electric powers of the absorption chiller, desiccant wheel, sensible wheel, geothermal sink and heat exchanger for the building .

The total electrical peak power needed for System I and system II is 10 kW and 11.6 kW, respectively. The total power for both systems to run simultaneously is 21.6 kW that is assumed to be provided by the PV panels.

Table 7 Design Loads for System I

Parameter	**Value**
Peak cooling load	839 kW (or 399.5 W/m^2)
Sensible Heat Ratio (SHR)	0.770

Peak sensible load	645.7 kW (or 307.5 W/m^2)
Latent load at peak sensible load	193.3 kW (or 92.0 W/m^2)
Peak sensible load occurs on	July at 16:00
Peak Latent Load	194.8 kW (or 92.8 W/m^2)
Sensible Load at Peak Latent Load	634.9 kW (or 302.3 W/m^2)
Peak Latent Load occurs on	June at 16:00
Average cooling load over cooling season	587.1 kWh/cooling season
Average sensible load over cooling season	453.9 kWh/cooling season
Average latent load over cooling season	133.2 kWh/cooling season
Outside dry-bulb temperature	45.7 °C
Outside wet-bulb temperature	29.9°C
Resulting relative humidity	44%

Table 8 Power rating and operational parameters and states of System I at peak load

Component	**Sub-component**	**Fluid**	**Inlet Temperature (°C) – State Number**	**Outlet Temperature (°C) – State Number**	**Flow Rate (L/s)**	**Thermal Power (kW)**	**Electric Power (kW)**
Absorption Chiller	Generator	Water	80 – State 13	72.4 – State 14	28.2	1175	9.1
	Condenser	Water	30 – State 10	37 – State 7	55.6	1881	
	Evaporator	Air	53 – State 2	12 – State 3	4400	705.5	
Desiccant Wheel	Regeneration	Air	71 – State 5	53 – State 6	4400	92.4	0.2
	Supply	Air	46 – State 0	67 – State 1	440		
Sensible Wheel	Supply	Air	67 – State 1	53 – State 2	4400	61.7	0.2
	Exhaust	Air	22 – State 4	35.5 – State 4’	4400		
Geothermal Sink	-	Water	37 – State 7	30 – State 10	55.6	-	-
Heat Exchanger	-	Water	80 – State 4’	63.2 – State 5	3	212	0.5

Table 9 Design Loads for System II

Parameter	**Value**

Peak cooling load	951.2 kW (or 404.7W/m^2)
Sensible Heat Ratio (SHR)	0.865
Peak sensible load	822.6 kW (or 350.0 W/m^2)
Latent load at peak sensible load	128.6 kW (or 54.7 W/m^2)
Peak sensible and latent loads occurs at the same time	
Peak sensible load and latent load occur on	June at 4:00 pm
Average cooling load over cooling season	685.1 kWh/cooling season
Average sensible load over cooling season	599.8 kWh/cooling season
Average latent load over cooling season	85.3 kWh/cooling season
Outside dry-bulb temperature	45.2 °C
Outside wet-bulb temperature	29.9°C
Resulting relative humidity	43%

Table 10: Power rating and operational parameters and states of System II at peak load

Component	**Sub-component**	**Fluid**	**Inlet Temperature (°C) – State Number**	**Outlet Temperature (°C) – State Number**	**Flow Rate (L/s)**	**Thermal Power (kW)**	**Electric Power (kW)**
Absorption Chiller	Generator	Water	80 – State 13	73.4 – State14	31	1281	10.7
	Condenser	Water	30 – State 10	36.3 – State 7	61.3	2050	
	Evaporator	Air	53 – State 2	12 – State 3^{o}	4800	769	
Desiccant Wheel	Regenerati^{o}n	Air	71 – State 5	51 – State 6	4800	101.3	0.2
	Supply	Air	46 – State 0	67 – State 1	4800		
Sensible Wheel	Exhaust	Air	22 – State 4	35.5 – State 4’	4800	67.5	0.2
	Supply	Air	67 – State 1	53 – State 2	4800		
Geothermal Sink	-	Water	36.3 – State 7	30 – State 10	61.3	-	-
Heat Exchanger	-	Water	80 – State 4’	63.2 – State 5	3	212	0.5

3.2 HVAC Electric Load Calculation

The electricity peak power of the HVAC systems should also be added to building electricity demand to obtain the total electricity requirements of building and systems as presented in Table *11*.

Table 11: Building peak electric demand.

Component	**Maximum Electric Peak Demand (kW)**
Auditorium HVAC System	11.6
Building (Excluding Auditorium) HVAC System	10.0
Total HVAC Electrical Demand	**21.6**

Note that the electric requirements of the chillers presented in Tables 8 and 10 consist of the electric needs for the chiller itself, cooling water pump, chilled water pump and the hot water pump. The need of each component varies from one vendor to another depending on many design criteria followed by the manufacturers. The power need for each pump typically ranges between 0.5 kW and 3 kW. The sensible and desiccant wheels power requirements are those needed to power their motors only. For this reason, they require minimal power (less than 1 kW). Lastly, the heat exchanger requires power to drive the two exchanging streams and such large components typically require less than 8 kW. In order to estimate how much power is needed for each component in our HVAC system we used product specifications of similar components. Such information can only be obtained from product specs of similar components (with similar capacity, flow rate, and so on).

For instance, the electric load of the sensible and desiccant wheel for both systems is that of the motors only. The power needed to run the motor of these wheels is at the maximum 1 kW (typically 0.2 kW for desiccant and 0.4-0.7 kW for sensible wheel). The same applies for the heat exchangers; small components consume minimal power (0.5 kW) and larger components consume around 8 kW. Lastly, the power needed for the absorption chiller is that of the chilled water pump, cooling water pump, hot water pump and the chiller itself (to power its sub-components). Each pump power depends on the flow rate, and is typically in the range of 0.5 kW to 3 kW. This is actually why absorption chillers, unlike electric chiller, require minimal electric needs.

4 Solar Technology Design

The annual sum of global irradiation in Dubai is around 2 MWh/m^2 and the average annual outdoor temperature is 28 °C. This shows that Dubai has high solar radiation and is a suitable place for harvesting the solar energy. The high outdoor temperature and the ventilation should be considered in the design of photovoltaic systems, which are sensitive to the temperature.

The solar technologies should provide the electrical demand of the building, the electrical demand of the air conditioning system, and the thermal energy demand for the absorption chillers. Therefore, various scenarios based on PV, PV/T, evacuated tube solar thermal, and parabolic trough solar thermal technologies will be considered for the building. This chapter summarizes the calculations and the technical issues related to the various solar technologies. In addition to the conventional solar technologies, the emerging Building-Integrated-Solar-Technologies (BIST) for applications such as windows, facades, and skylights will also be reviewed at the end of this chapter for their potential application in the Center of Excellence building.

In this chapter, we first summarize all the electrical and thermal energy requirement of the Center of Excellence building. In the following step, each solar technology will be sized based on the energy demand. Finally, the best combination of the solar technologies will be discussed.

4.1 Energy Demand of the Building

The energy demands of the building, which should be provided by the solar technologies, are:

1) Electrical energy demand of the building for running the electrical appliance and lightings,

2) Thermal energy demand of the absorption chiller (air conditioning),

3) Electrical energy demand of the air conditioning system.

Generally, the electricity demand is found using ASHRAE standard. For spaces whose description could be assigned as auditorium, ASHRAE specified a value of 10.76 W/m^2 (1 W/ft^2). In order to find the electricity demand of the auditorium based on typical standard values, the area of the auditorium has to be found first. The AUTOCAD drawings show that the auditorium, toilets, cloakroom and services have an area of 1,304 m^2. In addition, the auditorium circulation has an area of 1,041 m2. Adding these two values yields a total area of 2,345 m^2. The calculation leads to an electricity demand of 221 MWh/year. Based on the electrical demand standard of 90 kWh/m^2 per year that has been previously specified by the sponsor (Diamond Developers), the auditorium would need an amount of 211 MWh/year. As it could be noticed, these two values validate each other. Therefore, for all the building electrical demand we will use the 90 kWh/m^2 per year criteria. The Table 12 summarizes the surface area of each section in each floor. The required annual energy for the building was calculated based on the 90 kWh/m^2. Therefore, considering 40% over design, the total annual electrical energy demand for the Center of Excellence is 975 MWh/year. By considering the peak electricity demand of 10.76 W/m^2, which has been suggested by the ASHRAE, the peak electrical demand of the building is 83 kW. We considered the 40% overdesign for the annual energy demand, but for the peak electrical demand we will not consider it.

Table 12: Building Electricity Demand.

Floor	**Locations**	**Surface Area (m^2)**	**Annual Electricity Requirement (MWh/yr)**	**40% Over Design (MWh/yr)**
Ground Floor	Coffee Shop	180.8	16.3	22.8
	Exhibition Center	580.3	52.2	73.1
	Pre Function	407	36.6	51.3
	Crèche	55.5	5.0	7.0
	Lobby	695.1	62.6	87.6
	Auditorium + Toilets + Cloak Room + Services	1304	117.4	164.3
	Auditorium Circulation	1041.3	93.7	131.2
	Total GF	**4264**	**383.8**	**537.3**
First Floor	Pre Function	378.2	34.1	47.6
	Conference Center	363.1	32.7	45.7
	Auditorium + Services	367.4	33.1	46.3
	Auditorium Circulation	343.8	30.9	43.3
	Total 1F	**1452.5**	**130.7**	**183.0**
Second	Management	628	56.5	79.1

Floor	Circulation	367.2	33.0	46.3
	Auditorium	694.4	62.5	87.5
	Auditorium Circulation	332.8	29.9	41.9
	Total 2F	**2022.4**	**182.0**	**254.8**
Building	**Total Building**	**7738.9**	**696.5**	**975.1**

The electrical energy demand for the air condition system was calculated in the previous chapter (Table *11*), which is 21.6 kW. By considering constant peak performance of the air conditioning throughout the year the maximum annual electricity demand for the air conditioning is 0.2 MWh. It is obvious that the HVAC electricity demand is negligible compared to the building electric demand.

The peak thermal energy demand for generator of absorption chiller has been calculated in Table 8 and Table 10. The total peak thermal energy demands of the generator in systems I and II are 1174 and 1281 kW, respectively. By comparison to the electrical energy, it is obvious that the thermal energy demand for air conditioning is much larger than the electrical energy demand. In order to calculate the thermal energy consumption, we will consider eight month of cooling season (March to October). Therefore, the maximum annual thermal energy consumption is 14146 MWh/yr.

All the above-mentioned components of the building electrical and thermal energy demand are summarized in Table 13.

Table 13 Summary of the electrical and thermal energy requirement of the building

Component	**Max. Annual Energy Consumption with 40% overdesign (MWh/yr)**	**Peak Energy Demand[2] (kW)**
Air Conditioning (HVAC) Electricity Demand	0.2	21.6
Building Electricity Demand	975.1	83.3
Thermal Energy Demand for Air Conditioning[1]	14,146	2,456
[1] This is the thermal energy demand for the generator of the absorption chiller and		

does not consider 40% overdesign.

[2] The peak energy demand does not consider 40% overdesign

By knowing the electrical and thermal energy demand of the building, in the next step various solar technologies will be sized to provide the energy requirement of the building. For sizing the solar technologies, two approaches will be used the first approach is based on the annual energy consumption (MWh/yr) and the second approach is based on the peak energy demand (kW). Designing based on the peak energy demand will guarantee that the solar will provide enough energy even at the peak demand. The former approach based on the annual energy consumption will guarantee that the building will be zero net energy and fully sustainable.

4.2 Sizing the solar technology for thermal energy demand

In order to provide the thermal energy for the air conditioning system, the following solar technologies will be evaluated:

1) Photovoltaic-Thermal (PV/T)

2) Evacuated Tube Solar Collectors

According to the Table 8 and *Table 10* the maximum temperature required for the generator of the absorption chiller is 80°C. Therefore, we will consider one hot water storage tank with a constant temperature of 85°C. This tank should provide hot water for the generators of both System I and II (see Figure 13). Therefore, the solar technologies will deliver their thermal energy to the storage tank and the thermal energy will be used by the absorption chillers. The flow rates for the generator of absorption chillers in systems I and II are 28.2 and 31 L/s, respectively. Therefore, the total flow rate for the tank should be about 60 L/s.

4.2.1 PV/T System

Photovoltaic-Thermal (PV/T) panels are composed of photovoltaic (PV) panels, which convert the solar radiation into electricity. On the backside of these PV panels, there is a thermal collector (see Figure 14). The heat transfer fluid inside the thermal collector captures the heat from the PV panels. Using the PV/T panels will bring a combination of electrical and thermal energy and therefore increases the total efficiency of solar energy collection. Since the PV panels have lower efficacies at higher temperatures, the cooling should also increase the electrical output of PV/T panels. The high outdoor temperature in Dubai is one reason for the potential advantage of PV/T compared to PV panels.

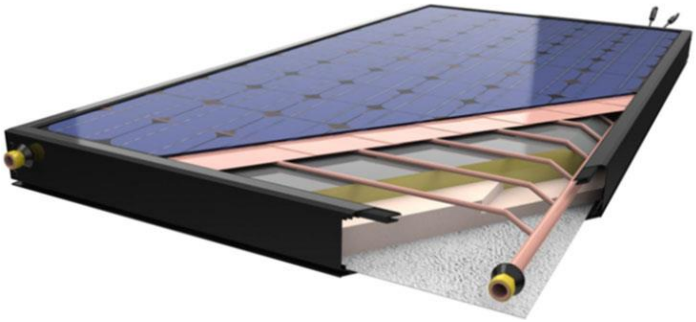

Figure 14 The PV/T panel components (Photo: Volther PowerVolt www.newformenergy.ie)

4.2.1.1 PV/T Panel Selection

We used the list of PV/T panels, which has been collected by Polysun Software group. In order to find the best collector suitable for Dubai environment, the following parameters should be considered.

1) PV electrical efficiency of the PV/T panel,

2) Temperature coefficient, which shows the degradation percent in the efficiency of PV panel by increasing the temperature,

3) Maximum tolerance temperature, which shows the maximum temperature that the PV/T panel can by functional without degradation of the components.

We used parameter-based decision-making process to find out the optimum PV/T panel for our project. For our modeling, calculation, and analysis we will use Solar Zentrum Wiosun PV-Therm PVT 200 panel. The technical specifications of PVT-200P are available in Appendix 2.

4.2.1.2 Energy Output of a Single PV/T Panel in Dubai

We have used the Polysun 8.0 Simulation Software for the analysis of the PV/T panels in Dubai. The simulation for a single PV/T panels shows that the maximum temperature that the PV/T panels can provide will be around 50^{o}C (Figure 15). Therefore, for reaching the temperature of 85^{o}C inside the tank, the tank should have an additional source of thermal energy such as electrical heater or gas burner. The electrical and thermal energy output of a single PV/T is shown in Figure 16. Therefore, we can conclude that since the output temperature of the PV/T panel is lower than the required temperature for the absorption chillers, using PV/T panels might not be a practical approach. However, for comparison the full simulation has been provided.

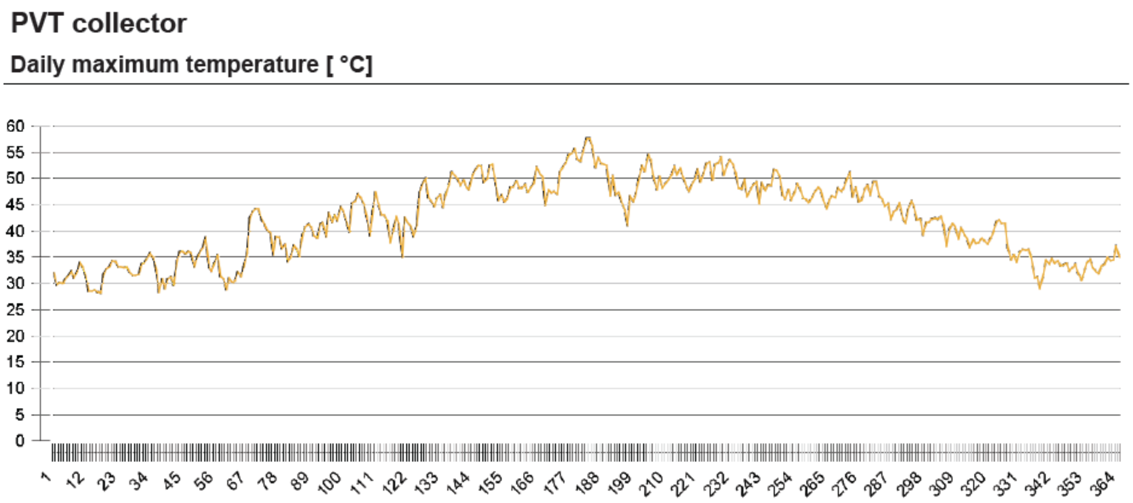

Figure 15 The daily maximum temperature of the PV/T panel (starting from January).

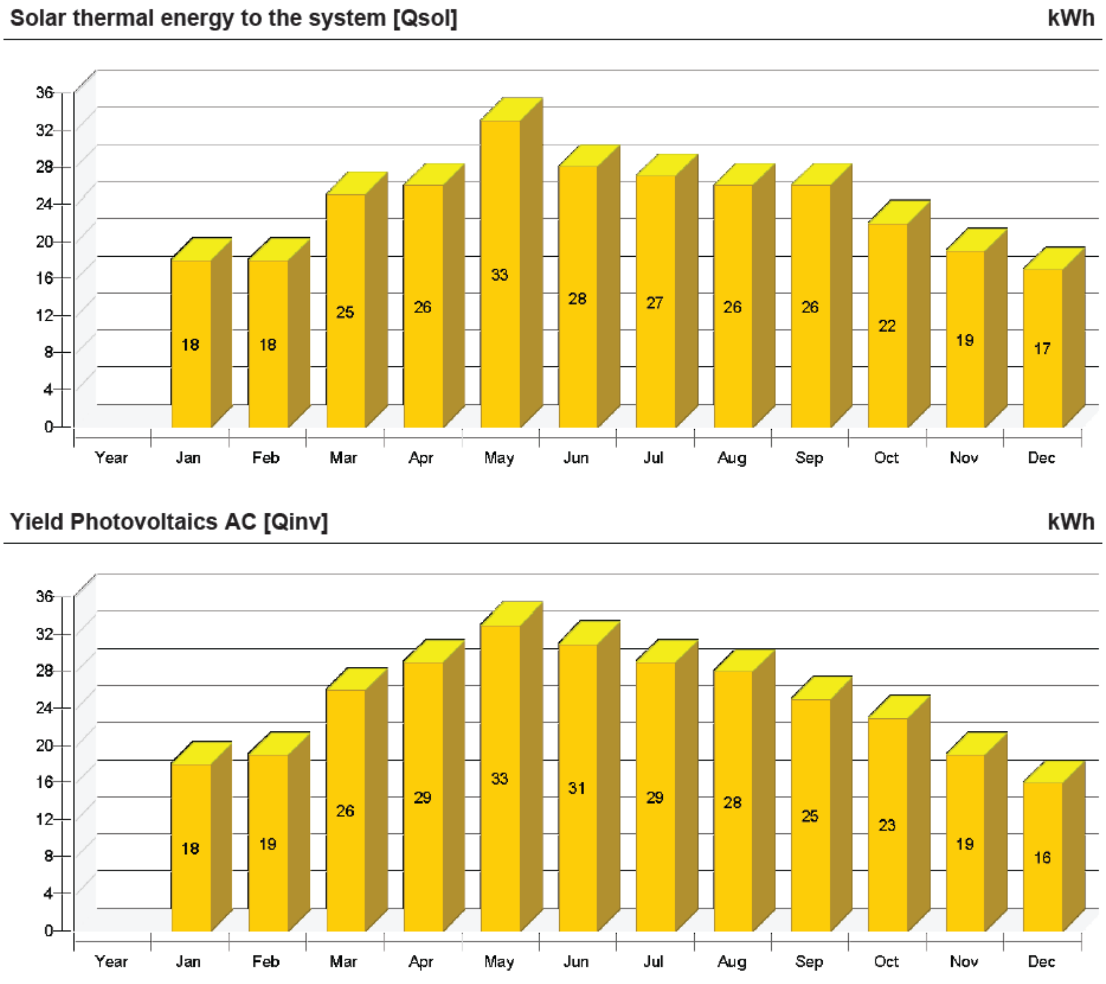

Figure 16 Thermal and electrical energy output of a single PV/T panel in Dubai. The total annual thermal and electrical output is 284 and 335 kWh, respectively.

4.2.1.3 Sizing PV/T System

According to Table 8 and Table *10*, the solar collector should provide hot water (80^{o}C) with the flow rate of 60 L/s. Since the PV/T collectors cannot reach the required temperature of 80^{o}C, an additional electrical heater source was added to the system. The schematic of the PV/T collectors, tank, and electrical heater is shown in Figure 17.

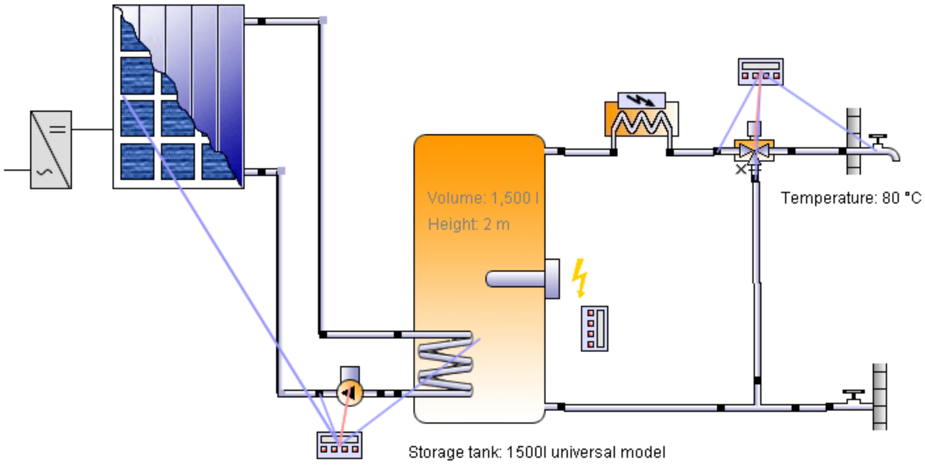

Figure 17 The schematic presentation of the PV/T system with storage tank and external electric heater.

The system was modeled for the eight months of March to October, which was mentioned in previous chapter. According to Table 8 and Table *10*, the inlet and outlet temperatures of the absorption chiller generator are 80^{o}C and 71^{o}C, respectively which are higher than the average output temperature of PV/T panels (around 50^{o}C). Hence, in this case the PV/T panels can only work as the water jacket around the storage tank, which not a technical advantage. Therefore, the PV/T scenario for connection with absorption chiller will not be considered any more. However, in the electrical demand calculations, we will compare the PV and PV/T panels for their performance in the high temperature environment of Dubai.

4.2.2 Evacuated Tube Solar Collectors

The evacuated tube solar collectors can reach high temperatures. They are composed of a heat pipe as their core, which is located inside a transparent vacuum tube for minimum heat loss. The schematic presentation of evacuated tube solar collectors is shown in Figure 18.

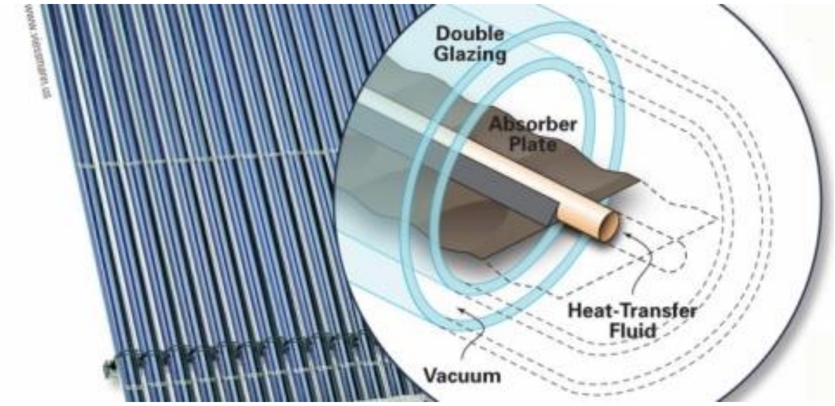

Figure 18 Schematic presentation of the components of evacuated tube solar collectors.(Image courtesy www.homepower.com)

There are various producers of evacuated tubes, however, there is not a major difference between the efficiencies. For our modeling we chose XL 34 P panel produced by Ritter XL Solar Gmbh.

4.2.2.1 Energy Output of a Single Evacuated Tube in Dubai

Modeling the system for a single panels shows that the average collector temperature reaches around 80^{o}C, which is shown in Figure 19.

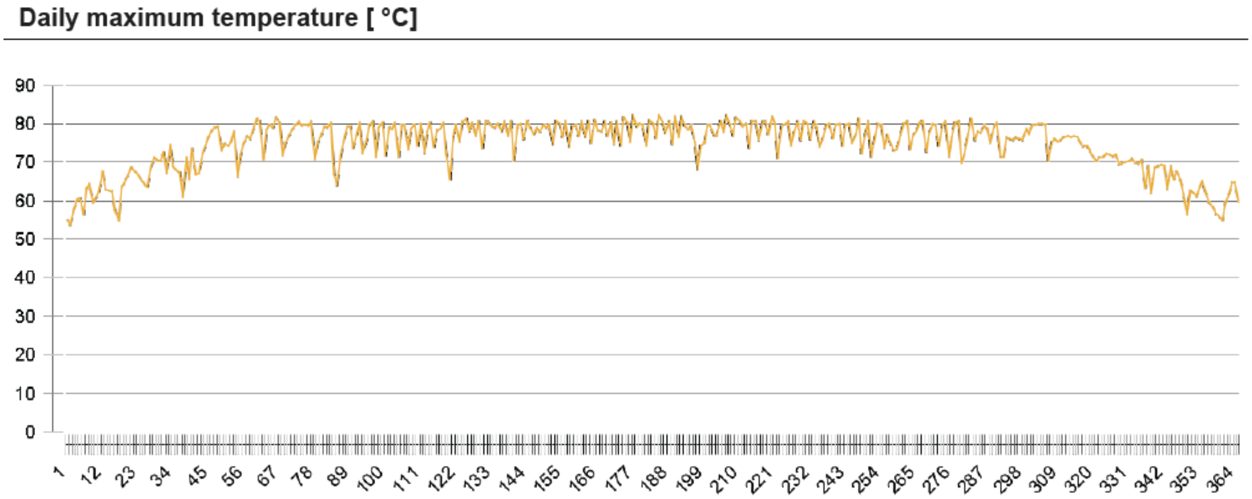

Figure 19 Maximum daily temperature of a single evacuated tube collector

One panel of evacuated tube solar collector can produce around 3,433 kWh/yr of thermal energy in Dubai. The monthly production of a single panel is shown in Figure 20.

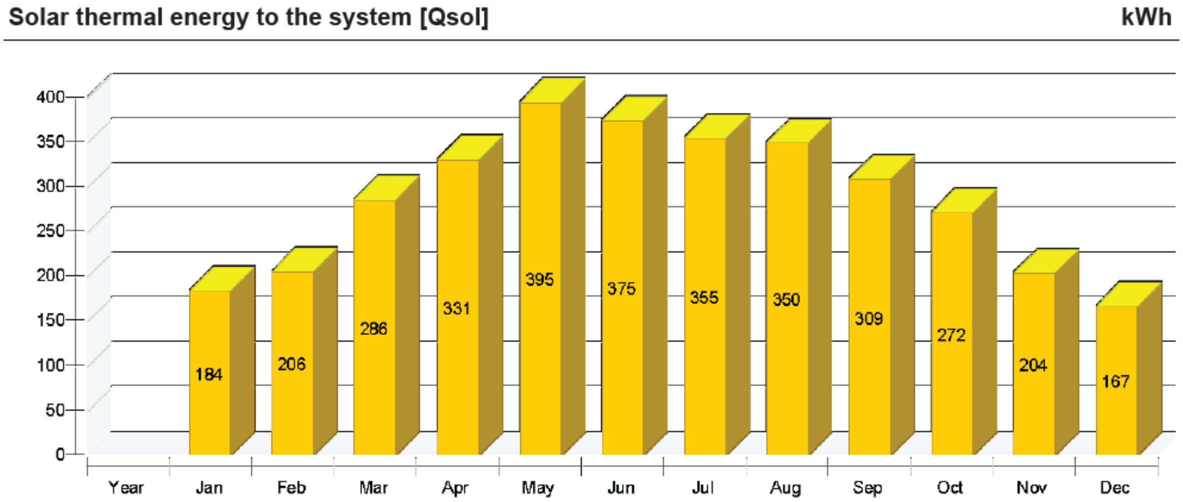

Figure 20 The monthly production of thermal energy by a single evacuated tube.

4.2.2.2 System Design Based on Evacuated Tube Solar Collectors

The integration of the evacuated tube to the absorption chiller has been schematically shown in Figure 21.

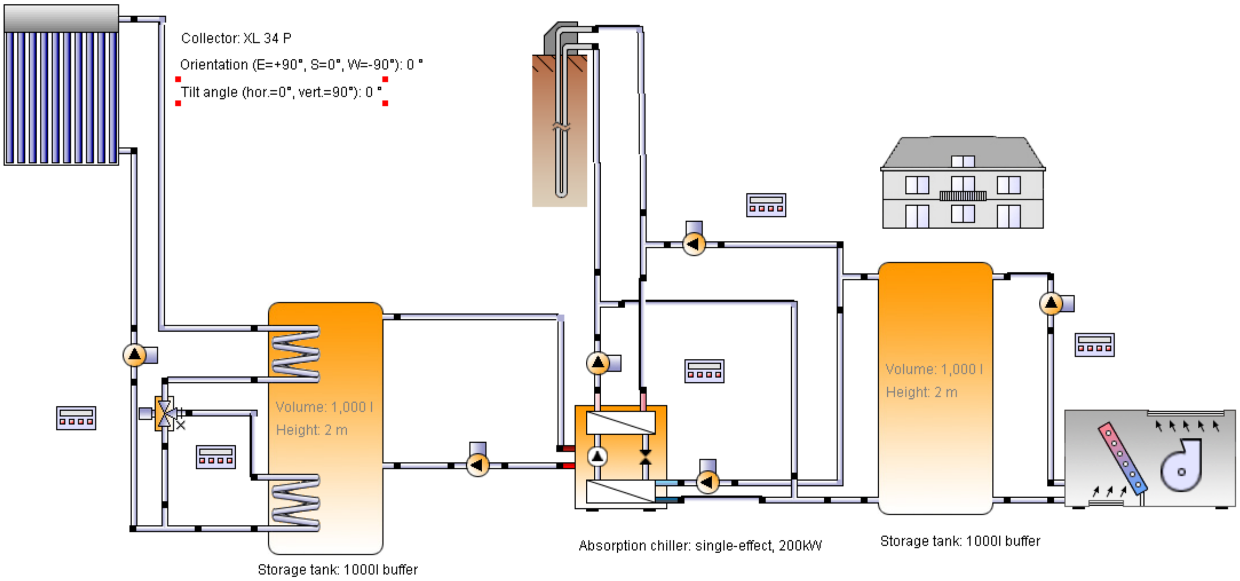

Figure 21 Schematic presentation of the evacuated tube solar collectors to the absorption chiller.

In order to provide the annual energy demand of the building 4,120 evacuated tubes with a total surface area of 13,600 m^2 is required.

4.3 Sizing Solar Technologies for Electrical Demand of Building

In this section, PV and PV/T technologies will be sized to provide the electrical demand of the building. Later, the potential application of building-integrated-photovoltaics for windows and facades will be discussed.

4.3.1 PV System

Photovoltaics (PV) can convert the solar energy directly to the electricity. On the other side, solar thermal technologies convert the solar energy to the thermal energy. Therefore, the proper selection of solar technologies depends on the thermal and electrical demand of the building. Various materials and methods have been used for the production of the PV panels. The majority of the commercial PV products are based on the silicon. Three major categories of the PV panels are monocrystalline, polycrystalline, and amorphous silicon solar cells. Monocrystalline has the highest and the amorphous silicon solar cells have the lowest conversion efficiency among silicon-based solar cells. After silicon-based solar cells, thin film solar cells have the second place in the solar cell market. Two main commercial thin film solar cells are Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS). In order to increase their voltage, solar cells are (typically 36 cells) connected in series, which are called solar modules. The conversion efficacies and nominal powers of solar cells are described based on their performance at Standard Test Condition (STC). According to standard, STC is the irradiation of 1000 W/m^2, cell temperature of 25^{O}C, and air mass of 1.5 (AM1.5).

Multiple modules which are connected in series a called a string. In string inverters, each string will be converted to AC. Central inverters uses a terminal box to merge all the strings. Our definition for the module orientation is South = 0, East = 90, West = -90 and for the tilt is floor = 0 and façade = 90.

Increasing the temperature of the module decreases its efficiency. However, the role of temperature depends on the type of PV module. Amorphous cell have the least sensitivity to the temperature. Soiling and degradation values for PV panels in Dubai were considered 2% for soiling and annual degradation of 0.5%.

4.3.1.1 PV System Components

There are different parameters, which are important for the selection of the right PV panel. Here the most important parameters for this project.

4.3.1.1.1 Efficiency

Panels with higher efficiency can produce the same energy with lower space required. Therefore, if the space availability is a challenge the high efficiency panels are recommended. Usually the monocrystalline silicon solar panels have the highest efficiency. However, there should be a compromise between the price and the efficiency as more efficient panels are usually more expensive.

4.3.1.1.2 Quality

In order to make sure that the PV panels have been produced form high quality materials. It is important to consider very well known and reputable panel producers. Since the life of PV panels are considered at least 25 years during the designs, it is important to make sure that the quality of the PV panels meet this requirement. Some companies decrease their prices but cutting the corners of the quality of the panels. It is recommends to have an independent laboratory test the quality of the panels. It is important that the producers provide long-term warrantee.

4.3.1.1.3 PV panels durable in hot and humid environments

The high temperature and humidity of the Dubai environment can increase the degradation rate of some of the PV panel components. A comprehensive review of the different degradation mechanisms of the PV modules has been presented in 2011.[3] Some of the main degradation mechanisms are: glass soiling, front-side delamination, anti-reflecting layer oxidation, mechanical and thermal stress-induced cracks, and back-sheet delamination. The failure of the PV system can happen due to the following reasons.

Broken interconnects	Hot Spots
Broken cells or Broken glass	Ground faults
Corrosion	Junction box and module connection failures
Delamination and/or loss of elastomeric properties of encapsulant	Structural failures
Encapsulant discoloration	Bypass Diode failures
Solder bond failures	Open circuiting leading to arcing

4.3.1.1.4 Standards

There are various standards for the measurement and verification of the quality of the PV panels. Some of these standards are listed here. Asking the PV producers to provide documentation of their compliance with these standards is a reliable way of verification of the long-term durability of the panels. Many of these standards utilize accelerated tests to model the behavior of the panel in the lifetime of 25 years.

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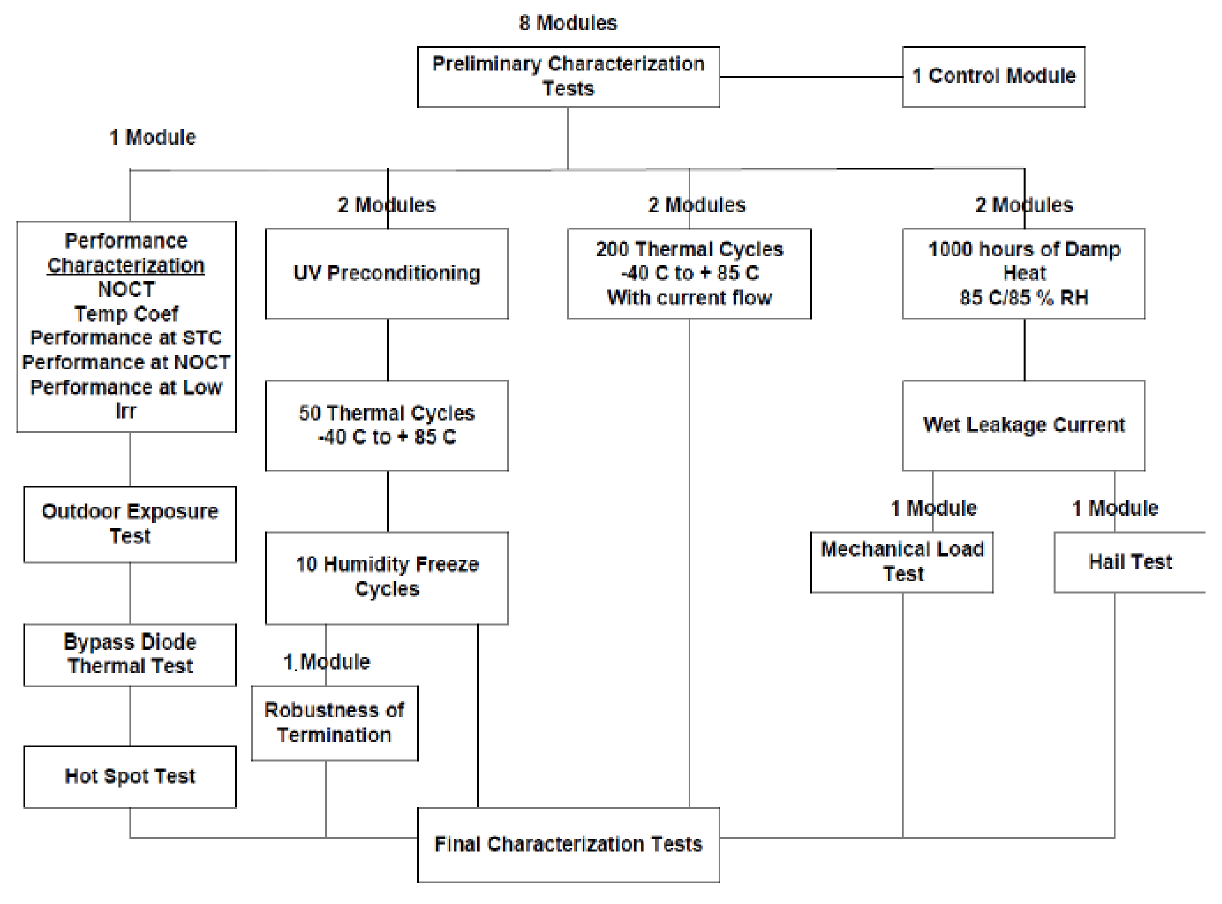
[3] Sánchez-Friera, Paula, et al. "Analysis of degradation mechanisms of crystalline silicon PV modules after 12 years of operation in Southern Europe. *"Progress in photovoltaics: Research and Applications* 19.6 (2011): 658-666.

- IEC 61215 for crystalline silicon modules
- ICE 61646 for thin film modules
- IEC 62108 for concentrated PV

Passing IEC 61215 is a minimum requirement in many commercial applications. It means that the modules are more likely to survive in the outdoor and do not have design flaws that could lead to early failure. The Schematic of the procedure for IEC 61215 test is shown below.



Reference[4]

Table 14 The accelerated test and their corresponding failure modes are summarized below. (NREL/PR-5200-54714)

Accelerated Test	**Failure Mode**	**Technology**
Thermal Cycle	Broken interconnect	Cry-Si & CPV

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[4] NREL/PR-5200-54714

	Broken cells Electrical bond failure Junction box adhesion Module open circuit – potential for arcing	Cry-Si & CPV All All All
Damp Heat	Corrosion Delamination Encapsulant loss of adhesion & elasticity Junction box adhesion Electrochemical corrosion of TCO Inadequate edge deletion	All All All All TF TF
Humidity Freeze	Delamination Junction box adhesion Inadequate edge deletion	All All TF
UV Test	Delamination Encapsulant loss of adhesion & elasticity Encapsulant & back sheet discoloration Ground fault due to back sheet degradation Degradation of Optics	All All All All CPV
Static Mechanical Load (Simulation of wind and snow load)	Structural failures Broken glass Broken interconnect ribbons Broken Cells Electrical bond failures	All Cry-Si & TF All Cry-Si & CPV All
Dynamic Mechanical Load	Broken glass Broken interconnect ribbons Broken Cells Electrical bond failures	Cry-Si & TF All Cry-Si & CPV All
Hot Spot Test	Hot spots Shunts in cells or at scribe lines Inadequate by-pass diode protection	All All All
Hail Test	Broken glass Broken cells Broken Optics	Cry-Si & TF Cry-Si CPV

By-pass Diode Thermal Test	By-pass diode failures Overheating of diode causing degradation of encapsulant, back sheet or junction box	All All All
Salt Spray Test	Corrosion due to salt water & salt mist Corrosion due to salt used for snow and ice removal	All All

It is useful to see if the PV panel has passed the requirement of the IEC 61730 which includes PV module safety against electrical shock hazard, fire hazard, mechanical and structural safety.

According to the NREL study of the degradation rate of more than 2000 PV modules, more than 78% of the modules around the world showed a degradation rate of less than 1% per year. They suggested a median of 0.5% per year for the calculations.[5]

In order to find the optimum panel, which has the highest efficiency and lowest temperature sensitivity, we ran a multi-criteria analysis. The following table of top-ten panel list shows the optimum panels among 48,800 PV panels by various companies.

catalog No	Name	Data Source	Manufacturer	Module Type	Galvanic Seperation Required	Temp Coefficient (%/K)	Efficiency STC	Nominal Power STC (W)	Gross Area (m2)	Output Voltage MPP-STC (V)	Output Current MPP-STC (A)	Voc	Isc
90033	JKM270M-60	Photon	Jinko Solar Co., Ltd.	monocrystalline	No	-0.04	0.16496	270	1.637	31.4	8.6	38.4	9.28
90038	JKM210M-72	Photon	Jinko Solar Co., Ltd.	monocrystalline	No	-0.04	0.16449	210	1.277	37.4	5.61	46.1	5.99
90043	JKM315M-72	Photon	Jinko Solar Co., Ltd.	monocrystalline	No	-0.04	0.16234	315	1.94	37.6	8.38	46.1	8.87
90032	JKM265M-60	Photon	Jinko Solar Co., Ltd.	monocrystalline	No	-0.04	0.1619	265	1.637	31.2	8.5	38.2	9.19
90048	JKM275M-96	Photon	Jinko Solar Co., Ltd.	monocrystalline	No	-0.04	0.16137	275	1.704	51.9	5.3	62.8	5.84
90037	JKM205M-72	Photon	Jinko Solar Co., Ltd.	monocrystalline	No	-0.04	0.16058	205	1.277	37.2	5.51	45.9	5.9
90042	JKM310M-72	Photon	Jinko Solar Co., Ltd.	monocrystalline	No	-0.04	0.15976	310	1.94	37.4	8.29	45.9	8.8
90031	JKM260M-60	Photon	Jinko Solar Co., Ltd.	monocrystalline	No	-0.04	0.15885	260	1.637	30.9	8.42	37.9	9.1
90047	JKM270M-96	Photon	Jinko Solar Co., Ltd.	monocrystalline	No	-0.04	0.15844	270	1.704	51.5	5.24	62.3	5.82

For our analysis, we chose JKM315 with a nominal power of 315 W. The datasheet for this panel is available in Appendix 3.

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[5] D.C. Jordan and S.R. Kurtz, Photovoltaic Degradation Rate: an Analytical Review, NREL/JA-5200-51664.

4.3.1.2 Inverter

Solar inverters convert the direct current (DC) output of the PV panel to the alternating current (AC) with utility frequency. The output AC current can be fed into the electrical grid or it can be used for the off-grid local network. The inverters are among the most important balance-of-system (BOS) components. The inverters, which are designed for integration with the PV system, included the maximum power point tracking (MPP) and anti-islanding protection. The output of the PV panels is described by a non-liner I-V curve. The MPP is the location on the I-V curve with the maximum power (power is the product of IxV). There are four algorithms for MPP-tracking: a) constant voltage, b) incremental conductance, c) perturb-and-observe, and d) current sweep.

Islanding refers to the situation of utility grid outage while some distributed generators continue to provide power to the local circuits. This situation is dangerous for workers who are trying to fix the circuit. Additionally, islanding might prevent the automatic re-connection of devices. Therefore, the distributed generators such as solar and battery connected inverters should stop producing power upon detecting the utility blackout. The mechanism for detecting and shutting down the power production is called the anti-islanding.

Based on the applications and the internal components the solar inverters can be classified to the following groups:

4.3.1.2.1 Stand-alone inverters

These inverters are used in off-grid applications. They are usually equipped with battery chargers and therefore, they are directly connected to the batteries. The batteries will be charged by the PV panel. Since these inverters are not connected to the grid they do not require anti-islanding protection.

4.3.1.2.2 Grid-tied inverters

These inverters should provide the utility sine wave with the same phase. Upon grid outage they will shut down for safety and therefore, they should not be considered as a backup power.

4.3.1.2.3 Battery backup inverters

These inverters are equipped with battery charges and therefore, they will manage the battery charging and they will send the excess energy to the grid. They can provide backup power during utility outage and therefore, they are equipped with anti-islanding protection.

4.3.1.2.4 Micro-inverters

The solar micro-inverters are integrated with a single PV panel. Therefore, each micro-inverter can find the MPP of each PV panel independent of other PV panels. The output of multiple micro-inverters can be combined before exporting the energy to the grid. The advantages of the micro-inverters compared to the string inverters are as follows:

a) In the case of shading, debris, snow, and failure of one panel, the energy output will not be affected significantly. Micro-inverter connected to each PV panels is working independent and the MPP of each PV panel will not be affected by other PV panels, which have partial/complete shade.

b) Easy installation: most of the micro-inverters are plug-n-play installation which also increase the fire safety.

c) Easier system design and increased power output because of individual PV panel MPP tracking.(Sher and Addoweesh 2012)

d) There is no need for large transformers, large electrolytic capacitors, and cooling. Therefore, the chance of failure and the need for maintenance is lower. The electrolytic capacitors of the large inverters will fail faster in the hot environments. Therefore, Micro-inverters have a higher reliability in hot environments.

The main drawback of the micro-inverters compared with string and central inverters are:

a) Higher initial capital cost,

b) More installation time. Some PV panel producers addressed this challenge by integrating the micro-inverter with the PV panel.

c) For those micro-inverters, which are not built-in, a sealing box is required to protect it against rain and other hazardous.

4.3.1.2.5 String inverters

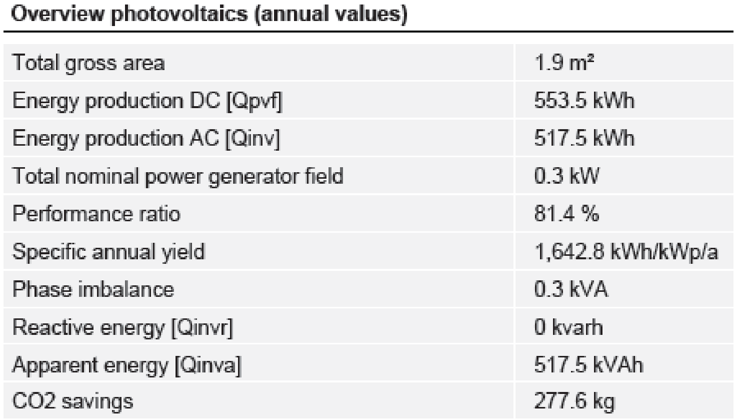
String inverters are usually used for integration with residential to medium size commercial PV installations. An array of PV panels is connected in series to produce 300 to 600 VDC. Each array is connected via one string to the inverter. The main challenge with string inverters is that the maximum current will be determined by the poorest performance PV panel in the array. Another parameter is that the ratings of the sting inverters are usually limited to some defined power ratings. Therefore, after the design of the PV array the closest power of the inverter to the array should be selected.

4.3.1.2.6 Central inverters

The central inverters are commonly used for large commercial and utility-scale PV installations. They require a specific location with well cooling systems for heat dissipation.

4.3.2 PV Design for the Building

For analysis, we chose micro-invertors. The summary of the performance and energy production of a single 315W panel (JKM315M-72) is shown below.



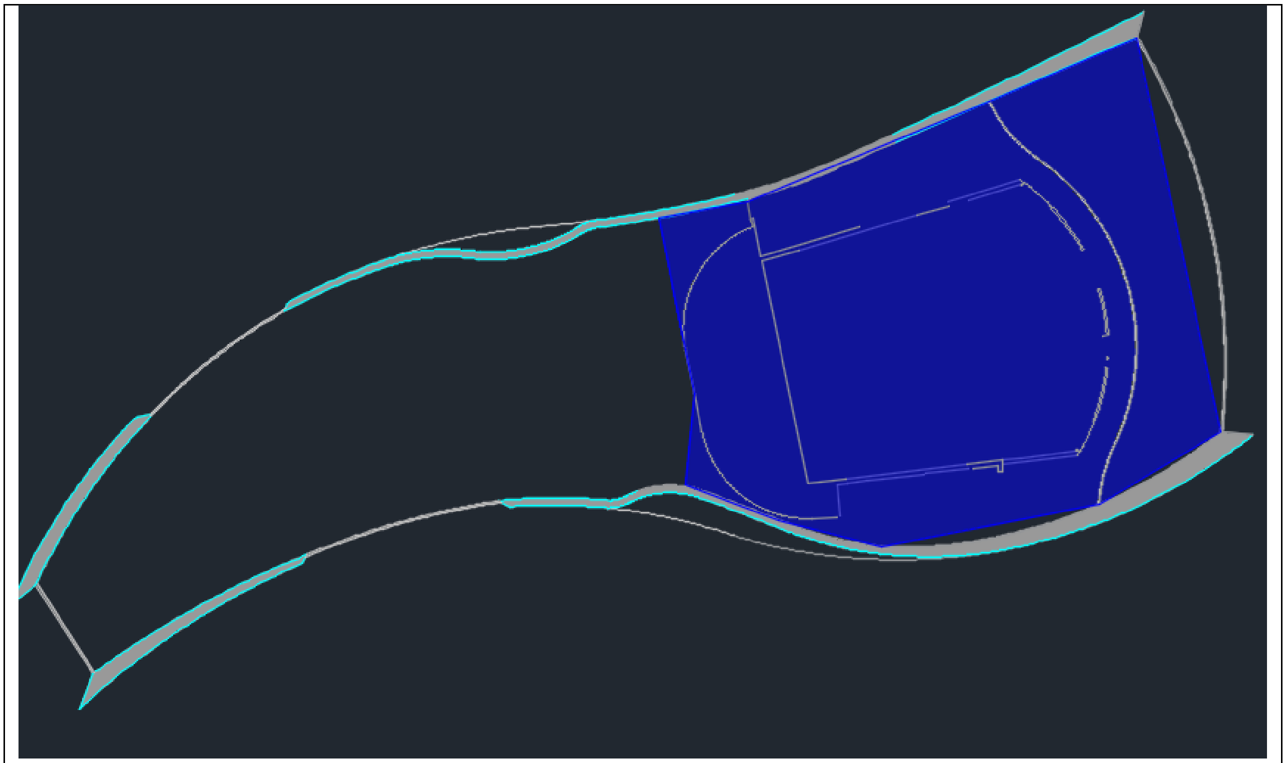
Overview photovoltaics (annual values)

Total gross area	1.9 m²
Energy production DC [Qpvf]	553.5 kWh
Energy production AC [Qinv]	517.5 kWh
Total nominal power generator field	0.3 kW
Performance ratio	81.4 %
Specific annual yield	1,642.8 kWh/kWp/a
Phase imbalance	0.3 kVA
Reactive energy [Qinvr]	0 kvarh
Apparent energy [Qinva]	517.5 kVAh
CO2 savings	277.6 kg

The number of panels to provide enough energy for the peak electrical demand (kW) and the annual electrical demand (MWh/yr) of the building are 334 and 1764, respectively. These number of panels will require 633 and 3351 m^2 of roof space, respectively.

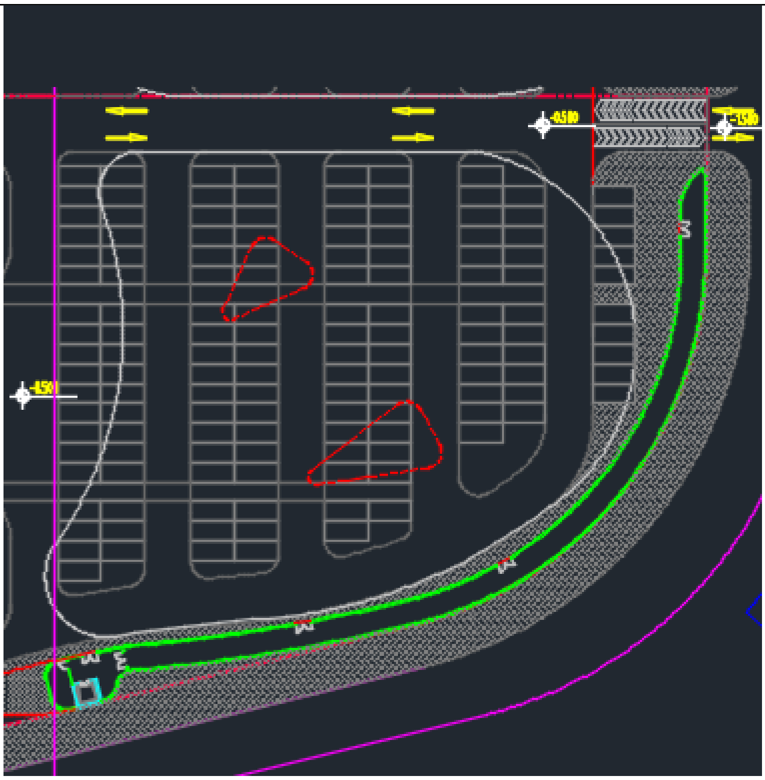
4.3.2.1 PV Panel Space Allocation

Based on the sponsor's comments, the roof of the auditorium is available for the PV installation. In addition to the roof of the building, the parking lot will also be covered by PV panels. The surface of the hatched area on top of the auditorium is about 2,300 m^2.



The hatched blue area shows the location for installation of the PV panels, which is around 2,300 m^2.

The surface area of the four rows of the parking shades is about 2000 m^2.



The surface on the parking lot shades for installation of the solar PV.

4.3.3 PV/T System

The PV/T technology was discussed in section 4.2.1. Here, we will only consider the electrical energy output of the PV/T in Dubai environment. The monthly electrical output of a single PV/T panel in Dubai is shown in Figure 22.

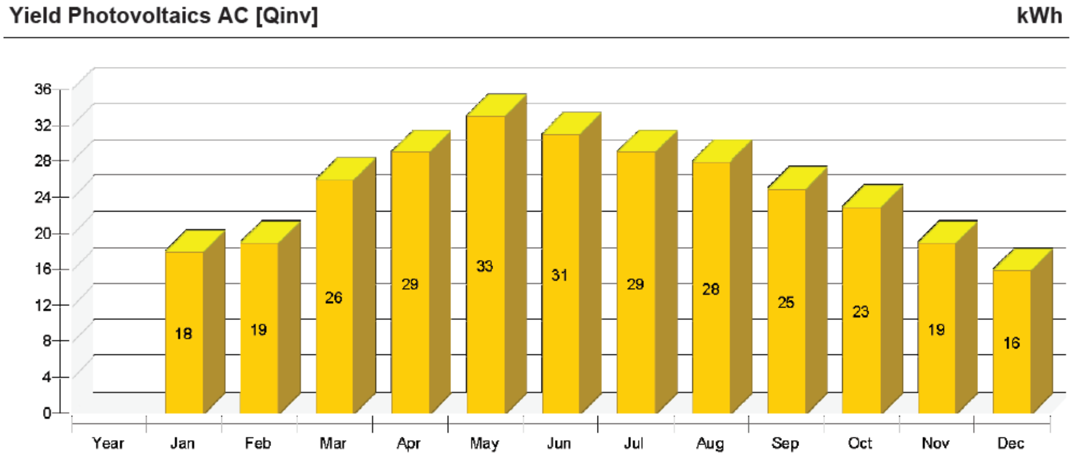


Figure 22 Monthly electrical output of a single PV/T

In order to meet the peak demand and the annual demand of the building 682 m2 and 3785 m2 of PV/T panels are required. By comparison with PV panels, it is obvious that the number of required PV panels is less, which is because of their higher efficiency. Therefore, we recommend using PV panels.

4.4 Building Integrated Solar Technologies

In this section, the building integrated photovoltaic technologies (BIPV) will be introduced. We will model the energy output of BIPVs for windows and facades of the building. BIPVs are becoming more mature and their applications in sustainable and energy efficient building is increasing. Since the Center of Excellence is a new building, it is a good opportunity for integrating such technologies with the building.

Various solar technologies have been developed and many of them are on sale; these include: stand alone photovoltaic cells, building area integrated photovoltaic cells (BAPV), building integrated photovoltaic cells (BIPV) and Building integrated thermal photovoltaic cells (BIPVT). More information is available in Appendix 5. One of the more lucrative solar technologies, BIPV, contains a number of simple designs that can go a long way in reducing the consumption of fossil fuels. The designs are broken down into three categories: glazing technology (solar powered windows, skylights and canopies), solar facades (shading technology, rain screens and curtain walls), and solar powered rooftops. What follows is an in depth analysis of each of these developed technologies and a recommendation of when and where to use them.

Although Stand Alone PV cells, BAPV cells, and BIPV cells are all renewable resources for energy, and each of them have their own pros and cons (Table 1). Stand-alone PV (SAPV) panels are not integrated into a buildings structure; instead, they are placed around the building and require a sizeable amount of space (Figure 1). Additionally, the excess land and the mounting supplies must be purchased in order to operate SAPV cells. As a result, one must put down a substantial amount of capitol investment when purchasing SAPV technologies. (BAPV) cells are usually mounted by supports onto a building; for example, standoff arrays are mounted above the roof where as rack-mounted arrays are typically installed on flat roofs at an optimal orientation to harness solar energy from the sun. However, BAPV technologies have a large investment cost because they require more racks and mounts to be securely placed on a building (figure 7). As a result, this presents a large capitol cost. BIPV cells are integrated within a buildings envelope in order to save on investment costs and look aesthetically pleasing. Instead of designating space for PV cells around a building or mounting PV cells onto a roof, BIPV cells can be integrated into a building through the following ways: windows, skylights, canopies, shading technology, rain screens, curtain walls and rooftops. With a method to reduce capitol costs and a method to keep long-term savings for renewable energy, one can determine that researching and developing different BIPV technologies will benefit mankind in the future by making solar products affordable.

4.4.1 Rooftop BIPV

Rooftop BIPV cells become the ideal candidates for solar technology within suburban neighborhoods because they can be designed to fit diverse home styles and can be optimized to work in different weather conditions around the globe. Many State and local governments within the United States have passed monetary incentives (tax relief, subsidization, etc.) to assist those who seek to install clean energy products that are available on the market, including rooftop BIPV technology (Building Integrated Solar 2015). Moreover, rooftop BIPV technologies are much more aesthetically pleasing than stand alone PV because they are directly integrated into a buildings structure, making them much less apparent when compared to stand alone PV cells. Additionally, BIPV technologies cost much less than standard PV cells because they offset the cost of roof shingles, and do not need to be mounted like stand alone PV cells (Figure 8). More importantly, BIPV technologies can be optimized to produce a high efficiency energy output at a relatively low cost. There are key design parameters to consider varying when optimizing the energy output and cost of rooftop BIPV technologies; these parameters include: the fin efficiency, lamination requirements, the thermal conductivity between a PV module and its supporting structure, and the type of material used to construct the BIPV cell.

4.4.1.1 The Tilt Angle

The angle and direction of the BIPV panels depends on the architectural design of the building in order to show the dependence of the energy output of the PV panels to the angle we performed the following calculation.

The annual energy production of a single JKM315M-72 panel versus the tilt angle was calculated to determine the optimum tilt angle range.

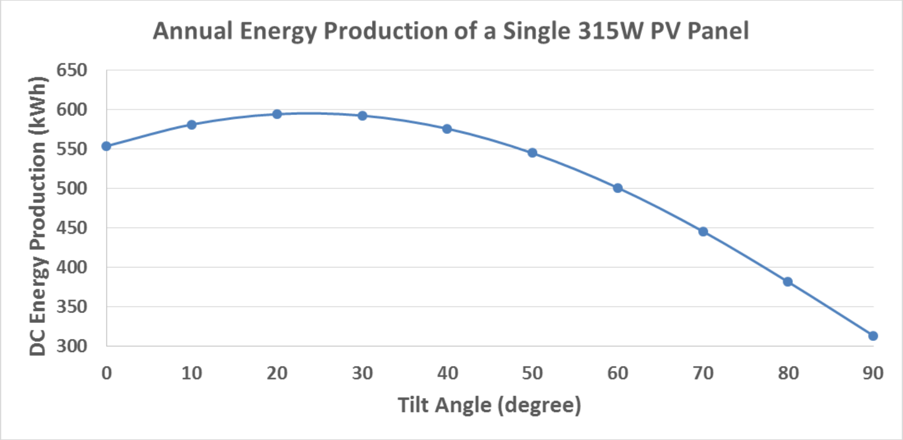


Figure 23 The sensitivity of energy output of PV panels versus the tilt angle

4.4.2 BIPV Façade

Solar Facades take a different approach to providing larger buildings with solar energy because the solar irradiation gathered could be used to provide both electrical power and thermal energy in order to comfort people inside the building. An array of PV cells around the structures envelope could produce the amount of electricity needed to sustain the optimal operation levels of the building (Figure 11). In addition to this, the solar energy that is not used as electricity is transported out of the façade through small tubes as usable thermal energy (Hwang 2012). This usable heat can be used to insulate the building and keep temperature levels consistent throughout the structures interior. To add to this, people inside the building will rely much less on artificial lighting because the solar façade can enhance the amount of natural light used within the building by varying its own transparency levels (Hwang 2012). Manufacturers of solar façade's advertise unique traits associated with their products; some of these qualities include: adjusting the façade throughout the day in order to allow just the right amount of light to permeate through the building and integrating newer façade's into older buildings to allow for greener infrastructure without high construction costs. In order to optimize the amount of solar energy harnessed from the sun, an inclined façade should be used on a building, this allows for the PV panels to capture a greater amount of the suns irradiation. Many offices around the world can drastically reduce their reliance on fossil fuels by installing solar façade's.

4.4.3 BIPV Window

BIPV windows are candidates for larger commercial buildings and office buildings because they can easily cover a vast amount of the structures envelope while optimizing the amount of energy yielded. By varying its transparency, BIPV windows allow the user to specify how much light can enter the building during various parts of the day (Hwang 2012). Furthermore, because the transparency of the window changes, it indirectly changes the amount of solar irradiation harnessed from the sun, which varies the amount of energy the building receives from the BIPV windows. Additionally, BIPV windows offset the cost of the electricity required by the building and the installation costs of the windows by combining each function into one working product (Figure 9). In order to produce the most optimal BIPV windows, one should consider a design in which high efficiency solar panels are bunched together inside the window; this would produce the greatest energy yield. However, the design must be translucent in order to provide those inside with an amount of light that is comfortable for them.

Table 15 Rooftop BIPV Products Available on the Market Today

Manufacturer	**Product**	η **(%)**	U_{oc} **(V)**	I_{sc} **(A)**	**FF**	**Website**
BIPV Rooftop						
Solardachstein	STEP	-	0.59	3	0.76	www.solardachstein.com
Lumeta Inc.	Solar S Tile	-	7.40	5.20	0.73	www.lumetasolar.com
Lumeta Inc.	Solar Flat Tile	-	7.40	5.20	0.73	www.lumetasolar.com
Sharp	ND-62RU1	-	10.8	8.00	0.72	sharpsolar@sharpusa.com
Sharp	ND62RU2	-	10.9	7.90	0.72	sharpsolar@sharpusa.com
Sunpower	SunTile	-	14.6	5.65	0.76	Us.sunpowercorp.com
Solon SE	Solon Black	13.7	44.5	5.01	0.78	Solon.com
Solon SE	Solon Ge	17.7	24.4	8.87	0.76	Solon.com
Soltecture	SCG-HV-RI	-	-	-	-	http://www.soltecture.com/solar-construction/solar-facades.html
Soltecture	SCG-HV-L	-	-	-	-	http://www.soltecture.com/solar-construction/solar-facades.html
Soltecture	SCG-HV-F	-	-	-	-	http://www.soltecture.com/solar-construction/solar-facades.html

η = Efficiency, U_{oc} = Open Circuit Voltage, I_{sc} = Closed Circuit Current, FF = Fill Factor (Unit less)

Table 16 BIPV Products Available on the Market Today

BIPV Façade’s						
Window’s						
Manufacturer	**Product**	**η (%)**	**U_{oc} (V)**	**I_{sc} (A)**	**FF**	**Website**
Schott Solar	ASI THRU-2-L	27%	111V	1.11A	-	www.schott.com
Schott Solar	ASI THRU-2-IO	20%	111V	1.11A	-	www.schott.com
Schott Solar	ASI OPAK-2-L	25%	111V	1.21A	-	www.schott.com
Yohkon Energia	YE6140MGG	11.0%	21.9V	8.47 A	-	https://www.linkedin.com/company/yohkon-energia-s.a?trk=company_logo
Smile Solar	SSNP-110TA30S	9.42%	78.4V	67A	-	http://www.smilesolar.com.tw/en/goods.php
Curtain Wall						
Manufacturer	**Product**	**η (%)**	**U_{oc} (V)**	**I_{sc} (A)**	**FF**	**Website**
Soltecture	Façade cassette	-	-	-	-	http://www.soltecture.com/solar-construction/solar-facades.html
Soltecture	SCG-HV-F	-	-	-	-	http://www.soltecture.com/solar-construction/solar-facades.html
Zigzagsolar	Hit	-	-	-	-	http://zigzagsolar.com/
Sapa	Façade 4150 EF	-	-	-	-	http://www.sapagroup.com/en/company-sites/sapa-building-system-ab/sapa_building_system_ab_gb/products/facades/
Rain Screen						
Manufacturer	**Product**	**η (%)**	**U_{oc} (V)**	**I_{sc} (A)**	**FF**	**Website**
Soltecture	SCG-HV-L	-	-	-	-	http://www.soltecture.com/solar-construction/solar-facades.html
Soltecture	SCG-HV-F	-	-	-	-	http://www.soltecture.com/solar-construction/solar-facades.html
Concrete Façade						

Manufacturer	**Product**	η **(%)**	U_{oc} **(V)**	I_{sc} **(A)**	**FF**	**Website**
Soltecture	SCG-HV-L	-	-	-	-	http://www.soltecture.com/solar-construction/solar-facades.html

4.4.4 Shade Analysis and Solar Energy Output Modeling

The System Advisor Model (SAM) software was used for the shade analysis as well as the energy output of the BIPV panels located at different location of the building such as the walls and windows. The summary of the input information and assumption are as follows:

- **System Advisor Model:**
  - BIPV Window
    - Module: Scheuten Solar Multisol Vitro
    - Inverter: Power-One MICRO-0.3HV-I-OUTD-US- 208 208V
    - Total Energy: 134,542 kWh
    - Total Surface Area Covered: 1381 m^2
  - BIPV Façade
    - Module: Corium 90 Façade
    - Inverter: ABB MICRO-0.3HV-I-OUTD-US-240-240V
    - Total Energy: 304,135 kWh
    - Total Surface Area: 3682 m^2

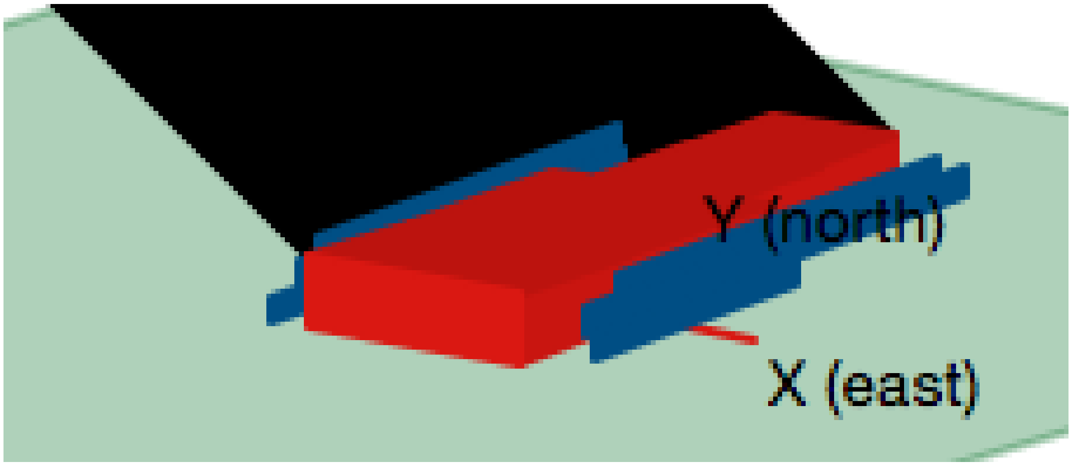


Figure 21: This image shows the Façade's mounted on the outside of the theatre in Dubai

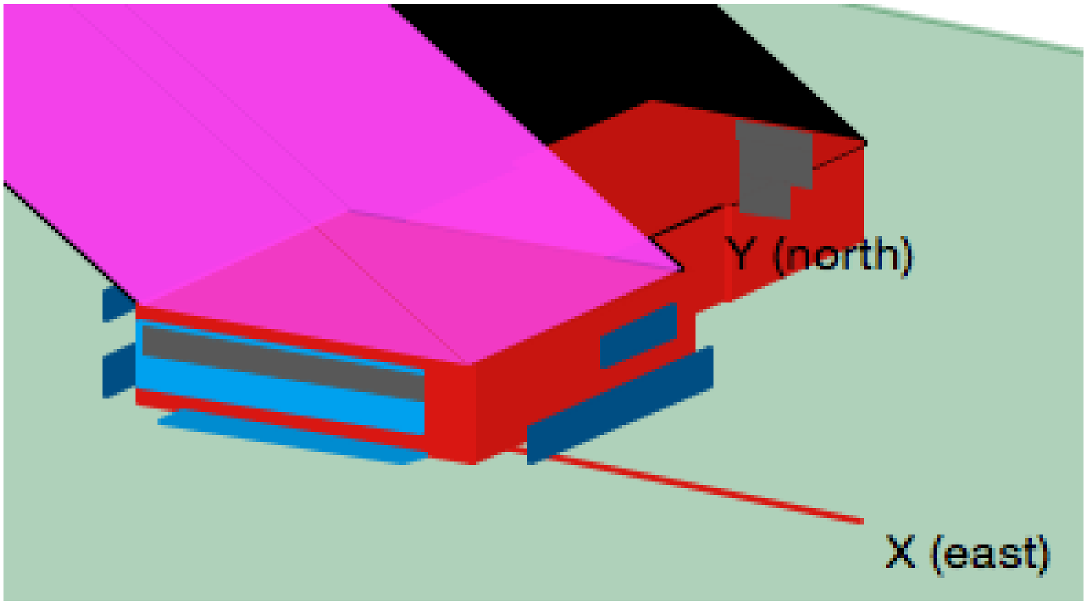


Figure 22: This image shows the windows mounted on the outside of the theatre in Dubai.

Note: The Pink and Black colors above the roof both represent the sun's rays shining down on the building.

The results of the modeling for façade-BIPV and window-BIPV of north, south, west, and east side of the building are summarized in the following tables.

Table 17 Summary of the energy production from Window-BIPV for each side of the building and for each floor of the building.

North			
Annual Energy for One Panel kWh	Available Surface Area of **Window** m^2	Total Energy of all Panels kWh	Number of Panels within Surface Area
Ground Floor			
144	42.0	3600	25
First Floor			
144	63.5	5616	39
Second Floor			
144	52.4	4464	31

South			
Annual Energy for	Available Surface	Total Energy of all	Number of Panels

One Panel kWh	Area of **Window** m^2	Panels kWh	within Surface Area
Ground Floor			
191	216.6	25212	132
First Floor			
191	216.6	25212	132
Second Floor			
191	204.885	23684	124

East			
Annual Energy for One Panel kWh	Available Surface Area of **Window** m^2	Total Energy of all Panels kWh	Number of Panels within Surface Area
Ground Floor			
97	254.6	15035	155
Second Floor			
97	83.7	5044	52

Annual Theoretical Energy for the Window – 132,014 kWh (132 mWh)

Actual Energy - 134, 542 kWh (134.5 mWh)

Note: The effects caused by the self-shading are negligible. This is due to the fact that the panels are stacked on top of each other and oriented to 90°.

Table 18 Summary of the energy production from Facade-BIPV for each side of the building and for each floor of the building.

East			
Annual Energy for One Panel kWh	Available Surface Area of **Façade** m^2	Total Energy of all Panels kWh	Number of Panels within Surface Area
Ground Floor			
57	441.2	31008	544

First Floor			
57	819.4	57627	1011
Second Floor			
57	562.1	39501	693

West			
Annual Energy for One Panel kWh	Available Surface Area of **Façade** m^2	Total Energy of all Panels kWh	Number of Panels within Surface Area
Ground Floor			
75	542.1	50175	669
First Floor			
75	681.2	63000	840
Second Floor			
75	636.2	58875	785

Annual Theoretical Energy for the Façade – 300,186 kWh (300.1 mWh)

Actual Energy – 304,135 kWh (304.1 mWh)

4.4.5 References

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4.5 Integrated Design

Based on the previous discussion, it is recommended to use PV panels for the electrical demand of the building and evacuated tubes for the thermal energy requirement of the absorption chillers. The summary of these calculation are shown in the following table.

Technology	Number of Panels	Required Surface Area (m2)
PV Panels	1764	3351
Evacuated Tube Collectors	4120	13600

Additionally, the potential of using BIPV for windows and facades has been demonstrated.

5 Life Cycle Analysis (LCA)

In this section the LCA for the solar technologies and the air conditioning technologies has been analyzed.

5.1 Solar Technologies

Today, there is much controversy over fossil fuel use due to large amounts of greenhouse gas (GHG) emission, as well as facilitating depletion of natural resources. To help mitigate these issues, different types of solar technologies exist which are able to capture solar radiation - a renewable and widely available resource - and convert it into usable electricity. Examples of such technologies are photovoltaic (PV), photovoltaic-thermal (PVT), concentrated solar power (CSP). Using these as an alternative to power residential and commercial buildings lessens the dependence on fossil fuel use and emission of GHGs into the environment, as these neither consume fossil fuels nor emit GHGs during their operation (Kannan et al. 2006). However, there are still energy requirements from sources such as manufacturing processes, transportation, installation, and final disposal, and these sources also emit GHGs (Kannan et al. 2006). Life cycle assessment (LCA) is a well-known procedure that can be used to calculate these energy requirements as well as the environmental impacts (material requirements, GHG emission) for a technology over its entire life cycle, which is typically from raw material extraction to final product disposal. Performing LCA to quantify the life cycle energy requirement and GHG emissions permits comparison of these solar technologies with each other as well as with existing fossil fuel technology. From here on, we will refer to the life cycle energy requirement as the embodied energy for simplicity.

A common way to compare technologies in terms of energy use is by calculating the energy payback time (EPBT) which is the time required to produce energy equal to the embodied energy,

$$EPBT = \frac{Embodied\ Energy}{Rate\ of\ Energy\ Production}.$$

Here the embodied energy is in units of energy, and the rate of energy production is in units of energy per time. To compare technologies based on EPBT, it is sufficient to select an arbitrary rate of energy production to be held constant for all technologies and determine the size of the system (and thus the embodied energy) required for each.

There are complications that arise in calculating the EPBT using the definition given above as well as GHG emissions due to sensitivity of both embodied energy and the rate of energy production. First, since the embodied energy is the sum of all energy requirements during a products life cycle, it is sensitive to changes in any of these steps, such as the type of manufacturing process used. GHG emissions are also sensitive to these same changes because each step emits GHGs. Second, the rate of energy production is sensitive to an expansive set of variables, some of which are module efficiency, local irradiation, ambient temperature, etc. Standard test conditions (STC) for a PV module are an irradiation of 1000 W/m^2 and an ambient temperature of 25 $°C$, and the actual operating conditions may vary greatly from STC. In a study performed by Kannan et al., PV modules heated to module temperatures greater than $60°C$ in Singapore (Kannan et al. 2006). PV modules decrease in performance due to heating of solar cells as characterized by a power temperature coefficient. For example, SUNPOWER X Series PV modules have a power temperature coefficient of $-0.3\%/°C$. For these reasons, it is of importance to calculate EPBT and GHG emissions based on a particular location while holding as many variables constant as possible, minimizing the need for sensitivity analyses.

Choice of Location

One such location chosen for this work is the United Arab Emirates (UAE), chosen for the relative absence of rain and cloud cover with 80-90% clear skies throughout the year (Assessment 2013), and an obvious abundance of sand as a source of silicon. Another reason for the choice of UAE is that there are several solar projects that either already exist or are expected to be constructed in the future such as utility scale solar power plants and solar panel manufacturing industries (Assessment 2013). The Research Center for Renewable Energy Mapping and Assessment (ReCREMA) at the Masdar Institute developed an atlas of the solar irradiance in UAE using satellite imagery with 15-minute time and 3 km space resolution (Assessment 2013). This procedure yielded results of 1800-2200 kWh/m^2 per year direct normal irradiation (DNI) between the years of 2008 and 2010 (Assessment 2013). The DNI atlas for years 2008 and 2010 are shown in the appendix.

Module Temperature

As stated earlier, the performance of a solar panel decreases with increasing module temperature. The module temperature is dependent on several ambient conditions, some of which are local irradiation, absorption and thermal dissipation behavior, glazing, tilt angle and wind speed. Mounting configuration also affects the module temperature; open rack modules have sufficient space underneath to allow for convective cooling of the module, while roof integrated modules do not. Most of the dependence of module temperature on these conditions have been shown to be lumped into a single parameter called the nominal operating cell temperature (NOCT), which is typically shown on panel specification sheets provided by the manufacturer. The calculation and use of NOCT is valid for very specific conditions, which are only for open rack mounted modules with a tilt angle at normal incidence to the direct solar beam at local solar noon, total irradiance of 800 W/m^2, ambient temperature of 20°C, wind speed of 1 m/s, and no electrical load (Alonso García and Balenzategui 2004). The simplifying fact that allows for quick calculation of the module temperature from NOCT is that the module temperature minus the ambient temperature is independent of all ambient conditions, and only scales linearly with local irradiation according to (Alonso García and Balenzategui 2004),

$$T_{module} - T_{ambient} = \frac{(NOCT - 20)}{800} E,$$

Where E is the local irradiation in W/m^2. This equation is also valid for crystalline and CIGS PV modules (Alonso García and Balenzategui 2004) under these same conditions. Since the equation above is only valid for open rack modules and no electrical load, an installed NOCT (INOCT) is typically used to take into account the mounting configuration and presence of an electrical load (Alonso García and Balenzategui 2004). INOCT is typically 3°C less than NOCT for open rack modules, and $10 - 20°C$ above NOCT for roof integrated modules depending on convective cooling (Alonso García and Balenzategui 2004). We will use the SAM software for modeling electricity production for PV panels, which uses an INOCT of 45C for open rack modules, and 50C for roof mounted modules.

About LCA

LCA accounts for only the environmental impacts of a given system and excludes economic or social impacts. A thorough LCA considers the entire life cycle of a system, from raw material extraction, product manufacturing, and ultimately to end of life disposal. The conventional procedure for LCA is divided into four phases according to the ISO 14040-2006 standard. These four phases are a) Goal and Scope Definition, b) Inventory Analysis, c) Impact Assessment, d) Interpretation of Results.

Goal and Scope

The goal and scope definition phase sets the framework for the entire LCA. The goal of the LCA is to identify the application, audience, and results of the system to be studied. The scope of the LCA describes the system, the functional unit, the system boundary, and any assumptions or limitations. A choice of functional unit is the relative basis for which all results are communicated. An example of this is choosing a functional unit of 1 kWhr of produced energy for solar PV modules, and thus all results are reported on the basis of this functional unit. The system boundary is chosen based on the unit operations that are to be accounted in the LCA.

Inventory Analysis

The inventory analysis phase concerns accounting of data regarding each unit process, such as material and energy requirements, production, and waste/emissions. There must also be a validation procedure for this data as well as relation to the functional unit.

Impact Assessment

The impact assessment phase quantifies possible environmental impacts in terms of specific categories and indicators, clearly stating all assumptions.

Interpretation of Results

The interpretation phase uses key findings from the inventory analysis and impact assessment phases and delivers results that align with the stated goal and scope definition, while also stating conclusions, limitations, and recommendations.

Past LCA Studies

Numerous LCA studies have been carried out which provide estimates for the embodied energy and GHG emissions of solar technologies. These studies often report embodied energy and GHG emissions per functional unit, chosen to be either m^2 of panel area, kWp of nominal power, or kWhe of produced electricity. These results can be used as a base for separate analyses.

Kannan et al. performed an LCA study of a 2.7 kWp distributed PV system in Singapore, obtaining results for an embodied energy of 2.91 MJ_t/kWh_e, CO2 emissions of $217\ g/kWh_e$, and an EPBT of 5.87 years. These results were for a “base case” and an improvement assessment was also performed, which considered the effects of: a 50% reduction in the energy use for manufacturing, using a concrete supporting structure (reducing aluminum use to 10%), and increasing the efficiency of the solar system to 10.6%.

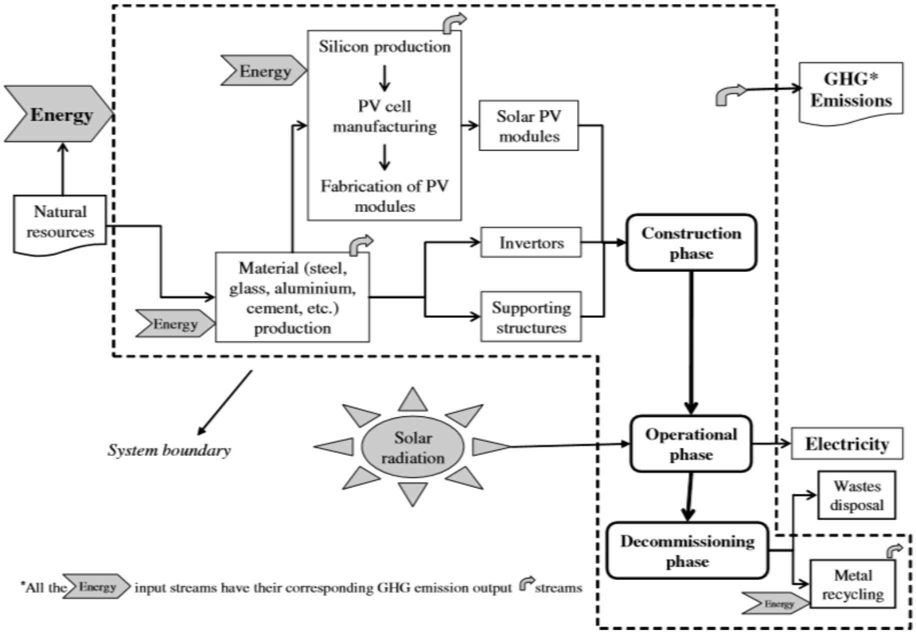

Figure 23 LCA evaluation for silicon photovoltaic panels

Alsema and Wild-Scholten conducted an analysis of the environmental impacts of crystalline silicon PV module production. The production method considered was the fabrication of solar

PV modules from silicon wafers. They considered one module type with 72 cells, glass/EVA/tedlar lamination, module area of 1.25 m^2, and a glass thickness of 3.6mm. They considered unframed and framed (3.8kg aluminum frame) modules, and assumed the module lifetime was 30 years. Their analysis was performed with the Simapro software.

Perpinan et al. performed an LCA comparison of tracking and fixed PV systems. They calculated EPBTs for double and horizontal axis tracking and fixed systems. According to their calculations, a grid connected PV system is able to produce from 6-15 times its embodied energy over a lifetime of 30 years.

Embodied Energy

The embodied energy for PV modules is composed of energy requirements from several life cycle unit operations. These unit operations are raw material extraction and feedstock generation, module fabrication, transportation, installation, operation, and disposal/recycling. For PV modules, it has been shown in previous studies that the fabrication energy for modules is roughly 80% of the embodied energy (Kannan et al. 2006) (Perpiñan et al. 2009), and that the remaining 20% is taken up by lesser contributions such as transportation, installation, and end of life disposal.

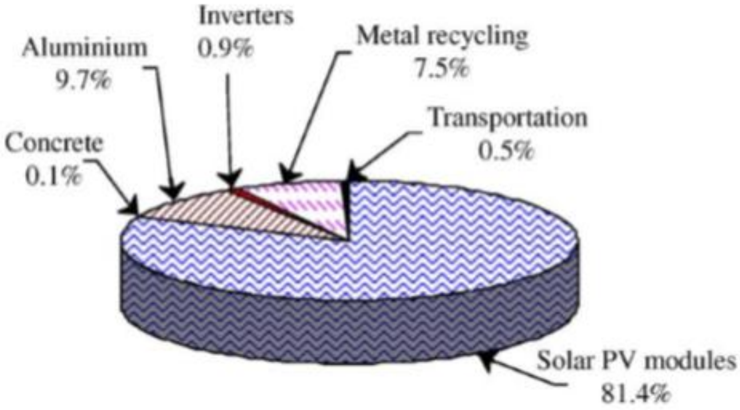

Figure 24 Percent contributions to the embodied energy of solar PV modules, reproduced with permission from Kannan et al. (Kannan et al. 2006).

These contributions present a large potential for sensitivity since there are numerous combinations of unit operations that can be selected for the entire life cycle. For example, the transportation energy depends on the method of transportation and the distance between the manufacturer and the operating location. The installation energy depends on the construction and materials used in the balance of system (BOS) and the inverters used. The disposal energy depends on the disposal method, and whether or not there is any recycling of material. For this reason, calculations of these contributions were neglected, and the embodied energy was scaled to 100% from the fabrication energy only assuming other factors remain constant at 20%.

Module Fabrication

The since the fabrication energy for PV modules is most of the embodied energy, the type of process used to manufacture the modules is of great importance. There are several options that can be used to manufacture the modules, each with their own fabrication energy. Past LCA studies either use values of the fabrication energy from other studies, or calculate it explicitly in the LCA study.

Kannan et al. reported values from other studies for the fabrication energy of monocrystalline PV panels based on the type of process used. These reported values considered the functional unit as 1 kWp of modules. From extracting mineral sand to module fabrication, the fabrication energy was 13.78 MWh_t/kWp. From growth of a silicon ingot to module fabrication, the fabrication energy was 16 MWh_t/kWp. From off-grade silicon to module fabrication, the fabrication energy was 12.4 MWh_e/kWp. From quartz to module fabrication, the fabrication energy was 17.70 MWh_e/kWp. From wafer sawing to module fabrication, the fabrication energy was 40.55 MWh_t/kWp (Kannan et al. 2006).

Alsema and Wild-Scholten calculated the fabrication energies for crystalline silicon modules in their study (Alsema and de Wild 2011). The manufacturing process they considered was Czochralski crystal growth followed by wafer sawing. Their results for fabrication energies were 5200, 4000, and 2600 MJ per square meter of panel for monocrystalline, polycrystalline, and CIGS, respectively. The relative contributions of each process step to the fabrication energies are shown below. The fabrication energy for CIGS modules is the lowest because of lower energy requirements in the crystallization and wafer step, as well as no silicon loss from wafer sawing (Alsema and de Wild 2011). The fabrication energy for monocrystalline module production is the highest because of the higher energy requirement for Czochralski crystal growth (Alsema and de Wild 2011). The relative contributions for each process step to the fabrication energy are shown below in figure 1. For all three module types, the frame, module assembly, and cell production contributions are approximately constant. The energy to obtain the silicon feedstock, grow the ingot, and saw the wafer compose most of the fabrication energy, and it can be inferred that improvements to these steps would have the most contribution towards reducing the fabrication energy.

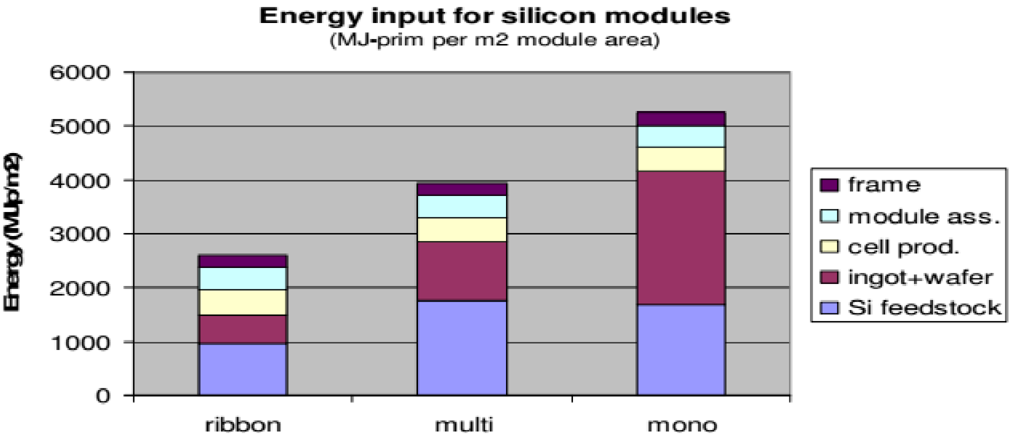

Figure 25 Energy input for crystalline silicon modules, in MJ per square meter, with the relative contributions of each step. Reproduced with permission from Alsema and Wild-Scholten (Alsema and de Wild 2011).

For the crystal growth to wafer sawing process, several other results for the energy breakdown of PV module manufacturing have been tabulated by Peng et al. in their review of life cycle assessment of solar PV systems (Peng, Lu, and Yang 2013).

GHG Emissions and Environmental Impacts

The GHG emissions were estimated assuming that results from previous studies are sufficient to act as emission factors for our methodology. Alsema and Wild-Scholten calculated the emission factors for crystalline silicon PV modules (Alsema and de Wild 2011), and the results are shown below in g CO2/kWh (kg CO2/MWh). The emission factors are comparable to biomass, but significantly lower than hard coal or gas turbine emission factors.

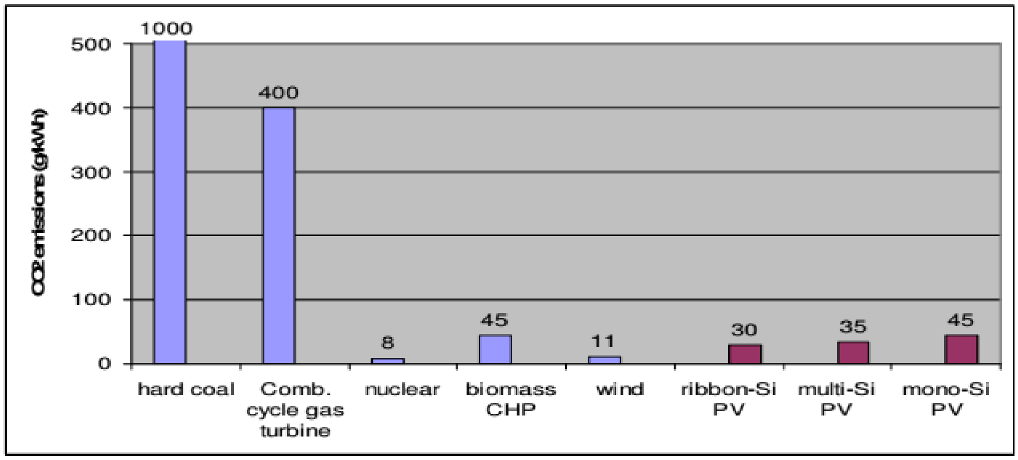

Figure 26 Greenhouse gas emission of silicon PV compared with other energy resources. (Alsema and de Wild, 2011)

CO2 emission factors typically show high variability of around 1 order of magnitude (Turconi, Boldrin, and Astrup 2013) mainly due to local conditions such as electricity and fuel sources, climate conditions, and panel types. Turconi et al. reviewed the GHG emissions of 22 LCA studies and found a range of 13-130 kg CO2/MWh.

It is important to note that purely considering CO2 emissions do not represent the full range of emission types and environmental impacts. For example, solar technologies also have lesser amounts of NOx and SO2 emissions. To correctly account for the overall emissions, all direct and indirect emissions must be accounted for. Indirect emissions from fossil fuels may represent up to 25% of the overall emissions, and this figure is even larger for renewable technologies (Turconi, Boldrin, and Astrup 2013). Corona et al. considered the following other environmental impacts in their LCA study (Corona, Miguel, and Cerrajero 2014)of a CSP plant: Human toxicity, terrestrial acidification, freshwater eutrophication, marine ecotoxicity, natural land transformation, water depletion, and fossil depletion.

EPBT

The EPBT will be calculated by dividing the embodied energy by the rate of energy production, which we will set constant at 1 MWh/yr of electricity. EPBT is sensitive to several factors, and thus a variety of sensitivity analyses can be performed to obtain a wide range of EPBTs. For example EPBT can be defined in terms of consumer energy use instead of on site energy production, which includes transmission and distribution losses. Kannan et al. found transmission and distribution losses to be around 4% in Singapore (Kannan et al. 2006). Another sensitivity analysis that could be performed is an improvement assessment. Kannan et al. performed an improvement assessment for their PV system in Singapore by considering a "base case" and several improvement cases (Kannan et al. 2006). These improvement cases included: A) reducing the fabrication energy by 50%, B) reducing aluminum use by 10%, and C) increasing solar system efficiency.

LCA Methodology

We will use an approximate LCA methodology conducted using the results of previous studies. Three types of solar technologies were analyzed: PV, PVT and CSP. For each technology, the embodied energy will be calculated based on a functional unit of 1 MWh/yr of annual electricity generation. The GHG emissions will be reported solely on CO2 emissions over the whole life cycle, in kg. The lifetime of the system will be 25 years.

The most detailed analysis will be performed on PV panels due to the high availability of information on the production processes of PV panels. For PV and PVT, we will mainly follow the results obtained by Alsema and Wild-Scholten (Alsema and de Wild 2011), as well as using information from PV panel specification sheets. The study by Alsema and Wild-Scholten was listed in the harmonization study by Hsu et al (Hsu et al. 2012), passing the quality, transparency, and modern relevance screenings, so we assume that their LCA procedure is thorough and reliable. For PV, we will use the energy modeling software SAM, and for PVT we will use the energy modeling software POLYSUN. The software will simulate the PV technologies in the climate of UAE. An approximate scaling analysis will be performed based on a site-specific LCA study by Corona et al. (Corona, Miguel, and Cerrajero 2014) performed for a CSP plant. We will use the results of this study because the local irradiation in Castilla La Mancha, Spain is 2030 kWh/m^2 per year, which is consistent with the expected range in the UAE. Also, the lifetime chosen for (Corona, Miguel, and Cerrajero 2014) was also 25 years, which we will also use.

For PV panels, the embodied energy and CO2 emissions were calculated for three types of panels: monocrystalline, polycrystalline, and CIGS. For monocrystalline panels, two models from SUNPOWER were used: X21-345, and E20-245. The polycrystalline panel used was the Sunperfect CRM255S156P-60. The CIGS panel used was the Stion STN-150. These were chosen as inputs into the SAM software to calculate the annual produced energy per panel. The parameters input into SAM for each panel were: the location of Abu Dhabi in the United Arab Emirates, a tilt angle of 0 degrees, and 9 modules per string with 2 strings in parallel. The number of panels necessary to produce at least 1 MWh/yr annually was calculated for all types of panels.

To calculate the fabrication energy for each panel, we used the results obtained by Alsema and Wild-Scholten of 5200, 4000, and 2600 MJ per square meter of panel for monocrystalline, polycrystalline, and CIGS, respectively (Alsema and de Wild 2011). The area of each panel was determined from the available specification sheet from the manufacturers, (shown in the appendix).

The embodied energy of the PV modules required for 1 MWh/yr annual production was calculated by scaling the fabrication energy from 80% to 100% for reasons stated above.

To calculate the GHG emissions, we again used the results obtained by Alsema and Wild-Scholten, which were GHG emission factors of 45, 35, and 30 g CO2 per kWh (also kg per MWh) of produced electricity for monocrystalline, polycrystalline, and CIGS, respectively (Alsema and de Wild 2011). These were multiplied by the produced energy over the panels' lifetime, normalized to 25 MWh, to obtain the total lifetime GHG emissions in kg CO2.

For PVT panels, the same methodology was followed as for PV panels (including all assumptions) except the production was modeled with the POLYSUN software instead of SAM. We used a Wiosun PV-Therm PVT 200 Polycrystalline Panel. The parameters input into SAM were the location of UAE, longitude 55.28 degrees, latitude 25.23 degrees, 1 module with 1.3 square meters aperture area, and a tilt angle of 0 degrees. POLYSUN calculated the electrical energy produced as well as the thermal energy produced.

For CSP, the embodied energy and CO2 emissions were calculated using the results from a separate LCA study (Corona, Miguel, and Cerrajero 2014) on a reference power plant based on parabolic troughs with wet cooling. The plant has a 50 MW capacity, synthetic oil as the heat transfer fluid, and a 7.5-h molten salt thermal energy storage system (Corona, Miguel, and Cerrajero 2014). The useful results for this LCA study are the embodied energy and emission factors, which are 1.15 MJ per kWh of produced electricity, and 26.6 kg CO2 per MWh of produced electricity. These values will be used with a hypothetical annual electricity production of 1 MWh/yr to calculate the EPBT.

Results

The results of our methodology indicate that for PV technologies, CIGS panels have the lowest embodied energy, CO2 emissions, and EPBT, making them an attractive option for use in UAE.

Model	Type	Production Per Panel [kWh/yr]	Panels for 1 MWh/yr	Embodied Energy Per Panel [MWh/panel]	Embodied Energy [MWh]	CO2 Emissions [kg]	EPBT [yr]
Sunpower X21-345	Mono	466	2.146	2.95	6.32	1125	6.32
Sunpower E20-245	Mono	394	2.538	2.24	5.68	1125	5.68
Sunperfect CRM255S156P-60	Poly	396	2.525	2.26	5.70	875	5.70
Stion STN-150	CIGS	256	3.906	0.98	3.83	750	3.83

The results are reasonable since for all panels the embodied energy, CO2 emissions, and EPBT are within a factor of 2 apart. The Sunpower X21-345 (Sunpower X) panel has the highest EPBT of all panels. Comparing the two monocrystalline panels, (Sunpower X and E), the Sunpower X requires less panels to produce 1 MWh/yr, but still has a higher embodied energy per panel due to the larger surface area. The EPBTs for the Sunpower E and the Sunperfect panel are the same, which is probably a coincidence. The EPBT for the Stion STN-150 is the lowest. Even though the STN-150 needs more panels to produce 1 MWh/yr, the reduction in embodied energy per panel is significant compared to all other panels. This can be attributed to the low fabrication energy of 2600 MJ per square meter of panel, since the surface area of a typical PV panel ranges from 1-1.6 square meters and is unlikely to vary too significantly between technologies. From our methodology it can be generalized that CIGS panels have the lowest GHG emissions because the electricity production is constant over all panels, making the GHG emissions entirely dependent on the CO2 emission factor.

The results for the Polysun model for PVT were that the electrical energy production for each panel was 335 kWh/yr, and the thermal energy production was 284 kWh/yr. The embodied energy was calculated to be 5.46 MWh since the Wiosun panel is polycrystalline. The CO2 emissions were calculated to be 1625 kg if the emission factor is multiplied by the sum of thermal and electrical energy, and 875 kg if the emission factor is multiplied with electrical energy only. The EPBT with electrical energy only was calculated to be 5.43 years, and 2.94 years including thermal energy. From these results we can see that the embodied energy, CO2 emissions, and EPBT of PVT panels are comparable with PV technologies considering only electrical energy, which is primarily because of using the same methodology. However, with the consideration of thermal energy the EPBT decreases significantly and this energy can also be used for other uses.

For the reference CSP plant, the embodied energy and emission factor yielded values of 7.98 MWh for the embodied energy, 665 kg for CO2 emissions, and 7.98 years for the EPBT. It is notable that the CSP model yielded the lowest CO2 emissions of all technologies considered, but at the price of a higher EPBT.

For the EVAC, the OI collector was determined to have an embodied energy of 156.52 kWh while delivering 20.3 kWh/yr of useful heat, leading to an EPBT of 7.51 years. CO2 emissions were not determined because of a lack of LCA studies performed on evacuated tube collectors.

Technology	Monocrystalline PV	Polycrystalline PV	CIGS PV	PVT	CSP	EVAC
CO2 Emissions [kg]	1125	875	750	875	665	N/A
EPBT [yr]	6.00	5.70	3.83	2.94	7.98	7.31

If electrical energy is the only concern, it is recommended to move forward with CIGS panels due to the low CO2 emissions and EPBT. If electricity and thermal energy are to be considered, it is recommended to use PVT panels because of the ability to supply thermal energy as well as having the lowest EPBT with low CO2 emissions as well. If CO2 emissions are the primary concern, it is recommended to use CSP technology due to having the lowest CO2 emissions.

It is important to note that the results of this LCA study are limited to the assumptions and methodology used. Notable assumptions include the 80%-100% scaling of the fabrication energy to represent the embodied energy for PV and PVT panels, as well as the choice for the embodied energy and CO2 emission factors based on past studies. This study was conducted using the SAM and Polysun software to model the electricity production for PV and PVT panels, but any software that can do this will suffice. A limited number of panels were used for the study, which prevents any sensitivity analyses from being performed. A further extension of this study would be to use a wider range of panels in order to examine relevant trends and possibly perform an optimization procedure. The methodology could also be extended to include amorphous Si or hybrid PV panels. For CSP, the main limitation is from the assumption that the results of the reference plant can be applied to a hypothetical plant in UAE based on similar annual irradiances. Realistically, constructing the same plant in UAE would change the embodied energy. The methodology used for the OI evacuated tube collector may be outdated, as the equation for the rate of useful heat was derived in 1978. Also, the results are limited to only a collector of the specified dimensions and materials. Another recommendation for further research would be to perform a rigorous LCA study for all technologies, and compare the results to our approximate study.

Conclusion

The approximate LCA methodology yielded reasonable results for the embodied energies, CO2 emissions, and EPBTs of the solar technologies studied. Further research related to this study could reveal trends about the dependence of specifications such as surface area and other operating characteristics on the CO2 emissions and EPBT of these technologies. The methodology and results of this study are useful for evaluating the environmental impacts of technologies for sustainable zero net energy building design.

5.2 Air Conditioning System

After coming up with a design that accurately suits the Center of Excellence in Dubai, it was important to perform some life cycle cost analysis in order to predict the initial capital cost of the components of the system. Please note that the numbers provided in this section are estimations of the cost found using online resources.

Table 19: Component capital cost.

Building absorption chiller	$110,000– 220,000
Auditorium absorption chiller	$110,000 – 220,000
Building Desiccant Wheel	$75,000
Auditorium Desiccant Wheel	$75,000
Building Sensible Wheel	$11,000
Auditorium Sensible Wheel	$11,000
Piping cost	$20,000
Solar Collectors	44,000 $
Total (For Max. Price)	**$636,000**
Annual Operating Cost	**$50,000**

Since the proposed project will be generating electricity, the amount of money saved will be compared to the capital cost of the proposed model. The procedure for Life Cycle Cost (LCC) analysis is shown below where A is the annual operating cost for each case, DR is the discount rate that was taken as 3% and n is the number of years:

$$\mathrm{DCF} = \frac{\mathrm{A}}{\mathrm{DR}^{\mathrm{n}}}$$

$$\mathrm{CDCF} = \sum_{1}^{\mathrm{n}} \mathrm{DCF}$$

The electricity charges in the State of Dubai are 38 fils/kWh for industrial applications who consume more than 10,001 kWh per month. The electricity demand was already found to be 975.1 MWh per year. Hence, the building would have needed 100,050$ worth of electricity per year. After considering the maximum HVAC electric need of $22,700 and $20,700 for the auditorium and building absorption chillers, and using a discount rate of 3% and lifespan of 50 years, the suggested system gave a payback period of 8 years.

5.3 References

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6 Social and Behavioral Studies: Promoting Energy Conservation from a Hybrid Solar-Air Conditioning System

In this chapter we address the human factors related to system performance and acceptability. Since the occupants' experience of cooling is largely the same with the proposed PVT system as a conventional HVAC system ubiquitous in the region (i.e., it provides centralized cooling operated by standard controls), the main concern with respect to social and behavioral considerations relates to control and acceptability of the temperature setting. Although there are cultural norms that influence thermostat settings in a given time and place, thermal comfort varies widely across individuals. The Sustainable Center of Excellence will attract people from around the world, each with their own needs, preferences, expectations, and priorities. The system design, particularly the expectation of delivering cooling to 24°C, will satisfy some occupants more than others. Ensuring system performance will require that occupants' behavior (i.e., use of the system) conforms to the expectations of the model, which may require certain changes by the occupants themselves.

As this chapter describes, we conducted a survey on thermal comfort in the workplace to gauge the acceptability of the system design among future occupants of Sustainable Center of Excellence. Based on those findings, we developed a multi-pronged strategy to encourage conservation among occupants and address the relevant human factors related to system acceptance. Based on the theory of behavior change, the physiological and cultural aspects of thermal comfort, and international best practice on thermostatic control, we developed recommendations for selecting controls technology, encouraging occupant acceptance and adaption, and empowering occupants to control temperature settings, in order to promote energy conservation and reliable system operation. In total we provide twelve recommendations on the human factors related to ensuring performance of the solar PVT system designed in the current project.

6.1 Technology & energy conservation

The first part of the strategy must be to ensure that the space is conditioned only as needed. This can be done through a variety of methods. Room thermostats can be programmed to deliver varying degrees of cooling when the space is: a) occupied, b) unoccupied overnight ("nighttime unoccupied"), and c) unoccupied for a short time between occupied periods ("daytime unoccupied"), the latter being the most complex. In order to ensure thermal comfort during the occupied times, the timing and temperature settings have to be established such that the desired temperature during occupied times can be reached before or soon after occupancy.

Inputting schedules in each thermostat requires programming each device according to the room's expected usage, which may change over the course of the year, depending on the room's purpose and the weather. Some thermostats make this very easy to accomplish. For example, several web-enabled thermostats on the market can be networked with others in a building and controlled from a central web portal[6]. Such technologies can save building facilities staff a substantial amount of time when changes are needed throughout the system with some regularity.

In addition to conserving energy when rooms are unoccupied, Diamond Developers has expressed the desire to conserve energy by nudging the default temperature slightly above what is considered standard by many in Dubai, namely 22°C. Together with Diamond Developers, we have identified 24°C as the preferred target temperature when the building is occupied. According to Diamond Developers' suggestion, our air conditioning calculations are based on the AC setting temperature of 22^{O}C. The technical design of the system has been completed with that target in mind, albeit with some built-in over-design to ensure reliability. Since slight changes in the temperature setting can have a substantial impact on the energy demand of the building without sacrificing thermal comfort, we have considered the implications of a higher temperature settings from behavioral, social, and educational points of view. Appropriate outreach activities and thermostatic control will be required to ensure that the building is conditioned in accordance with conservation goals and occupant needs. Recommendations to that end are outlined below.

6.2 Behavior & energy conservation

The higher set point (i.e., 24°C) will likely be embraced by some and resisted by others. Therefore, encouraging occupants to accept the system, along with its advantages and disadvantages, will be of critical importance.

To gauge the level of acceptance or resistance our recommendations are likely to face among building occupants, we created an online survey[7] to gather information on the indoor temperature preferences of likely building occupants, both regular and sporadic.[8] The thermal comfort survey was circulated among Diamond Developer staff. As individuals who work in environments similar to the future management

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[6] Examples include "smart" thermostats manufactured by ecobee (www.ecobee.com) and Telkonet's EcoTouch (https://telkonet.com).

[7] The survey is accessible at https://ucdavisbusiness.co1.qualtrics.com/SE/?SID=SV_4Jyy31mRaNpnfql.

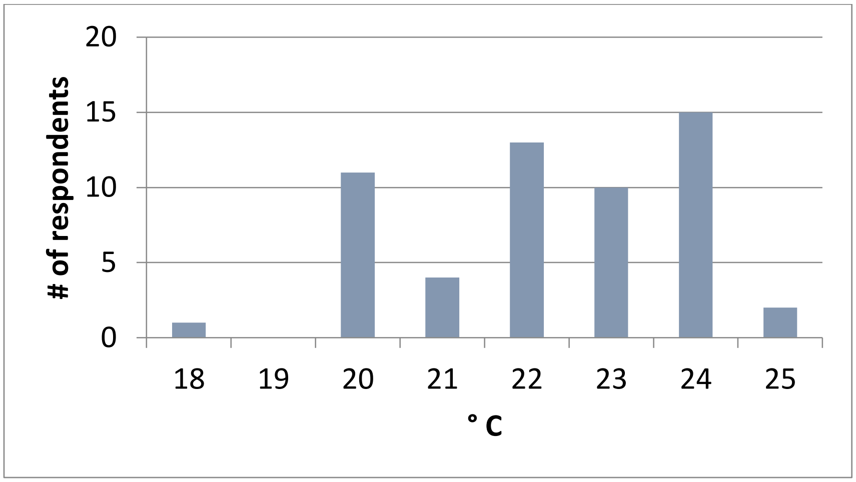
[8] The survey questions were derived in part from information gathered from UC Berkeley's Center for the Built Environment at http://smap.cbe.berkeley.edu/comforttool and the classic reference by Brager et al (1993).

offices of the Center of Excellence (e.g., workers with offices or cubicles), they serve as proxies for future building occupants. In addition, the survey was circulated among professional contacts of the research team, primarily from the Middle East, who represent the types of international visitors the Center might attract.[9] The results could provide useful guidance when selecting from among the various technical options for thermostatic control described below.

Data was collected from 57 individuals. Survey respondents are a diverse group reflecting the variation in occupants the Center is likely to attract. They are 58% female and relatively young (i.e., 53% under 31 years old, 35% 31-50 years old, 12% 51 years old or greater). Respondents work in a range of environments (e.g., closed office, cubicle, shared office, other), and their jobs range from very physically active to not at all physically active.

Sixty-one percent (n=35) have the ability, in terms of both access and permission, to change the temperature in their workplace. Respondents' preferred workplace temperature in summer ranges from 18° C to 25° C, averaging 22.3° C. In fact, 48% prefer a temperature greater than 22° C, and 30% prefer 24° C or greater. Figure 24 below shows the exact counts. On the face of it, this would suggest that less than one-third of respondents, and the future occupants of the Center of Excellence whom they represent, would be amenable to a temperature setting of 24° C. However, further probing in the survey uncovered greater willingness to accept higher temperatures, as is discussed below.

Figure 24 Histogram of preferred workplace temperatures in summer



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[9] Note that the survey was not submitted to the UC Davis Institutional Review Board for a Human Subjects Protection review. Since the survey was implemented solely for the purpose of collecting information for the Center for Excellence, and we make no claims of generalizability to the population more broadly, it is considered an organizational improvement activity, rather than research, per se. As such, it falls outside the purview of the IRB.

The distribution of *actual* workplace temperature settings respondents reported skews far more towards lower temperatures. As Figure 27 below indicates, the vast majority of respondents reported temperatures of 22° C or less, with some substantially lower.

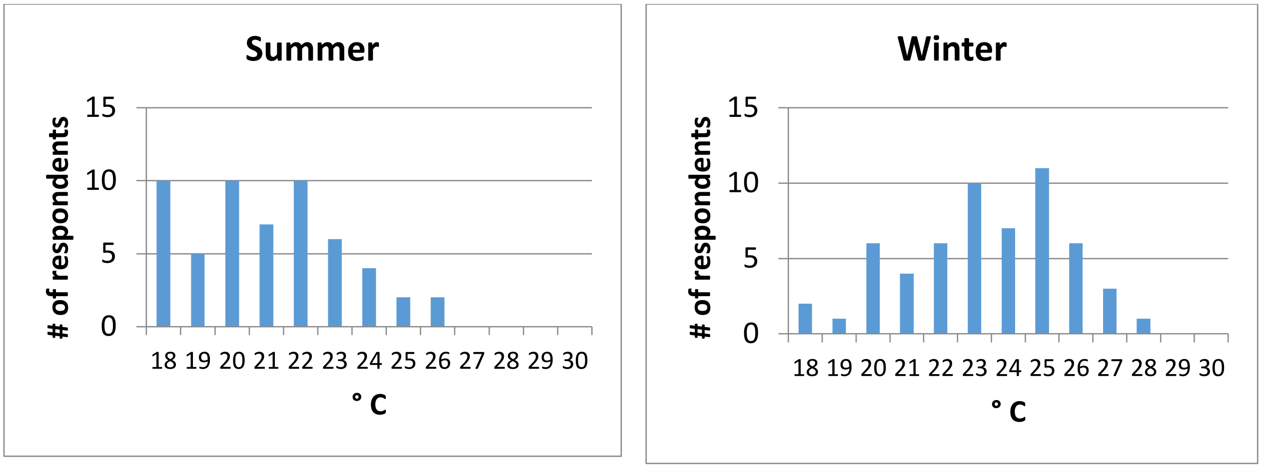


Figure 27 Typical temperature setting in the workplace, by season

As a point of comparison, respondents were also asked about the temperature settings in their workplace in winter. Those skew notably higher. Note that from an energy conservation standpoint, this is backwards. All else equal, far more energy is required to deliver the same cooling temperature, say 22° C, during the summer heat than during cooler winter months.

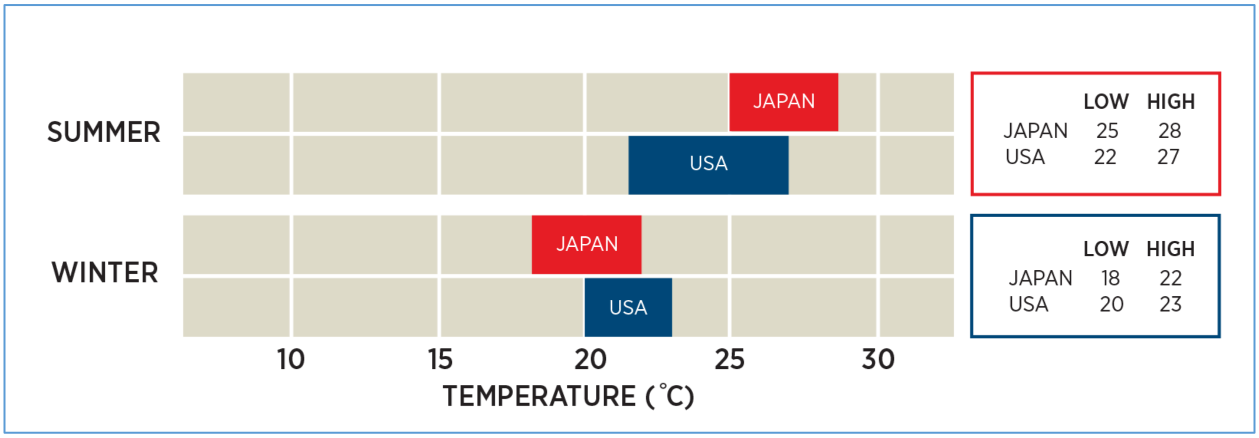
This is one area in which the Center of Excellence may want to raise awareness, as it is a basic concept of space conditioning that many individuals around the world do not understand. The idea of relative comfort – that a temperature is cool enough given that it is summer, for example – is well accepted in certain places around the world (e.g., Japan) and is worth promoting in the Center of Excellence. The text box below illustrates how international norms diverge on this point.

International variation in the seasonality of thermal comfort

The graphic below illustrates typical thermal comfort ranges utilized in the United States and Japan, as codified by ASHRAE and a Japanese manufacturer, respectively. As such, they indicate what may be considered acceptable comfort ranges in the U.S. and Japan,[10] during summer and winter. There are two key differences to note. The first is that the comfort ranges of the two seasons overlap in the U.S., whereas they do not in Japan, suggesting the Japanese expect (or at least accept) seasonal differences in thermal comfort. The result is that the overall thermal comfort range is much wider in Japan than in the U.S.

The second observation is that the comfort range in Japan is relatively warmer in the summer and cooler in the winter, relative to the U.S. All else equal, this drives down energy use in Japan, compared to the more aggressive ranges in the U.S.

Figure 28a Industry's thermal comfort range



Sources: Japan: http://www.crecer.jp/Q-A/HTML/A-11.html; US: ASHRAE guidelines

Note that the survey responses suggest that an even more extreme scenario is the norm in the Middle East, whereby thermostat set points are lower in summer than winter. This results in even greater energy consumption, all else being equal.

Two-thirds of respondents report a preferred temperature that is actually higher than the typical temperature in their workplace. Thus, there is a lot of scope of increasing indoor cooling temperatures without sacrificing comfort, at least for many individuals. It is significant to note that preferences and reality differ despite the fact that most respondents reportedly have the ability to change the temperature in their workspace. Issues of shared control are likely to blame. Several of the thermostatic control options recommended below address this issue explicitly.

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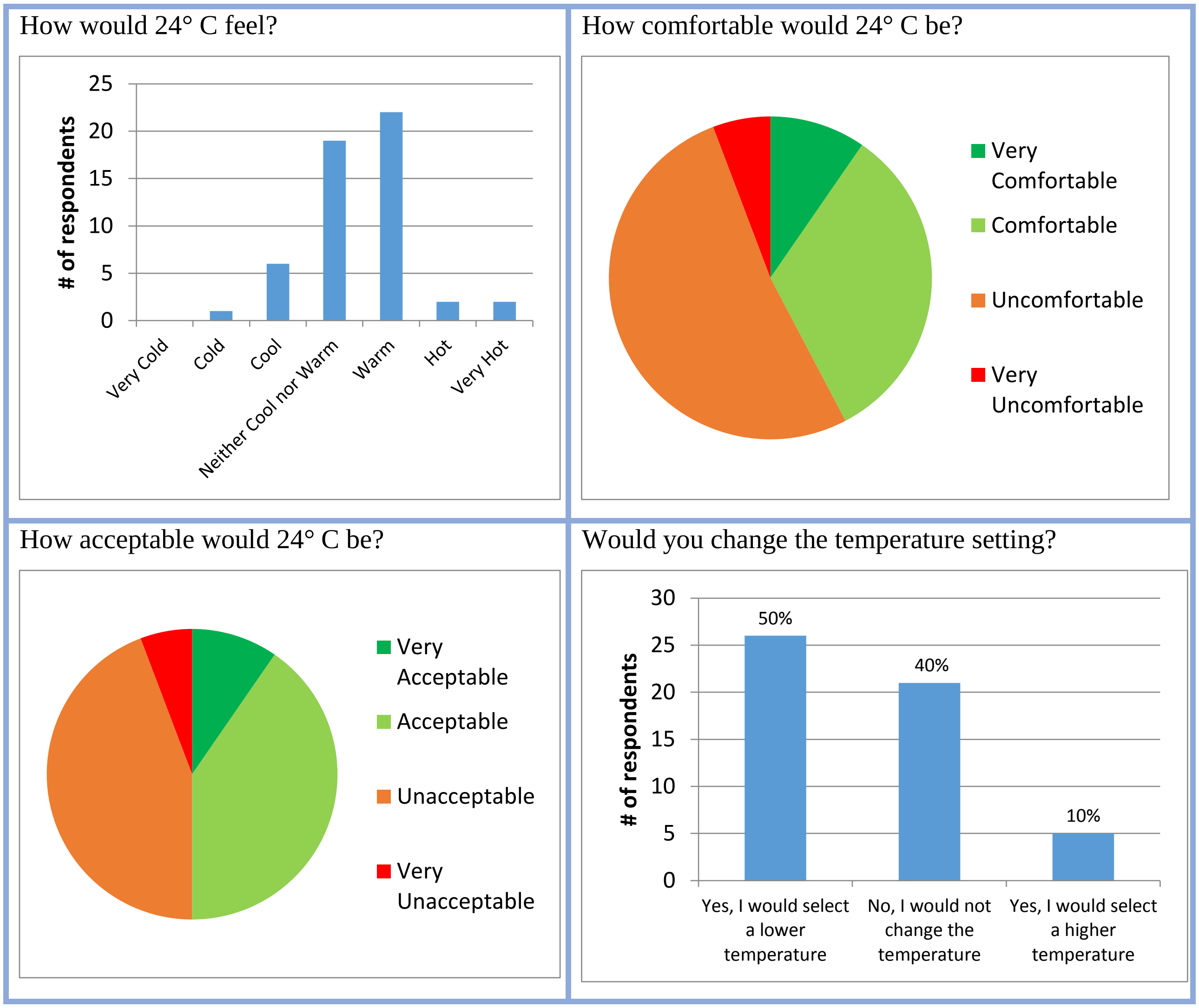
[10] Japan and the United States have very different thermal comfort standards and expectations. The pair illustrates the broad variations across the world with respect to thermal comfort.

To gauge respondents' level of receptivity to higher summertime temperature settings, they were asked a series of questions. Among others, these included questions about their attitudes towards a temperature setting of 24° C in the workplace in summer. Figure 28b indicates the responses to four questions about sensation, comfort, acceptability and desire to change. Overall, respondents reported that 24° C would feel neutral or warm, but they were relatively split on whether it would feel comfortable, with 58% reporting they would find it uncomfortable or very uncomfortable. Respondents were evenly split on whether they would find 24° C acceptable in their workplace in summer. Half reported they would lower the temperature, 40% would leave it, and 10% would increase the temperature setting.

Figure 28b Respondent attitudes regarding 24° C temperature setting in summer



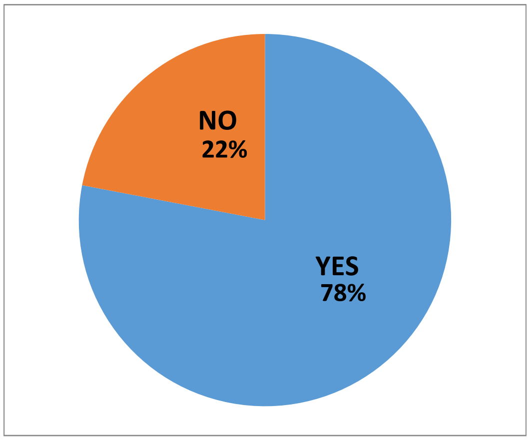
How would 24° C feel?

How comfortable would 24° C be?

How acceptable would 24° C be?

Would you change the temperature setting?

Environmentally friendly solar-powered air conditioning systems now exist that can cool an indoor space, but sometimes not to temperatures as low as conventional systems. ***If your workspace were cooled with such a system, would you be willing to accept indoor temperatures in your workspace of 24° C during the summer?***



Such variation is normal among a broad group of respondents. As the Progress Report noted, thermal comfort varies substantially across individuals, and is driven by numerous factors. Expectations of thermal comfort can be an important element. Thus, the survey asked a series of questions to determine whether respondents would be willing to tolerate a slightly higher temperature setting if doing so yielded an environmental benefit. In fact, 78% of survey respondents reported they would be willing to accept a temperature setting of 24° C in their workplace in summer if the space were conditioned by a solar-powered air conditioning system. Furthermore, 81% reported they would find such as scenario acceptable or very acceptable. Only 19% did not.

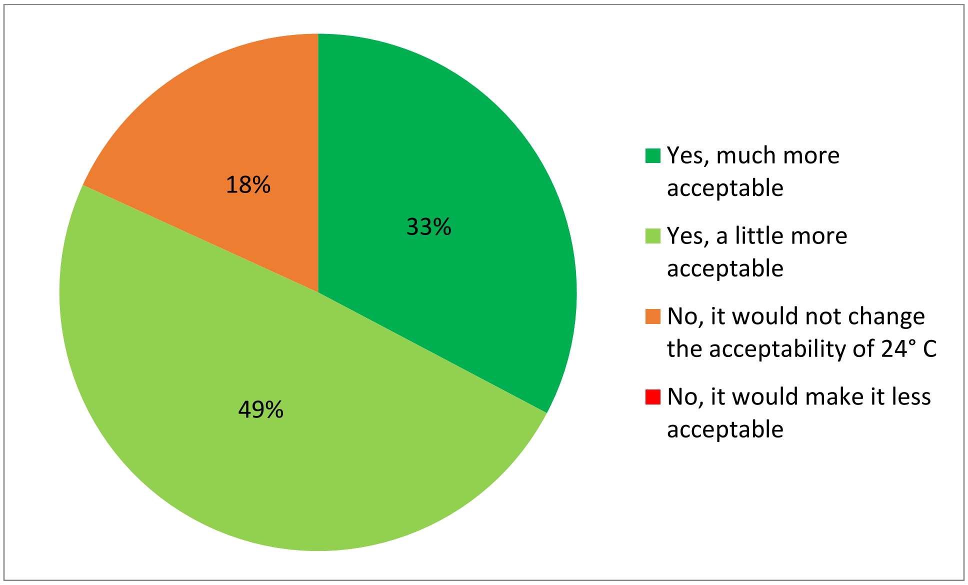
Individuals who reported an unwillingness to accept 24° C from a solar AC system were asked to explain why it was unacceptable. Answers ranged from simply stating that it was too warm, or that it was too warm given the outdoor temperature, solar gains from windows or the configuration of large office spaces. Note that the latter responses reflect a problem with thermostatic controls, rather than the set point, per se. Others expressed concern that warm temperatures would hinder their ability to work. This, too, is a valid concern that must be addressed for staff and employees at the Center, but perhaps would not be an issue for visitors.

Finally, respondents were asked about the acceptability of a variety of options that could help them adapt to warmer temperatures. First, they were asked whether the ability to demand short bursts of cooler air would improve the acceptability of a 24° C temperature setting. As Figure 29. below indicates, most respondents reported that such an option would make warmer default settings more acceptable. The technical details of this option are discussed further in a subsequent section. When asked, respondents reported the reasons bursts of cooling would help, ranging from environmental benefits to fast relief to helping maintain alertness. Many also explicitly acknowledged the tradeoff, reporting a willingness to compromise comfort for the sake of the environment. The following are several illustrative quotes from respondents:

- An active job resulting in leaving the office several times a day in the summer causes your body to heat up and so having shorter cooler bursts will help cool you down faster. Once body temp regulates cooler bursts won't be required
- perhaps [short burst of additional cooling] makes the cooler temp last longer
- Because it is the healthiest and most environmentally friendly option

On the other hand, respondents who were not positive about the burst of cooling option expressed concerns about occupants getting sick, becoming distracted by the bursts, or being left wanting more cooling.

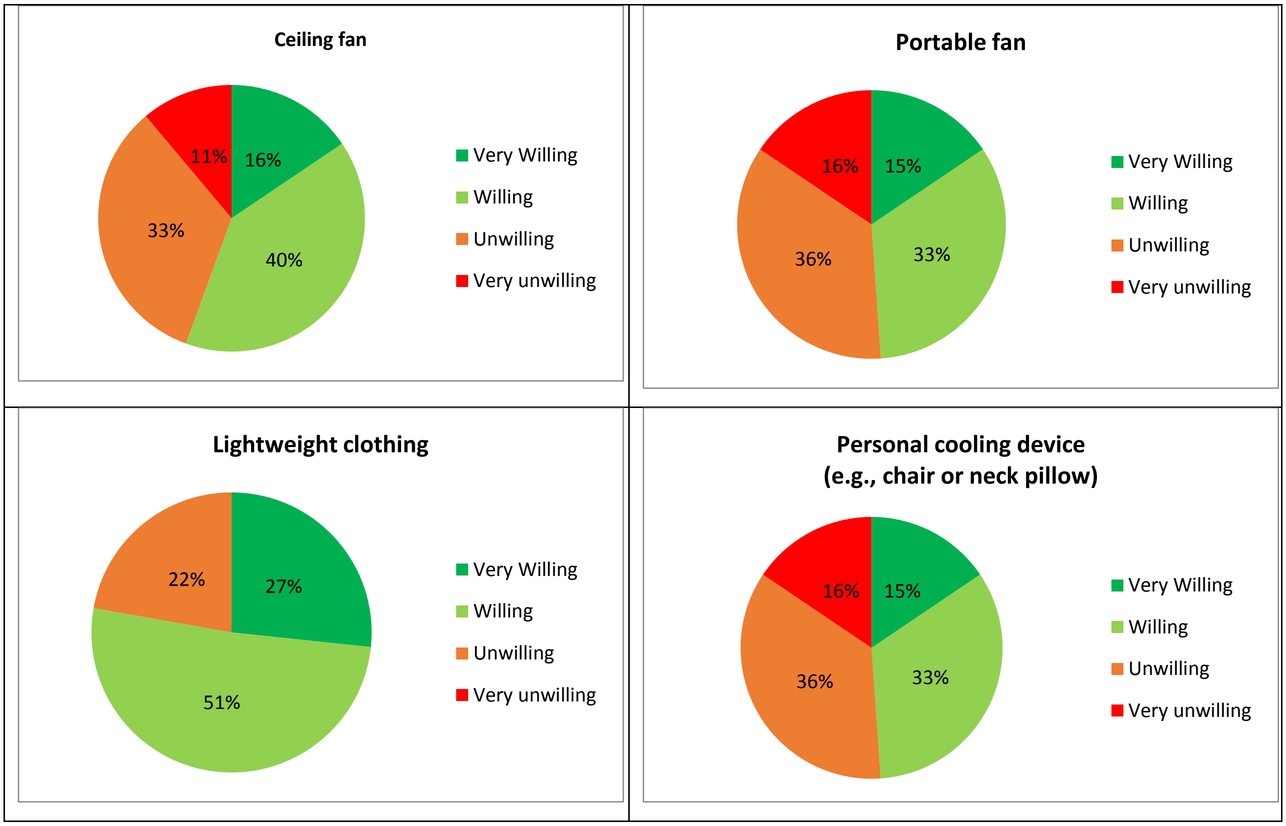
Figure 29 Effect of short bursts of cooling to mitigate warmer temperature settings



Respondents were then asked to offer their own ideas for what additional options might make 24° C more acceptable. Many of them mentioned common strategies such as lightweight clothing and fans. Some demonstrated a sophisticated understanding of thermal comfort issues, noting that blinds or tinted windows might help address solar gains. Others suggested that better insulation or fewer building occupants might make warmer temperatures more comfortable. Note, however, that again the issue of temperature setting is being conflated with thermostatic control and zoning. The factors listed are indeed important to ensure that the ambient temperature actually reflects the thermostat setting, and we have included recommendations to that effect in the sections below. More personal methods of seeking thermal comfort cited include drinking cold beverages, washing one's face, tying up one's hair, personal chillers/coolers, moving to another area of the building, and shifting working hours.

Respondents were asked about their willingness to utilize specific personal cooling devices designed to improve thermal comfort when indoor temperatures are slightly warm. Ceiling fans, personal fans, and personal cooling devices such as cooling chairs and neck pillows are acceptable to roughly half of respondents surveyed. More than three-quarters of respondents are willing to wear lightweight clothing to adapt to warmer indoor temperatures, as the charts below indicate.

Figure 30 Willingness to utilize alternative cooling methods



Finally, respondents were asked to provide their ideas on how to encourage people to accept slightly warmer indoor temperatures in a building utilizing solar AC. The most common recommendation is to raise awareness about the environmental benefits of reducing AC usage (or conversely the damage caused by AC usage). The following are selected quotes from respondents:

- “Building occupants should be given awareness on how much energy they are saving due to this 1C slight increase in indoor air temperature (from 23C to 24C) - Awareness on how HVAC systems are responsible for approximately 70% of energy consumption in Dubai. - The annual carbon footprint reduction of having a thermostat set to 24C instead of 23C. - An equivalent number of trees that would have to be planted to offset the carbon footprint of setting the thermostat to 23C instead of 24C."

- "The fact that the energy is renewable and efficient has to be heavily communicated to people. I think the severe lack of education and common knowledge amongst people about the topic is what perpetuates poor energy practices."

Another suggestion provided by several respondents is to inform occupants of the health benefits of turning up the thermostat (e.g., AC can be drying).

Overall, the survey provides evidence that many likely occupants of the Center of Excellence, including staff and occasional visitors, would be willing to accept warmer temperature settings, such as 24° C, especially when it benefits the environment. Many respondents also reported a willingness to utilize numerous strategies to improve their comfort when indoor temperatures are warmer than usual. Nevertheless, there are a significant number of respondents who reported resistance to higher temperatures. Thus, the acceptability of a 24° C cooling set point varies widely among respondents, as it will among building occupants. The sections below describe how to engage building occupants across the spectrum to ensure that an acceptable balance of energy conservation and thermal comfort is achieved.

6.2.1 Theory of behavior change

Many aspects of the recommended approach involve urging some behavior change on the part of building occupants. According to the Fogg Behavioral Model[11], there are three key elements of behavior change. As Figure 31 below illustrates, these are motivation, ability, and a trigger, which can be described as follows:

- **Motivation** encompasses elements such as needs, wants, beliefs, and incentives. Individuals must have the motivation to take action (e.g., tolerate a higher temperature).
- **Ability** relates to the time, cost, effort, knowledge, access and permission related to a particular course of action (e.g., adjust the temperature temporarily).
- **Triggers** are often required to overcome the inertia of the status quo, even when the motivation and ability to change exist.[12] Triggers can come in various forms, but they each serve to significantly raise the motivation or ability (or both) to take a certain action, such that the initial barriers are overcome and action is taken (e.g., discomfort triggers a switch to lightweight clothing).

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[11] See http://www.behaviormodel.org/ and Fogg (2009) for an overview.

[12] See Fogg 2009; and http://www.behaviormodel.org/triggers.html for an overview.

Figure 31 ***Formula for behavior change***

In order to ensure the success of the recommended approaches, each element of behavior change (i.e., motivation, ability and trigger) must be adequately addressed. The discussion of the recommendations that follows reflects that.

Note, however, that the necessity of an external behavioral trigger is largely circumvented by the recommended approach to thermostatic control. With a higher (energy conserving) set point, occupants will not have to actively choose to save energy. In this case, we are using the power of the status quo bias and the "hassle factor" – which both conspire to encourage occupants not to interfere with the thermostat settings, in turn saving energy relative to the typical 22°C setting.[13] The new default will require that individuals take action – by accepting, adapting, or demanding additional cooling – in accordance with their own self-interest. Thus, as long as their ability to take such actions is facilitated, their motivation should be adequate to prompt action, as desired. A discussion of each of the three possible types of reactions – and ways to encourage those that conserve energy - follows. Specifically, we propose a three-pronged approach to increase the acceptability of the system, with efforts aimed at: 1) encouraging acceptance of the system, 2) encouraging adaptation to the system, and 3) empowering occupants to make small changes to the indoor temperature to improve comfort and satisfaction. Each are discussed in turn.

6.2.2 Encouraging acceptance

Delivering energy savings and thermal comfort, while maintaining a higher-than-normal cooling set point, requires that occupants have both the motivation and ability to accept and adapt to the changes. In a non-residential setting, intrinsic motivation to conserve energy is the primary lever for behavior change, since most occupants do not typically derive the benefit of associated cost savings, a sometimes-powerful extrinsic motivator.

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[13] For an overview of these concepts, see http://www.ideas42.org/blog/principle/status-quo-bias/ and http://www.ideas42.org/blog/principle/hassle-factors-2/.

Motivation to conserve energy may be derived from a range of factors including environmental attitudes, social value orientation, and pressure from social norms.[14] However, note that individuals are also motivated by personal comfort, which will be in direct conflict with energy conservation, for those who prefer cooler indoor temperatures in summer. While conditioning a space involves an inherent trade-off between thermal comfort and energy conservation, there is also evidence to suggest that these factors can be mutually reinforcing. In particular, research has shown that individuals are more tolerant of, and even comfortable in, higher cooling temperatures when they have a strong motivation to conserve energy.[15] Thus, stimulating individuals' motivation to conserve energy is critical to gaining their acceptance of a slightly higher cooling set point.

However, it should be noted that solar power has been shown to present a perverse incentive to energy conservation.[16] Some occupants of zero-net energy buildings, powered primarily by solar PV, have expressed confusion about or resistance to energy conservation through higher cooling set points. Their belief is that there is no need to conserve because the solar power has no detrimental environmental effect. However, they do not appreciate the cost or environmental impact of providing additional solar panels, nor the ability to offset grid supply with excess generation, should the solar PV system produce more electricity than is needed.

Indeed, there are many aspects of solar-powered AC systems that typical building occupants do not understand. Thus, the primary method we recommend for increasing building occupants' motivation to conserve energy is to raise their knowledge and awareness. This would require providing building occupants with relevant information about how the AC system works; the relationship between temperature, energy consumption and system design; the environmental impact of energy savings/consumption; and social comparisons regarding thermal comfort. Providing this type of information could be achieved with a variety of outreach tools (i.e., touchscreen displays, public installation, thermostats). Several options are outlined to illustrate how each would work to promote acceptance and, indirectly, thermal comfort.

Few individuals understand how an AC system works, let alone a solar-powered one. The Center can play a vital role in changing that. Tablets or large touchscreens could provide visitors (and employees)

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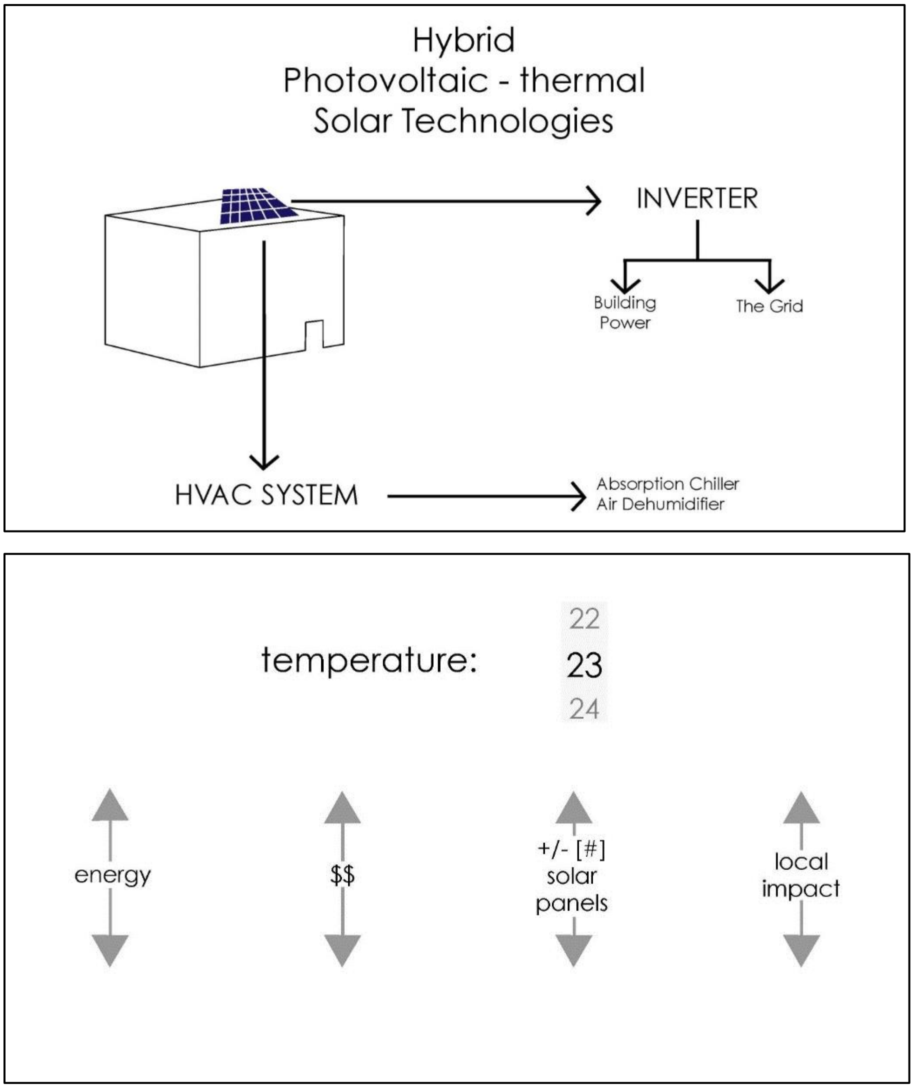
[14] Abrahamse et al (2005) presents a review of empirical studies on the effect of such factors. For a discussion of social norms and energy conservation, see http://www.ideas42.org/social-norms-and-energy-conservation/ and Alcott, 2011; Schultz, et al, 2007.

[15] Outcault, et al., 2014b

[16] Outcault, et al. 2014b;

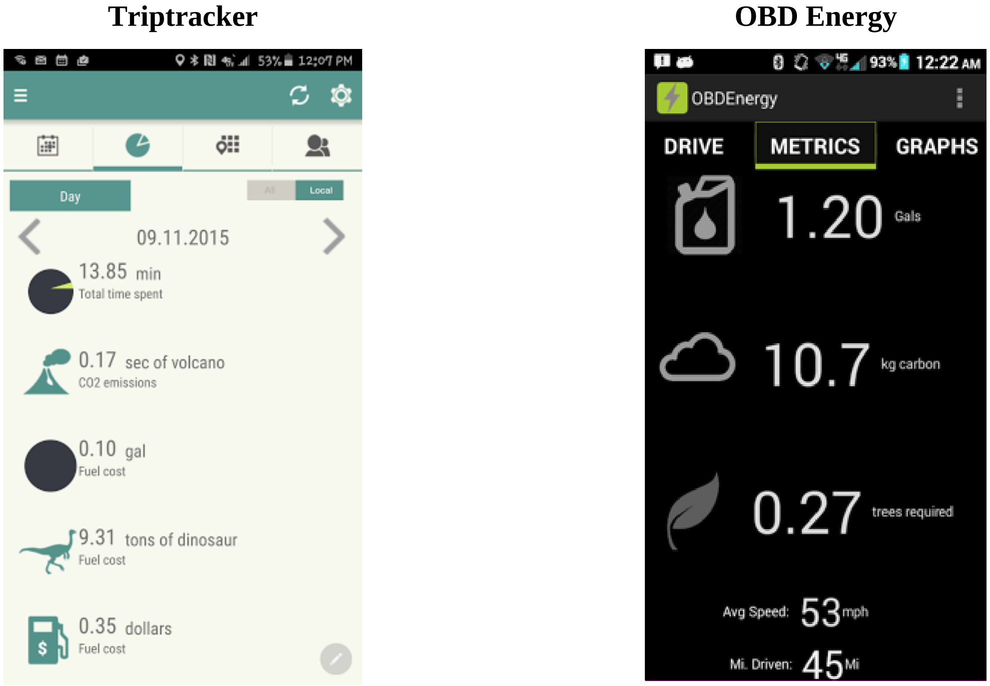
with access to a program that visualizes the solar PVT system and explains how it works. An interactive component could illustrate the effect of raising or lowering the temperature (in terms of system size, energy use and environmental impact). For example, by sliding the temperature setting on the screen up or down, users could see the knock on effects, in terms of the building's energy consumption, number of solar panels required and environmental impacts. Figure 32 includes a very rough mockup of two elements of such a program: one illustrating the system design and the other showing the relationship between temperature setting, system size and environmental impact.

Figure 32 Rough mockup of interactive program illustrating solar PVT AC system and the impacts of its use



While the above illustrates the straightforward relationships between temperature, energy and environment, more creative and impactful options exist. These include displaying equivalent energy saving activities (to emphasize the relative ease of saving energy through turning up the thermostat), carbon offsets, or energy consumption relative to conventional AC systems. Figure 33 provides two examples of energy consumption dashboards relating to transportation, designed by UC Davis researchers. Both provide concrete, alternative metrics to help users grasp the impact of their actions. Something similar could be incorporated into the touchscreen display illustrating the impact of temperature settings at the Center.

Figure 33 Examples of energy consumption feedback displays



Source: UC Davis' Consumer Energy Interfaces Lab http://tkstapleton.des157.net/des157/cenergi/projects.html

Social comparisons have also been successfully used to motivate behavior change with respect to energy conservation.[17] The user interface program could leverage the power of social norms by providing users with information about cooling norms around the world. For example, each temperature on the sliding scale (say, from 20 to 30°C) could be paired with the name of one or more countries for which that is the typical cooling temperature (e.g., 24°C in the United States,[18] 28°C in Japan[19]). Such information would

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[17] Allcott, 2011; Schultz et al., 2007; http://www.ideas42.org/social-norms-and-energy-conservation/

[18] HC 7.11, "2009 RECS (Residential Energy Consumption Survey) Survey Data," U.S. Energy Information Administration. http://www.eia.gov/consumption/residential/data/2009/xls/HC7.11%20Air%20Conditioning%20in%20West%20Region.xls.

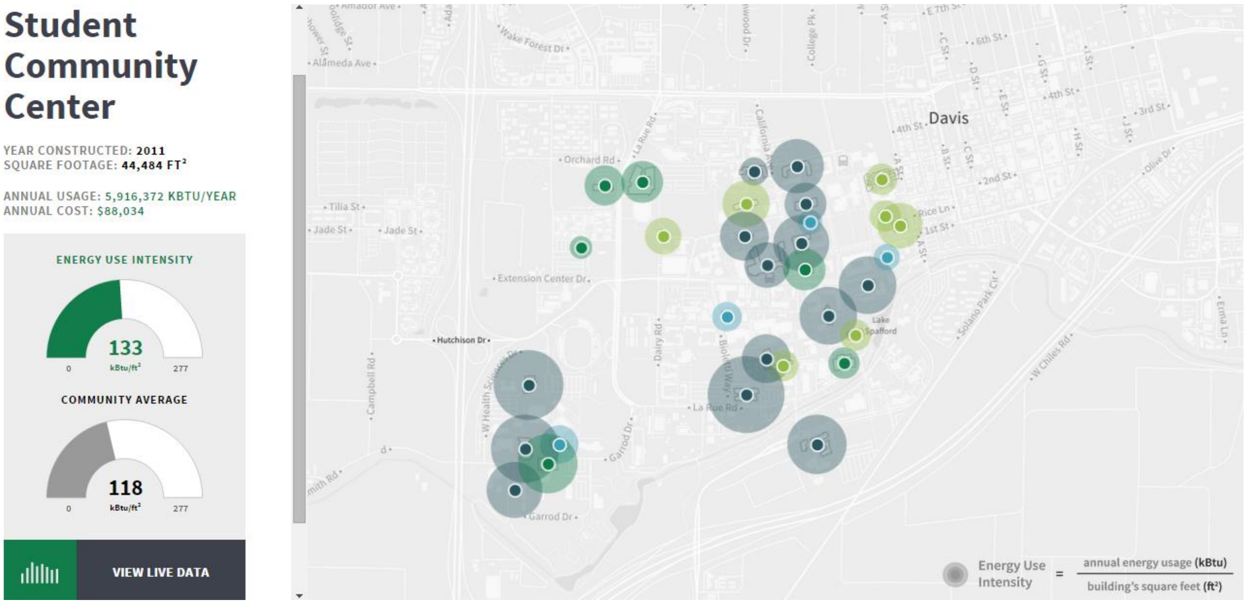
[19] *Household Energy-Saving Handbook*. Tokyo Metropolitan Governments. http://www.tokyo-co2down.jp/ecology/home/

serve to raise awareness about the heterogeneity of global cooling norms, subtly challenging the status quo, with the ultimate aim of changing expectations among visitors to the Center.

The design of a user interface program to inform visitors and regular occupants about the building's solar PVT AC system, energy consumption, environmental impacts and social norms would need to be intuitive, engaging, informative, and aesthetic. Many initiatives to promote energy conservation at the community level have utilized such an approach. Figure 34 below includes two examples: a dashboard from Oberlin College and another from UC Davis. Both provide users with information about building energy consumption over time and relative to some other factor (generation in the case of Oberlin and other buildings in the case of UC Davis). A user interface with a similar aim could be designed for touchscreens to be displayed at the Center.

Figure 34 Examples of energy consumption feedback displays

Source: http://buildingdashboard.net/oberlin/#/oberlin/ajlc



Student Community Center

YEAR CONSTRUCTED: 2011
SQUARE FOOTAGE: 44,484 FT^2

ANNUAL USAGE: 5,916,372 KBTU/YEAR
ANNUAL COST: $88,034

ENERGY USE INTENSITY: 133 kBtu/ft^2

COMMUNITY AVERAGE: 118 kBtu/ft^2

Energy Use Intensity = annual energy usage (kBtu) / building's square feet (ft^2)

Source: http://ceed.ucdavis.edu

The purpose of the touchscreen devices would be to provide detailed information and a participatory experience. However, it is important to engage and inform those individuals who will not take the time to interact with these resources. Thus, we also recommend the installation of a large-scale feedback device to support the Center's mission and purpose. In particular, a dynamic, public display of energy consumption or conservation, either against a goal or over time, could be an effective tool for engaging and informing visitors and regular occupants. We suggest Diamond Developers consider designing and installing a 3D, dynamic infographic – e.g., a sculpture that moves or lights up – to illustrate the building's AC-related energy use (or energy savings from the use of solar technology) in a way that captivates viewers. Again, UC Davis researchers have experience designing such a device, images of which are provided below to illustrate the concept. Note that the Social Energy Sensing Monument (SESEME) sculpture pictured below is part of an integrated interactive system that also allows users access additional information from smartphones. As a visitors center, we expect that the touchscreen displays recommended above would be a better format for providing such information to building occupants.

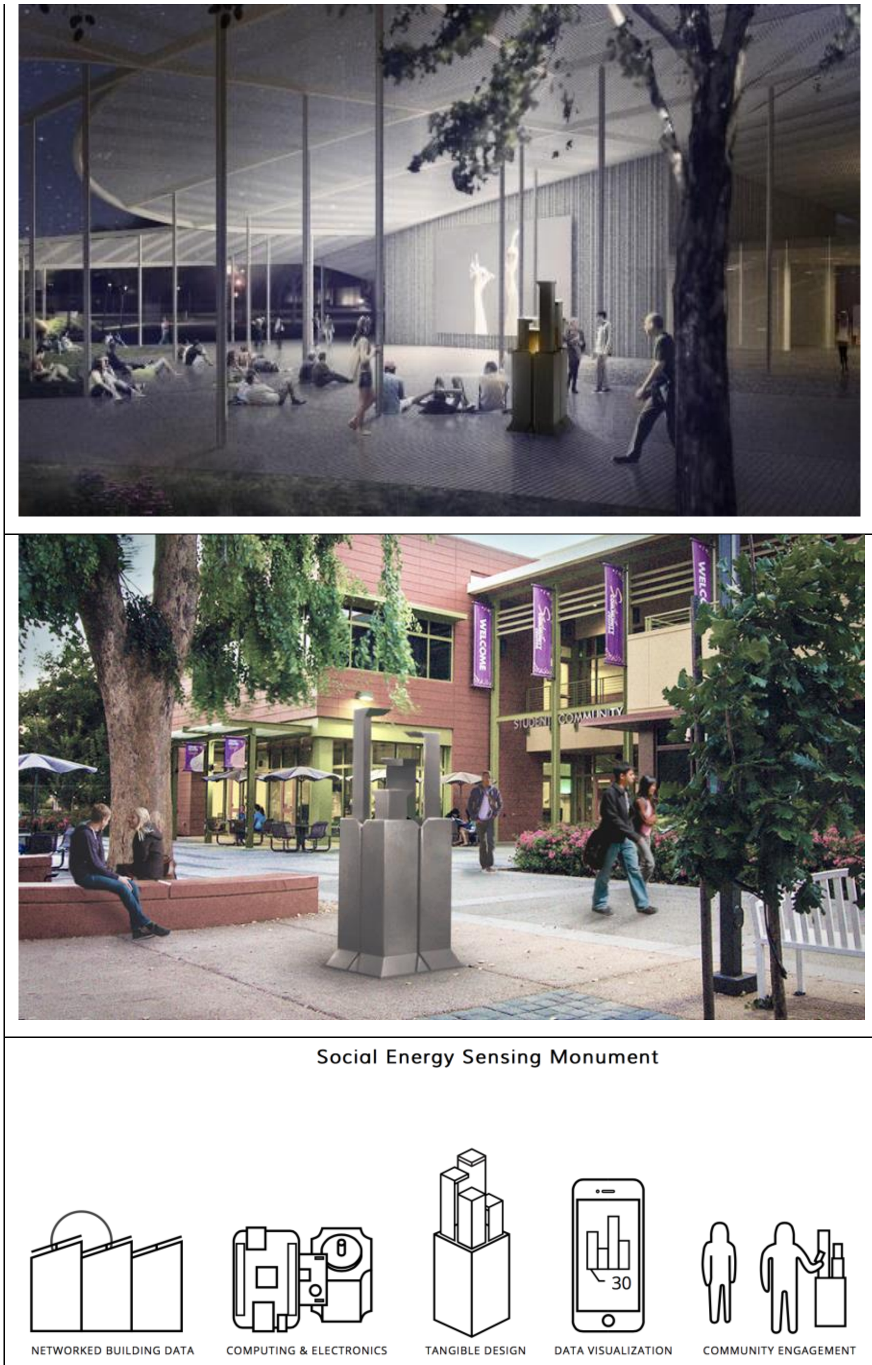


Figure 35 Example of 3D display illustrating energy consumption. Source: UC Davis' Consumer Energy Interfaces Lab. Temporary website: http://tkstapleton.des157.net/des157/InteractivePrototype/3.0/projects.html#

Finally, the typical device through which occupants interact with the HVAC system is the thermostat. Traditionally, thermostats have provided only minimal information, and no behavioral nudging. However, space conditioning-related products (e.g., thermostats, wall unit air conditioners and heaters) are increasingly being designed with feedback mechanisms built in to encourage conservation. It is recommended that the thermostats installed at the Center of Excellence be programmed to display an encouraging message when the temperature is set to 24°C or higher. The selected symbol or phrase should be appropriate for the context and universally understood, as the Center will attract visitors from diverse locations. Examples of symbols used by existing technology include a smiley face, happy Earth, green leaf, and changing the background display color or design. Customized options are possible, too, if the user interface is design especially for the Center.

The recommendations above focus on the intrinsic motivations to conserve energy by accepting a higher cooling set point. These will likely be adequate for occasional visitors, as the survey results presented above indicate. However, individuals who occupy the building very frequently, especially staff and employees, may require additional outreach measures to encourage acceptance of a higher cooling set point. Not only will they have greater exposure to the building, but employees often resist conservation measures urged by their employer because they may expect a certain level of comfort at work,[20] feel they require greater cooling to be productive at work (as noted by several respondents), and resent making sacrifices for which only the employer reaps the (direct) benefits, primarily through cost savings.

There is evidence that expectations influence one's reporting of thermal comfort.[21] Thus, future staff of the Center of Excellence should be made aware of the intended set point and provided with information explaining the reasoning behind it. They should also be given the opportunity to engage with the touchscreens, thermostats and large installation intended to raise awareness and acceptability.

Furthermore, Diamond Developers should consider exploiting the power of extrinsic motivations (e.g., awards, acclaim, money) for energy conservation. Prior research has shown that having a *concrete* motivation related to conservation is essential to maintaining sustained conservation behavior. Goal setting,[22] competition,[23] and commitments[24] have all proved successful mechanisms for encouraging behavior change. Each of these could be even more effective if paired with an extrinsic motivator. Thus, it is recommended that the Center of Excellence consider running competitions among its staff (either intra-agency or against a target) or encouraging staff to set goals and make commitments to reduced AC usage, and offering rewards as appropriate. Such activities could be essential to support sustained

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[20] Karjalainen, 2009
[21] Brager & deDear, 1998; Mishra & Ramgopal, 2013
[22] Becker (1978) is a classic reference.
[23] For example, see the City of Oberlin's electricity competition at: http://buildingdashboard.net/oberlincity/#/oberlincity/.
[24] See Seligman, 1977; Ashraf et al, 2006

behavior change until the desired outcome (i.e., reduced AC usage by maintaining a higher set point) becomes an ingrained habit.

6.2.2.1 Recommendations

- Install interactive touchscreen displays that inform users about the AC system, energy consumption, thermal comfort and environmental impacts
- Install a public installation to illustrate the building's AC-related energy use
- Install thermostats that provide feedback to encourage conservation
- Manage expectations by informing incoming staff who will work in the Center of Excellence of the default temperature settings

6.2.3 Encouraging adaption

In addition to *accepting* a slightly higher cooling set point, occupants of the Center of Excellence should be encouraged to *adapt* to the warmer indoor temperature. By raising the temperature, the default state will be conservation. This eliminates the problem many conservation schemes face when they depend on occupants to take some action in order to conserve. This approach uses the power of defaults and inertia to save energy.

But this does not have to mean that occupants will be uncomfortable. The human body is highly adaptable.[25] Building occupants can learn to accept warmer conditions, as described above, or they can take active steps to adapt. Their primary motivation for doing the latter will be personal comfort. Self-interest is indeed a powerful motivator. Here, the key is to facilitate occupants' *ability* to adapt, since they will likely already have the motivation to do so.

There are several ways occupants, particularly employees of the Center, could adapt to warmer indoor temperatures. As described in the January 2015 Progress Report, clothing is a critical element of thermal comfort. Through the formal dress code policy and employee training sessions, employees of the Center (e.g., management office workers, custodial staff, coffee shop workers) should be allowed and encouraged to wear lightweight clothing that would enable them to work comfortably despite slightly higher than normal indoor air temperatures. In addition, any uniforms issued should be designed for comfort in slightly warmer indoor temperatures, especially those for coffee shop and custodial workers whose jobs are active and located in potentially warmer areas of the building. Of course, it should be made very clear that the dress code calls for appropriate clothing to be worn at all times, and that the

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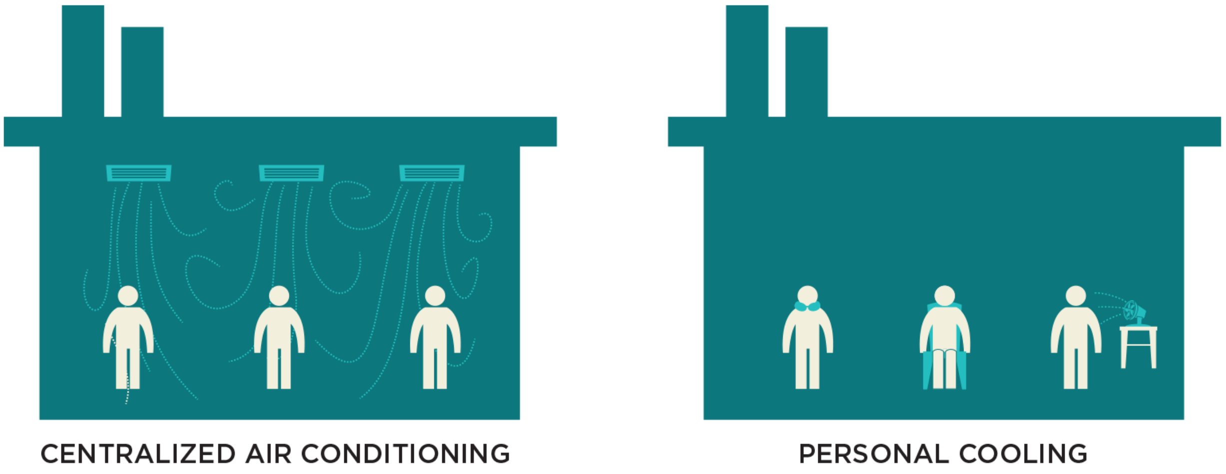
[25] Humphreys & Nicol, 1998; Mishra & Ramgopal, 2013

weight and breathability of the fabric is the only concession that should be made to the warmer temperatures (i.e., the standard rules about modesty and formality would still apply).

Other highly efficient means of adapting to warmer temperatures exist, including the use of personal cooling devices. By directly cooling occupants, instead of the air around them, such devices can ensure that occupants remain comfortable even when the thermostat is a bit higher.[26] Doing so avoids the need to cool an entire space, and thus avoids the associated energy consumption. Figure 36 illustrates how personal cooling devices focus on the microclimate of an occupant, unlike central cooling.

Figure 36 Visualization of two different cooling strategies



Examples of personal cooling strategies include the following:

- personal fans – small desk fans that increase air circulation lowering the perceived temperature around a person in a particular location
- cooling neck wrap – a reusable cloth filled with material designed to cool the user through direct contact without the use of energy
- cooling chairs – specialized seating designed to cool a person through direct contact with cooling technology

Figure 37 Personal cooling devices

Cooling neck wrap	**Cooling chair**

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[26] Information on current research in this area can be found at http://www.cbe.berkeley.edu/research/personal-comfort-systems.htm and http://www.cbe.berkeley.edu/research/wireless-power-transfer.htm.

Source: http://www.rei.com/product/691097/kafkas-kool-tie

Source: www.aquonchair.com

Of course, the energy consumption related to such devices, if applicable, must be accounted for, and be more than offset by the energy savings from increasing the cooling set point. For example, simple fans, although efficient, are often left on even when not in use. Smarter fans can detect a human present and turn off when the user has moved away. A policy allowing energy consuming cooling devices would have to ensure that the overall effect is improved comfort without the erosion of energy savings. We recommend that the use of personal cooling devices be considered as part of the thermal comfort strategy of the Center of Excellence.

6.2.3.1 Recommendations

- Develop appropriate dress codes that promote adaptive clothing
- Purchase uniforms (if appropriate) that are adapted to the warmer temperatures
- Develop a policy that allows efficient use of appropriate personal cooling devices

6.2.4 Empowering occupants to change temperature

Besides promoting the motivation to conserve energy, another way to increase the acceptability of higher set points is to increase occupant control over indoor temperatures. Numerous studies [e.g., Leaman and Bordass, 2001; van Hoof, 2008; Humphreys and Nicol, 2002; Haldi and Robinson, 2008; Paciuk, 1989] have documented the positive affect on thermal comfort of providing individual control of temperature. One by Karjalainen (2009), for example, found a strong correlation between satisfaction with room temperature and the perceived level of control over room temperature, in both home and office environments. Thus, one way to increase the acceptability of a higher cooling set point is to give occupants some level of control over the temperature. With proper design, such a compromise could allow the system to deliver both thermal comfort and energy conservation.

There is little scope for concern about occupants' motivation to change the temperature, albeit temporarily. The motivation will be comfort. As before, this reverse framing of energy conservation, i.e., that conservation mode is the default, avoids the need to create a behavioral trigger. The key will be ensuring that occupants have the *ability* to demand temporary relief from the higher set point, the success of which will depend on the user interface. The typical device occupants use to modify indoor temperatures is a thermostat, but their mere existence in a space does not guarantee occupants' ability to use them. For example, Karjalainen and Koistinen (2007) found that poor access, usability and knowledge of thermostats made their presence nearly irrelevant. In addition to motivation, occupants must have:

- Access, in terms of permission and physical reach; and
- Ability, that is, physical and mental capacity to operate the thermostat[27].

Both physical access and permission to use thermostats can be a significant problem, particularly in non-residential settings. Granting access to thermostats is somewhat complicated by the fact that they are almost always operated by multiple users. The fact that no single individual is the "owner" of the thermostat may result in a failure to implement an optimal schedule of set points. Researchers have uncovered collective use of thermostats to be a significant problem in commercial buildings.[28] What adaptations are made to accommodate collective use and mitigate its impact on energy use, focus primarily on "locking out" users. Doing this runs the risk of compromising occupant satisfaction and comfort.

Establishing differing levels of access can be a promising solution. For example, some sophisticated thermostats can be programmed to offer a different interface (and set of options) to "Administrators" and "Occupants". The former would be responsible for establishing an appropriate setback schedule, as described earlier, while there are a variety of options for the latter, as discussed below.

The key to balancing energy conservation and thermal comfort through occupant control is to establish mechanisms for selectively increasing cooling to an extent that improves comfort without completely eroding energy savings. In addition to the adaptive techniques described above, to make the higher cooling set point more palatable, we recommend that the system be designed to allow occupants to demand temporary temperature reductions, when needed.

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[27] Access and ability reflect what Wyon (1996) calls the 3I-Principle, which says that for effective temperature control, users must have Insight (i.e., understanding of how the HVAC system and thermostat work), Information (i.e., knowledge of how to use the thermostat), and Influence (i.e., the power to make temperature adjustments).

[28] Karjalainen & Koistinen, 2007

As discussed above, a schedule of setbacks should be programmed into the building's thermostatic controls to ensure that the space is not conditioned during off-hours (e.g., nights, holidays). However, given the intended purpose of the Center of Excellence, predicting room occupancy more precisely than that will be challenging, or impossible. Thus, the controls system should be designed to account for room occupancy such that the temperature is lowered to the desired set point only when the room is occupied.

Thermostatic control options

There are a range of ways thermostatic control can be accomplished, each with its advantages and disadvantages. A brief overview of the options is provided. Controls systems are either reactive – i.e., responding to occupancy, or proactive – i.e., responding to a demand for conditioning. In addition, the demand for conditioning may be determined by humans or by technology. The table below illustrates the intersection of these two dimensions, and provides examples of each type of the mechanism.

Matrix of thermostatic control options

	Reactive	Proactive
Human-driven	▪ Override ▪ Timer ▪ Voting	▪ Programmable thermostat
Technology-driven	▪ Occupancy sensor ▪ Occupancy sensor fusion	▪ Predictive programming

Reactive controls include the following five options:

- **Override** – Thermostats (or other specially designed devices) allow occupants to request a time-bound override of the existing program. In this case, occupants would be allowed to lower the temperature from the default of 24°C by a degree or two, for example. The override would last a pre-determined amount of time, likely between 1 and 4 hours, which is referred to as a "hold". More energy is saved by selected a shorter hold period.

- **Timer** – Timers can be installed that allow the temperature to be lowered by a preset amount (likely one or two degrees) for a user-defined period of time. Again, the shorter the maximum time period allowed, the more energy is saved.

- **Voting** - A technology called Comfy has recently been developed by Build Robotics which allows building occupants to "vote" for their desired temperature through an app on their mobile phone.[29] The system then attempts to balance competing needs of the occupants who submit their preferences.

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[29] See http://www.buildingrobotics.com/comfy/.

- **Occupancy sensor** – A traditional infrared occupancy sensor is designed to sense when a room is occupied and adjust the temperature according to a preset mandate (i.e., drop from the setback temperature to the active cooling temperature of 24°C).

- **Occupancy sensor fusion** – Cutting edge technologies now merge data gathered from infrared sensors, CO_2 sensors, mobile phone signals, and lighting to determine occupancy more precisely.[30] Since infrared sensors alone detect only motion, they are imperfect at determining the presence and concentration of sedentary occupants, especially in large rooms. The fusion approach aims to address such shortcomings.

All reactive technologies have the disadvantage of adjusting the temperature only after the space has become occupied (excluding the possibility of voting remotely). The implication is that the space may initially be uncomfortably warm. By contrast, proactive technologies anticipate the conditioning needs of building occupants and typically trigger additional cooling in advance of occupancy. The latter delivers greater comfort, but uses more energy. Proactive thermostats include the following two main types:

- **Programmable thermostat** – These rely on humans to set schedules to condition the space to selected temperatures at selected times. In non-residential buildings this is often done by an administrator, either remotely for many thermostats at once or manually on each device. Programmable thermostats are widely available, fairly inexpensive, and familiar technology. They are most appropriate for spaces with predictable occupancy schedules. However, they can be difficult to program (and re-program when times or schedules change) and are not well suited to irregular occupancy.

- **Predictive programming -** Thermostats relying on artificial intelligence (e.g., Nest) attempt to circumvent the challenges users experience in programming their thermostats by carrying out that function themselves after an initial learning period. But there are some shortcomings to the technology. Field studies by the research team (Outcault, et al, 2014a) and other researchers have documented significant problems with usability with "smart" thermostats (Yang and Newman, 2013), especially when occupancy is irregular.

Above, seven mechanisms for changing the temperature to respond to occupancy are described. Each has its pros and cons. Additionally, there are options for how the AC system responds to occupancy. The traditional system response is to lower the cooling set point, either for a fixed or variable amount of time, depending on the controls technology. Recently researchers have been exploring an alternative, energy-saving approach in which systems are designed to offer an initial blast of cooling, and then allow the

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[30] Kleiminger et al, 2014

temperature to drift upwards.[31] This strategy draws on the principle of adaptive thermal comfort, which describes how the human body adjusts to gradual changes in temperature. Thus the initial blast of cold air-cools occupants, and they remain cool for a period of time even after the blast of cool air has ended. This strategy might be appropriate in small rooms, which are occupied sporadically, for relatively short periods of time (e.g., conference rooms).

Determining the optimal controls device and cooling strategy requires thinking carefully about how a space will be used, when, and by whom. As a baseline, programmable thermostats should be installed in each discrete space and networked to allow for centralized control. Each should be programmed in a manner appropriate to their anticipated occupancy, with reasonable setbacks for times when the building is closed and when the space is temporarily unoccupied during the day, as mentioned earlier.[32] Large spaces that hold many occupants and take a long time to cool down (e.g., auditorium, lobby) would be best cooled proactively through scheduling or adjustments to the schedule. Small changes around the set point could be made by occupants through voting technology as a way of engaging occupants and encouraging conservation. As a side note, we recommend that entrance to the Center be designed to supply a blast of cooling that is colder than the standard set point. This will help occupants cool down quickly after coming inside, making the slightly warmer 24° C set point more comfortable after adaptation.

For smaller spaces used by repeat occupants (e.g., management offices, conference rooms), we would recommend controls technology that requires user input. Although much of the latest technology is being designed to exclude ongoing human input, we believe that is a mistake. Human-driven options shift the responsibility for demanding additional cooling to the occupants themselves. This has (at least) two distinct benefits: it raises awareness about energy consumption by engaging occupants and (indirectly) improves occupant comfort by empowering occupants to influence the indoor temperature. There is support for this approach in the thermal comfort literature. According to Peffer et al. (2011), the "optimal path is to provide choices in the balance between user control and automated features." We agree with this approach.

To that end, we would recommend Diamond Developers consider installing devices that facilitate shared control, where appropriate. These could include room thermostats, "blast buttons", timers, or thermostat voting technology. Room thermostats could be programmed to allow occupants to temporarily demand

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[31] See Krioukov & Culler (2012) for an example.
[32] Note the setback temperatures may be different for these two cases.

up to two degrees cooler (down to 22), and up to 4 degrees warmer. On that latter point, it is important to note that occupants could be offered a range of thermostatic control options, including fixed or variable set points that temporarily raise or lower the temperature by a predetermined or user defined amount, respectively[33]. Again, such overrides would be time limited, typically ranging from 1-4 hours.

Alternatively, “blast buttons” could be installed that allow occupants to demand a short-term burst of cold air. These have the advantage of being simple, requiring no decisions about intensity or duration of additional cooling. However, occupants who desire prolonged periods of additional cooling would need to activate the blasts repeatedly.

Thermostat timers would allow multiple users to demand additional cooling for a user-defined period of time. The associated set point would be pre-programmed, again eliminating the need for users to decide on the desired temperature. Thermostat timers have the advantage of a simple, easy and intuitive user interface.

Finally, technology that allows building occupants to vote on their preferred temperature (e.g., Comfy, UC Davis’s Thermostat[34]) is another option. Unlike the others, these technologies acknowledge the fact that thermal comfort varies across individuals and therefore preferences may differ, and attempts to mitigate the “thermostat wars” that sometimes ensue in shared spaces.[35] Figure 38 presents several images from UC Davis’s app called Thermostat, which is used to collect feedback on thermal comfort and energy use. Note, the image of a cow was selected because it has symbolic meaning in the UC Davis community. An application designed for the Center of Excellence would benefit from following that example and utilizing a locally meaningful icon. It is widely believed that more highly targeted user interfaces are more effective than generic ones.

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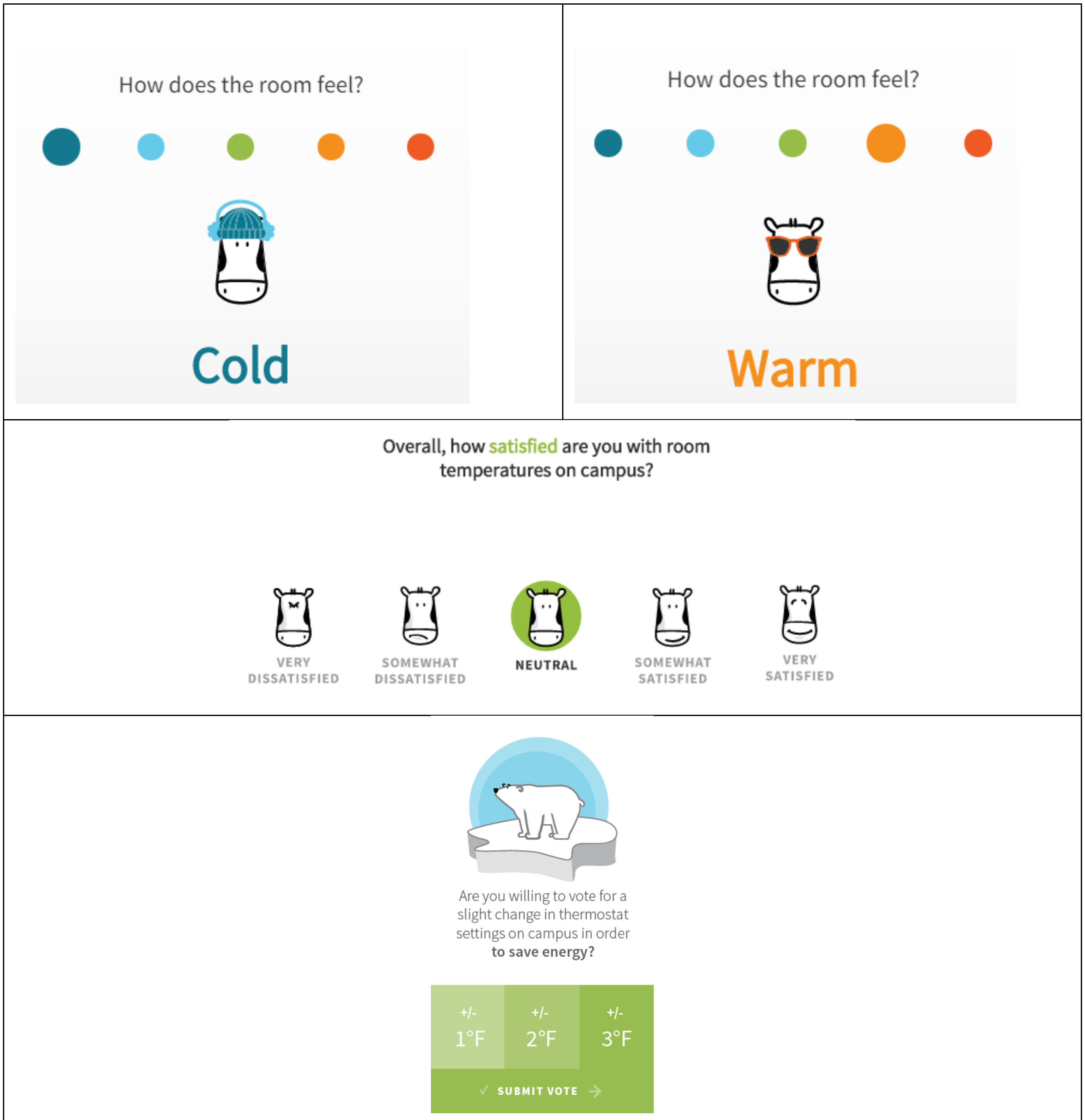
[33] Allowing occupants to increase the temperature, and therefore conserve energy more aggressively, would emphasize the request to conserve energy and improve thermal comfort for those who prefer warmer temperatures.

[34] See http://thermoostat.ucdavis.edu. Note that input collected through the Thermostat interface do not yet influence thermostat settings, although that is the eventual goal.

[35] McCalley et al., 2005

Figure 38 Selected images from the UC Davis Thermostat mobile application



How does the room feel?

How does the room feel?

Overall, how satisfied are you with room temperatures on campus?

Are you willing to vote for a slight change in thermostat settings on campus in order **to save energy?**

Source: http://thermoostat.ucdavis.edu

In public spaces this type of interface would require users to have a mobile phone, the app, and data service, while office workers could access voting technology through their smart phones or computers. Alternatively, custom devices could be designed to promote access to voting (e.g., wall-mounted voting units, handheld devices in the armrest of auditorium seats). Of course, to ensure that such diffuse control does not lead to greater energy consumption, the temperatures from which occupants are permitted to select would have to be relatively conservative.

Each of the above options would allow occupants to demand cooling and feel a sense of control, which would both directly and indirectly improve thermal comfort, respectively. Some are very simple to operate, while others require greater user engagement. Each has advantages and disadvantages in a given setting.

Ideally, a variety of technologies would be installed along with monitoring devices to measure how well each technology performed in each setting, and the associated energy consumption/savings. There is a great need for information on field performance of leading edge thermostat technologies, and the Western Cooling Efficiency Center at UC Davis has experience conducting field experiments such as this.[36] Using the Center of Excellence as a test site could be one way in which the Center accomplishes its mission of education and outreach.

In addition, all of the above options leverage the principles of behavioral science to conserve energy; each reverses the logic of a traditional programmable thermostat by defaulting to an energy saving setting unless greater cooling is demanded. This frames the decision to engage with the thermostat (or other control device) differently: changes to the settings are motivated by a desire for cooling, expressed explicitly through interaction with the device - rather than a desire for conservation, as is the case with programming setbacks or manually turning up the thermostat. To the extent that comfort is a more potent motivator than conservation, this approach can be a powerful tool for energy conservation, while providing some measure of occupant control.

Interface design

Assuming access to the selected technology (or technologies) is granted to end users, their ability to effectively use controls is affected by the level of effort, knowledge, physical and mental capacities required to operate them. In fact, one study of thermostat use in office buildings found that the presence of room thermostats is nearly irrelevant if they have poor usability.[37] Even highly motivated users can be put off by unappealing user interfaces, confusing directions, or simply forgetting to change settings when appropriate.

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[36] See project report at http://wcec.ucdavis.edu/wp-content/uploads/2014/10/OutcaultACEEE_Thermostats.pdf.
[37] Karjalainen & Koistinen, 2007

Although many modern thermostats have attempted to improve user interface (see Meier et al., 2010 for examples), many are still found to be hard to understand and difficult to learn and remember (Pfeffer et al. 2011). Symbols are not uniform across systems, which confounds learning and retention. A lab study by Meier et al. (2011) found that some thermostats are so difficult to use that 50% of users failed even the simplest task assigned (e.g., switching from “off” to “heat”). Thermostat manuals can be long and confusing, and are unlikely to be utilized by typical occupants in a non-residential building such as the Center of Excellence.

Thus, while the motivation to change the temperature will exist, the *ability* to demand temporary temperature reductions will hinge on well-designed occupant-friendly thermostatic control devices. The technology selection or design process should bear this in mind.

Furthermore, whichever technology is utilized to deliver sporadic cooling, as demanded by occupants, the interface design should be such that the motivation to conserve energy is reinforced. Thermostats, or other devices that allow occupants to demand cooler temperatures for a short period, should be designed to remind occupants of the additional energy consumption associated with additional cooling. User interfaces could be programmed to provide negative feedback (e.g., snowflake, red symbol, discouraging phrase) when demanding additional cooling. Such reminders about the increased energy use will nudge occupants to use overrides or blast buttons sparingly.

Conversely, a device that enables occupants to increase the temperature temporarily, if such is selected, should “reward” the user who chooses a temperature higher than the default (24°C) with positive feedback (e.g., an encouraging phrase, or symbol). For example, the UC Davis Thermostat app displays more or less ice and blue sky (as shown in the Figure below) depending on the number of degrees by which users are willing to increase the cooling temperature setting, thereby conserving energy.

+ 1°F	+ 2°F	+ 3°F

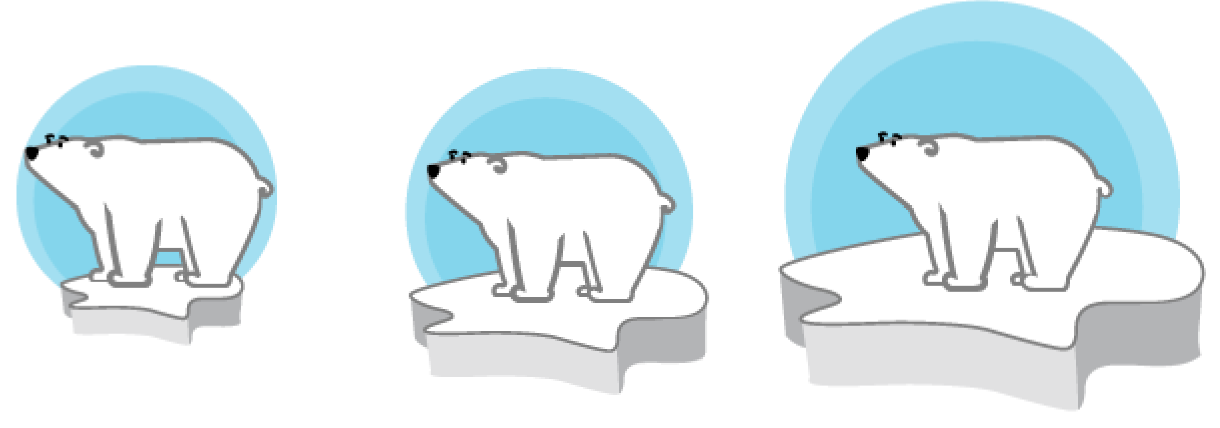

Figure 39 Thermoostat's feedback on voluntary temperature changes. Source: http://thermoostat.ucdavis.edu

Extending some measure of control over the building's air conditioning to the occupants within, if done carefully, can be a powerful conservation strategy. Empowering occupants to change settings, even within an approved narrow range, can improve thermal comfort both directly and indirectly, and save energy while doing so. Balancing the often-competing goals of energy conservation with occupants' thermal comfort requires thoughtful understanding of and engagement with building occupants, as well as appropriate technology choices.

6.2.4.1 Recommendations

- Establish conservative setback schedules reflecting anticipated occupancy
- Select controls technologies that allow occupants to demand additional (or reduced) cooling for limited periods of time. Technology choice should be driven by how each space will be used, when and by whom (see Table X below for more details).
- Deliver additional cooling at entrances to the Center to promote rapid adaptation to indoor temperatures
- Consider obtaining a customized controls solution that facilitates limited occupant control and incorporates best practice in interface design and feedback to reinforce conservation behaviors.
- Consider utilizing the Center of Excellence as a test site for monitoring controls performance – in terms of occupant comfort and energy use – of selected technologies

6.3 Conclusion

Conserving energy related to space conditioning requires selecting appropriate technology and developing a partnership with building occupants. The latter must be informed, engaged, empowered, and motivated to accept, adapt to, and control the thermal conditions in ways that save energy. Accomplishing this requires careful consideration of the social and behavioral factors that drive attitudes and decisions regarding thermal comfort. With thoughtful implementation, the Center of Excellence can strike a balance between comfort and conservation, and raise awareness about sustainable AC systems among visitors and regular occupants alike.

In the above, twelve recommendations are provided. Eleven of them are location-specific. That is, their applicability depends on the way a particular space will be used, when and by whom. The table below identifies the locations within the Center of Excellence to which each of the ten recommendations is most applicable.

Summary of the recommendation for various section of the Center of Excellence Building.

Recommendation	Locations				
	Coffee Shop	Lobby	Auditorium	Conference Rooms	Management Offices
Informing occupants					
Install interactive touchscreen displays to inform users about the AC system and its impacts		x			
Install a public installation to illustrate the building's AC-related energy use		x			
Install thermostats that promote conservation through feedback	x			x	x
Manage expectations by informing future staff of the default temperature settings	x			x	x
Empowering occupants to adapt to ambient conditions					
Develop dress codes that promote adaptive clothing	x			x	x
Purchase light-weight uniforms	x				
Develop a policy that allows efficient use of appropriate personal cooling devices	x			x	x
Controlling ambient conditions					
Establish conservative setback schedules based on occupancy	x	x	x	x	x
Select controls technologies that allow occupants to demand additional (or reduced) cooling for limited periods of time	x	x	x	x	x
Programmable thermostat	x	x	x	x	x
Predictive thermostat	x	x			x

Occupancy sensor	x			x	x
Override				x	x
Voting	x	x	x	x	x
Timer				x	x
Deliver additional cooling at entrances to the Center to promote rapid adaptation to indoor temperatures		x			
Consider obtaining a customized controls solution that facilitates limited occupant control and incorporates best practice in interface design and feedback mechanisms	x	x	x	x	x

6.4 Next steps

We have provided twelve recommendations on the human factors related to ensuring performance of the solar PVT system designed in the current project. As development of the Center of Excellence progresses, many decisions will need to be made regarding technology choice and occupant engagement. To ensure that the sustainability goals are met, occupants must change their behavior to meet expectations. Facilitating behavior change will require ongoing interventions to inform, educate, and nudge occupants toward the desired energy use habits. Further research would be valuable to determine which technologies and interventions would be most effective at influencing occupants' choices and delivering sustained energy savings.

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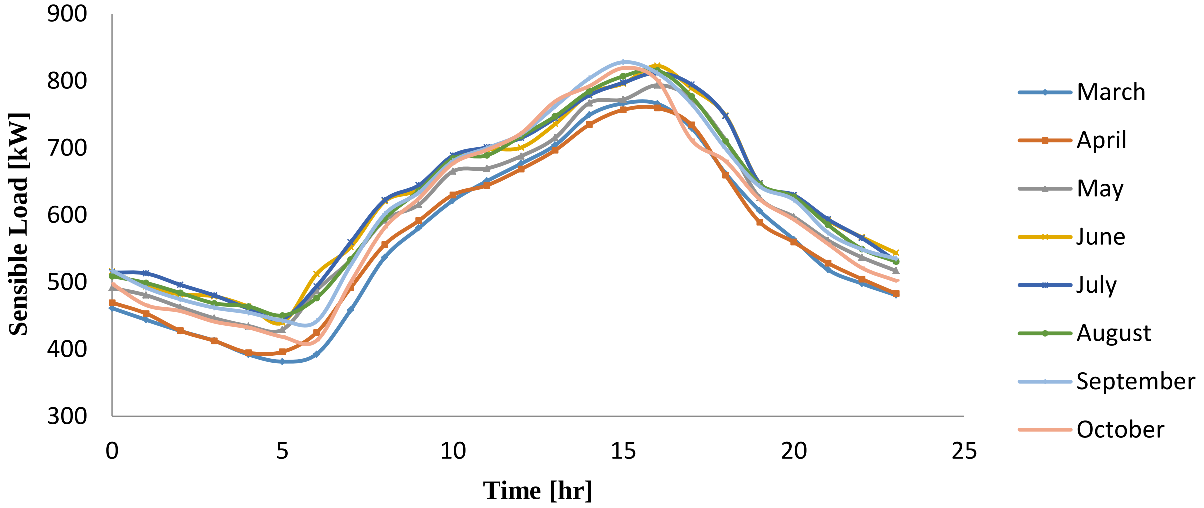
Conclusions and Next Steps

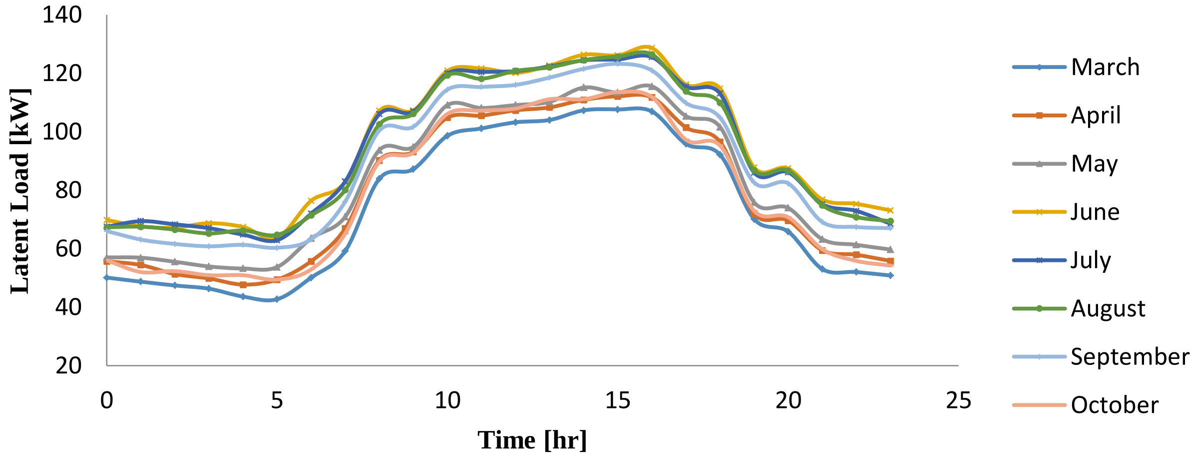
The thermal comfort analysis showed that for 9 months of the year the cooling and dehumidification air conditioning is required for the building. Since the Center of Excellence is composed of a large auditorium, which might not be in use all the time, two independent air conditioning system based on absorption chillers were considered for the building. The input energy for the absorption chillers will be provided by evacuated tube solar thermal collectors. The photovoltaic panels will be used to provide the required electrical energy for the building. We also evaluated the use of building integrated photovoltaics as windows and facades. The life cycle analysis of the solar powered air conditioning shows a convenient payback time of 4 years. In the next step, we prepared a social and behavioral study to understand the thermal comfort criteria for the people living in the region. Based on the social study we proposed educational and sustainable practices for various sections of the building.

The next steps will require detailed design of the solar powered air conditioning for Diamond Developers engineers and contractors. Some of the social/behavioral studies will require the preparation of real-time data collection, visualization, educational and human interfaces. The preparation of these platforms could be among the next steps of the project. For consideration of the building integrated solar technologies, detailed design based on collaboration with building architectural design engineers and the recent data from solar providers is required.

Appendix 1



Auditorium Sensible Load Vs Time for Cooling Season



Auditorium LatentLoad Vs Time for Cooling Season

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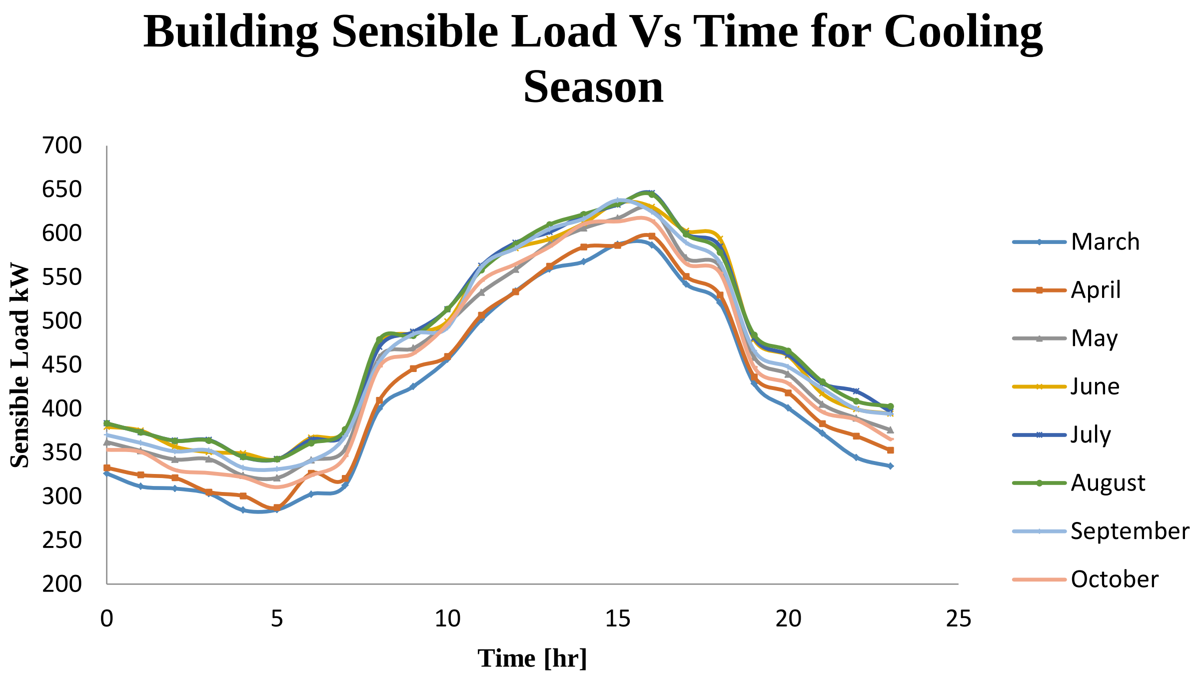
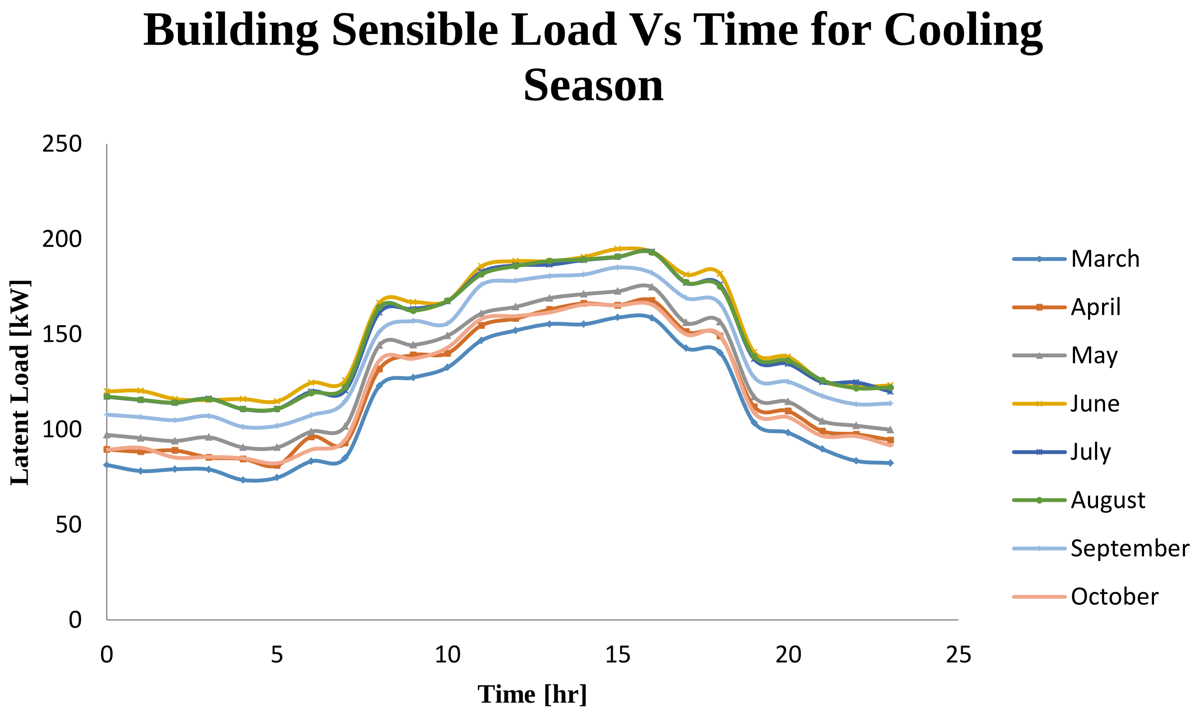

Building Sensible Load Vs Time for Cooling Season
Sensible Load kW
700
650
600
550
500
450
400
350
300
250
200
0
5
10
15
20
25
Time [hr]
March
April
May
June
July
August
September
October


Building Sensible Load Vs Time for Cooling Season
Latent Load [kW]
250
200
150
100
50
0
0
5
10
15
20
25
Time [hr]
March
April
May
June
July
August
September
October

Appendix 2

WIOSUN® COMBINED MODULE PV-Therm polycristalline

General

Cells	48 (6x8) polycristalline	Cellsize	156 x 156 mm
Frame	Polyurethan, black	Front glass	3.2 mm Solarglass
Connection	none, 3 bypass-diodes	Wire	4 mm² Solar cabel, 1300 mm length
Connector	MC4 compatible	Power tolerance	0 to + 4.99 Wp

Electrical Datas (STC*)

MODULETYPE			PVT-190P	PVT-195P	PVT-200P
Nominal Power	P_{MPP}	Wp	190	195	200
MPP-Voltage	U_{MPP}	V	24.20	24.40	24.50
MPP-Current	I_{MPP}	A	7.85	7.98	8.05
Open-circuit voltage	U_{OC}	V	29.04	29.28	29.52
Short-circuit current	I_{SC}	A	8.65	8.80	8.95
Module efficiency	η%		14.50	14.88	15.26
Cell efficiency	η%		17.40	17.60	17.80

Electrical Datas (NOCT**)

Nominal Power	P_{MPP}	Wp	163.59	166.89	169.99
MPP-Voltage	U_{MPP}	V	23.99	24.19	24.38
Open-circuit voltage	U_{OC}	V	28.52	28.76	28.93
Short-circuit current	I_{SC}	A	7.12	7.25	7.39

Thermal Datas

Receptive surface	1.305 m²
Connections	DN 15
Liquid capacity	3.88 l
System pressure	max. 1.5 bar
Test pressure	max. 2.5 bar
Flow rate per module	30-100 l/h
Delta T	5K / STC
Operating temperature	-20 °C to 75 °C
Stagnation temperature	75 °C
Efficiency (η_0)	71.5 %
Collector energy output (η_0)	ca. 930 W_{th}
Thickness heat exchanger	0.8 / 1.5 mm

Thermal Datas II

Thermal Datas II	not insulated	insulated
Collector efficiency (η_0)	71.5 %	71.5 %
Heat loss coefficient b_1 ($T_m=T_u$)	22.89 $\frac{W}{m^2K}$	7.98 $\frac{W}{m^2K}$
Collector power output ($T_m-T_u=5K$)	781 W_{th}	878 W_{th}

Temperature coefficients

Temperature coefficients I_{SC}	+ 0.04 % / K
Temperature coefficients U_{OC}	- 0.34 % / K
Temperature coefficients P_{MPP}	- 0.48 % / K
NOCT	48 °C ± 2 °C

Limits

System voltage max.	600V / 1000V
Reverse current max.	24 A
Operating temperature	- 40 °C – 80 °C
Maximum load	5400 Pa/m² = 550 kg/m² (75 lbs/ft²)
Safety class	II

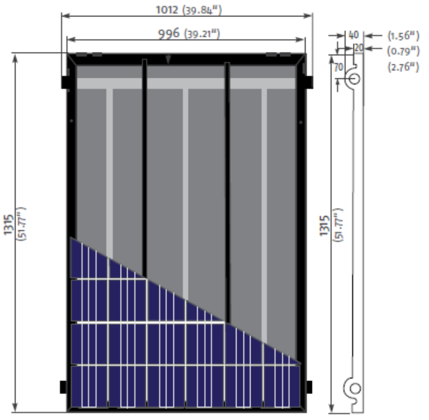
Certifications and warranty

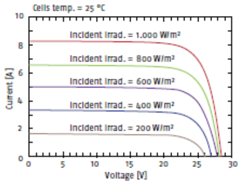
TÜV	IEC 61215, IEC 61730, 1703 i. p.
Product warranty	5 years
Performance warranty	linear 25 years

Mechanical Datas

Dimensions	1315 x 1012 (996) x 20 mm ±1 mm 51.77 x 39.84 x 0.79 inch ±0.03 inch
Weight	40 kg | 88.18 lbs

Technical drawing



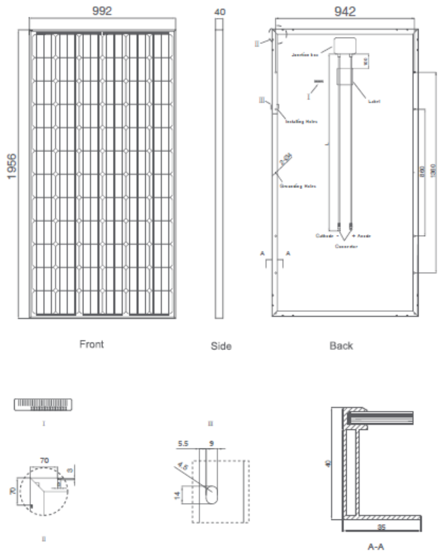


PV CYCLE CE

Your WIOSUN® Dealer

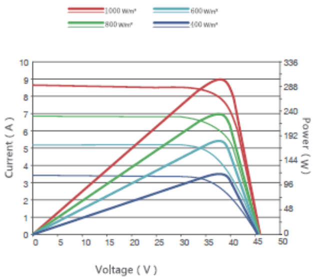
Appendix 3

Engineering Drawings

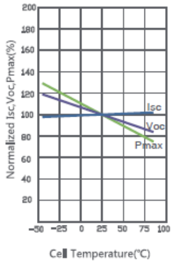


Electrical Performance & Temperature Dependence

Current-Voltage & Power-Voltage Curves (300W)



Temperature Dependence of Isc,Voc,Pmax



Mechanical Characteristics

Cell Type	Mono-crystalline 156×156mm (6 inch)
No.of cells	72 (6×12)
Dimensions	1956×992×40mm (77.01×39.05×1.57 inch)
Weight	26.5 kg (58.4 lbs.)
Front Glass	4.0mm, High Transmission, Low Iron, Tempered Glass
Frame	Anodized Aluminium Alloy
Junction Box	IP67 Rated
Output Cables	TÜV 1×4.0mm², Length:900mm

Packaging Configuration

(Two boxes = One pallet)

25pcs/ box, 50pcs/pallet, 600 pcs/40'HQ Container

SPECIFICATIONS

Module Type	JKM300M		JKM305M		JKM310M		JKM315M		JKM320M	
	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax)	300Wp	222Wp	305Wp	226Wp	310Wp	230Wp	315Wp	234Wp	320Wp	238Wp
Maximum Power Voltage (Vmp)	37.0V	35.1V	37.2V	35.3V	37.4V	35.5V	37.6V	35.8V	37.8V	35.9V
Maximum Power Current (Imp)	8.11A	6.32A	8.20A	6.39A	8.29A	6.47A	8.38A	6.54A	8.47A	6.62A
Open-circuit Voltage (Voc)	45.5V	42.8V	45.7V	43.2V	45.9V	43.5V	46.1V	43.9V	46.4V	44.1V
Short-circuit Current (Isc)	8.64A	6.96A	8.72A	7.01A	8.80A	7.06A	8.87A	7.10A	8.98A	7.15A
Module Efficiency STC (%)	15.46%		15.72%		15.98%		16.23%		16.49%	
Operating Temperature(℃)	-40℃~+85℃									
Maximum system voltage	1000VDC (IEC)									
Maximum series fuse rating	15A									
Power tolerance	0~+3%									
Temperature coefficients of Pmax	-0.40%/℃									
Temperature coefficients of Voc	-0.29%/℃									
Temperature coefficients of Isc	0.05%/℃									
Nominal operating cell temperature (NOCT)	45±2℃									

STC: Irradiance 1000W/m² Cell Temperature 25°C AM=1.5

NOCT: Irradiance 800W/m² Ambient Temperature 20°C AM=1.5 Wind Speed 1m/s

* Power measurement tolerance: ± 3%

Appendix 4- Thermal Comfort Survey

This section contains the questions, which was used for the online thermal comfort survey.

Sustainable City - Thermal comfort survey

Q1 In preparation for the design of the Center for Excellence at the Sustainable City, this survey has been prepared for Diamond Developers to gather input on preferences regarding indoor air temperatures in the workplace. Please take a few moments to provide us with your feedback. Your responses will be gathered anonymously and used to improve the design of various aspects of the Center for Excellence. Thank you!

Q2 Who is your employer and what is your position?

Q3 In a typical week, how many hours do you spend in your current workspace?

○ 1 - 10 hrs. (1)
○ 11 - 30 hrs. (2)
○ 31 or more hours (3)

Q4 Which option best describes the workspace in which you spend most of your working hours?

○ Cubicle (1)
○ Closed office (shared) (2)
○ Closed office (not shared) (3)
○ Other open space (4)
○ Other closed space (5)

Q5 Do you have the ability (both access and permission) to change the temperature in your workspace?

○ Yes (1)
○ No (2)

Q6 How physically active is your job?

○ Very (1)
○ Somewhat (2)
○ A little (3)
○ Not at all (4)

Q7 How old are you?

○ 30 years or younger (1)
○ 31-50 years of age (2)
○ 51 years or older (3)

Q8 What is your gender?

○ Male (1)
○ Female (2)

Q9 What is your preferred temperature (in degrees Celsius) in your workspace in summer?

Q10 Is central AC the primary method used to cool the building in which you work?

○ Yes (1)
○ No (2)
○ I don't know (3)

Answer If Is central AC the primary method used to cool the building in which you work? I don't know Is Selected Or Is central AC the primary method used to cool the building in which you work? No Is Selected

Q45 Are there wall or window AC units in your workspace?

○ Yes (9)
○ No (10)

Answer If Are there wall or window AC units in your workspace? No Is Selected

Q11 Without central AC, window or wall AC units, how is your office cooled?

Q13 At what temperature is the AC typically set (in degrees Celsius) in your workspace while it is occupied in the winter? If you're unsure, just provide your best guess.

	18 (1)	19 (2)	20 (3)	21 (4)	22 (5)	23 (6)	24 (7)	25 (8)	26 (9)	27 (10)	28 (11)	29 (12)	30 (13)
°C (1)	○	○	○	○	○	○	○	○	○	○	○	○	○

Q12 At what temperature is the AC typically set (in degrees Celsius) in your workspace while it is occupied in the summer? If you're unsure, just provide your best guess.

	18 (1)	19 (2)	20 (3)	21 (4)	22 (5)	23 (6)	24 (7)	25 (8)	26 (9)	27 (10)	28 (11)	29 (12)	30 (13)
°C (1)	○	○	○	○	○	○	○	○	○	○	○	○	○

Q16 When you are in your workspace in the summer, how does the temperature you indicated in the previous question feel to you?

○ Very Cold (1)
○ Cold (2)
○ Cool (3)
○ Neither Cool nor Warm (4)
○ Warm (5)
○ Hot (6)
○ Very Hot (7)

Q17 When you are in your workspace in the summer, how comfortable is the AC temperature you indicated above?

○ Very Comfortable (1)
○ Comfortable (2)
○ Uncomfortable (3)
○ Very Uncomfortable (4)

Q18 When you are in your workspace in the summer, how acceptable is the AC temperature you indicated above?

○ Very Acceptable (1)
○ Acceptable (2)
○ Unacceptable (3)
○ Very Unacceptable (4)

Q19 If given the option, would you change the temperature setting in your workspace in the summer?

○ Yes, I would select a higher temperature (1)
○ Yes, I would select a lower temperature (2)
○ No, I would not change the temperature (3)

Answer at what temperature is the AC typically set (in degrees Celsius) in your workspace while it is °C...
- 22 Is Not Selected

Q20 When you are in your workspace in summer, how would 22° C in your workspace feel to you?

○ Very Cold (1)
○ Cold (2)
○ Cool (3)
○ Neither Cool nor Warm (4)
○ Warm (5)
○ Hot (6)
○ Very Hot (7)

Answer at what temperature is the AC typically set (in degrees Celsius) in your workspace while it is °C...
- 22 Is Not Selected

Q21 When you are in your workspace in summer, how comfortable would 22° C in your workspace feel to you?

○ Very Comfortable (1)
○ Comfortable (2)
○ Uncomfortable (3)
○ Very Uncomfortable (4)

Answer at what temperature is the AC typically set (in degrees Celsius) in your workspace while it is °C... - 22 Is Not Selected

Q22 When you are in your workspace in summer, how acceptable would 22° C in your workspace be to you?

○ Very Acceptable (1)
○ Acceptable (2)
○ Unacceptable (3)
○ Very Unacceptable (4)

Answer at what temperature is the AC typically set (in degrees Celsius) in your workspace while it is °C... - 22 Is Not Selected

Q23 If given the option, would you change the temperature setting from 22° C in your workspace in the summer?

○ Yes, I would select a higher temperature (1)
○ Yes, I would select a lower temperature (2)
○ No, I would not change the temperature (3)

Answer at what temperature is the AC typically set (in degrees Celsius) in your workspace while it is °C... - 24 Is Not Selected

Q24 When you are in your workspace in summer, how would 24° C in your workspace feel to you?

○ Very Cold (1)
○ Cold (2)
○ Cool (3)
○ Neither Cool nor Warm (4)
○ Warm (5)
○ Hot (6)
○ Very Hot (7)

Answer at what temperature is the AC typically set (in degrees Celsius) in your workspace while it is °C... - 24 Is Not Selected

Q25 When you are in your workspace in summer, how comfortable would 24° C in your workspace feel to you?

- ○ Very Comfortable (1)
- ○ Comfortable (2)
- ○ Uncomfortable (3)
- ○ Very Uncomfortable (4)

Answer at what temperature is the AC typically set (in degrees Celsius) in your workspace while it is °C... - 24 Is Not Selected

Q26 When you are in your workspace in summer, how acceptable would 24° C in your workspace be to you?

- ○ Very Acceptable (1)
- ○ Acceptable (2)
- ○ Unacceptable (3)
- ○ Very Unacceptable (4)

Answer at what temperature is the AC typically set (in degrees Celsius) in your workspace while it is °C... - 24 Is Not Selected

Q27 If given the option, would you change the temperature setting from 24° C in your workspace in the summer?

- ○ Yes, I would select a higher temperature (1)
- ○ Yes, I would select a lower temperature (2)
- ○ No, I would not change the temperature (3)

Q28 Environmentally-friendly solar-powered air conditioning systems now exist that can cool an indoor space, but sometimes not to temperatures as low as conventional systems. If your workspace were cooled with such a system, would you be willing to accept indoor temperatures in your workspace of 24 °C during the summer?

- ○ Yes (1)
- ○ No (2)

Q29 How acceptable or unacceptable would 24° C be in your workspace in summer if the building used a solar-powered AC system?

- ○ Very Acceptable (1)
- ○ Acceptable (2)
- ○ Unacceptable (3)
- ○ Very Unacceptable (4)

Answer how acceptable or unacceptable would 24 degrees be summer at your workspace? Unacceptable Is Selected Or How acceptable or unacceptable would 24 degrees be summer at your workspace? Very Unacceptable Is Selected

Q30 What are one or two reasons you feel 24° C is an unacceptable temperature in your workspace during the summer in a building that uses a solar-powered AC system?

Answer how acceptable or unacceptable would 24 degrees be summer at your workspace? Unacceptable Is Selected Or How acceptable or unacceptable would 24 degrees be summer at your workspace? Very Unacceptable Is Selected

Q31 What would make 24° C a more acceptable standard setting in a building that uses a solar-powered AC system?

Q32 If the AC system were designed to give you and other building occupants the ability to demand short bursts of cooler temperatures, would it make 24° C a more acceptable temperature setting in summer?

- ○ Yes, much more acceptable (1)
- ○ Yes, a little more acceptable (2)
- ○ No, it would not change the acceptability of 24° C (3)
- ○ No, it would make it less acceptable (4)

Answer if the AC system were designed to give occupants the ability to demand short bursts of cooler temperatures, would it make 24 degrees a more acceptable standard temperature set... No, it would make it less acceptable Is Selected

Q33 Why would such an option make 24° C a less acceptable standard temperature setting?

Answer if the AC system were designed to give occupants the ability to demand short bursts of cooler temperatures, would it make 24 degrees a more acceptable standard temperature set... Yes, much more acceptable Is Selected Or If the AC system were designed to give occupants the ability to demand short bursts of cooler temperatures, would it make 24 degrees a more acceptable standard temperature set... Yes, a little more acceptable Is Selected

Q34 Why would such an option make 24° C a more acceptable standard temperature setting?

Answer If the AC system were designed to give you and other building occupants the ability to demand short bursts of cooler temperatures, would it make 24° C a more acceptable temperature setting in summer? No, it would not change the acceptability of 24° C Is Selected

Q35 Why wouldn't such an option change the acceptability of 24° C as a standard temperature setting?

Q36 Besides the ability to deliver short bursts of cooler temperatures, what are one or two other ways that would make 24° C a more acceptable standard temperature setting?

Q37 How willing would you be to utilize the following supplemental cooling methods in your workspace if you found 24° C to be uncomfortably warm?

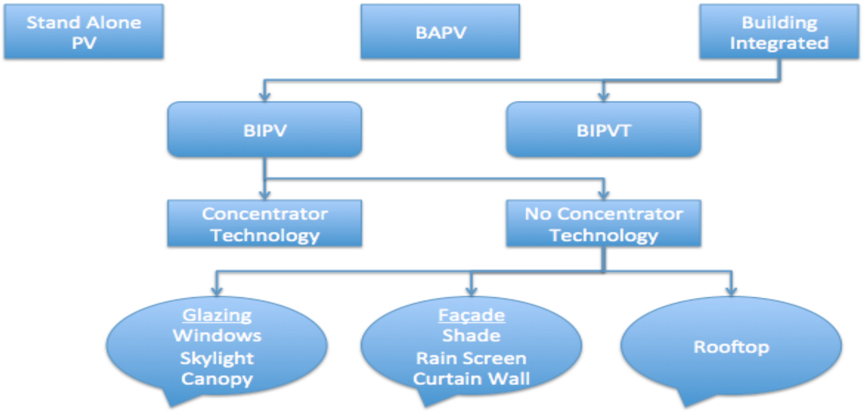
	Very Willing (1)	Willing (2)	Unwilling (3)	Very Unwilling (4)
Ceiling fan (1)	○	○	○	○
Portable fan (2)	○	○	○	○
Wearing lightweight clothing (3)	○	○	○	○
Personal cooling chair (e.g., chair, neck pillow) (4)	○	○	○	○

Q38 Please describe any other ways you would stay cool if you found 24° C uncomfortably warm in your workplace (besides changing the temperature setting).

Q39 Please share any other comments or suggestions you may have for encouraging people to accept a slightly warmer indoor temperature in a building cooled by renewable energy.

Appendix 5 BIPV Technologies

Various Types of Photovoltaic Technologies



<u>Key</u>

<u>SAPV</u> – Stand Alone Photovoltaic

<u>BAPV</u>- Building Area Photovoltaic

<u>BIPV</u> – Building Integrated Photovoltaic

<u>BIPVT</u> – Building Integrated Photovoltaic Thermal

Examples of SAPV, BAPV & BIPV Technologies

Figure 5-1: SAPV technology

"Stand Alone Photovoltaic System Design."

Retrieved July 13, 2015, 2015

<u>SAPV</u> – Stand Alone Photovoltaic Technology

Figure 5-2: BIPV Canopy

Unknown (2015). "Building Integrated Solar BIPV"

Retrieved July 13, 2015, 2015

Figure 5-3: BIPV Solar Shade

Singh, T. (2012). "Building-Integrated Photovoltaic Market Projected to Quadruple to $2.4 billion by 2017." 8/22/12.

Figure 5-4: BIPV Rain Screen

Gieseking, M. (2015, July 13, 2015). "Building Integrated Photovoltaic (BIPV) "New Light"."

August 29, 2012.

Figure 5-5: BIPV window

Gieseking, M. (2015, July 13, 2015). "Building Integrated Photovoltaic (BIPV) "New Light", August 29, 2012.

Figure 5-6: BIPV Curtain Wall

Gieseking, M. (2015, July 13, 2015). "Building Integrated Photovoltaic (BIPV) "New Light"." August 29, 2012.

Examples of SAPV, BAPV & BIPV Technologies

Figure 5-7: BAPV Rooftop

"Stand Alone Photovoltaic System Design."

Retrieved July 13, 2015, 2015

<u>BAPV</u>: Building Area Photovoltaic

Figure 5-8: BIPV Rooftop

Gieseking, M. (2015, July 13, 2015). “Building Integrated Photovoltaic (BIPV) “New Light” August 29, 2012.

Figure 5-9: BIPV Window

Gieseking, M. (2015, July 13, 2015). “Building Integrated Photovoltaic (BIPV) “New Light” August 29, 2012.

Figure 5-10: BIPV Roof Shingles

Petter Jelle, B., et al. (2012). "Building integrated photovoltaic products: A state-of-the-art review and future research opportunities." <u>Solar Energy Materials and Solar Cells</u> **100**: 69-96.

Figure 5-11: BIPV Skylight

Gieseking, M. (2015, July 13, 2015). “Building Integrated Photovoltaic (BIPV) “New Light” August 29, 2012.

Figure 5-12: BIPV Façade

"Application Examples BIPV." PVP Photovoltaik.

Comparison of the Different Photovoltaic Technologies

	SAPV	BAPV	BIPV
Space required around building?	Yes	No	No
Mounting required?	Yes	Yes	No
Inside Building Envelope?	No	No	Yes
Most Suitable For?	Remote Areas	Home & Business	Home & Business

Table 1: Lists pro’s and con’s associated with each type of photovoltaic technology.