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Net-Zero Energy Study for a Multi-Purpose Building

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ABSTRACT

Energy studies were performed on a multi-purpose building as part of net-zero energy consumption study for the building. With limited world energy supply, the incentive and necessity has grown for net-zero energy (zero net energy consumption) buildings or buildings close to net-zero where energy is utilized efficiently and also harvested on-site. Measured data of actual energy utilization by the building for a continuous period of over 30 months were collected and studied. The U.S. Department of Energy (DOE) EnergyPlus software was used to simulate energy requirements for the building. Alternative energy sources such as ground source heat pump, solar photovoltaic (PV) electric energy generation and day-lighting modifications were applied to redesign the energy requirements for the building towards meeting net-zero energy utilization. Results show that it is possible to achieve the aim of net-zero energy supply for the building. The results also show significant reduction in energy use for the building with the net-zero design as well as the extents of the contributions of the individual energy reduction measures. The directions to proceed towards achieving complete net-zero energy status for the building were identified.

Keywords: *Net-Zero; Renewable energy; Building energy*.

1. INTRODUCTION

The standard of living and the nature of buildings have changed considerably in the last two centuries. As the economy grows with rising cost of energy, the need for specialization in the area of creating and maintaining modern living rises. Today, buildings consume the most energy when compared to other sectors such as transportation and the industries. In the United States alone buildings consume almost forty percent of the nation's annual energy supply [1]. Energy Conservation is necessary in order to reduce environmental effects, increase financial capital and promote economic security. With the help of energy conservation, consumption of energy and demand for energy can be reduced leading to reduced requirement for new power plants. Also, energy conservation contributes greatly towards environmentally friendly solution of the problem.

Studies related to this one include Chantrasrisalai [2] which experimentally validated an EnergyPlus [3] low temperature radiant model by comparing measured data with results predicted by the model for a radiantly heated and cooled residence. Using the EnergyPlus program, Crawley et al. [4] investigated whether radiant systems are viable for a building in a given climate. The study showed that the low temperature radiant model used was sensitive to both the construction parameters, including specification of the thermal mass, and the system parameters. Wang et al. [5] investigated whether night ventilation is a suitable strategy for office buildings with lightweight construction located in cold climates. EnergyPlus software was used to simulate indoor thermal environment and energy consumption in typical office buildings with night mechanical ventilation. Factors influencing night ventilation performance were investigated. The results show that more energy is saved in office buildings cooled by a night ventilation system than the ones that do not employ the strategy. Using the EnergyPlus software, Zhou et al. [6] discovered that fixed shading devices in buildings can be used to save energy consumption and prevent undesirable heat coming through windows during overheated periods, as in summer. A typical dwelling house with two kinds of fixed shading devices (overhangs and vertical-shading devices) was simulated using the program. The study determined the optimum dimensions for horizontal shading devices and found that with optimum dimensions, a horizontal shading device can save nearly 5% of the energy used for air conditioning.

Mertz et al. [7] studied a proposed net-zero energy house and identified the least cost for the house and the least cost for a CO_2 neutral house. Carrilho da Graca et al. [8] explored the feasibility of solar net-zero energy building system for a typical single family home in mild southern European climate zone and identified possible optimum system configuration based on financial and environmental considerations. Stephens [9] studied the effects of geography and climate on the feasibility of residential net-zero energy buildings. Results of simulations revealed that electricity production from photovoltaic (PV) systems can produce enough energy to cover hourly demand less than two-thirds of the typical year. Siddiqui et al. [10] reported on modeling of a net-zero town house incorporating a ground source heat pump with

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floor radiant heating using TRNSYS (Transient Systems Simulation Program). Results for this building which is located in Toronto, Canada showed that for colder climates, the impact of thermal mass in buildings is more significant in winter than in summer. Mertz et al. [11] discussed the conceptual design and analysis of a net-zero energy use in a campus residence. Topics covered included energy impacts of occupant behavior, appliances and lights, energy conversion and distribution systems and building envelope. Simulations performed show that total energy requirements for the simulated house could be reduced substantially when compared to similar older houses. Leckner and Zmeureanu [12] presented results of the study of an energy efficient house that uses available solar technologies to generate the primary energy use for the house over the course of the year. Computer simulations for the house show that it is possible to reach the goal of net-zero energy supply for the building in the cold climate of Montreal, Canada.

This present report is on an energy study that was performed on a multipurpose university campus building as part of a net-zero energy study for the building. The EnergyPlus software was used to simulate energy requirements for the building. Measured data of the present energy utilization by the building collected over a period of 33 months was analyzed. Alternative energy sources such as ground source heat pump, use of solar photovoltaic electric energy generation and daylighting modifications were applied to redesign the energy requirements for the building towards meeting net-zero energy utilization.

2. BUILDING DESCRIPTION

The multi-purpose Student Center building in the university campus was selected for the study. This is a five-level building with approximate height of nine feet for each floor and net conditioned floor space of about 18,600 m^2. This is about five acres of floor space. The building is home to a wide range of offices, restaurants, stores and activities. Table 1 gives more information on the floor and wall space specifications.

Table 1: Building Floor Space Specifications

	[m^2]	[ft^2]
Net Conditioned Building Floor Space	18618.9	200412.40
Gross Wall Area	7423.78	79908.83
Window Opening Area	1838.95	19794.27

The building basically consists of the basement, the first floor, second floor, third floor and the fourth floor. There is a lower level lounge in the basement. The basement contains offices, an art gallery and related items, some audiovisual rooms and a craft shop.

The first floor is divided into the north end and the south end. The north end consists of a video games area, Automated Teller Machine (ATM) area, bowling and billiards lounge, a computer room used mostly for email activities by students, an information center, a television lounge, the university bookstore and a vending area. This end also contains substantial space for a number of dining establishments such as McDonalds and Starbucks Coffee. Connected to this space is a large sitting area for eating. The south end consists of a number of meeting rooms, a solicitation area for distributing flyers and an ***Athletic Hall of Fame*** open area. There are also some other restaurants in this area.

The second floor is also divided into the north end and the south end. The north end consists of office rooms, several meeting rooms, a restaurant and a big study lounge. The south end consists of the ***welcome center***, alumni association office, an art alley, an auditorium, ballrooms and several study areas. The third floor consists of activity rooms and meeting rooms and the student government offices. The fourth floor consists of several offices, a video lounge, a radio broadcasting station and a TV broadcasting station.

The composite walls and roof are made of different materials and masonry units. Table 2 shows some of the relevant properties of materials used for the roof, walls, doors and windows in the building.

Table 2: Some Materials and their Properties

Name	Thickness (m)	Conductivity (W/m-K)	Density (kg/m^3)	Specific Heat (J/kg-K)
F08 Metal surface	0.0008	45.28	7824	500
I01 25mm insulation board	0.0254	0.03	43	1210
I02 50mm insulation board	0.0508	0.03	43	1210
G01a 19mm gypsum board	0.019	0.16	800	1090

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M11 100mm lightweight concrete	0.1016	0.53	1280	840
F16 Acoustic tile	0.0191	0.06	368	590
M01 100mm brick	0.1016	0.89	1920	790
M15 200mm heavyweight concrete	0.2032	1.95	2240	900
M05 200mm concrete block	0.2032	1.11	800	920
G05 25mm wood	0.0254	0.15	608	1630

The energy supply and control equipment located in the basement, server rooms, freezers and coolers run for 24 hours. There is no occupancy monitoring sensors in the building. Thermostats located in the ball rooms, auditorium, lounge and restaurants are manually controlled by staff based on occupancy. There is a direct digital control system for controlling the mechanical equipment in the building. Escalators in the building operate daily from 6.00 a.m. to 1.00 a.m.

3. CITY WEATHER

Weather data is very important in this type of study as it helps to determine availability and magnitude of the wind and solar energy in the location of the building. The weather data reported here for the Carbondale city area were obtained from global weather data [13 and 14]. Figure 1 [13] shows the global average annual air temperature distribution at a height of 10 m generated for a continuous period of 22 years (1983 to 2005).

Figure 2 shows the average monthly wind speed distribution data for a typical year in the area. Average speeds of above 3.5 m/s occur from November to April. However, the maximum speed which generally occurs in April is above 17 m/s. The graph also shows that as expected, the average wind speed in the winter season is higher than that in the summer. Ding and Buckeridge [15] showed that a high frequency of over 800 hours per year occurs for the wind speed range of 3.2 m/s to 7.9 m/s. Figure 3 shows the average monthly direct normal solar radiation distribution data [14] for a typical year in the Carbondale city area.

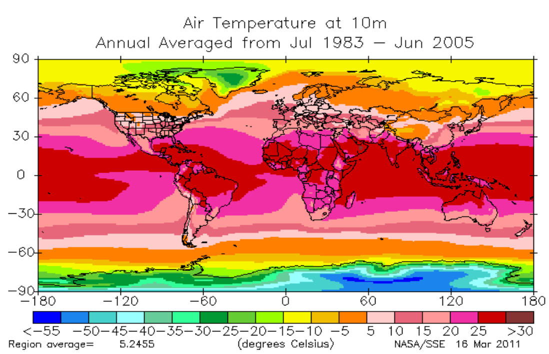

Figure 1: Global Annual Average Air Temperature at 10 m

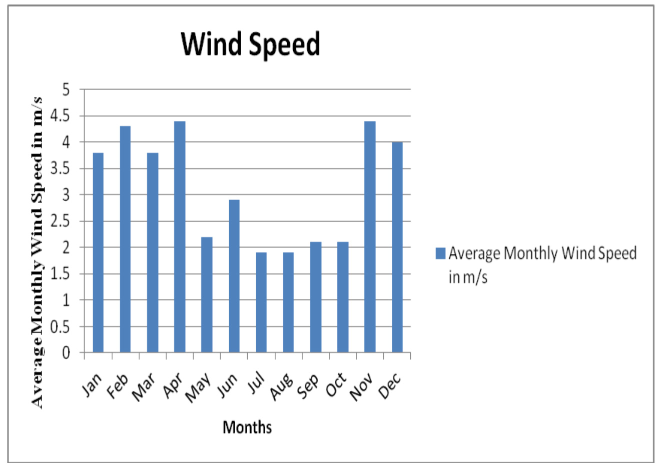

Figure 2: Average Monthly Wind Speed

The maximum dry bulb temperatures occur in July and August. The average direct solar radiation in the winter season is less than that in the summer as expected.

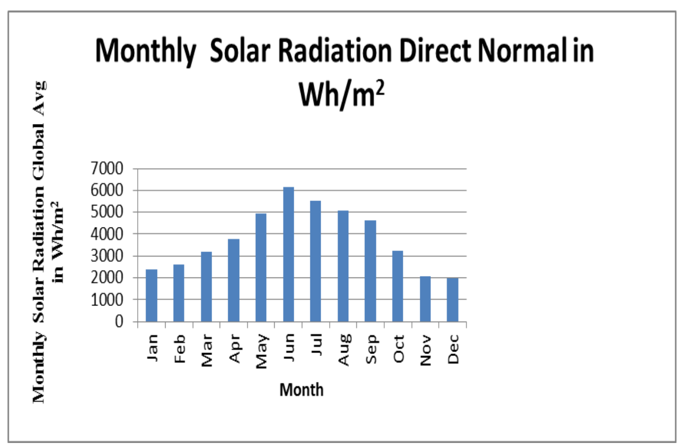

Figure 3: Average Monthly Solar Radiation

Figure 4 shows the average monthly outdoor dry bulb temperature distribution data [14] for a typical year in the city area. The maximum dry bulb temperatures occur in July and August.

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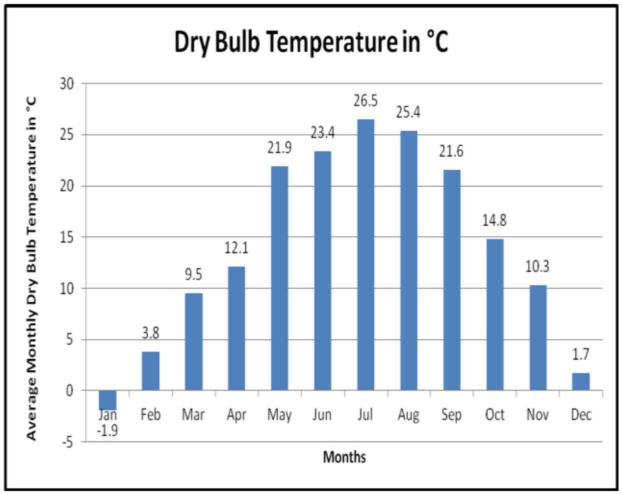

Figure 4: Average Monthly Dry Bulb Temperatures

For this study, simulation of the building energy requirements and determination of the alternative energy sources as well as the extents of their contributions were made using information from the city weather and the building information. The maximum daily building energy requirement was determined from results of the computer simulation.

4. BUILDING ENERGY CONSUMPTION

The utility consumption of the building is based on steam, electricity, chilled water, natural gas and water provided by the central power plant. Figure 5 shows the contributions of these energy sources to the building for the peak design day. Steam supplied from a steam plant is used for heating the building. Chilled water supplied from a steam driven centrifugal chiller located at an adjacent building is used for cooling the building. Some air handling units have been renovated since after construction of the building. Based on measured data of actual energy utilization collected over the period studied, the average daily peak energy consumption month of July was determined to be 181 GJ (171.6 MBtu). This is made up of electricity, natural gas and chilled water energy utilization. Figure 6 shows the actual total building energy consumption data for the period (33 months) during which the energy data shown was collected. The data for the years 2007 and 2010 are

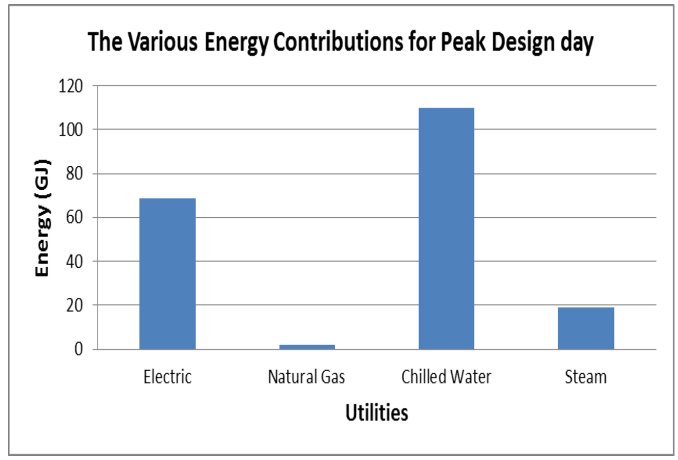

Figure 5: Energy Contributions for the Peak Design day

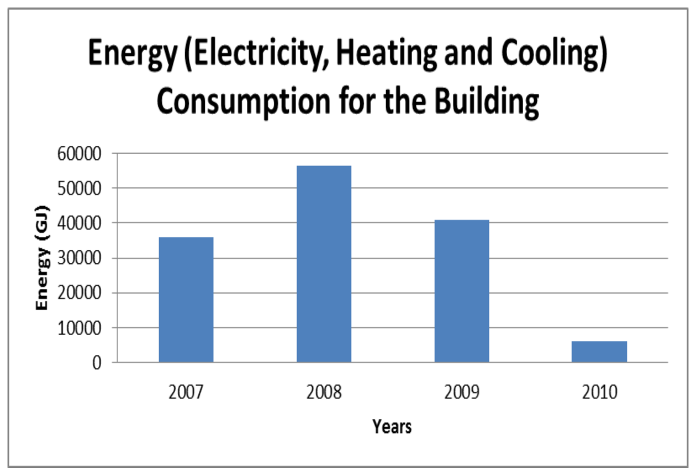

Figure 6: Actual Energy Consumption for the Building

The maximum dry bulb partial as data shown were collected starting from July 2007 and ending in March 2010. The decrease in energy consumption from 2008 to 2009 seen in the figure was observed after some energy conservation measures were implemented in the building in 2009.

5. BUILDING ENERGY SIMULATION

Energy requirement for the building was obtained by constructing a simulation model using the EnergyPlus software and the city weather file generated from the program. EnergyPlus is a simulation program developed by the Building Technologies Program of DOE to model cooling, heating, ventilating, lighting, and other energy flows in buildings. For the basement, the boundary conditions for the exterior surfaces

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included the ground conditions whereas for the rest of the floors, the boundary conditions for the exterior surfaces included the outside environmental conditions. The geometric model was constructed using Google Sketch-up with open studio plug-in created by NREL (National Renewable Energy Laboratory) for DOE. Material properties for the building construction including those for the windows and doors, details on the internal loads (such as lighting, equipment and occupancy), schedule of operations for different parts of the building and the city weather data amongst others were used as input in the program for the simulations. The Peak design day for the city was determined to be July 21. The average maximum temperature for the day is 32.8°C whereas the average temperature for the day is 29°C.

The alternative energy sources considered towards meeting net-zero energy requirements for the building were ground source heat pump, application of solar photovoltaic (PV) panels for electricity generation and day-lighting modifications. Geothermal heating and cooling uses the relatively constant temperature of the earth to heat and cool buildings with 40 to 70 per cent less energy than conventional systems. While conventional furnaces and boilers burn a fuel to generate heat, geothermal heat pumps use electricity to simply move or transfer heat between buildings and the earth allowing for much higher efficiencies. Solar PV application is a method for generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect.

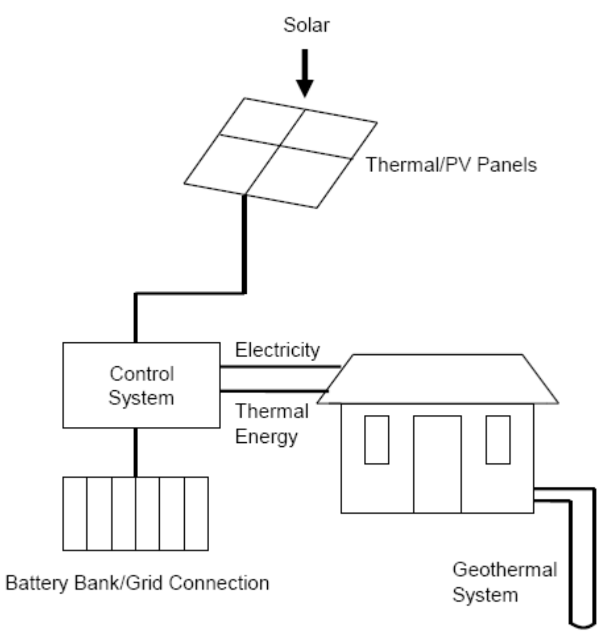

Figure 7: Outline showing Application of the Results Based on Alternative Energy Sources

PV power generation employs solar panels containing a photovoltaic material. Daylighting harvesting technique uses daylighting control systems that dim the electric lighting in response to interior daylight levels.

Figure 7 illustrates the outline of the building and applications of the results from the simulation, based on the alternative energy sources of geothermal, solar (PV, thermal and passive) and applied daylighting design. The automatic control system shown is a power electronic controller. The renewable source for the electricity is from solar energy system which is a grid connected system with battery energy storage so that when the system is unable to obtain power from solar and energy storage, it automatically takes the grid power. Some additional components not shown in the diagram are photovoltaic inverter, a distribution board and export/import meters for grid connection. The inverters are required to convert the DC electricity produced by the PV panels into alternating current (AC) electricity normally required for use in the building.

6. SUMMARY OF THE RESULTS

Following application of results from the simulation based on alternative energy sources the following methods were recommended:

(1) ***Applied Daylighting Design***: - Daylight harvesting technique which uses daylighting control systems that dim the electric lighting in response to interior daylight levels.

(2) ***Geothermal Heating and Cooling*** which uses the relatively constant temperature of the earth to heat and cool buildings more efficiently than conventional systems.

(3) ***Solar Photovoltaics* (PV)** system which generates electric power by converting solar radiation into direct current electricity using semi-conductors. PV power generation employs solar panels composed of a number of cells containing a photovoltaic material.

Figure 8 shows the daily energy load contributions for the building based on these alternative energy methods selected. Computations show that the total energy load for the building was distributed between alternative energy methods as follows: 5.4% through daylighting modifications, 58% through geothermal energy source and 36.6% from solar PV-generated electricity. The study found that implementation of applied daylighting design will contribute about 9.81 GJ of energy to the building energy requirements. This reduces the regular electric energy demand by that amount. It was found that this reduces the building energy demand by at least 5%. The total

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energy requirement for the building obtained for the net-zero design was found to be less than the actual present consumption as obtained from the measurements. This shows that it is possible to achieve the aim of net-zero energy supply for the building. The peak demand based on the net-zero (alternative energy) design was found to be 10 percent less than the present actual peak demand (obtained from the measurements).

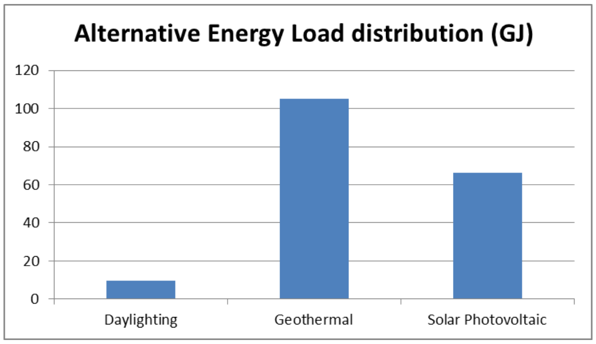

Figure 8 : Energy Load Distribution for meeting net-zero requirements

The study recommended that heating and cooling load requirements will be met by installing geothermal vertical loops in the ground each on the west side of the building where there is adequate space for the installation. By not using chilled water for cooling the saving per year was determined and compared to what is being paid presently for the chilled water. Using the simple payback method, the payback period was computed to be less than 15 years. Table 3 gives the PVWatts identification and related information for the city while Table 4 shows the solar radiation (kW/m^2/day) for the city along with the AC energy that can be obtained from solar PV panels for each of the 12 months of the year.

Table 3: PV Watts Identification for the City

City Identification/PV/Energy Specification	
Latitude	37.9 ° N
Longitude	89.2 ° W
PV System DC Rating	4.00 kW
PV System AC Rating	3.08 kW
PV System Array Type	Fixed Tilt
PV System Array Tilt	37.9°
PV System Array Azimuth	180.0°
Cost of Electricity	3.08 kW

Table 4: Monthly PVWatts Results for the City

Month	**Solar radiation** (kWh/ m^2/day)	**AC Energy** (kWh)
1	3.37	331
2	3.85	334
3	4.84	446
4	5.71	491
5	5.58	482
6	5.81	472
7	5.82	477
8	5.68	470
9	5.51	455
10	4.91	438
11	3.51	315
12	3.08	296
Year	4.81	5007

For the peak design day, the area to be used for the PV panels was calculated to be 11843 ft². The roof of the building which was recommended for the installation was found to be adequate as the total roof area is much more than this. The amount of PV energy required was obtained as 767,361 Watts. Using standard installed expense for PV cells, the installation cost was determined. Relative to the energy obtained through this method, the cost was found to be more expensive compared to the geothermal energy installed cost. However, the solar photovoltaic modification is necessary for the provision of electrical energy requirements for the building. Using the simple payback method, the payback period was calculated to be more than 15 years. To meet net zero requirements for this building, the study found that it is economical after daylighting modifications to distribute the heating and cooling load through geothermal installation and the rest of the load through solar photovoltaic installation.

7. CONCLUSIONS

This paper presents a summary of the studies performed on a multipurpose building for meeting net-zero energy requirements. Results show that it is possible to achieve the aim of net-zero energy supply for the building. The alternative energy sources studied could provide enough energy to meet the requirements for the building. The study identified the directions to proceed towards meeting net-zero energy requirements for the building. Implimentation of the alternative method of geothermal energy was found to be cheaper than the solar photovoltaic energy modification. However, the solar photovoltaic modification is necessary for the provision of electric energy requirements for the building. The area to harvest geothermal energy for the building was available.

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Due to the relatively cheap energy costs and lower level of technology existing at the time of the building construction (which is the case for many existing buildings today), the energy systems do not currently operate at the best performance level. With buildings constituting a substantial part of the nation's energy consumption, and with steady increase in fossil energy costs as seen over the past few decades, building owners are looking more seriously at alternative energy systems. Today, there is the urgent need to explore the implementation of net-zero energy buildings where energy is utilized efficiently and also harvested on-site.

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