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Defining a Pathway to Zero Energy Building: A Case Study on Retrofitting an Old Office Building into a Net Zero Energy Building for Hot-Humid Climate

Kwame B. O. Amoah

***Abstract*—**This paper focuses on retrofitting an old existing office building to a net-zero energy building (NZEB). An existing small office building in Melbourne, Florida, was chosen as a case study to integrate state-of-the-art design strategies and energy-efficient building systems to improve building performance and reduce energy consumption. The study aimed to explore possible ways to maximize energy savings and renewable energy generation sources to cover the building's remaining energy needs necessary to achieve net-zero energy goals. A series of retrofit options were reviewed and adopted with some significant additional decision considerations. Detailed processes and considerations leading to zero energy are well documented in this study, with lessons learned adequately outlined. Based on building energy simulations, multiple design considerations were investigated, such as emerging state-of-the-art technologies, material selection, improvements to the building envelope, optimization of the HVAC, lighting systems, and occupancy loads analysis, as well as the application of renewable energy sources. The comparative analysis of simulation results was used to determine how specific techniques led to energy saving and cost reductions. The research results indicate that this small office building can meet net-zero energy use after appropriate design manipulations and renewable energy sources.

***Keyworks*—**Energy consumption, building energy analysis, energy retrofits, energy-efficiency.

I. INTRODUCTION

THE dream of designing and constructing buildings that generate as much or more energy than their actual use has become a reality. Buildings are widely viewed as the most significant greenhouse emission source, calculated to be close to one-third of the total global emissions [1]. The buildings' share of global emissions' impact has triggered interest in recent years among researchers and industry stakeholders on the NZEB issues. NZEBs play a crucial role in mitigating the impact of building effects on the environment.

The hot-humid environment of Florida poses a particular challenge for building energy efficiency. At the same time, the state takes pleasure in having one of the highest rates of incoming solar radiation in the country, making it a paradise for photovoltaic energy generation. Florida Power & Light's (FPL) "Solar Together" project is the most extensive solar program in the nation, helping make the state a leader in solar energy production. The first step in achieving NZEB is to lower the building's energy usage through various passive and active measures. Reference [2] identified a methodology for converting conventional energy to net-zero buildings. The authors used validated solar energy using photovoltaic panels. Kwame et al. [3] conducted a comparative study involving simulation analysis for selecting energy efficiency measures (EEMs). In two different climate zones, Kim and Moon [4] performed a comparative study to improve wall, roof, and window installation. Khan et al. [5] applied various sustainability techniques in an integrated design approach using ECOTECH software to undertake the energy modeling exercise. The authors also conducted a solar access analysis to understand the on-site energy generation. Reference [6] reviewed design approaches and technologies to reduce new & existing buildings' energy requirements. The accurate source energy multipliers vary based on each region and over time [7]. Reference [8] compares three major zero-energy measures; the authors explain the key features of three Zero Net Energy (ZNE) metrics used to assess building energy performance and ZNE. Reference [9] has certified different types of commercial NZEBs, including – the Leon County cooperative building in Tallahassee, the TD Bank branch in Ft. Lauderdale, and Anna Maria Historic Green Village. The rest have PNC Financial Services Net-Zero energy bank branches in Ft. Lauderdale and NASA Propellants Complex 39 of Kennedy Space Center in Melbourne, FL. Zero Energy renovation projects are gaining much traction, and it is deemed less expensive than building an entirely new house. ASHRAE has assigned a target of net-zero energy-building fulfillment by 2030 [10]. Existing buildings should be subjected to an energy auditing process [11] and apply cost-efficient EEMs to reduce building energy consumption before considering renewable energy as a complementary energy source. Kwame et al. [12] used Autodesk Revit as both design and simulation tools for the analysis and System Advisor Model (SAM) as a tool for the study to implement the photovoltaic system to reach the net-zero energy goals.

The objective of this research is to look at cutting-edge methodologies and energy-efficient building technologies to enhance building performance utilizing a case study building, minimize energy use, and analyze appropriate energy generation possibilities in order to achieve net-zero energy goals.

Kwame B.O. Amoah is Assistant Professor with Department of Civil, Architectural and Construction Management, University of Cincinnati, Cincinnati, OH, USA (phone: +1513-556-1897; e-mail: amoahkb@ucmail.uc.edu).

II. EXISTING (OLD) BUILDING CONDITION

The system of interest is the Alumni Center on the Florida Institute of Technology's campus. The facility is commonly used for office space by 4 - 5 people. The total square footage of the building is approximately 2350 ft^2 and the overall electrical use for the year 2017 was 16,688 kWh. The space provided is not optimally utilized and will be renovated to help incorporate all the awarded grant's energy efficiency requirements. A walk-through energy audit of the building was used in the research to get a feel of the energy use of the current structure. Fig. 1 (a) was the picture of the structure—the actual building energy usage/cost data for 2016 and 2017, presented in Fig. 1 (b).

(a)

(b)

Fig. 1 (a) Old (existing) alumni office building, (b) Monthly energy consumption cost for 2016 and 2017

The building was originally a lower-middle-class residential building that was converted into an institution office space. With an East orientation, the building is of a concrete block construction coated by white stucco. The roof is a white lacquer color upon weathered asphalt pavement on a standard wood frame. The ground floor's interior finish is carpet with no pad on an 8-inch concrete construction exposed to earth contact. There are three exterior doors; an East glass door 1/4-inch-thick, a North facing standard solid wood door, and a West facing 1/8-inch-thick, 8 Ft wide sliding glass door. There are no energy-efficient light fixtures. The total average occupancy of 6 people was determined for the building. The occupancy schedule was set based on the season's definitions, allowing the building operation to run from 8 a.m. to 5 p.m., Monday through Friday, except for holidays. The building had a central heat pump unit (split system-single zone) rated at 36,000 BTU/hr. that serves the entire building except for the conference room. The conference room had a dedicated window unit (terminal unit) rated at 18,500 BTU/hr. The setpoints for the cooling and heating units for different reasons include;

- Cooling winter 75°F (23.89 °C), spring & fall 73°F (22.78 °C) & summer 70°F (21.11 °C);
- Heating winter 69°F (20.56 °C), spring 68°F (20 °C) & summer 68°F (20 °C) and cooling 76°F or (24.44 °C) winter, spring/fall summer;
- Heating (70°F or 21.11 °C winter, spring/fall summer) for the split system unit and the packaged terminal unit, respectively.

III. PROPOSED NEW BUILDING

The study building demonstrates a scalable zero-energy building design tailored for Florida climates applicable to new construction and renovation of commercial buildings, employing high-impact energy efficiency technologies coupled with onsite solar energy and an intelligent energy management system to achieve a cost-effective zero-energy design. The proposed construction increased the existing footprint, making room for a designated area for conferences and special events. A new addition to the existing footprint incorporated a new conference room designated for meetings and other events after the construction. This addition brought the square footage of the building to approximately 3,324 ft^2. The facility intends to serve as office space for 4-6 users operating from 8 am – 5 pm, excluding weekends and holidays. The rest of the section describes the building envelope optimization, selection, and HVAC system proposed for the case study building.

The Building Envelope

The research includes analyzing and selecting energy efficiency in walls, roofs, and windows. We evaluated different envelope measures to determine energy performance, cost savings, and payback options. The initial cost of each measured envelope is based on the latest construction estimates provided by our General Contractors, Subcontractors, and Suppliers. The list of envelopes analyzed in this study includes the following: (1) Structural Insulated Panels-Walls, (2) Structural Insulated Panels-Roof, (3) CMU Block Walls System, (4) Thermoplastic polyolefin (TPO) Roofing System, (5) Single Glazing Reflective Tint Windows, Low-E Double Glazing Windows.

Structural Insulated Panels (SIPs)

The insulated foam core between two hardboard sheathing materials consisting of expanded polyurethane (EPS), extruded polystyrene (XPS), and polyurethane (PUR) is pressure laminated with R-values directly related to their thickness [11]. The team explored the impact of SIPs in our simulation analysis for exterior walls and roofs. Specifications considered include; Structural Insulated Panel (SIP) wall 6½" (R-23.3 ft^2·°F/BTU) and 10" (R-36 ft^2·°F/BTU) for the roofing. The rest of the R-value for SIPs retrofit panels include 3" (R-10 ft^2·°F/BTU), 4" (R-13 ft^2·°F/BTU), 5" (R-17 ft^2·°F/BTU), 6" (R-20 ft^2·°F/BTU), 6.25" (R-23.3 ft^2·°F/BTU), 8.25" (R-31 ft^2·°F/BTU), 10" (R-36 ft^2·°F/BTU), 10.25" (R-38 ft^2·°F/BTU) & 12.25" (R-41 ft^2·°F/BTU).

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CMU Block Wall

Concrete block houses are disaster-resistant, energy-efficient, fire-resistant, noise-reducing, pest-resistant low-maintenance, and healthy. The thermal mass of a concrete wall system and insulation creates a tight thermal building envelope. A home with a tight thermal envelope conserves energy. A study by the Portland Cement Association found that houses with concrete walls had 5 to 9% greater energy savings than wood-framed homes [12]. The other option considered by this paper for the design and simulation analysis is the CMU blocks. Table I presents the specifications of CMU considered in the design and simulation analysis.

TPO Roofing System

TPO is a single-ply roofing membrane type that consists of two main classifications within the roofing industry (single-ply), as defined by the National Roofing Contractors Association [13], comprised of thermoplastic and thermoset membranes. TPO belongs to the thermoplastic membrane family. The red oval shape (see Fig. 2) shows the typical TPO design specifications incorporated in our model.

TABLE I
DETAIL OF CMU REQUIREMENTS

Inputs		
Envelope Measures	8” CMU block wall with 3- part stucco • 1 ½” rigid insulation (R-5/inch) • 1 5/8” metal. Stud. Furring 24” o.c • 5/8” gyp Boar	R-7.5

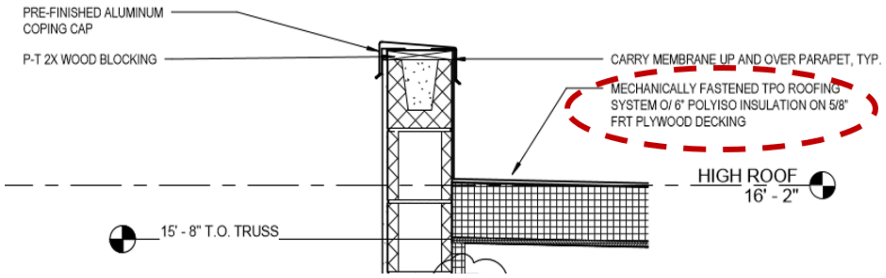


Fig. 2 TPO roofing system

Windows

Windows are a significant source of heat gain in buildings because of their relatively lower R-value compared to the walls and their transmissivity, allowing solar irradiation into the building. Window area or a window-to-wall ratio (WWR) is an important variable affecting energy performance in a building. The building has 13 windows. Window areas will impact the building's heating, cooling, and lighting and relate it to the natural environment regarding access to daylight, ventilation, and views. The WWR measures the percentage area by dividing the building's total glazed area by its exterior envelope wall area. Table II shows the building orientation, WWR, and glazing type.

TABLE II
WWR

The building		Glazing System
Zone Orientation	WWR	Glass
South	30.61%	Single Glazing Reflective tint - SHGC 0.25
North	13.73%	Single Glazing Reflective tint - SHGC 0.25
West	16.53%	Single Glazing Reflective tint - SHGC 0.25

HVAC System

The HVAC system for the proposed building includes two 17.0 SEER/9.6 HSPF Split HP < 5.5-ton and one 17.5 SEER/9.6 HSPF Split HP < 5.5-ton.

Assigning spaces in the building to zones to help manage energy simulation and data sharing/export is essential. The building has three thermal zones (shown in Fig. 3). Zones 1 and 2 share both 17.0 SEER/9.6 HSPF Split HP < 5.5-ton HVAC systems, while the third zone shares 17.5 SEER/9.6 HSPF Split HP < 5.5-ton. The energy analytical model indicated using the layout assigned zones is generated and simulated through the cloud to produce desirable results.

Energy Use Intensity (EUI)

There is much difficulty comparing the energy uses between buildings without a standard or benchmark [14]. The utilization of the Energy Use Intensity (EUI) indicator allows to examine how energy is used in different types of buildings and analyze ways to reduce total energy consumption.

When employing EUI, energy usage is stated as a function of a building's footprint, according to Amoah et al. [14]. In the United States, EUI energy is typically expressed per square foot of building footprint per year, calculated by dividing the total gross energy consumed in one year (measured in kBtu or GJ) by the building's actual gross square footage. Currently, the model's EUI stands at 11 kBtu/ft^2/year compared to the National/ASHRAE 90.1-2010 of 14 kBtu ft^2/year [15]. EUI for the existing building before the retrofit was 24.2 kBtu/ft^2/year.

IV. ENERGY SIMULATION

There is much difficulty comparing the energy used between buildings. We developed the energy model using the Autodesk Revit predictive modeling software. The Autodesk Revit environment allows stakeholders to run the entire project environment or individual 3D configurations in the family editor environment. We imported the architectural model from the design partner's BIM360 collaborative platform in this research. The imported design is "linked" to the Mechanical, Electrical, and Plumbing (MEP) template for the energy analysis. Revit analyzes, simulates, and generates design data through the cloud via Autodesk Green Building Studio – Building Performance Analysis. Revit calculates the building's annual energy consumption based on information on the building's location in Melbourne, FL, construction type, HVAC systems, occupancy, and operation. Fig. 3 shows the building layout and the assigned zones.

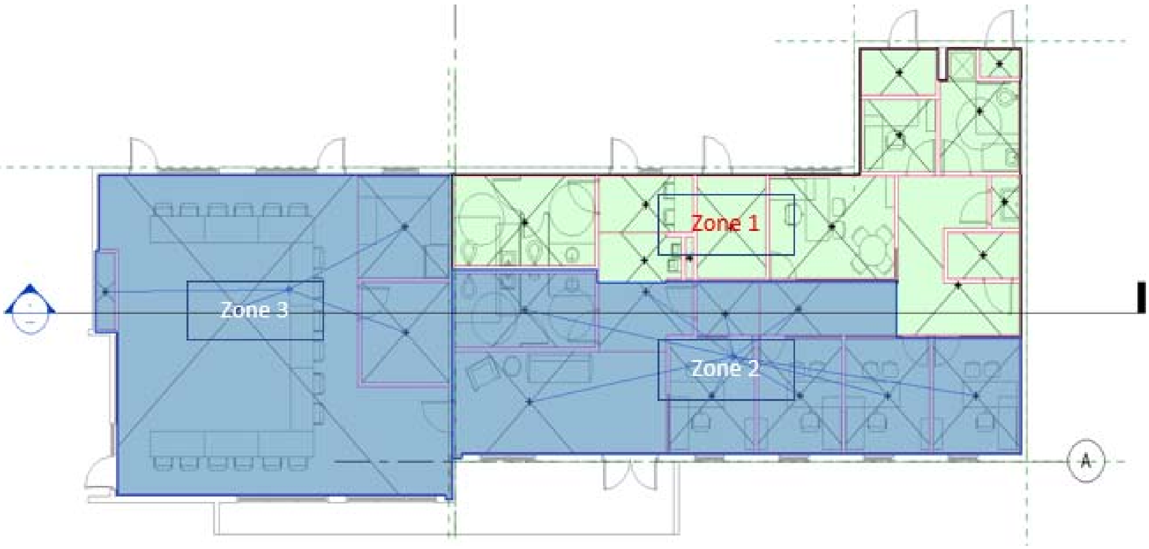


Fig. 3 Building layout showing the assigned zones

TABLE III
INTERIOR LIGHTING POWER DENSITY

Energy Use Vs Allowance Summary

		Allowance		Luminaries				
Area	Area (ft²)	Allowed (w/ ft²)	Allowed Watts	#	Type	Watt	Designed Watts	Designed (w/ ft²)
Conference Room	1,282	1.2	1,538	3	B	15	465	0.4
Break Room	98	1.1	108	2	B	15	30	0.3
Computer Area	55	1.1	61	2	B	15	30	0.5
Entrance Hall & Other	327	1.0	327	2	B	15	30	0.09
Hallway	250	0.8	200	6	B	15	90	0.3
Office 1	148	1.1	163	1	B	15	15	0.3
Office 2	107	1.1	118	3	B	15	45	0.3
Office 3	107	1.1	118	2	B	15	30	0.3
Office 4	105	1.1	116	2	B	15	30	0.3
Office 5	110	1.1	121	2	B	15	30	0.3
Office 6	101	1.1	111	2	B	15	30	0.3
TOTAL	**2,762**		**3,038**				**995**	**3.59**

Rates and Summarized Model Assumptions

Utility rate analysis is based on 2017 data from the FPL monthly electric bills with an annual energy consumption of 16,688 kWh and the corresponding cost of $1,867.41. Electric costs used a blended rate of $0.12/kWh, including yearly average base rate and demand charges for Florida commercial buildings. Table IV summarizes all the critical EEMs and assumptions considered in the simulation analysis for this study.

Renewable Energy with Solar PV System

The research team investigated the PV system using the SAM [16] to determine solar power generation on-site and estimated the required system size. We utilized a schematic design of a canopy structure and PV system placement. The building location and the potential shading may impact the PV system's performance, and also performed an analysis to account for the shading for the nearby structures and trees. The shading effect results from the surrounding buildings and trees accounted for, using the SAM's shading analysis tool, and showed that shading could reduce the total output from the solar PV system by 3.8%. The study predicted 30 Panasonic Photovoltaic Module HIT (330 W) with a nominal efficiency of 19.7% installed on a 14 feet high canopy on the west side of the building.

V. SIMULATION RESULTS AND DISCUSSION

The study analyzed the impact and performance of EEMs options to determine the best optimal option: Tables V and VI present the proposed EEMs options considered for the analysis. The building envelope, including the foundation, walls, windows, and roof, forms the primary thermal barrier between the interior and exterior environments [17]. The envelope determines comfort, natural lighting, ventilation, and how much energy is required to heat and cool a building. According to [18], envelope technologies account for approximately 30% of the primary energy consumed in residential and commercial buildings.

TABLE IV
ENERGY EFFICIENCY MEASURES IMPLEMENTED IN THE REVIT MODEL FOR THE ENERGY SIMULATION AND ANALYSIS

System Description	EEMs Implemented
	Building Envelope
Roof	TPO (TPO) Roofing System
Walls	SIP (SIPs) & CMU Block Walls System - 8” CMU block wall with 3- part stucco (R-7.5) - 1 ½” rigid insulation (R-5/inch) - 1 5/8” metal. Stud. Furring 24” o.c - 5/8” gyp Board
Windows	Single Glazing Reflective tint & Low-E Glazed Windows
Overhang shading	Revit considers a default 15% for the overall Overhangs. Does not make provisions for individual overhangs
Roof color	White surface
	HVAC System
SEER Value	- Zone 1 and 2 shares both 17.0 SEER/9.6 HSPF Split HP < 5.5-ton & - Zone 3 17.5 SEER/9.6 HSPF Split HP < 5.5-ton
Type of Control	- Cooling -74ºF when occupied & 82 ºF unoccupied including weekends /holidays. - Heating -72ºF when occupied & 62 ºF when not. - Most lights are turned on at 7:00 AM and off at 7:00 PM. - Infiltration: “Medium” (0.038 cfm/sqft.)
Schedule of Operation	- Common Office occupancy (8:00 AM – 5:00 PM) for existing area - Conference Room: 2 hr. per day
	Lighting
Schedule of operation	- All Lighting changed to LED - On a typical day, 90% of the installed lighting is turned on (ignoring daylight harvesting controls but including occupancy sensors).
Lighting Specs	- 15 Watts LEDs
Dynamic Shading	Universal 15% shading factor

Windows contain a separate analysis report for this project. We studied the results of the energy simulation analysis of the two building envelope options. The roof and walls are analyzed together. The energy savings with using SIPs over the CMU would be 988kWh, about 8.68%. Comparing SIPs to the baseline consumption of 16,688 kWh, the SIPs produced energy savings of 6,296 kWh, representing approximately 37.7%. The CMU option yielded energy savings of 5,307 kWh, about 31.80%. Additional insulation could be added to the CMU walls to increase the R-value, reducing the building's energy usage. Any changes to the assumptions and EEMs options will result in a different outcome. Fig. 4 shows the details of the annual energy consumption breakdown for the selected EEM packages analyzed for the SIPs & CMU option.

Fig. 5 (a) details monthly energy production results for the Solar PV analysis and the associated cost with the maximum amount of electricity production in May, about 1,687 kWh. The minimum value obtained for December with 1,142 kWh. The total annual electricity production for the first year resulted in 16,837 kWh. Fig. 5 (b) demonstrates the annual electricity production from the PV system for over 25 years, considering a degradation rate of 0.26 %/year.

TABLE V
RESULT FOR SELECTED EEMS PACKAGE FOR OPTION 1

	Inputs	R-Value	Energy Consumption
Building Envelope Measures	Roof Insulated Panels (SIP) • Asph. Siding (AR02) • Bldg. Paper Felt (BP01) • Plywd 5/8in (PW04) • Polystyrene 91/4in w/48in o.c SIP wall frame • Plywd 5/8in (PW04) • Gywd 5/8 in (GP01)	R-36	10, 393 kWh/year
	SIP s (SIP) wall 61/2in • Stucco 1in (SCD01) • Bldg. Paper Felt (BP01) • Plywd 5/8in (PW04) • Polystyrene 51/2in w/48in o.c SIP wall frame	R-26 U-Value: 3.13 W/(m^2-K)	
	Window: Low-E double glazing - SHGC 0.76		

TABLE VI
RESULT FOR SELECTED EEMS PACKAGE FOR OPTION 2

	Inputs	R-Value	Energy Consumption
Building Envelope Measures	TPO Roof • Mechanically fastened TPO roofing system 0/6in insulation on 5/8in frt. plywood decking	R-30	11, 381 kWh/year
	8” CM block wall with 3- part stucco • 1 ½” rigid insulation (R-5/inch) • 1 5/8” metal. Stud. furring 24” o.c • 5/8” gyp Board	R-7.5	
	Window: Single Glazing Reflective tint - SHGC 0.25	U-Value: 5.91W/(m^2-K)	

Costs Analysis

The financial assessment was conducted for the two models to verify if the investment would be worth considering energy and cost savings. The cost estimate for the SIPs small office building stood at $164,456.00 for walls and roofs with no installation cost. The estimate for the installation totaling $56,000.00 came from the general contractor. The total cost, including material and labor for CMU, was $141,819.00. Further assessment was conducted to see if the savings of using the SIPs would be worth the investment. For 50 years, SIPs would save an additional 6,650 kWh, referenced in Table VI. Below is a simple cost-saving analysis:

1. SIPs savings over 50 years: 6,650 * $0.12 = $798.00
2. Total price for the SIPs, including savings: $220,456.00 - $798.00 = $219,658.00
3. Increase in cost for SIPs compared to CMU: $219,658.00 – 141,819.00 = $77,839.00

We considered the following assumptions for the calculations above:

1. Electricity cost was constant.
2. The electricity cost is 12 cents/kWh.
3. The team calculated the savings by subtracting the energy savings cost from the initial cost of construction.
4. The efficiency of walls and roof will remain constant over

50 years.

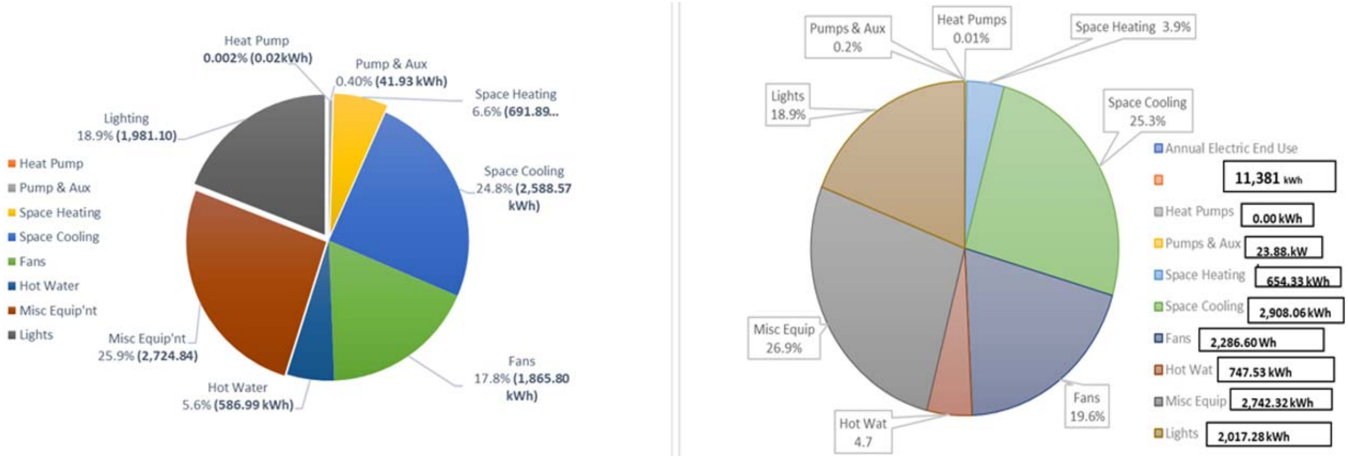
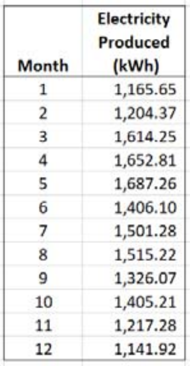
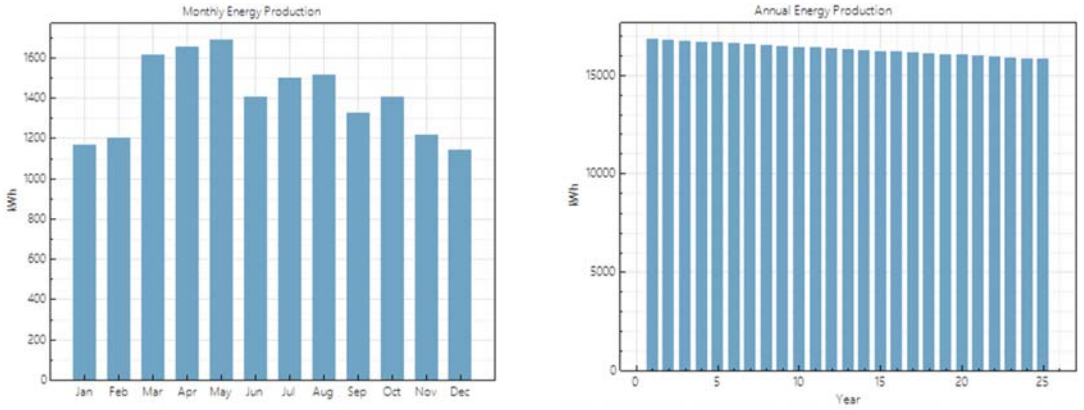


Fig. 4 Annual energy consumption breakdown for EEM option 1 and EMM option 2



Month	Electricity Produced (kWh)
1	1,165.65
2	1,204.37
3	1,614.25
4	1,652.81
5	1,687.26
6	1,406.10
7	1,501.28
8	1,515.22
9	1,326.07
10	1,405.21
11	1,217.28
12	1,141.92



(a) (b)

Fig. 5 Annual & Monthly electricity cost and production from the PV system

VI. Conclusion and Future Study

The study evaluated the energy performance of EEMs package options proposed for the simulation (Fig. 4) as cost considerations for selecting a viable option. We opted for EEM option package 2, including CMU walls, TPO roofing system, Low E, etc., over EEM option package 1, consisting of a SIP based on several factors. The SIPs system will help speed up construction time, approximately four weeks, and better savings of 10,393 kWh/year. CMU walls with a TPO roofing approach produced better cost ($141,819.00) due to labor availability, the proximity of construction materials, and a little over 7.5 weeks of construction time.

The annual energy savings for EEM option 2 stood at 11,381 kWh/year, leaving an energy usage deficit of 5,307 kWh. The on-site solar PV energy generation provided annual electricity of 16,837 kWh; this will offset the usage deficit to pave the way for net-zero energy with an excess energy surplus of 11,530 kWh/yr. The extra power will be stored at the battery charging station for future use if the solar panels do not produce electricity.

Going forward, this NZEB serves as an experimentation platform for data collection & model validation to enhance Building Energy Model (BEM) practices and predictive accuracy for building design and operation. This exercise will improve BEM predictive accuracy via model calibration & validation, enhanced modeling capabilities in occupant behavior, and dynamic shadings. The future work will also enable modeled predictive control (MPC) for building operations and deliver an extensive outreach program to promote BEM values in building design and operational function.

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