Concept, Design, and Energy Performance of a Net Zero-Energy Building (ZEB) in the Middle East Climate

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ABSTRACT

The world is facing several environmental problems, and scientists and researchers are always trying to find sustainable solutions as it is a responsibility to save energy and non-renewable sources for coming generations. Oman is one of the countries that face a lot of challenges to provide sustainability, especially in buildings that consume the highest energy compared to several sectors. To maintain this problem, save the largest amount of energy, reduce carbon emissions, and provide all the necessary requirements of the building in a sustainable way, zero-energy buildings can be the perfect solution. The main objectives of this study are to explore and evaluate existing building sustainability and zero-energy building. Besides, the study aims to design a new zero-energy building and determine the most relevant renewable energy resources and technologies that can be installed to enhance the performance of the building reaching zero energy. The methodology used to accomplish the project is mainly primary data such as an interview with experts to gain knowledge and data needed for the project achieving the first objective which is the comparison between SQU eco house and other normal residential building in Oman considering number of factors such as dimensions, materials used, water usage, construction waste and cost. Besides, Auto Cad software was used for designing the 2D plan of new zero-energy building, Revit software used to design the 3D plan and IESVE software was used to provide an analysis of performance of the new zero energy building and improve it to the maximum. The main outcome of this research is to compare the performance of normal existing buildings with SQU eco house that reaches the highest percentage towards zero energy that reaches to 97% approving that eco houses are more sustainable considering number of factors. Using the established eco houses in Oman and considering Oman's climate a new design of ZEB was prepared, identify several innovative technologies and systems that can be used in zero-energy buildings and determine the most relevant renewable energy sources. This project is special as it achieves sustainability from construction stages, reaching to operation stages and it can be helpful for researchers and engineers to have a good understanding of suitable and sustainable buildings which suits the future by saving energy and reducing environmental issues.

Introduction

Our world, environment is the place we live with other creatures safely using all the resources given to us freely, however, this concept should be fixed and managed to suit the needs and requirements of today and the future, and human beings should be less selfish in using all these resources, especially which are non-renewable by consuming less as possible and saving it to next generations, besides it is essential to follow all techniques and behavior that lead to a sustainable world. Engineers play an essential and massive role in achieving sustainability, especially in the building sector and are responsible for several hazards such as leading to about 23% of air pollution, and 50% of climate change (GoContractor, 2017). Oman is one of the countries that consume high amounts of energy in the building sector, for example, it uses about 76%-83% of electricity compared to the amount used in the USA (Authority for Electricity Regulation-Oman, 2016), besides suffering from pollution generates from construction wastes, therefore, it was decided and aimed for 2040 vision that environmental conservation conducted from different institutions and raise awareness and knowledge towards sustainability methods by setting a number of environmental perspectives such as providing policies, rules, decisions in planning and construction of different projects (Al Nasser, 2020). ZEB is considered an economic structure despite the expensive technologies that can be used in designing stages, but it saves amounts of money in the long term run over as less as those types of building are 60% to 90% over energy efficiency baseline and lead to fewer maintenance costs (Chanchpara, B, 2019). The main aim of this report is to compare SQU eco house and normal residential buildings considering a number of factors and design a new ZEB in Muscat that considers several sustainable technologies during construction and operation. Our environment is facing daily challenges due to human activities that harm it and creatures on and they are mainly related to construction sector as it can be responsible for about 23% of air pollution, 50% of climate change, 40% of water pollution, and the high consumption of energy and non-renewable resources that are required for living that reaches up to 40% (Sikra, 2017). Due to this environment suffering, the ZEB can be a solution that implement several systems and technologies that save high amounts of energy.

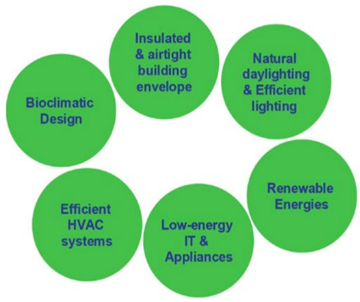


Figure 1. Principles and applications of designing a ZEB (Shehadi, 2020).

The research's main aim is to study the differences between existing residential buildings compared to SQU eco house considering a number of factors related to design stages, construction stages, and performance of buildings during operation. Besides, the report aims to design a new zero-energy building that suits Muscat's climate and circumstances considering providing the most relevant renewable energy resources and technologies:

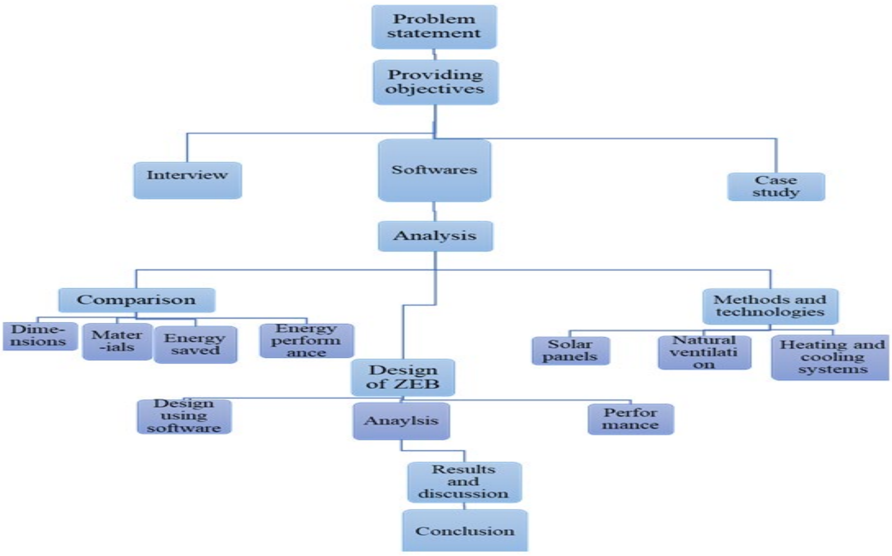
1. To explore, evaluate and study the performance of existing building sustainability compared to zero energy building.
2. To provide a new design of a zero-energy building considering several Omani conditions.
3. To determine the most relevant renewable energy sources and innovative technologies that can be used in zero energy building considering several design features.

Research Methodology

Figure 2. Research design to accomplish objectives

Description of Research Design Diagram

Figure 2 above shows an illustration to simplify the stages followed to achieve the objectives and get reliable outcomes. The diagram starts with finding the problem that the research would be helpful to solve or at least limit its impact of it. After choosing the topic related to the problem the next step was choosing the objectives that suits the main aim and relying on several method types to get reliable findings. In this case, three methods were followed which are the interview with specialists in civil engineering or environmental engineering to achieve the first objective which is a comparison between the residential villa and SQU eco house to approve the high efficiency of SQU eco house that reaches about 97% zero energy, then designing of a new ZEB using design and analyzing software, and a case study about technologies and systems that enhance the sustainability of the building to reach zero energy.



Results and Discussion

After implementing the methodology stages, all the findings, results, comparisons, and discussions would be mentioned in this chapter following the objectives.

Comparison Between a Residential Building and SQU Eco House Considering the Factors

Location, Area, and 2D Architectural Plan

SQU eco house: This building is located in the Muscat region specifically beside the SQU campus. The dimensions and other data were taken from interviews (Al Saadi, and Shaaban, 2019).

Table 1. Areas of floors and components for SQU eco house (Al Saadi, and Shaaban, 2019).

Built up area	$279.32m^3$
Ground floor area	$\mathbf{147.81\ m^3}$
First-floor area	$\mathbf{131.51m^3}$
Ground Components	Majlis, dining room, family room, guest bedroom, two bathrooms, kitchen, and store
First-floor components	Living room, three bedrooms, two bathrooms

Residential Building

The building chosen is located in the Al Mudaybi region which is about 1h30min from Muscat. This building was chosen as it has close values of SQU eco house dimensions, number of floors, and distribution of rooms, therefore the comparison can be more reliable (EM 1).

Table 2. Areas of floors and components for SQU eco house (EM 1).

Built up area	$397m^3$
Ground floor area	$\mathbf{234\ m^3}$
First-floor area	$\mathbf{163m^3}$
Ground Components	Majlis, dining room, family room, guest bedroom, two bathrooms, kitchen, and store
First-floor components	Family hall, three bedrooms, two bathrooms, and 2 open terraces.

Energy Saved

SQU Eco House

To calculate the saving energy and determine the energy performance of the SQU eco house a field experimental set up for one full year facing real different climate conditions throughout the year. A number of sensors and devices such as water and irrigation sensors, indoor environment sensors, and others were installed to calculate the energy produced by several systems in the building. The final output was saving 97% of energy therefore, this building was in shortage of 3% to reach zero energy (Al Saadi and Shaaban, 2019).

Residential Building

Using the website 'home energy saver calculator' an estimation was done to calculate the energy saved from the residential building identified. Some data regarding the building such as house shape, size, types, and dimensions of doors and windows, lighting, foundation dimensions, walls and floor, major appliances such as cooking and dishwashers, small appliances such as kitchen appliances, besides a number of people using the building, was entered and results were obtained as follows:

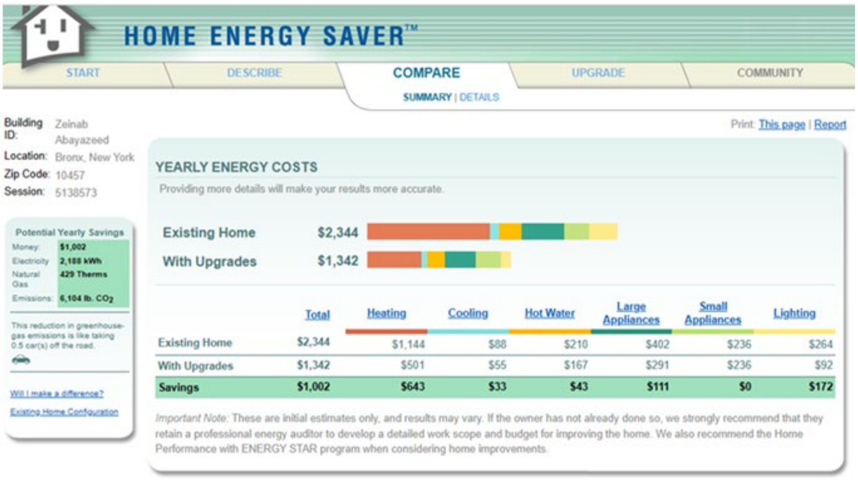


Figure 5. Yearly energy saving costs (home energy saver, 2022).

YEARLY WHOLE HOUSE RESULTS

		Existing Home	With Upgrades	Savings	Percentage Reductions
Whole House	Energy Bill	$2,344	$1,342	**$1,002**	43%
	Electricity	5,295 kWh	3,107 kWh	**2,188 kWh**	41%
	Natural Gas	982 Therms	553 Therms	**429 Therms**	44%
	Emissions	14,109 CO2	8,005 CO2	**6,104 lb. CO_2**	43%
Heating	Energy Bill	$1,144	$501	**$643**	56%
	Electricity	488 kWh	230 kWh	**258 kWh**	53%
	Natural Gas	753 Therms	327 Therms	**426 Therms**	57%
	Emissions	9,040 lb. CO_2	3,941 lb. CO_2	**5,099 lb. CO_2**	56%
Cooling	Energy Bill	$88	$55	**$33**	38%
	Electricity	479 kWh	300 kWh	**179 kWh**	37%
	Emissions	239 lb. CO_2	149 lb. CO_2	**90 lb. CO_2**	38%
Hot Water	Energy Bill	$210	$167	**$43**	21%
	Natural Gas	150 Therms	119 Therms	**31 Therms**	21%
	Emissions	1,752 lb. CO_2	1,390 lb. CO_2	**362 lb. CO_2**	21%

Figure 6. Heating, cooling, and hot water energy savings results (home energy saver, 2022

This software is based on US standards, and it may differ from actual results, but it can show an approximate estimation of energy saved from several features of the residential building. It was observed from the results that the total saved cost is 1000$. It was clear from the results that the least part producing CO2 emissions is small appliances, however, heating is the most generator of the emissions, therefore, it is recommended that the client thinks of sustainable alternatives to enhance efficiency and save the environment at the same time.

Design of 2D and 3D Plans of Zero Energy

Site investigation: Muscat laboratory was contacted to get the details of soil tests in the Muscat Al Rusayl area to identify the type of foundations that can suit the design. After implementing some geotechnical tests, it was found that the isolated footing or raft foundation can be suitable to design. In this case, the isolated footing was chosen as it is much more economical especially since the building is not a massive project and its shape mainly is square or rectangular and sometimes circular slab of uniform thickness (Muscat Lab, 2022).

Table 4. Recommended s depths of foundation with allowable bearing capacity

Sr. No.	Depth of Foundation (m)	Net allowable Bearing pressure (Kpa)		Modulus of Subgrade Reaction (KN/m³)	
		Isolated pad foundation	Raft foundation	Isolated foundation	Raft foundation
1	1.0 ~ 2.0	200	150	24,000	9,000
2	2.1 ~ 3.0	250	200	30,000	12,000
3	3.1 ~ 4.0	300	250	36,000	15,000

Choosing sustainable materials: Several sustainable construction materials would be chosen to enhance the efficiency of the building and reduce the environmental harm from construction stages. One of the materials is Geopolymer concrete which is a suitable alternative to normal concrete that replace cement with fly ash as it is known that cement produces high amounts of CO2. It consists of fly ash, aggregate, and alkaline solution. Besides, recycled glass and precast beams and columns can be used as they are more sustainable materials.

Final 2D Design of ZEB Using Auto-Cad Software

The built-up area of the zero-energy building that would be designed is 320 mm^2 as it consists of two typical floors each with an area of 160 mm^2.

Final 3D Design of ZEB Using Revit Software

Figure 7. Architectural Auto-Cad plan for the design of ZEB

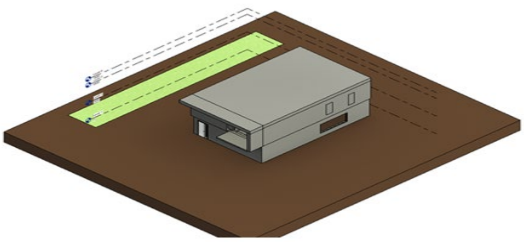


Figure 8. Revit 3D design of ZEB

Energy Analysis Data Using IESVE Software

The steps followed to analyze and study several energy aspects of ZEB started with setting the location and site data according to Oman weather, then simulation weather data and simulation calendrer.

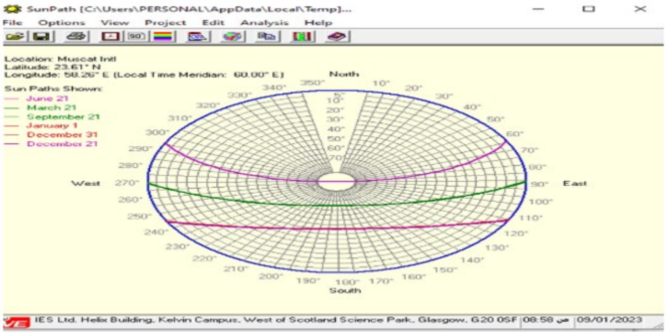
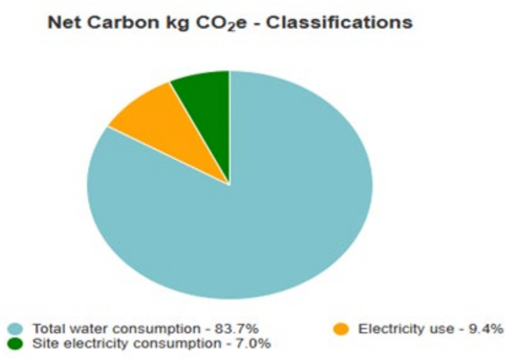


Figure 9. Sun path in Muscat region in different times of the year

The next step is linking the IESVE software with a navigator called One click LCA, and add several data related to the design aiming to get outputs related to analyzing of energy data**.** The results obtained from analyzing process was illustrated in pie charts as following:



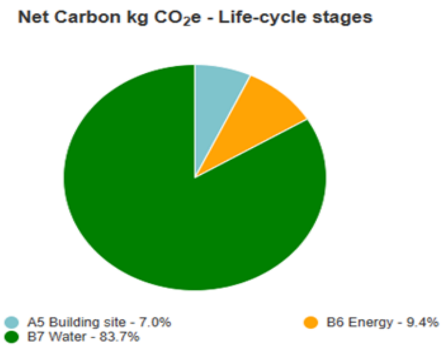


Figure 10. The net carbon kg CO2-Life cycle stages **Figure11.** The net carbon kg Co2 classifications

Figure 12 shows the amount of carbon produced from this design was produced mainly from the building site, water, and energy. The highest percentage was due to water with 83.7%, therefore it is essential to install several technologies or systems related to management of water uses such as collecting rainwater, water harvesting system, solar water heating, grey water filtration, blackwater filtration, and installing features in bathrooms and kitchens to reduce usage of water (Horspool, 2022). Figure 13 represents the main sources of energy consumption that lead to high net carbon, and it was observed that the least consumption is due to site electricity consumption and this because of the number of activities followed on site to reduce amount energy on sites.

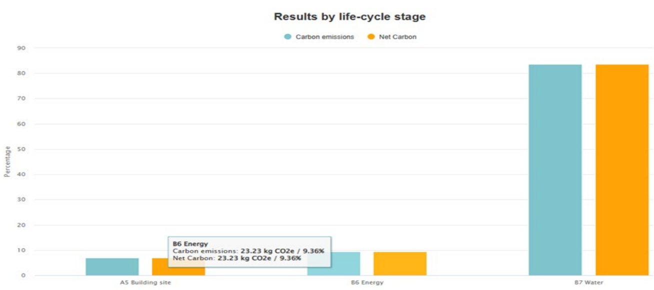


Figure 12. Carbon emissions due to energy consumption

One of the main aims to find the energy consumption and the carbon emissions due to its production, in this case it was recorded as 23.23Kg Co^2, which means it was close to achieve zero carbon emission, with some improvements in systems and choosing alternatives of materials the aim can be achieved successfully. Achieving zero carbon emissions can save our environment from several risks such as global warming or climate changes. Figure 15 shows the carbon footprint due to the building site being 17.31 Kg CO^2. This shows that several construction processes would affect emissions and should be taken into consideration to reduce the environmental risks as much as possible.

Comment on Analyzing Results

The final results of analyzing the design ZEB, shows that there is a shortage in reaching the zero energy as the building based on the software calculations can produce 23% of carbon, and this can refer to some errors of calculations on software, and approve the requirement of site tests that gives more accurate results. Besides, it was observed that several systems and features for water should be considered in future designs to reduce the shortage and reach to the main aim, which is getting zero energy consumption, therefore zero CO^2 emissions, saving the environment and non-renewable resources needed for coming generations.

Technologies and Systems to Be Installed to Achieve Zero Energy Building Covered by A Case Study of Previous Successful Zebs Designs

To enhance the efficiency and reach zero energy in the building number of systems would be installed as ZEB's main concept is producing the required energy on-site depending on renewable sources to generate the electricity and heating or cooling activities of the building (Goodier, 2019).

- Solar PV panels: This system is an essential need to reach zero energy as it used the most renewable resource which is sunlight to generate the necessary energy for several building activities. It is known that the sun can provide the consumption required for humans throughout the year, especially in this hot region it is essential to take the maximum benefit of this climate by generating energy and reducing using non-renewable resources and limiting harm to the environment during several energy production processes. A design of solar panels was done according to (Leonics, 2013), and it was found that the rate of solar charge controller is 40A.
- Ventilation system: This system is required in ZEBs to allow natural outdoor to enter the spaces of the building aiming to enhance the thermal indoor comfort and reduce indoor pollution. The factors that were considered were the speed and direction of the wind, the orientation and footprint of the ZEB, the outdoor temperature changes and humidity values, the size, location, material, and other features of the windows.
- Heating and cooling systems: One of the innovative technologies that are widely used in ZEBs is geothermal systems that work to heat or cool single houses or whole communities such as college campuses. There are mainly two situations the first is when the ground temperature is warmer than ambient temperatures, so the geothermal pump would remove the heat from the fluid collected and transfer it directly to the building, on the other hand, when the ground is cooler than the ambient the heat pump converts the heat from the building to the underground (US department of energy, 2022).

Conclusion

The first objective was accomplished using several methods to compare between a residential building and ZEB in Oman taking several factors in to account. It was approved that ZEBs are much sustainable than normal residential building and save much energy, however in SQU eco house it was focused on achieving sustainability in operation stages not considering construction stages that can lead to high number of pollutions and consumes energy, therefore the new design would focus on construction stages so waste treatment can be done beside to choosing more sustainable and economical material in construction.

To design a new ZEB, the area selected for the design was in Al Rusayl, Muscat. The built-up area of the zero-energy building that would be designed is 320mm2 as it consists of two typical floors each with an area of 160mm2. Sustainable materials were selected. Using Auto Cad, the 2D plan was prepared and Revit for the 3D outlet shape.

Using IESVE software the energy analysis of the designed ZEB was provided and discussed. It was founded from results obtained that the ZEB designed reaches 23% carbon emissions which recorded result as well, however several improvements especially in water systems are required to reach zero energy that means zero CO^2emisssions.

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