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Energy and Economic Evaluation of Green Roofs for Residential Buildings in Hot-Humid Climates

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Abstract: Green roofs may be considered a passive energy saving technology that also offer benefits like environmental friendliness and enhancement of aesthetic and architectural qualities of buildings. This paper examines the energy and economic viability of the green roof technology in the hot humid climate of Saudi Arabia by considering a modern four bedroom residential building in the city of Dhahran as a case study. The base case and green roof modelling of the selected building has been developed with the help of DesignBuilder software. The base case model has been validated with the help of 3-month measured data about the energy consumption without a green roof installed. The result shows that the energy consumption for the base case is 169 kWh/m^2 while the energy consumption due to the application of a green roof on the entire roof surface is 110 kWh/m^2. For the three investigated green roof options, energy saving is found to be in the range of 24% to 35%. The economic evaluation based on the net present value (*NPV)* approach for 40 years with consideration to other environmental advantages indicates that the benefits of the green roof technology are realized towards the end of the life cycle of the building.

Keywords: green roof; buildings energy conservation; sustainability; energy-savings; net present value; hot humid climates

1. Introduction

The world experiences a variety of energy and environmental challenges driven by factors like population and infrastructure growth, modernization, and urbanization [1,2]. These include depletion of natural resources, fast growing energy demand, fuel poverty, energy insecurity, and global warming [3–5]. Global warming is the main environmental concern for the world which is leading to sea level rise and climate change. There are wide ranging subsequent implications of climate change like seasonal disorders including frequent and more intense weather related disasters such as flooding, storms, droughts and wildfires. The 2015 United Nations Climate Change Conference (UNFCCC) in Paris (also referred to as the Paris Climate Deal) is evidence of the global realization of the need to tackle the environmental problems.

The building sector has an important role in global energy and environmental scenarios as it is responsible for 40% of the overall energy consumption, 40% of atmospheric emissions, 30% of raw materials use, and 25% of water use [6–9]. The building sector needs to make a vital contribution to the global drive for sustainability [10]. Countries across the world are actively pursuing sustainable buildings. Sustainability in the built-environment involves using processes that are environmentally responsible and resource-efficient technologies throughout the building life-cycle [11]. For a building to be considered sustainable, it must satisfy certain requirements. These requirements include: the reduction of waste, pollution, and environmental degradation; efficient use of energy, water and other resources; and protection of occupant's health throughout the building's life cycle [12,13]. Green roof technology is an energy efficient technology that is used to help improve sustainability of buildings [10]. This reality forms the basis for numerous research efforts that have been undertaken in recent years towards decarbonisation of the building sector. These include the development of energy efficiency strategies, building energy conservation and management, and innovative concepts such as net zero energy building (NZEB) [14–16].

Iqbal [17] describes a NZEB as "a home that optimally combines commercially available renewable energy technology with the state of the art energy efficiency construction techniques". To achieve a NZEB, various sustainable passive strategies can be employed. Passive design is understood as an approach that eliminates the need for active mechanical systems while maintaining or improving occupant comfort [18]. Passive design strategies for NZEB could be approached through innovative design of the building envelope. This may include optimizing the building orientation, maximizing the R-value of the wall and roof assemblies, optimizing the window-to-wall ratio, incorporating a Low-e glazing façade, increasing the thermal mass, incorporating shading devices, etc. Also, in the optimal design, efficient management and maintenance of active systems in buildings such as lighting and heating, ventilation, and air conditioning (HVAC) systems will contribute towards the achievement of NZEBs. On the global scene, the performance of green roofs has been investigated as a potential energy-saving strategy in buildings [19–21]. Thermal/energy performance of three types of green roofs versus white and black roofs, in a temperate climate, were compared. The study's results indicated that intensive, semi- intensive, and extensive green roofs provide about 20%–60%, 10%–45%, and 20% of energy-savings, respectively [22]. Another study was done in Singapore, comparing a cool roof and a green roof in terms of mitigating heat island effect; the results showed that a green roof is preferable in reducing the nocturnal urban heat island effects in a tropical city. [23]. Research analyzed the thermal performances of different layering solutions when compared to a reference traditional roof. The results indicate that green stratigraphy increases the thermal inertia on a traditional building, also, the thermal inertia of the opaque envelope of the air-conditioned buildings has a high influence on the energy transfer through the roof or wall in dynamic conditions [24]

Green roofs provide a wide range of sustainability and ecological benefits while also enhancing the aesthetic qualities and architectural presentation of buildings [19]. Green roofs, like other sustainable strategies, have been successfully used in many countries around the world [25–27]. Studies have shown the effectiveness of green roofs in hot climates as well [28].

Saudi Arabia is one of the most prominent countries in the Middle East for its population, economy, and energy infrastructure. To satisfy the requirements of a fast-growing population, the country is making an extensive investment in infrastructural development [29,30]. The results of rapid infrastructure growth and development are also being realized in the form of a steep rise in energy demand [31]. The situation presents significant energy, environmental, and economic challenges for the country. The cost of energy in Saudi Arabia is relatively cheap when compared to other parts of the world due to government subsidization. However, Saudi Arabia is now keen to reduce the energy load imposed by the building sector by employing energy efficient and sustainable strategies. The subject of sustainable buildings is relatively new in the country, and there is a lack of academic scholarship on it. Green roof technology is one of the sustainable building technologies which has not been duly explored yet. The present work's target is to contribute to the knowledge in this filed. It aims to investigate the technical and economic effectiveness of green roofs as a possible passive technology in reducing building energy consumption in hot humid climates. This is achieved through the following set of objectives:

1. Develop a green roof model for a selected four bedroom residential building with the help of DesignBuilder software.

2. Validate the result of the developed model using experimental data.
3. Determine the energy saving potential of different green roof options.
4. Undertake economic assessment of the developed green roof.

In the first part of the study, the authors present an overview of green roof technology, an insight to energy and environmental challenges in Saudi Arabia, and the green roof model development and validation. Subsequently, the paper also assesses the performance of different green roof options as a possible passive strategy for energy savings on a four bedroom housing facility at King Fahd University of Petroleum & Minerals (KFUPM) in the eastern province of Saudi Arabia. This is achieved with the the aid of the DesignBuilder software tool; green roof modeling has been undertaken for the selected roof after having described its detailed structural features. Finally, a net present value analysis has been conducted to determine the economic viability of green roofs.

2. Overview of Green Roof Technology

Green roof technology is a phenomenon that refers to the installation of vegetation on a roof top [19]. In various parts of the world, especially in Europe, the application of green roofs is well established. It is also a fast-growing technology in North America and parts of Asia [32]. This can be attributed to the significant environmental and economic benefits that it presents [33]. The main idea of green roofs is to reduce the total direct and diffuse radiation incidences on the roofs [34]. Green roofs not only provide insulation for Energy-savings, but also modify the temperature fluctuations experienced by the roof membrane [32]. This reduces the thermal stress and heat aging of the roof membrane, and, thus, the life span of the roof membrane is prolonged [35]. Incorporating a layer of vegetation on the rooftops of buildings also affects the relative humidity [36]. Green roof technology offers a wide range of benefits such as enhanced air quality, green roof habitat creation, mitigation of heat island effects, in addition to the reduction in the annual energy demand for buildings [32]. Additionally, it helps improve the thermal comfort of building occupants, especially where the climate is characterized by high temperature and solar irradiance values during the day [37]. Energy-savings that are achieved from the application of green roof technology are related to the reduced cost of maintaining the indoor environment [33].

The performance and efficiency of green roofs depends on the climatic conditions inherent at the site of its installation. Findings of research carried out in the warm and humid climate of Hong Kong show significant energy reduction for sedum rather than peanut applied as thermal insulation [38]. Another study conducted in Jordan to examine the effects of green roofs on the energy consumption of HVAC systems in buildings indicates a total Energy-saving of 17% [39]. Similarly, a comparative study between a green roof and a conventional roof system in an arid climate in Egypt has been conducted. The findings suggest an economic benefit of green roof systems, providing annual Energy-savings in the range of 15%–32% depending on the soil thickness and the thermal conductivity of the soil [40].

Green roofs also present the advantage of reducing the surface temperature by as much as 20 °C when compared with the surfaces of conventional roofs [35]. A simulation conducted by a group of scientists in Singapore showed that green roofs could reduce the surface temperature by 7.3 °C and, thus, decrease the ambient air temperature by 0.5 °C when compared with conventional roofs during the day [41]. The performance and efficiency of green roofs also depend on the nature of the substrate layer [42]. Research conducted by [43] showed that a substrate layer of clay is able to increase the thermal resistance of the roof by 0.4 $m^2 \cdot kW$ for each 10 cm increase in thickness. Also, changes in the physical characteristics of plants influence their environmental contribution [44]. Another advantage of the green roof technology is its use in storm water management [45,46].

3. Energy Challenges Facing Saudi Arabia

Saudi Arabia has experienced a steady growth in its construction sector in general and residential sector in particular. The residential sector is growing parallel to the steady rise in population, which has been suggested to be around 2.5% annually [10]. While only 24% of Saudi nationals own their own homes, estimates suggest that in order to meet the needs of the growing population, the country has to build 2.32 million new homes by 2020 [3]. This reality suggests a proportionate impact on the national energy scenario.

According to the Saudi Electric Company (SEC), electricity generation for the kingdom was 220 TWh in 2011, which is a result of an increasing total energy intensity of 1.8 percent/year between 2000 and 2011 [47]. The building sector is responsible for 80% of electrical energy use. Due to the hot climate prevalent in Saudi Arabia, thermal comfort is maintained through the use of the HVAC system, which consumes 70% of the energy use. The residential sector alone accounts for about 51%; this figure can be attributed to the fact that the country's development is based on energy-intensive industries, as well as the electricity-intensive lifestyles in the country [1]. The existence of about 70% of residential buildings without thermal insulation, and the low level of awareness of energy efficient products are some of the contributing factors to the high levels of energy use in the residential sector.

Statistics show an ever-increasing demand for energy, especially in the building sector and, thus, an increasing interest in exploring energy conservation opportunities in Saudi Arabia. To address this challenge, energy policies, efficient measures to minimize electricity consumption in existing buildings, and the use of thermal insulation in new buildings have been formulated by the Saudi Arabian government [48].

4. Green Roof Model Development

A four-bedroom single family faculty residence at King Fahd University of Petroleum & Minerals (KFUPM), Saudi Arabia, depicting the modern regional building design trends was used in the study (See Figures 1 and 2). A base case simulation model of the house was developed using DesignBuilder, which provides a graphic user interface. Since DesignBuilder uses EnergyPlus as its simulation engine, the authors assume the same balance equation as mentioned by [29]. The workflow starts with the selection of the proposed location for the analysis. Then, the tool allows the creation of the building's geometry and other defined parameters such as internal loads, construction types, windows, doors, lighting, material selection, and HVAC systems. Table 1 shows the summary of construction features of each thermo-physical system. In addition to these, emphasis is also given to infiltration in terms of airtightness depending on the number of openings, and organization and usage of the house. The airtightness in DesignBuilder is expressed in terms of a constant rate air changes per hour (ACH) schedule. Each floor has been assumed to have different levels of airtightness. Though the standard value these days for airtightness has been adopted as 0.5 ACH, the same could not be observed in the case of the base model development. As the lower level has many openings in comparison to the upper one, the airtightness is assumed to be 1 ACH and 0.5 ACH respectively.

Table 1. Key structural features of the building.

Building Features	Description of the Housing
Location	Dhahran (26.27 N latitude, 50.15 E longitude, and 17 m above sea level)
Orientation	Front Elevation facing East
Floor to Floor Height	3.5 m
Occupancy Density	8
Floor Area	367.3 m^2 (Gross); 192.0 m^2 (Ground Floor); 175.0 m^2 (First Floor)
Window to Wall Ratio (WWR)	10%
Weather File and relative humidity (RH)	Dhahran: 2012 and 55% relative humidity
Exterior Walls	0.016 m Plaster (Dense) + 0.1 m Concrete Block (Medium) + 0.05 m Extruded Polystyrene + 0.1 m Concrete Block (Medium) + 0.013 m Plaster (Lightweight)
Roof	0.04 m Concrete Tiles (Roofing) + 0.0002 m Polyethylene (High Density) + 0.05 m Extruded Polystyrene + 0.004 m Bitumen Felt + 0.059 m Cement Screed + 0.3 m Reinforced Concrete (Cast, Dense)
Infiltration	1.25 air changes per hour (ACH) (Ground Floor), 0.75 ACH (First Floor)
Lighting Power Density	21 W/m^2 (Ground Floor); 13 W/m^2 (First Floor)

Heating, ventilation, and air conditioning (HVAC) System Type	Residential System Direct Expansion (DX) Air Conditioner (AC)
Window	0.004 m tinted glass +0.012 m air gap + 0.004 m tinted glass

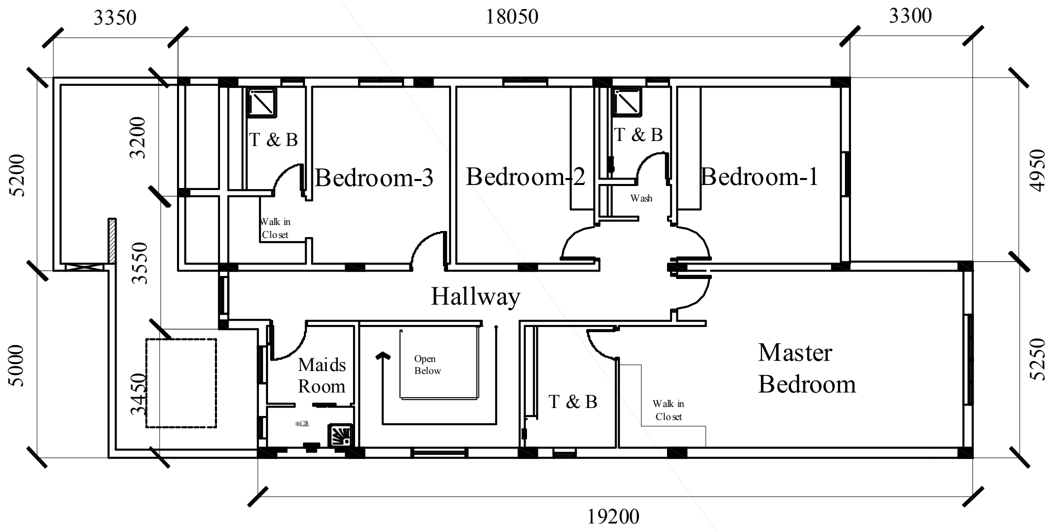

Figure 1. Building first floor plan.

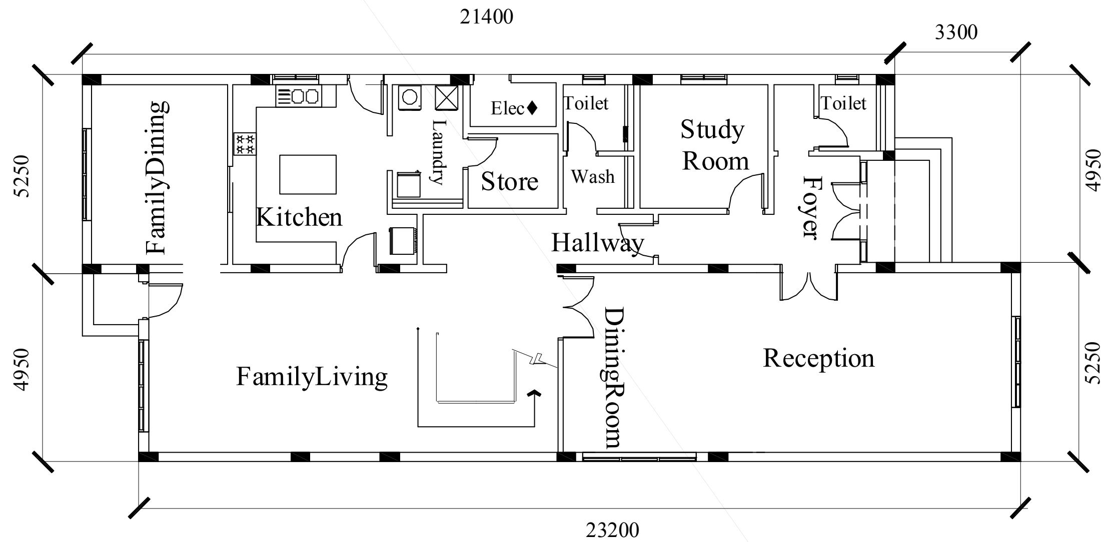

Figure 2. Building ground floor plan.

4.1. Validation of the Model

Energy consumption of the base case building was monitored during the summer season for three months, spanning from July to September. Measured data of energy performance for the base case with no green roof installed were obtained and used to validate the simulation model in DesingBuilder, as shown in Table 2. Subsequently, the green roof was applied on the validated building model. This formed the background for a review of the simulation model and verification of the base case model with green roof and customization of the green roof base on the vegetation growth pattern of the local weather conditions. The three green roof options were employed in the evaluation based on the area of coverage and green roof orientation. Finally, the derived simulation results and cost information collected from local and international manufacturers and contractors/product distributors were used to perform an economic evaluation of the various green roof options.

Table 2. Measured and simulated data.

Month	Measured Data KWh/m²	Simulated Data KWh/m²
July	25.8	24.6
August	28.1	25.8
September	23.8	20.9
Total	77.7	71.3

5. Simulation Techniques for Energy Analysis

To evaluate the energy and cost saving potentials, a set of three different green roof options were considered for simulation and analysis. The options were based on the area of coverage and green roof orientation which was intended to facilitate the cost benefit analysis. The first option considered for analysis was installing the green roof on the entire roof area of the building which is approximately 175 m². Simulation was performed and the results obtained were compared against the base case model. The other two options are presented as shown in Figure 3.

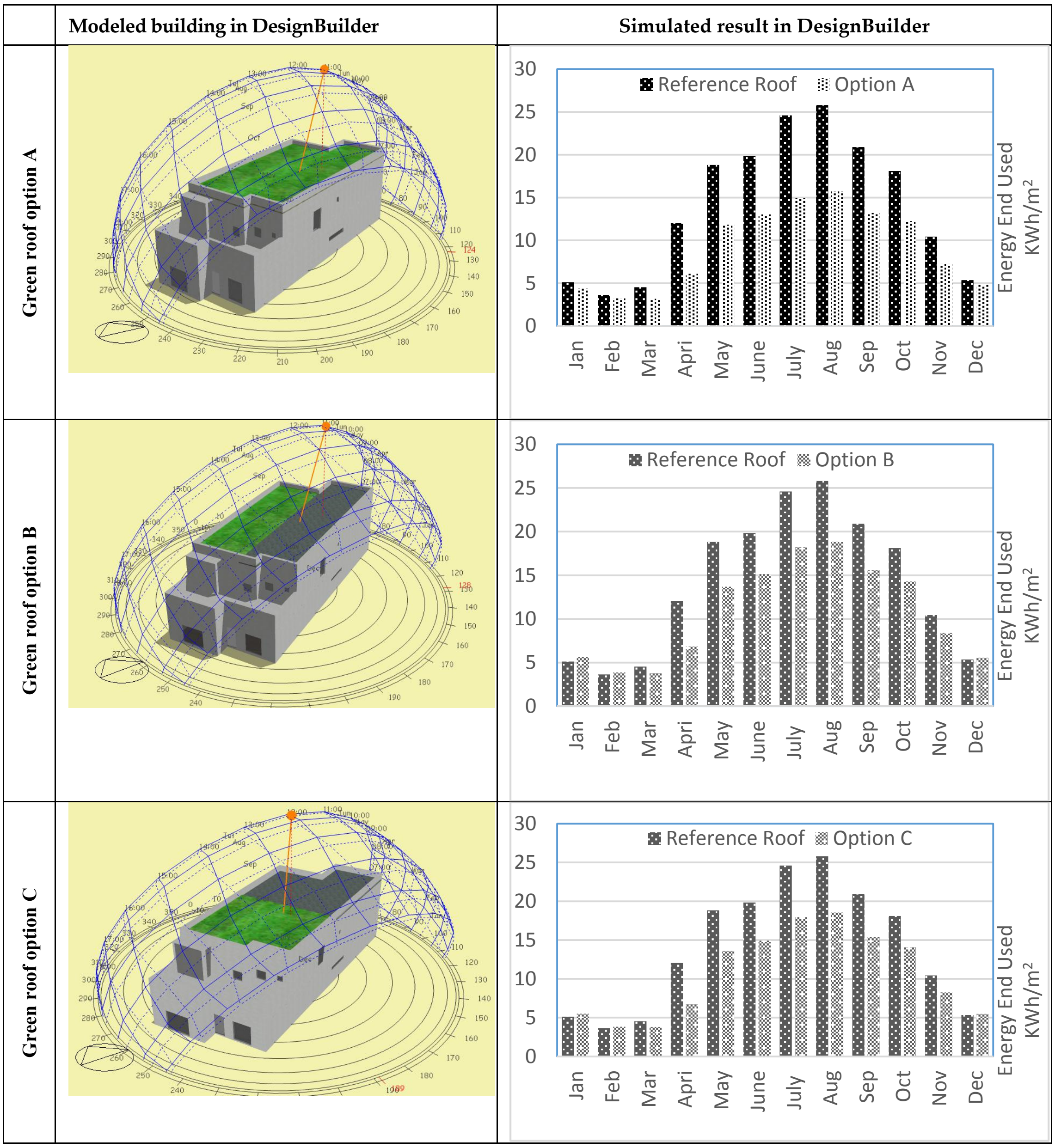

Figure 3. Simulated green roof options.

A cross section of the green roof components has been shown in Figure 4. The performance of this green roof was compared against that of the conventional roof through a simulation analysis. It is noteworthy that values for some of these parameters have been adopted from literature for validation of the base model, as shown in Table 3.

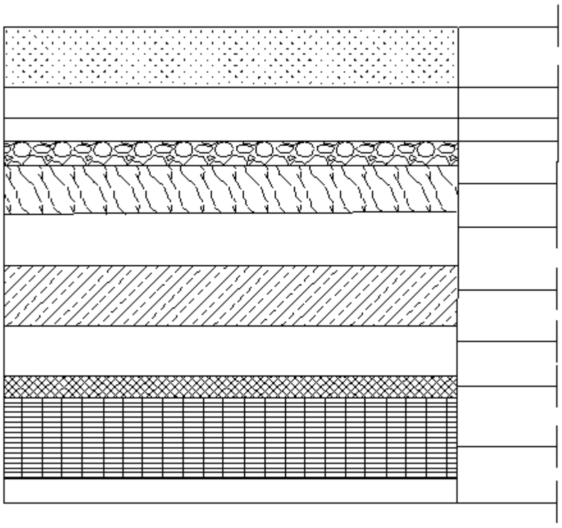

Figure 4. Cross section of roof component construction in DesignBuilder program with vegetation.

Table 3. Extensive green roof model parameters for input in DesignBuilder.

No.	Properties	Value
1	Thermal Conductivity (W/(m·K))	0.30
2	Height of Plants (m)	0.30
3	Leaf Area Index (LAI)	5.00
4	Leaf Reflectivity	0.40
5	Leaf Emissivity	0.95
6	Minimum Stomata Resistance (s/m)	50.0
7	Maximum Volumetric Moisture Content at Saturation	0.50
8	Minimum Residual Volumetric Moisture Content	0.20

6. Economic Evaluation

An economic evaluation is crucial to enumerate the potential costs and benefits of a proposed strategy or initiative and, ultimately, its feasibility. It also allows the comparison of alternatives, hence, providing a systematic process for decision-making and trade-offs. The test of net present value (*NPV)* is a standard method for assessing present value of competing projects over time. An investments should be realized only if $NPV > 0$, while in this study, the roof option with the highest *NPV* indicates the preferred option. The *NPV* is computed using the following equation presented by [49]:

$$NPV = -C_0 + \sum_{t=1}^{n} \frac{F_t}{(1+P)^t} \quad (1)$$

where:

- t is the time period, usually computed yearly.
- F_t the net cash flow for year t, computed as $F_t = B_t - C_t$.
- B_t represents the inflows or benefits accrued for the year t (which in this study is taken as the cost of Energy-savings in year t and the cost of other potential benefits).

- C_t represents the cost outflows for year *t* (which in this study is taken as the total operations and maintenance cost for year *t*).
- C_0 represents the initial investment (including all costs of materials and installation).
- *p* the cost of capital taken as 2% (Source): [50].
- *n* is the number of years for which the economic evaluation is desired (40 years for this study).

Potential environmental benefits of green roofs require quantitative appraisals to estimate the financial benefit. However, information on such benefits is not common and mostly subjective with rational hypothesis. The assessment presented in this section takes into account numerous accessible sources that justify the economic rewards of green roofs. Environmental evaluation of green roof benefits such as longevity benefit, green roof enhanced air quality, green roof habitat creation, and mitigation of heat island effect are estimated to be around SR 5.1/m^2. See Table 4 for their values and sources.

The cost of yearly energy-savings has been computed through the multiplication of the simulated Energy-savings in kWh/m^2, the total area of the roof, and the Saudi energy consumption tariff provided by [51]. The net cash flows are computed yearly and are assumed to be constant over the investment's lifetime. Table 5 is a presentation of the *NPV* computation for the three roofing options.

Table 4. Sources for net present value (*NPV)* computation parameters.

Variable	Value	Source
Installation cost for extensive green roofs (including the soil and equipment needed)	SR 88 per square meter	Local practitioners
Annual operations and maintenance cost	Varies	Local practitioners
Saudi energy consumption tariff	SR 0.113 /KWh	[51]
Compound factor	2%	[50]
Longevity benefit	SR 2/m^2	[52–56]
Green roof enhanced air quality advantage	SR 0.09/m^2	[57]
Green roof habitat creation advantage	SR 2.5/m^2	[58]
Mitigation of heat island effect	SR 3/m^2	[59–61]

Table 5. Computation of *NPV* for various green roof types (Saudi Riyals SR).

S/No.	Parameters	Amount (SR)		
		Option A	Option B	Option C
1	Initial investment (C_0)	15,429	7715	7715
2	Energy-saving benefits	1171	770	803
3	Longevity benefit	350	175	175
4	Green roof enhanced air quality advantage	15.75	7.88	7.88
5	Green roof habitat creation advantage	437.5	218.75	218.75
6	Mitigation of heat island effect	525	262.5	262.5
7	Cost inflows i.e. total benefit (B_t)	2499.25	1434.13	1467.13
8	Cost outflows i.e. operations and maintenance cost (C_t)	1500	1000	1000
9	Cash flow ($F_t = B_t - C_t$)	999.25	434.13	467.13
10	Net Present Value (*NPV)* (40 years)	11,905.96	4160.83	5063.57

7. Result and Discussion

7.1. Energy Analysis

Saudi Arabia is facing rapid growth in energy demand due to population growth, urbanization, modernization, and infrastructure growth. This has formed the basis of research efforts and projects carried out to examine the application of potential energy-saving strategies across various sectors. The building sector in particular is responsible for most of the energy consumed. Therefore, this study aimed at examining the application of green roofs as an energy-saving strategy for residential buildings in Saudi Arabia. The study has employed the DesignBuilder software to simulate the energy performance of the building based on the Dhahran weather file. The results obtained for the annual energy consumption based on the simulation of three green roof options are shown in Figure 5. The energy use was simulated using the HVAC System for a residential system Constant-Volume DX AC. However, the equipment's efficiency was not considered in this study. The AC operation has different performances for the two seasons (winter and summer) and, thus, the annual energy use was assumed from the energy needs for heating and cooling.

The three different green roof options considered in the developed model show separate performances as shown in Figure 3. The energy consumption of these three options and the base model was observed to be within a close range in the months of January, February, March, November, and December, since these months, which are winter months, are characterized by low diffused solar radiation. Furthermore, the results show that energy consumption decreases with increased radiation in the summer months for all roof options. On the other hand, in the winter season, the energy consumption reduction is barely significant due to heat losses during winter, when the outdoor temperature is lower than the indoor one.

Figure 5 summarizes the results of the simulated energy performance of the base case model and the green roof options. It can also be observed that energy consumption increases in April, May, June, July, August, September, and October due to increasing solar radiation in these months. The total yearly energy consumed by the base case model (without the vegetative layer) is 169.2 kWh/m^2 per annum, while green roof option A gives a total annual energy consumption of 110 kWh/ m^2 and, thus, a reduction of 35%. The Option B consumes a total energy of 126 kWh/m^2 per year with an estimated energy reduction of 25%, while the option C consumes a total energy of 128 kWh/m^2 annually and, thus, an energy reduction of 24%.

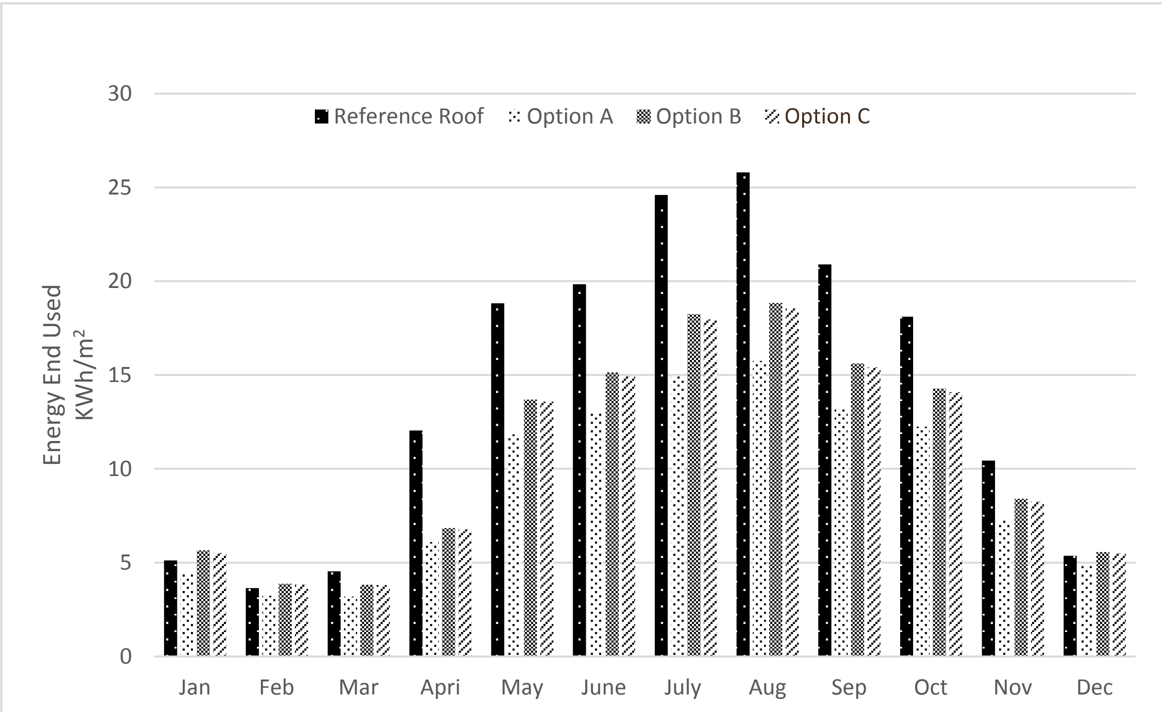

Figure 5. Monthly energy consumption of green roof options.

The results confirm that there is significant Energy-saving potential in the application of green roofs as an energy conservation strategy in buildings in hot, humid climatic conditions. Although as much as 35% in Energy-savings was realized, the green roof technology can only be considered a viable strategy to contribute NZEB if accompanied by competitive costs.

7.2. Economic Analysis

An economic evaluation is necessary to determine the economic viability of green roofs.

As shown in Figure 6, the results of an economic assessment employing the *NPV* approach show that all assessed green roof options have their *NPV*s less than zero until the end of the 19th year. At the end of the 20th year the *NPV* of all the options becomes positive, but only the option A at the 40th year shows a significant numerical value. Thus, it can be concluded that the benefits will only be fully achieved towards the end of the life cycle of the building. The results, therefore, suggest that the green roof technology, as a potential energy conservation strategy, is not an economically viable option. This can be attributed to the subsidized tariff rates for electricity in Saudi Arabia.

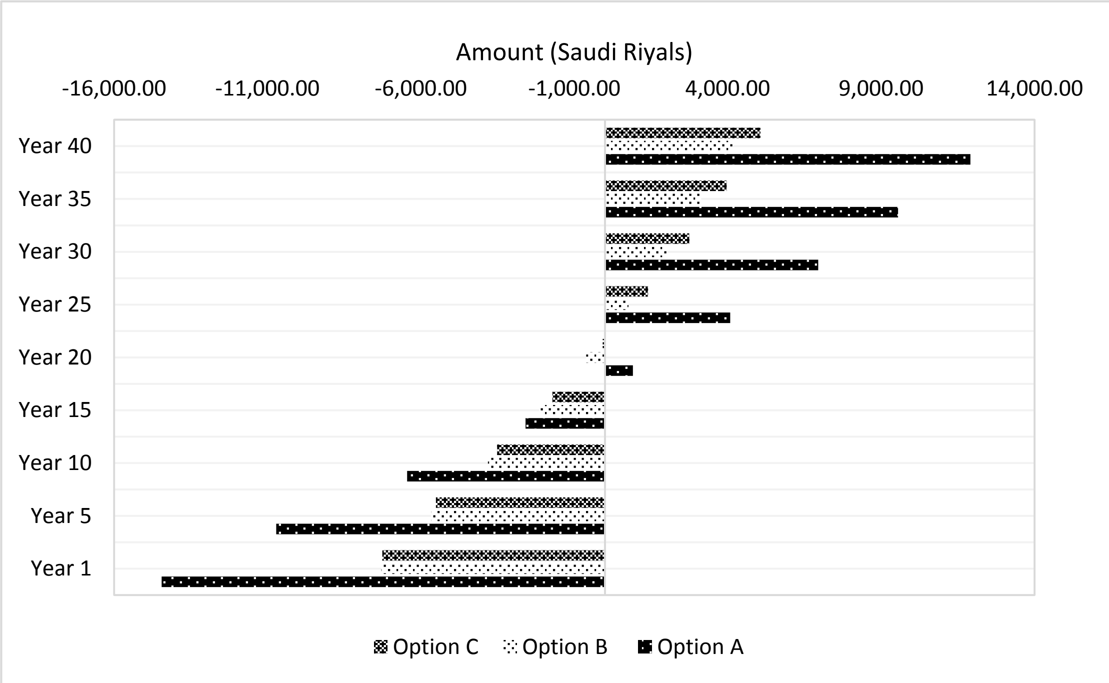

Figure 6. Yearly Net Present Value (*NPV)* for the green roof options (Saudi Riyals).

The average electricity tariff rate is about $0.03 kWh for residential buildings [51], which is low when compared to other countries. However, Saudi Arabia has plans to remove this subsidy. It is envisaged that the subsidy removal will be implemented in 2020. This envisaged rise in electricity tariffs will catalyze a rapid adoption of Energy-saving strategies such as green roofs. It will also improve the economic viability of such energy conservation strategies. Additionally, the green roof concept provides environmental benefits such as: reduction of urban heat island effect; sound absorption; capture of CO_2; and mitigation of air pollution. Such environmental benefits will increase the total quantifiable benefits of the green roof concept as indicated in Figure 7. The green roof concept can further be enhanced through botanical and horticultural studies on the various kinds of plants that are more conducive to the Saudi Arabian environment and will require little or no maintenance, hence a reduction in cost outflows. It is also noteworthy to mention that green roofs is one strategy that can be employed for energy conservation in buildings.

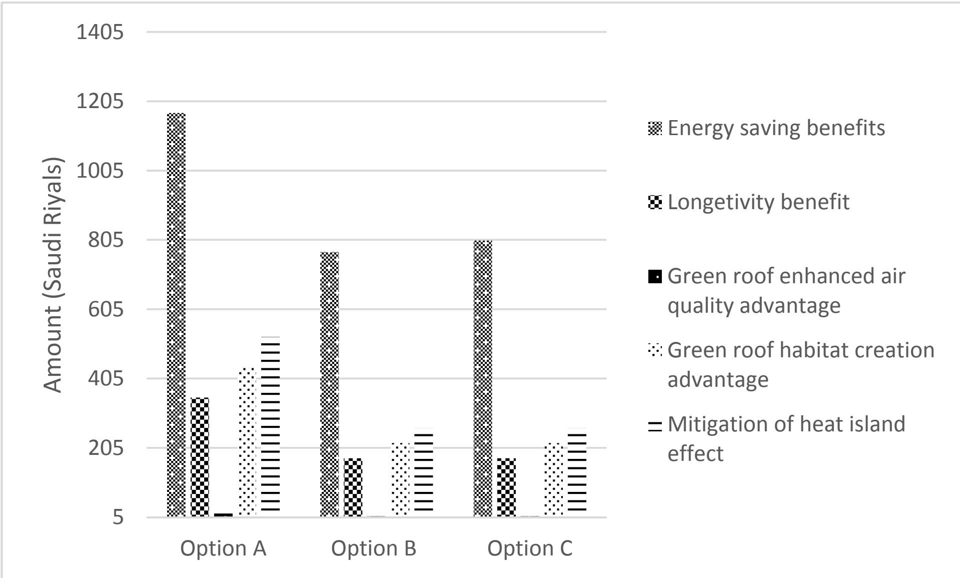

Figure 7. A comparison of the contribution of other benefits.

8. Conclusions

The building sector has an important role to play towards addressing energy and environmental challenges, as it accounts for almost 40% of energy consumption and one third of environmental emissions at the global level. The situation requires a paradigm shift in the energy consumption trends in the building sector and also an advocacy for radical energy efficiency measures. The de-carbonization of the built environment, and the achievement of NZEBs can be achieved through a number of sustainable and energy efficient strategies. Green roofs may be a potential energy-saving strategy and they have been adopted in some countries. Green roofs were investigated in this study within the context of hot-humid climates. The findings of this work reveal that green roofs offers significant Energy-saving potential in hot and humid climates. The case study showed that the energy consumption for the base case was 169 kWh/m^2, while the energy consumption due to the application of green roofing on the entire roof surface is 110 kWh/m^2. For the three investigated green roof options, energy saving is found to be in the range of 24% to 35%. In this study, no comparison was made between extensive and intensive green roof types. The harsh exterior weather conditions in Saudi Arabia are potentially an obstacle to the application of intensive green roof types. Moreover, an economic assessment employing the *NPV* approach shows that all assessed green roof options have negative *NPV*s at the end of the 19th year. However, at the end of the 20th year, the *NPV* becomes positive, but the value only become relatively high at the end of the 40th year. Thus, the economic viability of green roofs as a potential energy conservation strategy is not encouraging in Saudi Arabian due to a highly subsidized electricity tariff. The research concludes that though green roofs offer significant energy saving potential, it is currently not an economically promising technology for Saudi Arabia. The tariff increments planned by the Saudi government, however, will improve its economic viability. The authors suggest that other energy conservation technologies including cool roof, innovative roofing, and façade techniques should also be investigated towards the achievement of NZEBs.

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