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Impact of Green Roofs on Energy Demand for Cooling in Egyptian Buildings

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Abstract: Energy consumption for cooling purposes has increased significantly in recent years, mainly due to population growth, urbanization, and climate change consequences. The situation can be mitigated by passive climate solutions to reduce energy consumption in buildings. This study investigated the effectiveness of the green roof concept in reducing energy demand for cooling in different climatic regions. The impact of several types of green roofing of varying thermal conductivity and soil depth on energy consumption for cooling school buildings in Egypt was examined. In a co-simulation approach, the efficiency of the proposed green roof types was evaluated using the Design-Builder software, and a cost analysis was performed for the best options. The results showed that the proposed green roof types saved between 31.61 and 39.74% of energy, on average. A green roof featuring a roof soil depth of 0.1 m and 0.9 W/m-K thermal conductivity exhibited higher efficiency in reducing energy than the other options tested. The decrease in air temperature due to green roofs in hot arid areas, which exceeded an average of 4 °C, was greater than that in other regions that were not as hot. In conclusion, green roofs were shown to be efficient in reducing energy consumption as compared with traditional roofs, especially in hot arid climates.

Keywords: Design-Builder; energy consumption; green roofs; thermal conductivity

1. Introduction

The building sector as a whole consumes around 40% of the world's energy, exceeding the requirements of other sectors such as industry, agriculture, and transport [1]. The energy requirement for buildings is of the order of several hundred kilowatt-hours of primary energy consumption per square meter per year. Buildings are responsible for approximately 40% of the country's electricity consumption in Egypt [2]. Hence, in June 2010, the Egyptian Electricity and Energy Ministry (MEE) implemented a plan to cut overall energy consumption. Subsequently, efforts were initiated to reduce electricity usage by 50% in public buildings and street lighting in all governorates [3]. In line with the government's intent, this research was conducted to evaluate the efficiency of applying the green roof concept in Egypt to improve cooling inside buildings and thereby reduce energy consumption.

Thermal comfort in the buildings is a key target of architectural design. The thermal environment and the use of cooling energy in a warm environment are closely linked, where achieving thermal comfort is responsible for a significant portion of the energy consumption in buildings. Consequently, thermal comfort and energy consumption in hot arid regions have been achieved over the last few decades through the use of passive cooling techniques such as vernacular elements in buildings [4]. Passive building designs such as green roofs have recently been used to enhance energy efficiency and to develop more efficient electrical supply strategies, boost the thermal performance of buildings and abate the detrimental effects of urban heat islands (UHIs) [5–7].

The world is now going through a decisive stage where the exploitation of eco-friendly technology is pursued. A major objective here is to adapt to modern social and economic standards while developing new technology that would help to maintain environmental sustainability. In this context, green roofs are designed to meet these needs and provide valuable opportunities for the betterment of the climate and the economy. A green roof is defined as a living roof covered by vegetation and a growing medium on the top of a building [8–10]. It is an insulation layer that can mitigate the negative effects of solar radiation while it generates a cooling effect through the evaporative process. It is even more effective when thermal insulating materials are used under the green roof layers [11].

Green roofs adapt to contemporary social norms by creating a comfortable environment for the building's inhabitants. The concept is economically feasible when compared with conventional roofs. Environmental benefits have been derived from this strategy across nearly all climatic regions. More building owners are, therefore, exploring ways to reduce energy costs by installing green roofs, while governmental authorities are also taking an interest from the viewpoint of energy efficiency. In this regard, the scientific community that is responsible for the development of these green roof systems is faced with a huge challenge. Recent research on green roofs has provided valuable insights into its advantages, drawbacks, challenges, and future opportunities. Such research has capitalized on various approaches such as numerical modeling [12], pilot-scale studies [13], and empirical measurements [14].

Several studies have been carried out on green roof applications in different locations. Ayata et al. [15] reveal that green roofs are effective in decreasing air temperatures over cities in Turkey. Moghbel et al. [11] reported that the average air temperature above green roofs in Tehran was 3.06 to 3.7 °C cooler than the temperatures under a reference roof. Rafael [16], who analyzed the effect of green areas on air quality in Porto, found that such areas had a significant impact on air quality by increasing air pollutant dispersion. In another study, a green roof was installed on a nursery school in Athens, and its energy efficiency, environmental quality, and efficiency were monitored. A mathematical approach was developed in that study to estimate the cooling and heating loads during the summer and winter seasons, and to analyze energy efficiency across the building [17].

The green roof is one of several passive cooling strategies that is still uncommon in bioclimatic studies [18]. To date, most published simulation work has been confined to individual climate scenarios designed to test specific properties of the simulated envelope such as adaptive insulation [19] and glazing [20,21]. Green roofs are categorized as intensive or extensive, based on the height of the plant [22,23]. The thickness of the growing media is less than 20 cm for the extensive type and above 20 cm for the intensive ones [24]. The former is more common; it can be accommodated easily on an established roof without extensive modifications to the roof structure. Moreover, it needs minimum maintenance in comparison with the intensive type [25,26]. Extensive green roofs are, therefore, typically suitable for arid climates [27]. Intensive green roofs, on the other hand, are featured in complex vegetation communities; they include ground coverings, small shrubs, and trees with depths of more than 20 cm in planting medium. These are often built as roof-gardens and usually require irrigation, maintenance, and additional structural strengthening of the roof.

The design of the appropriate green roof system is a complicated process that relies on different aspects of sustainability, encompassing social, cultural, climatic, and environmental factors. Therefore, systematic selection methods (e.g., Multi-Criteria Decision Making (MCDM)) are a viable approach to solving the complexities in choosing the right option [28]. At the same time, the installation of green roofs above buildings must meet the technical requirements, building regulations, and energy efficiency standards for new buildings, with evidence that the proposed green roof or facade satisfies performance specifications. For instance, Australia stipulates certain green-roof conditions that have to be met before a building permit is granted. They include stipulations of a sufficient set back from the street, adequate structural load-bearing ability, and appropriate drainage and waterproofing management to ensure that the health of the occupants is not put at risk [27].

Owing to the lack of awareness in Egypt about the quantitative benefits of achieving the best thermal conditions and energy efficiency in buildings, green roofs are still unfamiliar systems that are yet to be implemented on a wide scale. In the present research, school buildings were chosen for the case study since such buildings had in the past been constructed without specific climatic considerations in all Egyptian cities. Nonetheless, they feature significantly in electricity consumption, particularly for cooling purposes. Thus, this paper explores new opportunities for energy savings in school buildings through the installation of green roofs. According to the General Authority for Educational Buildings (GAEB), there were about 53,587 schools across the republic, with 1931, 999, and 777 school buildings in Cairo, Alexandria, and Aswan, respectively [29]. This research examined different variations of green roofing to evaluate their effectiveness in reducing energy requirements for cooling and the ensuing thermal comfort. These results can be generalized for public buildings in Egypt and in other places with similar environmental conditions.

In the present study, the effects of the soil thickness and thermal conductivity of the proposed green roofs on the energy saved under various climatic conditions were examined in the following phases:

(i) The determination of the climatic characteristics of selected cities (Cairo, Alexandria, and Aswan) with detailed descriptions of the studied building models (traditional model and green roof models).
(ii) The validation of the traditional model in Aswan city by comparing the results of the simulation process with the thermal measurements and energy bills for the building study model.
(iii) A comparison of the traditional roof and proposed green roof vis-à-vis different variables such as the energy demand for cooling, thermal comfort conditions, and cost feasibility for the successful proposed green roof case.

This study comprises five sections. The first section is an introductory discussion of related literature on green roof operational efficiency. The second section describes the location of the studied cities as well as the main climatic characteristics of each city. The third section covers the research method, including a description of the conceptual model, model development, and model validation. The results and discussion appear in the fourth section, which focuses on the effect of the proposed green roof using various criteria, viz., the energy demand for cooling, the thermal performance of the proposed cases, and the cost analysis of these proposed cases. The study ends with the conclusion, which summarizes the advantages of the proposed models for guiding decision-makers.

2. Study Area

Egypt lies between the latitudes 22° and 32° North, and the longitudes 25° and 36° East. The area known as Upper Egypt lies south of the 30° North latitude and is a hot dry zone. The northern part of the Nile Delta and the northern coast, known as Lower Egypt, has a Mediterranean climate or coastal climate. Figure 1 shows the eight main regional climates in Egypt according to the Housing and Building Research Centre (HBRC), based on temperatures, humidity, and solar heat gains. Three cities—Cairo, Alexandria, and Aswan—that represented three different climatic regions were selected for this study (Table 1).

Table 1. Climatic characteristics of Cairo, Alexandria, and Aswan [31].

	Cairo	**Alexandria**	**Aswan**
Climatic region	Cairo and Delta zone	Northern coast zone	Southern Egypt zone
Record high temperature	47.8 °C	45 °C	51 °C
Record low temperature	1.2 °C	0 °C	2.4 °C
Average relative humidity	56%	67.92%	26.2
Mean monthly sunshine hours	3451	3307.1	3862.8
Precipitation range per month	0–5.9 mm	0–52.8 mm	0–0.25 mm

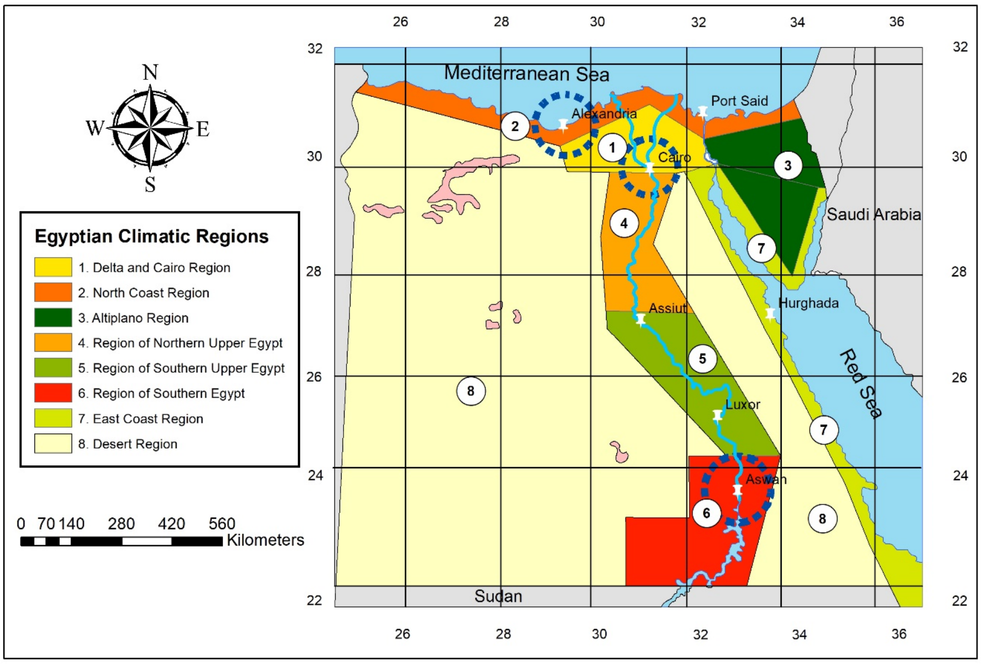
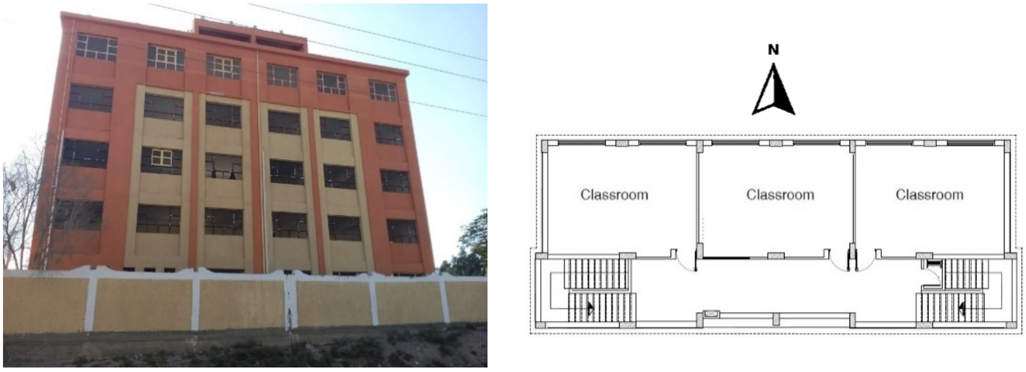


Figure 1. Climatic regions of Egypt [30].

3. Research Method

3.1. Conceptual Model

A primary school building consisting of five floors was selected as a case study. Except for the ground floor and the first floor, each floor had three classrooms, each with an area of approximately 38 m^2 as shown in Figure 2. Each classroom, occupied by an average of 30 students, was mechanically ventilated, while the computer lab and staff rooms were cooled by air conditioning in addition to mechanical ventilation. Recently, many classrooms had also been air conditioned for young students, although this study was conducted under the assumption that all classrooms were mechanically cooled.



(**a**) (**b**)

Figure 2. The modeled building. (**a**) Facade of the school building; (**b**) Typical floor plan.

The orientation of this school building was based on the site features. Like many schools, it was oriented towards the north to increase the distribution of daylight in certain classrooms.

3.2. Model Development

This research used a quantitative method to evaluate both the energy demand for cooling the interior of a school building during the study periods and the thermal performance upon installing a green roof on a typical school building model. Design-Builder version V5.5.2.007 (Design Builder Software Ltd., London, UK) was used to simulate the energy demand for cooling and to determine the efficacy of various green cover types in terms of building energy, carbon, lighting, and thermal comfort performance [32]. While the study was conducted in three Egyptian cities with different climatic conditions, the building model was of the same design and orientation in all the models. Two types of roofs were investigated. The first was the traditional roof fabricated with custom material (Table 2) while the second type was the green roof varying in soil depth and soil thermal conductivity (Table 3).

Table 2. Summary of data entries for the traditional roof.

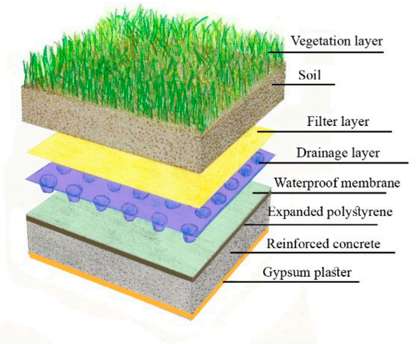
Material	Thickness (mm)	U-Value (W/m^2-K)
Cement tiles	20	0.602
Mortar	20	
Sand	60	
Ordinary concrete	70	
Bitumen layer	4	
Expanded polystyrene	30	
Reinforced concrete	150	
Gypsum plaster	20	

Table 3. Summary of data entries for the green roof.

Material	Thickness (mm)	U-Value (W/m^2-K)
Vegetation layer	-	0.311–0.347–0.353 0.288–0.337–0.347 0.269–0.328–0.340
Soil	100–150–200	
Filter layer	5	
Drainage layer	60	
Waterproof layer	7	
Expanded polystyrene	30	
Reinforced concrete	150	
Gypsum plaster	20	

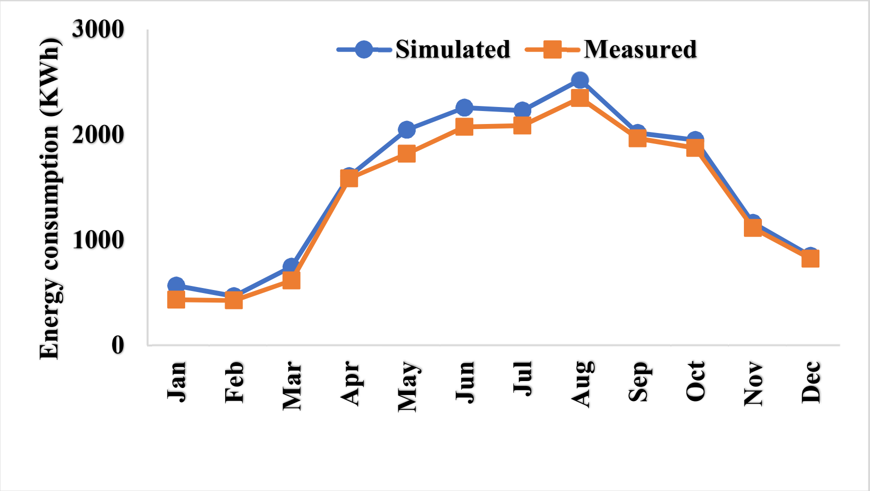
The proposed green roof was composed of eight layers. The outer layer was grass, typically 10 cm in height. Different types of soil with varying thermal conductivity (0.3, 0.6, and 0.9 W/m-K) and depths (10, 15, and 20 cm) were examined. Then, a filter layer was installed to separate the soil from the drainage layer to prevent the penetration of smaller particles such as soil fines and plant debris into the drainage layer. The filter layer also acted as a root barrier membrane. The fourth layer was the drainage layer, which removed surplus water away from the roof. The fifth layer was the waterproofing layer to prevent the leakage of water on the roof. Additional layers such as the thermal insulation layer, reinforced concrete, and the internal plaster were common layers for all roof types. In the study, various types of green roof were tested with the same basic primary school building designs in the three climatic regions. The input for the simulation process consisted of data from the different green roof types such as the specific heat (SH, the heat capacity of the green roof components divided by their mass) (J/kg-K), density (D, the mass of green roof components divided by their volume) (kg/m^3), leaf area index (LAI, the dimensionless ratio of the projected leaf area for a unit ground area) (m^2/m^2), height of plants (HP) (m), and leaf emissivity (EI), typical values of which appear in Table 4.

Table 4. Simulation matrix of green roof types.

General Specifications	Thermal Conductivity of the Soil (W/m-K)	Soil Depth (m)
	0.3	0.1
		0.15
		0.2
	0.6	0.1
		0.15
		0.2
Characteristics of the soil: Specific heat = 1000 (J/kg-K), D = 400 Kg/m^3 Characteristics of the plants: Leaf area index = 4, height of plants = 0.1 m, leaf emissivity = 0.9	0.9	0.1
		0.15
		0.2

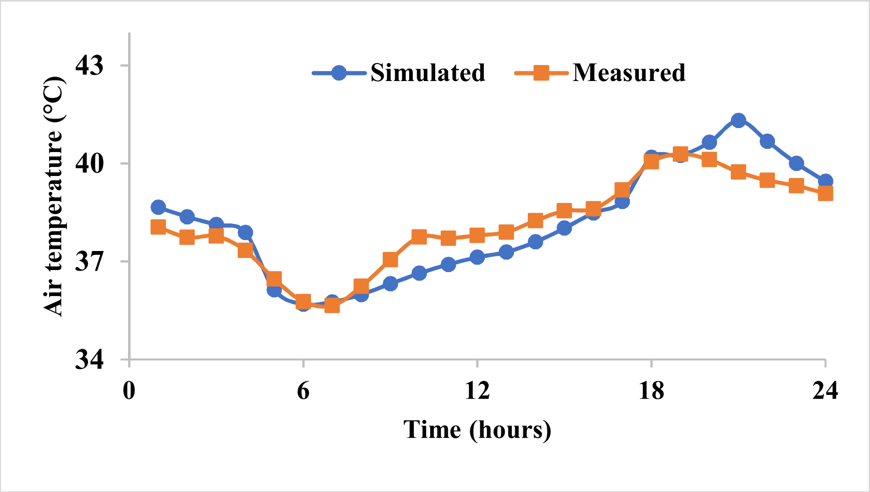
3.3. Model Validation

An annual simulation was created to validate the traditional model in Aswan city. A thermal validation (indirect) for the traditional model was undertaken on 15 April 2019. The actual energy consumption was obtained from the energy bills for 12 months for comparison with the output results using the simulation software. The average error in the energy simulations reached 10.6%, as shown in Figure 3. Another validation (indirect) was conducted to verify the thermal results. Air temperature and relative humidity data from the Hobo U12 data logger (Onset Computer Corporation, Bourne, MA, USA) indicated that the air temperature simulation produced results that were comparable with the field measurements. The differences between the measured and simulated values were approximately 0.54 K. Upon the completion of the validation process, the model was used to examine the impact of the green roof types and soil thicknesses on the air temperature and the energy consumption for cooling purposes.



(**a**)

Figure 3. *Cont.*



(**b**)

Figure 3. Indirect validation for the school building model: (**a**) energy validation and (**b**) thermal validation.

4. Results and Discussion

The study results are divided into three sections. The first section discusses the effectiveness of the proposed green roof types with different soil depths and thermal conductivities in terms of the cooling process and the annual energy consumption. The second section identifies the most effective types of green roof with regard to the thermal conditions of the interior spaces. Thus, air conditioners were first used in the simulation process to evaluate the energy consumption for cooling the building. Then, the building was modeled without air conditioning to evaluate the thermal effect of the proposed parameters of the green roof. The third section presents the economic benefits of using the selected green roof types.

4.1. Evaluation of Annual Energy Consumption

The Design-Builder thermal simulation tool was used to evaluate the effects of the green-roof types on the school cooling loads under different climate conditions. The estimated energy consumption was used as an indicator of the efficiency of each green roof type for the cooling process with respect to changes in thermal conductivity (0.3, 0.6, and 0.9 W/m-K) and soil depth (0.1, 0.15, and 0.2 m) on the roof. Other parameters such as the leaf area index (LAI) and thermal insulation layers were unchanged.

The results indicated that the green roof effectively reduced the energy demand for cooling as compared to the traditional roof under all the examined climate conditions (Figure 4). Among the cities studied, Aswan benefitted the most in this regard, with the reduction in cooling energy exceeding 39% for green roofs with all soil depths and soil thermal conductivities. By comparison, the average percentage of energy savings did not exceed 35% in the other two cities. Thus, it can be concluded that the green roof technique is more effective where the environment is especially hot and arid.

Figure 4 shows that a green roof with 0.1 m soil thickness demonstrated higher cooling efficacy than the other tested roofs, even at a high soil thermal conductivity of 0.9 W/m-K, in all three cities. The installation of a green roof with a 0.1 m depth and 0.9 W/(m-K) decreased the energy required for cooling by 32.31%, 34.89%, and 39.74% and reduced the annual energy consumption for the cooling process by 18,102.07, 22,633.13, and 32,267.08 kWh compared to the traditional roofs in Alexandria, Cairo, and Aswan, respectively. The results showed that a layer of shallower soil had slightly better performance than a deeper layer. This could be attributed to its higher ability to eliminate the excess heat that accumulated during the night in the early hours of the day in comparison to that of the deeper soil. The internal temperature remains warmer at night, due to the green roof's increased inertia. Thus, a very hot day reduces the likelihood of passive night cooling, because the temperature never gets lower for enough time to discharge the heat generated during the day. In addition, high LAI values increase the shading effect on the roof surface, thereby slightly reducing the effect of soil thickness during the day as regards the cooling process [33]. This finding was consistent with all the tested thermal conductivities. In addition, higher soil thermal conductivity was found to be more efficient in improving the cooling process than the lower soil thermal conductivity. This finding is consistent with that in previous studies [34–36] that shows that a higher soil thermal conductivity in the green roof combined with an increased moisture content in the soil contributes to an increase in the evaporation rate, thus reducing the heat flow within the interior spaces.

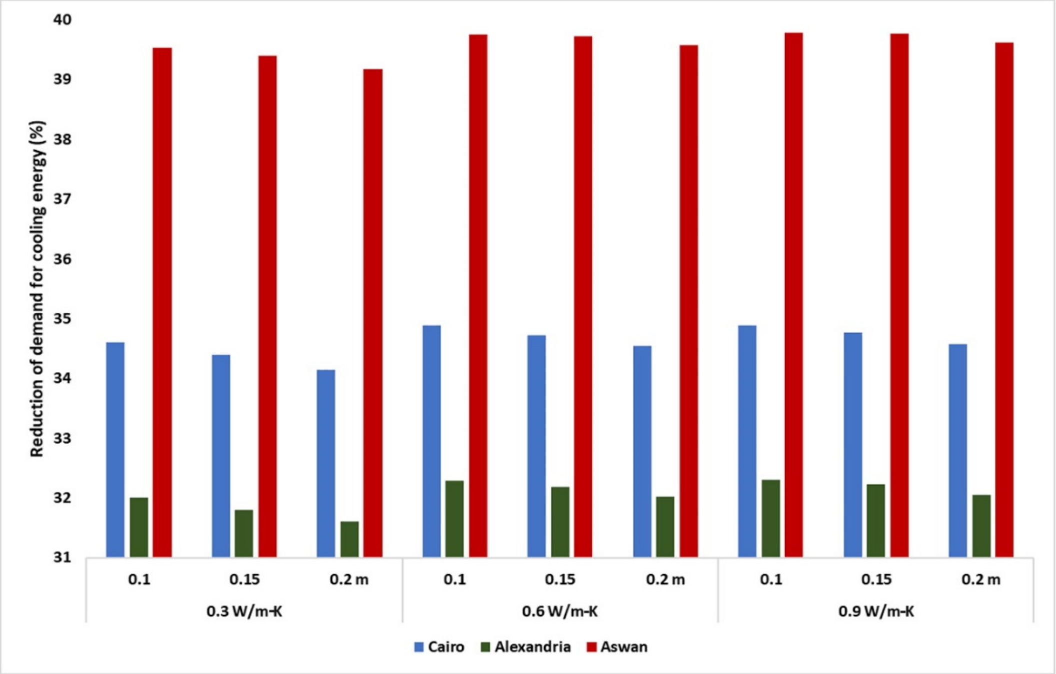


Figure 4. Effect of green-roof soil depth (m) and soil thermal conductivity (W/m-K) on the reduction (%) of demand for cooling energy in three cities. Soil depth and thermal conductivity measurements are the values in the upper row and lower row of the *x*-axis, respectively.

It might, therefore, be concluded that the cooling effectiveness in the building bears a negative relationship with the soil depth that is associated with a high LAI and a positive relationship with the soil thermal conductivity of the green roof. This is in agreement with Kamel et al. [36], who reported a negative relationship between the roof soil depth and cooling performance.

4.2. Thermal Performance of the Green Roof Types

The thermal performance of the most successful green roof type among the variations studied (K = 0.9 W/m-K, soil depth = 0.1 m) was evaluated. A comparison between the traditional and green models in the selected regions was conducted in terms of operative temperature (which represented an internal thermal comfort index reflecting the blend of air temperature effects) and mean radiant temperature. This comparison was conducted on the 15th April, the hottest day in the second semester.

The results revealed a difference across the studied climatic zones between the indoor operative temperature and outside dry-bulb temperature (Figure 5). There was a reduction in the indoor operative temperatures compared with the dry-bulb temperature in the daylight hours in Cairo and Aswan, although the indoor operative temperatures during the night hours were higher than the dry-bulb temperature. In Alexandria, on the other hand, the indoor operative temperatures throughout the daytime were higher than the dry-bulb temperature.

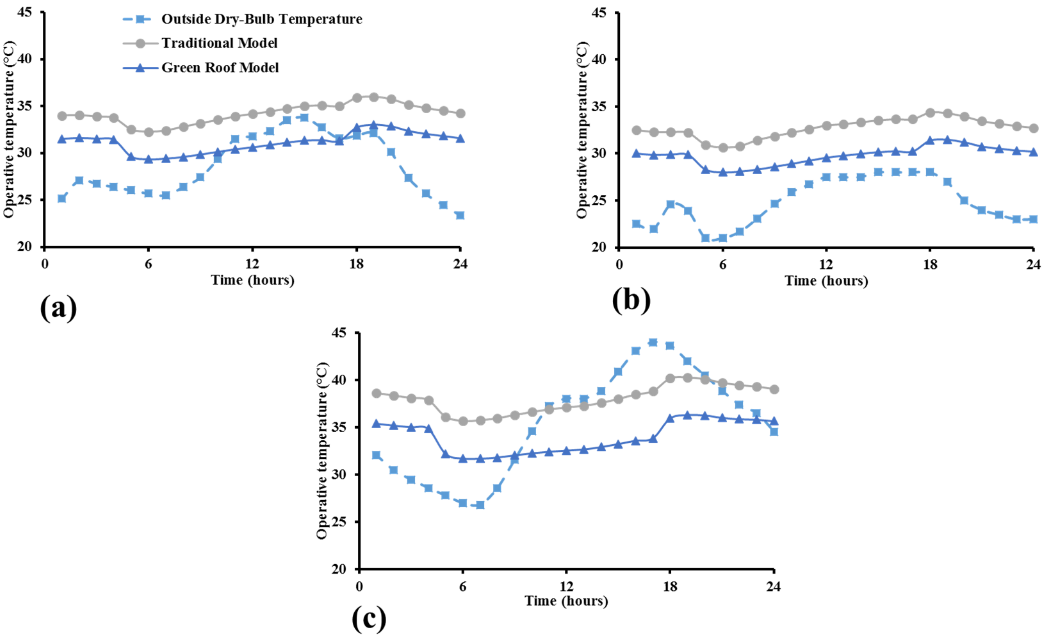


Figure 5. The operative and dry bulb air temperature profiles of the traditional and green roofs on 15 April for (**a**) Cairo, (**b**) Alexandria, and (**c**) Aswan.

The operative temperatures during the working hours, from 8:00 till 15:00, were examined in greater detail for the traditional and green roof models on the 15th April. The temperature differences between the two models are shown in Table 5. The operative temperatures showed high agreement with the energy consumption and energy-saving levels in the studied cities. For example, the larger difference between the traditional and the green roof models in terms of the operative air temperature was recorded in Aswan city; there was a higher amount of energy saved than in the other two cities. The difference between the traditional and the green roof models ranged between 4.17 and 4.78 °C in Aswan during the occupancy hours, whereas it did not exceed 3.68 °C and 3.39 °C in Cairo and Alexandria, respectively, as shown in Table 5. In general, these results reflected the significantly higher effectiveness of installing green roofs on the buildings in Aswan than that in the other two cities, which were less hot and arid, in terms of thermal load reductions and energy saving.

Table 5. The operative temperatures in the traditional and green roof models for Cairo, Alexandria, and Aswan.

Time	Cairo			Alexandria			Aswan		
	Traditional Model °C	Green Roof Model °C	Difference °C	Traditional Model °C	Green Roof Model °C	Difference °C	Traditional Model °C	Green Roof Model °C	Difference °C
8:00	32.81	29.58	3.23	31.44	28.30	3.13	35.99	31.82	4.17
9:00	33.18	29.85	3.33	31.86	28.60	3.26	36.32	32.05	4.27
10:00	33.53	30.12	3.41	32.22	28.91	3.32	36.64	32.26	4.38
11:00	33.90	30.40	3.50	32.60	29.24	3.36	36.91	32.43	4.49
12:00	34.18	30.61	3.57	32.99	29.56	3.43	37.13	32.55	4.58
13:00	34.42	30.84	3.58	33.14	29.78	3.37	37.29	32.67	4.62
14:00	34.74	31.12	3.62	33.33	29.97	3.36	37.60	32.92	4.68
15:00	35.00	31.32	3.68	33.54	30.15	3.39	38.02	33.24	4.78

4.3. Cost Analysis

Decision-makers in Egypt have always considered the need to reduce the cost of operating government buildings. However, the tendency has been to reduce the number of hours for which air conditioning is switched on. The government recently embarked on a policy of passive climate solutions, but weakness in cost-effectiveness is an impediment to its implementation. Using primary school buildings as models, this research paper examined the feasibility of using the green roof system as a more economical alternative.

While the results of this study showed that the proposed green roofs could be energy-saving, it was also essential to examine their financial benefits in terms of both energy and cost savings. Thus, a cost analysis (in US dollars, USD) was performed, where the additional investment was calculated for the various soil depths in conjunction with the thermal conductivity K = 0.9 W/m-K. The three options were K = 0.9 W/m-K and soil depth = 0.1 m, K = 0.9 W/m-K and soil depth = 0.15 m, and K = 0.9 W/m-K and soil depth = 0.2 m. The initial cost of the irrigation system was neglected in each option due to the unnecessity of these irrigation systems in the extensive green roof type. Meanwhile, the main elements of the construction cost were assumed to be the same for the traditional roof and for the green roof options. The additional investment and the simple payback period (SPP, in a number of years) were calculated as [37]:

Additional investment = Total material cost of each selected green roof option − the total material cost of the traditional roof.

$$\mathrm{SPP} = \frac{\text{Additional Investment}}{\text{Annual Saving}}$$

The unit costs (USD/m^2) of the traditional and green roof layers were obtained from international suppliers, and other costs were obtained from the local market. Table 6 summarizes the recent prices for the materials used.

Table 6. Unit costs of materials.

Materials	Unit Cost USD/m^2
Cement tiles + mortar + sand	6.5 [b]
Ordinary concrete (sloped concrete)	7.5 [b]
Bitumen layer	11 [b]
Expanded polystyrene	14 [a]
Reinforced concrete	30 [b]
Gypsum plaster	7 [b]
Filter layer	5 [a]
Waterproof layer	2 [a]
Drainage layer	3 [a]

[a] www.alibaba.com. [b] Arab Contractor Company, Egypt.

The total annual energy costs, total construction costs, annual savings, and SPP for the various options are presented in Table 7. In terms of energy saving, Option 1 (K = 0.9 W/m-K and soil depth = 0.1 m) is obviously the most promising option. It has the lowest 6.27 y SPP. Such a green roof is, therefore, considered the best overall green roof type among the options compared because of its efficiency and low SPP.

Table 7. Cost analysis summary.

Green Roof Options	Construction Cost (USD)	Additional Investment (USD)	Energy Cost (USD/year)	Annual Saving (USD/year)	SPP (No. of Years)
Option 1	29,700	17,280	4173.10	2752.19	6.27
Option 2	30,600	18,180	4171.22	2754.06	6.60
Option 3	32,400	19,980	4181.63	2743.65	7.28

Option 1: K = 0.9 W/m-K and soil depth = 0.1 m; Option 2: K = 0.9 W/m-K and soil depth = 0.15 m; Option 3: K = 0.9 W/m-K and soil depth = 0.2 m.

5. Conclusions

This study was undertaken with the objective of improving the energy efficiency of indoor spaces. School buildings in three selected Egyptian cities were used in this study; they had been built without taking into consideration the climatic conditions in the locale. A building model was developed to assess the impact of green roof characteristics (soil thermal conductivity and depth) on the energy demand for cooling and operative temperature inside the school building. The parametric study of the green roof showed that all the proposed green roof types were effective in reducing the energy demand for cooling in the three selected cities. The results showed, quantitatively, that the proposed green roof types have the potential to significantly reduce the energy demand for cooling, especially in Aswan city. The effectiveness was less prominent in the other two cities that were less demanding in terms of energy requirements for cooling, indicating that the green roof is more effective in warmer and more arid regions. The results also suggested that soils with 0.9 W/m-K thermal conductivities attained more energy savings than those with 0.6 W/m-K and 0.3 W/m-K thermal conductivities. The 10 cm-thick soil, which was associated with a high value of the LAI, turned out to be more efficient than the other thicknesses assessed (15 and 20 cm).

In addition to the environmental advantages of this type of green roof, the cost analysis suggests that the proposed green roof type with the following characteristics—K = 0.9 W/m-K and soil depth = 0.1 m—seems to be the most economically feasible option for the modeled building. The other proposed options, though not as advantageous, appear to be promising as well. In general, the installation of green roofs on public buildings such as schools meets the objectives of the new energy policy for Egypt. It should also lead to the maximization of environmental and economic benefits, as well as the promotion of the principles of energy conservation and sustainability. The concept can be addressed by decision-makers in the early stages of architectural design. These systems ought to be among the mandatory requirements for the design and operation of public buildings. Future research on green roof technologies should take into account the differences in the climatic conditions of each specific region. Further research should be developed to assess the impact of other green roof parameters (such as the leaf area index and leaf emissivity) on their effectiveness in keeping the interior of buildings cool, thus reducing energy consumption by buildings in hot arid regions. Further empirical work is required to extend the applicability of the findings to other parts of Egypt as well to other regions of the world with similar climatic conditions.

Author Contributions: A.R. conceived the ideas and research design of this paper; A.R. performed data analysis; A.R. and A.A. acquired the data; A.R. developed and validated the model; A.R. and A.A. wrote the paper. All authors have read and agreed to the published version of the manuscript.

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