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Article

A dual-resource rooftop system for water-energy sustainability: a case study at Near East University's grand library

Youssef Kassem[1,2,3,4]*, Hüseyin Çamur[1,4], OmaimaThaer Abdullah Abdullah[1], Saeed Hussein Alhmoud[5]

[1]Department of Mechanical Engineering, Engineering Faculty, Near East University, 99138 Nicosia (via Mersin 10, Turkey), Cyprus
[2]Department of Civil Engineering, Civil and Environmental Engineering Faculty, Near East University, 99138 Nicosia (via Mersin 10, Turkey), Cyprus
[3]Energy, Environment, and Water Research Center, Near East University, 99138 Nicosia (via Mersin 10, Turkey), Cyprus
[4]Science, Technology, Engineering Education Application, and Research Center, Near East University, 99138 Nicosia (via Mersin 10, Turkey), Cyprus
[5]Department of Interior Design, Faculty of Art and Design, Applied Science Private University, Amman, Jordan

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*Corresponding author
Email address:
yousseuf.kassem@neu.edu.tr
youssef.kassem1986@hotmail.com

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ABSTRACT

The present paper introduces a novel rooftop hybrid system that integrates a solar power system (SPS) and a rainwater harvesting system (RHS) at the Grand Library of Near East University in Northern Cyprus. In this study, ground-based rainfall measurements from 2015 to 2023 were compared with six satellite-derived precipitation datasets (CHIRPS, CFSR, ERA5, ERA5-AG, ERA5-LAND, and MERRA2) to determine the potential for rainwater collection. The results demonstrate that the ERA5-AG dataset produced the highest accuracy based on the values of key metrics (R-squared, Root Mean Squared Error, and Mean Absolute Error), and was used to estimate rainfall harvesting potential. Based on maximum and average daily rainfall, the winter season provided the most potential, with up to 1,665.12 m^3 and 373.51 m^3 of collected rainwater, respectively. Moreover, the environmental and economic viability of the proposed RHS-SPS system is evaluated through mathematical modelling. The results indicate that a tilt angle of 34° and a north-oriented face generated the highest annual energy output (735,316.3 kWh) and the best capacity factor (19.52%) among the various orientation angles. Furthermore, the Levelized Cost of Energy (LCOE) for the system varied from 2.860 to 5.503 cents/kWh. Besides, a 34° tilt produced the most reduction in CO2, according to analysis of the environmental assessment. According to the findings, the RHS-SPS system aims to address two critical challenges in semi-arid regions (renewable energy production and water conservation) and achieve the Sustainable Development Goals.

1. Introduction

Freshwater resources, sustainability, and energy shortages are among the primary worldwide challenges of the twenty-first century that have been impacted by climate change [1,2]. The frequency and intensity of droughts and floods have increased due to rising temperatures and altered precipitation patterns, creating new obstacles to effective water management and necessitating the creation of sustainable solutions [3, 4]. Developing strategies to reduce greenhouse gas (GHG) emissions while transitioning to clean, renewable energy sources is one of the new demands on the global energy climate [5,6]. Conventional rainwater harvesting (RWH) is widely utilized as a localized water supply option, particularly in urban and semi-arid areas [7]. RWH systems have the potential to decrease stormwater flow, augment traditional water supplies, and encourage groundwater recharge by collecting, storing, and using rainfall from rooftops and other surfaces [8]. Furthermore, in low-rainfall areas with unpredictable distributions that frequently fall short of needs, these systems would significantly mitigate the effects of climate change [9].

Abbreviations

GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
KIB-TEK	KibrisTürkElektrikKurumu
LCOE	Levelized cost of energy
NEU	Near East University
NEU-GL	Near East University Grand Library
PV	Photovoltaic
RHP	Rainwater harvesting potential
RHS	Rainfall harvesting system
SPP	Simple payback period
SPS	Solar power system

Furthermore, rooftop solar photovoltaic (PV) systems are becoming increasingly popular worldwide as an affordable and sustainable energy source [10]. The rooftops of buildings are untapped potential sites for photovoltaic panels, which might convert solar energy into environmentally safe electricity. This is particularly true for sizable institutional structures. They complement one another because both solar and rainwater harvesting systems need comparable structural infrastructure to be installed, primarily on rooftops [11, 12]. This overlap presents a unique opportunity to collaboratively design integrated systems that optimize water and energy production.

1.1 Water resources in Northern Cyprus

Northern Cyprus's water resources are divided into four resources [13] as shown in Figure 1. The region's total surface and groundwater capacity is roughly 173.18MCM [14]. At Bafra, Eastern Mediterranean University, and Girne, there are also three small private desalination plants with capacities of 730,000, 365,000, and 545,000 m3/year, respectively [15]. Generally, groundwater in the Güzelyurt basin, located in the western region of Northern Cyprus, is discovered to be an unconfined aquifer. Quaternary deposits constitute the majority of the aquifer in the area, while pre-Quaternary layers serve as boundaries for the impermeable or semi-permeable aquifer [16]. Groundwater levels are 45–50 meters below sea level, according to earlier studies [17, 18]. With a water reserve of about 920 mm3, the Güzelyurt aquifer provides water for irrigation and other uses in the area [19, 20]. According to previous studies, the main farming activities in the Güzelyurt district have a significant positive impact on Northern Cyprus' economy. Besides, uneven rainfall distribution and water resource conditions, including agricultural water deficit, have an impact on the region's overall agricultural output. Also, since the 1970s, drought and salinization have been issues, and 75% of all water withdrawals are for crop irrigation [16-20]. Furthermore, the area of Güzelyurt, which has an abundance of agricultural land, is currently dealing with serious water issues, which have caused a sharp decline in water supply and a decline in the quality of agricultural output. Additionally, agriculture is separated into irrigated and rain-fed systems, which are widely used to grow a variety of crops, with almonds being the most common crop [16, 18].

1.2 Energy situation in Northern Cyprus

In general, the growth of educational institutions and an expanding economy in many sectors has led to an increase in energy demand in Northern Cyprus [21, 22]. Nevertheless, the energy industry faces serious obstacles as a result of this growing demand, particularly due to the fact that there aren't enough domestic energy resources to meet the nation's demands. Besides, summertime energy shortages are especially severe due to high demand and inadequate capacity for energy generation [23]. About 30% of the energy is used for business purposes, and 20% is used for residential purposes. Recently, Northern Cyprus has been mainly dependent on fossil fuels, which provide 94% of its electricity, with only 6% coming from renewable sources according to the Cyprus Turkish Electricity Authority, KibrisTürkElektrikKurumu (KIB-TEK). Due to price rises and a significant increase in greenhouse gas emissions, this reliance on imported fuel affects both the economy and the environment. To address these concerns, the country has made the development of clean, affordable, and sustainable energy a primary goal. The government's plan calls for implementing energy-saving strategies and focusing on the development of renewable energy sources, particularly solar energy. Additionally, KIB-TEK has implemented a net metering system to encourage the development of solar power systems [24-26]. Thus, customers can now export excess energy to the grid from their solar installations. This effort has been hampered by the grid system's isolation, which limits its capacity to handle expanding PV installations. According to the Renewable Energy Board (Yek-Kurulu), single-phase grid-connected consumers can currently install up to 5 kW of PV systems, while three-phase customers can install up to 8 kW [27]. Moreover, the country is well-positioned to use solar energy, with 320 sunny days per year and an average solar radiation of 1600–2200 kWh/m^2 (see Figure 2) according to the Global Solar Atlas.

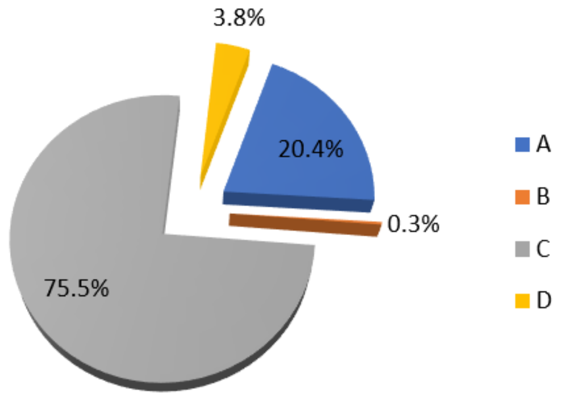

Figure 1. Cyprus' water resources: (A) surface water reservoirs, (B) semi-perennial low-discharge springs, (C) groundwater resources, and (D) small-scale desalination facilities

1.3 Importance of the study

According to the Intergovernmental Panel on Climate Change (IPCC), water scarcity affects 80% of the world's population [28]. Additionally, 1.8 billion people are anticipated to live in regions with serious water scarcity by 2025 [29]. According to Matomela et al. [30], population expansion and climate change have made water scarcity a serious worldwide issue, particularly in semi-arid and arid regions where precipitation highly fluctuates. Furthermore, a water catastrophe is imminent in many nations, particularly those in the Middle East and North Africa, according to Daoudy et al. [31].

Figure 2. Global horizontal solar irradiation map

Moreover, technologies and renewable energy sources could help solve the world's energy issues. According to Kassem et al. [32], solar energy can be an important part of Northern Cyprus's strategies, not only to add a new capacity but also to increase energy security, addressing the environmental concerns. In this context, the integrated rainfall harvesting system (RHS) and solar power system (SPS) are an efficient technique for sustainable management of energy and water resources in developing countries such as Northern Cyprus. Therefore, this paper presents a techno-economic feasibility analysis on the development of an Integrated rooftop RHS-SPS system to collect rainwater and produce electricity for the Near East University Grand Library (NEU-GL), North Nicosia, Northern Cyprus. NEU-GL is an outstanding illustration of a large institutional building with a large rooftop that can be utilized for such a dual-purpose system. The Grand Library's broad roof structure provides a platform for a state-of-the-art system that integrates solar energy and rainwater collection, complementing the university's sustainability goals. To this aim,

a) Several satellite-derived precipitation datasets (CHIRPS, CFSR, ERA5, ERA5-AG, ERA5-LAND, and MERRA2) are evaluated and compared with ground-based rainfall measurements collected by the Meteorological Department in North Nicosia, Northern Cyprus, between 2015 and 2023. Based on the most accurate dataset, the rainfall harvesting potential is then determined using average and maximum daily rainfall data.

b) The environmental and economic viability of the proposed RHS-SPS system is investigated through mathematical modeling. The Simple Payback Period (SPP), Levelized Cost of Energy (LCOE), and carbon emission reductions are among the significant metrics that are assessed under different solar panel tilt angles.

2. Materials and Methods

2.1 Study area

The Cyprus map, including Near East University Grand Library (NEU-GL), is shown in Figure 3. The NEU-GL is located on the NEU campus in North Nicosia, Northern Cyprus.

It is one of the most well-known and extensively resourced libraries in the Eastern Mediterranean. It is an important intellectual hub for scholars, researchers, and students. The Grand Library is crucial to NEU's research and academic achievement because of its extensive book collection, digital resources, and state-of-the-art facilities.

2.2 Design description of the RHS-SPS system

The integrated RHS-SPS system (Figure 4) on the roof of the Grand Library of Near East University (NEU) combines sustainable water management with renewable energy in an innovative approach. In order to address water energy challenges and promote environmental sustainability, this system optimizes energy efficiency and water conservation. The used surface area of this system is approximately 2220.6 m^2. As a result, this vast area is being effectively utilized for both the installation of solar panels and the careful channeling of rainwater. The orientation angles of the solar system were determined to maximize solar radiation while simultaneously enabling rainwater to penetrate the collection channels. However, the angle also enables the panels to produce more energy while avoiding the accumulation of water. Furthermore, the panels are fixed with flexible supports that shield them from wind, earthquake damage, and other environmental factors, guaranteeing their long-term dependability and durability. The adaptability of this configuration reduces structural stress and increases the solar panels' lifespan. Additionally, the device has an automated lift mechanism that is interfaced with satellite sensors. By continuously monitoring the surroundings and modifying the panel position in real-time throughout the day and across the seasons, these sensors guarantee excellent solar energy capture. To optimize energy production, the panels are always positioned to receive the optimal amount of sunshine thanks to the creative positioning system. Rainwater collected by the red-colored channels in the system design shown in Figure 4 is directed toward a network of interconnecting pipes from the solar panels. Water is then directed into two sizable main storage tanks by the system to ensure effective collection and storage.

Figure 3. Cyprus map including NEU-GL location

Rainwater that is collected must be stored for non-potable use, including chilling and irrigation, rather than for human consumption. Moreover, the system has an AI-driven solar system cleaning procedure to guarantee maximum performance and sustain ideal energy production. The automatic sprinkler system will be in sync with AI-powered monitoring sensors to continuously track the solar panels' performance. The sprinklers are turned on for cleaning as soon as the sensors identify a decrease in energy production brought on by the buildup of dust. This feature is crucial during the dry season since the buildup of dust and debris can drastically lower solar performance. To prevent abrupt temperature changes that could harm the panel and cause thermal stress on the glass, the sprinklers are also only turned on after sunset.

2.3 Rainfall dataset

This study includes measured rainfall data from the Meteorological Department at Lefkoşa, Northern Cyprus, and several satellite-based and reanalysis datasets, making up the rainfall dataset used in this study. The measured data are utilized as a primary source for evaluating the performance of satellite-based and reanalysis datasets. In this study, CHIRPS, CFSR, ERA5, ERA5-AG, ERA5-LAND, and MERRA2 were selected. It should be noted that these datasets were selected due to their widespread utilization and reliability for accuracy in rainfall estimation, particularly in regions with few data or a lack of measured rainfall data. Refs. [33-37] provide the description of the selected datasets in detail. Besides, Figure 5 presents the main specifications of these datasets.

2.4 Solar Radiation dataset

Designing solar energy systems has been quite a challenge in extremely remote areas, particularly when no/limited measuring data are available.

Integrating climatic datasets obtained from satellites becomes crucial to solving this issue. The first step is to compare the datasets to locally measured data to ensure their reliability and quality. They are only useful for evaluating the efficiency of solar energy systems in specific areas following this type of verification. Therefore, a useful asset in this domain is NASA's Earth Science Research Program, which utilizes its satellite network for providing an extensive variety of model-based and satellite-derived products. It provides global weather and solar data with a 0.5° × 0.5° geographic resolution from 1981 to the present [38]. Moreover, the data is publicly available, which enhances both its accessibility and use. Numerous studies were conducted in various locations to assess the solar energy potential using the NASA POWER database, which has, by all accounts, stood the test of reliability and usefulness [39-41]. These studies have shown a strong relationship between the NASA dataset and the observed data on solar radiation. Therefore, this analysis used daily weather data from 2015 to 2023 for selected dams and reservoirs of Northern Cyprus from the NASA POWER database.

2.5 Estimating rainwater harvesting potential

In regions with seasonal rainfall or water scarcity, rainwater collection is an effective and sustainable method of supplementing water supplies. Rainwater from rooftops or other catchment surfaces can be collected and stored, reducing the need for traditional water sources in households and communities. Assessing rainwater harvesting's potential helps with the design of appropriate storage systems and the understanding of whether or not they can be implemented in a given area. The rainwater harvesting potential (RHP) can be estimated using Eq (1) [42].

$$RHP = R \times A \times C \quad (1)$$

where R is the annual rainfall in meters, A is the catchment area in m^2, and C is the runoff coefficient, it assumes 0.85 for tilted solar panels (smooth glass surface).

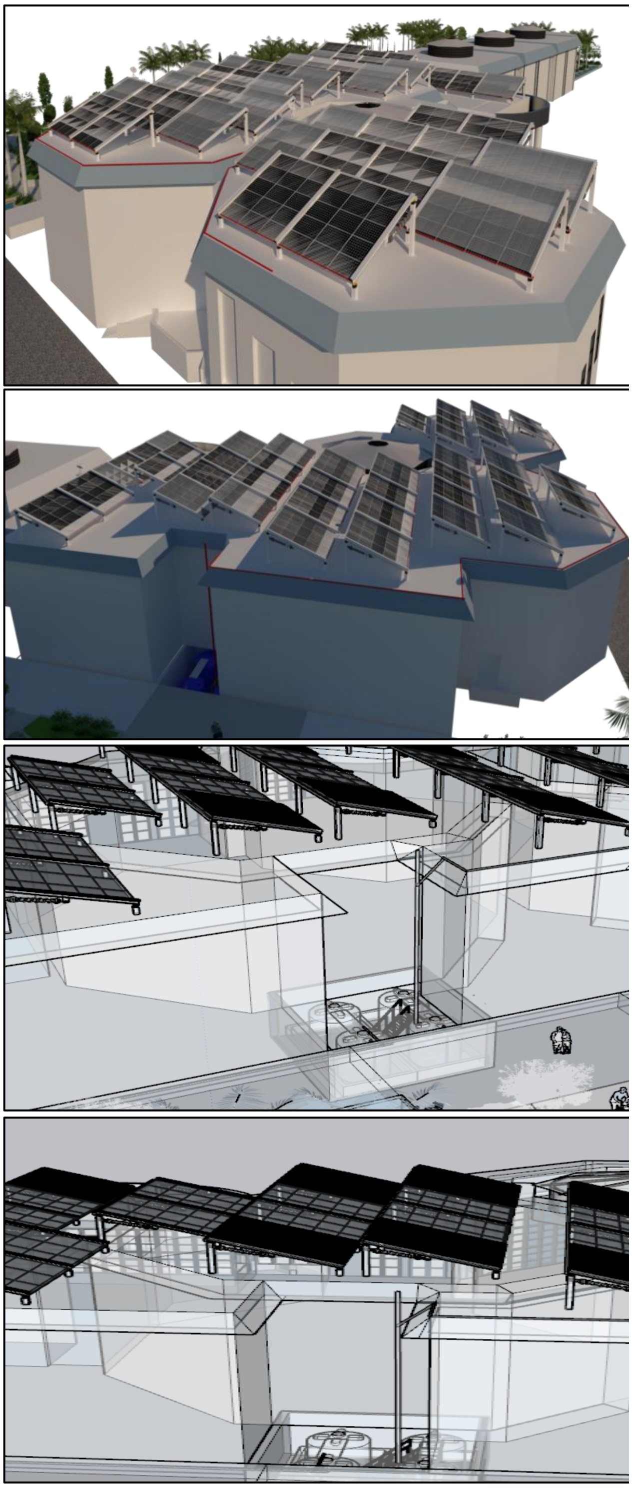

Figure 4. Visual design for rooftop RHS-SPS system

2.6 Solar radiation incident on tilted surface

Solar radiation received by a surface is composed of three main components: direct (beam) radiation, diffuse radiation, and radiation reflected from the Earth's surface [43]. These components contribute to the total solar irradiance on a tilted surface. However, due to the limited availability of measurement tools and methodologies, it is rare to find recorded data specifically for inclined surfaces [32]. This challenge necessitates the use of mathematical models to estimate the total solar irradiance on tilted surfaces based on known parameters.

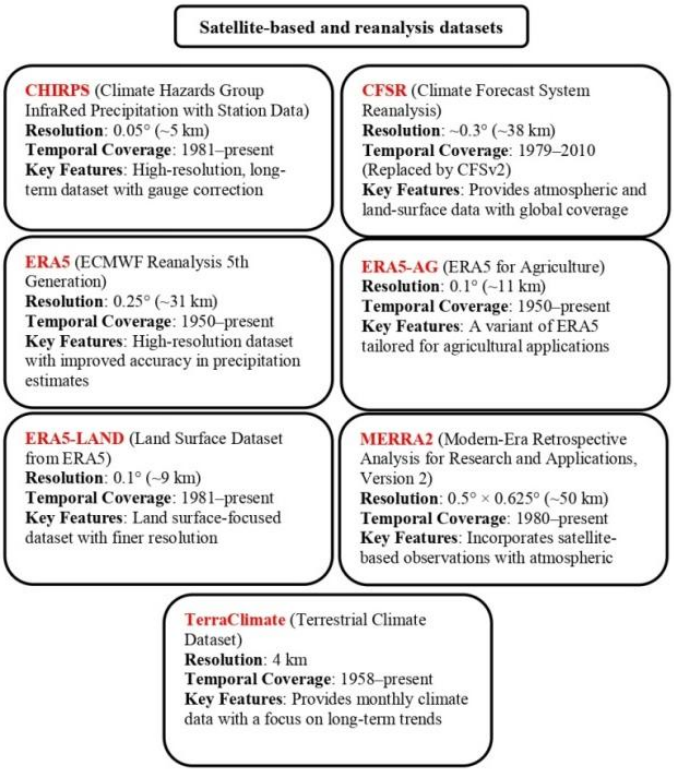

Figure 5. Main specifications of the selected datasets

The incident global solar irradiance on an inclined surface (GSI_i) can generally be broken down into three components: beam component (Gb), diffuse component (Gd), and reflected Component (Gr), and can be calculated using the equations below [43].

$$GSI_i = G_b + G_d + G_r \quad (2)$$

$$G_b = \frac{G_{DH}}{cos\theta_z} cos\theta_i \quad (3)$$

$$cos\theta_z = sin\phi \cdot sin\delta + cos\phi \cdot cos\delta \cdot cos\omega \quad (4)$$

$$cos\theta_i = sin\delta \cdot sin\phi \cdot cos\beta - sin\delta \cdot cos\phi \cdot sin\beta \cdot cos\alpha + cos\delta \cdot cos\phi \cdot cos\beta \cdot cos\omega + cos\delta \cdot cos\phi \cdot sin\beta \cdot cos\alpha \cdot cos\omega + cos\delta \cdot sin\beta \cdot sin\alpha \cdot sin\omega \quad (5)$$

$$\omega = 15(12 - LAT) \quad (6)$$

$$LAT = standard\ tim\ (clock\ time) \pm 4(standard\ time\ longitude - longitude\ of\ location) + EOT \quad (7)$$

$$EOT = 229.18\left(0.000075 + 0.001868 \cdot cos\left(\frac{360\cdot(N-1)}{365}\right) - 0.032077 \cdot sin\left(\frac{360\cdot(N-1)}{365}\right) - 0.014615 \cdot cos2\left(\frac{360\cdot(N-1)}{365}\right) - 0.04089 \cdot sin2\left(\frac{360\cdot(N-1)}{365}\right)\right) \quad (8)$$

where G_{DH} is the direct horizontal solar irradiance, θ_z is the solar zenith angle, θ_i is the incidence angle of the beam radiation on the tilted surface, δ is the solar declination angle, ϕ is the location's latitude, ω is the hour angle, β is the surface tilt angle concerning the horizontal plane, and α is the surface azimuth angle, LAT represents the local apparent time, N is the day of the year. It should be noted that the first correction for LAT applies to the eastern hemisphere with a negative sign, while the western hemisphere applies to the positive sign.

2.7 Electricity generated by the PV system

A solar PV system's monthly energy output can be estimated by considering key factors such as the installed system capacity, the peak sun hours at the location, and a derate factor that accounts for the combined effects of component efficiencies, system losses, and environmental conditions. The amount of electricity that a photovoltaic system is anticipated to produce can be estimated with this method. To calculate the monthly energy output in kWh, utilize the formula below [44]:

$$E_M = N_d \times f_m \times \frac{H_c}{1\ kW/m^2} \times P_{IC} \quad (9)$$

where f_m is the average monthly derate factor or performance ratio, N_d is the number of days in the month, H_c is solar radiation on the plane of the solar PV array in kWh/m²/day, and P_{IC} is solar PV installed capacity in kW.

2.8 Economic viability and emission analysis

The economic viability of installing a PV system is assessed in this study using a variety of financial factors. These provide a comprehensive view of the project's financial performance, including the simple payback period (SPP) and the levelized cost of energy (LCOE). The simple payback period (Eq. (10)) provides a quick estimate of how long it will take for the initial investment to be recouped by the system's energy savings or revenue, making it a useful tool for evaluating investment risk and identifying projects with faster returns [43].

$$SPP = \frac{Investment\ cost}{,Annual\ Saving} \quad (10)$$

Furthermore, the LCOE (Eq. (11)) represents the average cost per kilowatt-hour of electricity generated during the system's lifespan and accounts for all capital, operating, and maintenance costs. This metric is crucial for assessing the PV system's cost-effectiveness in comparison to other energy sources and technologies, enabling informed decisions about long-term energy planning and investment. Collectively, these measures help stakeholders assess the short- and long-term financial sustainability of solar energy projects [43].

$$LCOE = \frac{C_o + \sum_1^n \frac{C_{i,t} + C_{O\&M,t}}{(1+i)^t}}{\sum_1^n \frac{E_t}{(1+i)^t}} \quad (11)$$

where C_o is the investment cost, n is the project's economic life, $C_{i,t}$, $C_{O\&M,t}$, and E_t are the investment cost (such as replacement cost), operation and maintenance cost, and electricity generated per year, respectively.
Moreover, the proposed solar power plant's carbon mitigation analysis is estimated using the following methodology [45]:

- The greatest CO_2 emissions that the solar power plant might reduce are given by Eq (12).

$$CO_2\ mitigation\ by\ PV\ system = Annual\ energy\ generation \times Emission\ factor \quad (12)$$

- Solar power plants cannot be fully regarded as emission-free power-producing systems. Therefore, it is necessary to estimate the amount of CO_2 released per kWh of power generated by the solar plant. This uses Eq (13) to determine the emission released from the PV plant.

$$CO_2\ emission\ from\ PV\ sytem = Annual\ energy\ egneration \times CO_2\ mitigation\ by\ PV\ system \quad (13)$$

- The net reduction in CO_2 emissions from the solar PV facility is computed using Eq (14).

$$Net\ CO_2\ reduction = CO_2\ mitigation\ by\ PV\ system - CO_2\ emission\ from\ PV\ sytem \quad (14)$$

3. Results and discussion

3.1 Measured data and comparison of multi-rainfall products

The monthly scale defines the rainfall products. Figure 6 illustrates a comparison between the measured monthly rainfalls and rainfall products from 2015 to 2023. Besides, the annual rainfall is illustrated in Figure 6. It should be noted that the measured data have been collected from the station location at Lefkoşa (North Nicosia). Moreover, the temporal correlation coefficient between the measured rainfall and rainfall products is calculated and shown in Table 1 based on the data characteristics. It is found that there are significant correlation coefficients between the rainfall products and measured rainfall for all periods.

Moreover, the significant variation in performance between satellite-based rainfall datasets and actual rainfall data is measured using three crucial metrics (R-squared, Root Mean Squared Error (RMSE), and Mean Absolute Error (MAE)) as shown in Figure 7. According to the R-squared value, a score closer to 1 denotes a stronger correlation between the satellite and actual rainfall data. The results demonstrate that ERA5-AG seems to have the strongest correlation with actual rainfall readings, as evidenced by the highest R-squared value of 0.9977 among the datasets. This is seen by the relatively low MAE (13.74) and RMSE (26.12) values, which demonstrate that ERA5-AG is a reliable and accurate rainfall forecaster.

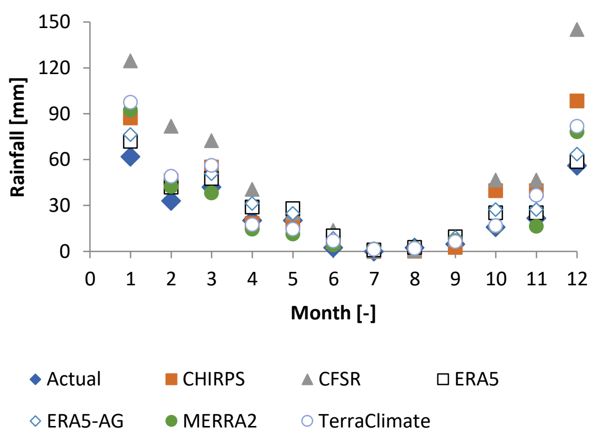

Figure 6. Monthly rainfall data collected from different sources

According to previous studies [46-49], ERA5-AG produces the best rainfall estimation results due to several significant factors related to its resolution, data assimilation methods, and temporal and spatial coverage. One of the main reasons for its outstanding performance is its high temporal and spatial resolution. ERA5-AG's high spatial resolution of 0.1°, or around 10 km, allows it to catch finer variations in rainfall patterns than datasets with lesser resolution. ERA5-AG can better estimate regional and micro-scale rainfall variations because of this increased resolution, which allows it to more correctly replicate the local features of rainfall. Additionally, ERA5-AG benefits from advanced data assimilation techniques that incorporate observational data, such as satellite and weather station readings, into the model, thereby improving the representation of real rainfall patterns and mitigating model biases, which increases the accuracy of the dataset. Data assimilation allows ERA5-AG to better match real rainfall measurements and adapt to changing weather conditions. ERA5-AG is based on the ERA5 reanalysis dataset, which is derived from a combination of global observations and climate model simulations.

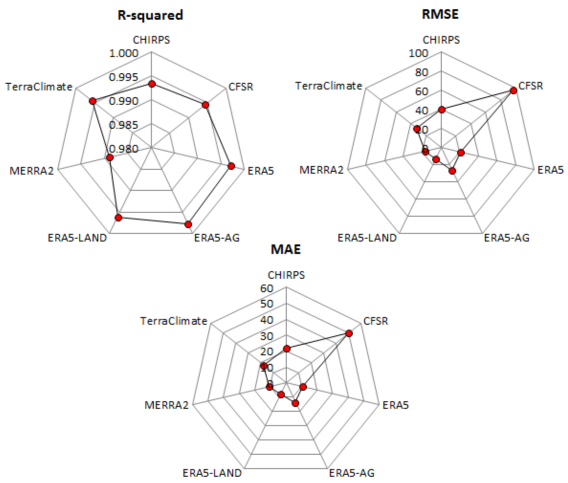

Figure 7. Statistical comparison of R-squared, RMSE, and MAE

3.2 Rainwater harvesting potential

RHP is computed using both average and maximum daily rainfall data collected from ERA5-AG to ensure a well-rounded design. In general, the average daily rainfall provides a reliable estimate of typical rainfall to determine system capacity and storage needs under normal conditions. Besides, storms and other extreme weather events are taken into account in the maximum daily rainfall data to make sure the system can control peak flows and prevent overflow. Figure 8 and Figure 9 display daily rainfall data for the season, including the maximum and average rainfall amounts. As shown in Figure 8, the maximum value of rainfall is recorded in March with a value of 7.68mm. The average rainfall for each season varies significantly, with winter receiving the most (186.89 mm) and spring following in second (105.66 mm). Summer, which is typically the driest season, receives only 12.53 mm of rainfall, and fall receives 78.60 mm. Moreover, Figure 9 shows that March had the most rainfall, 43.99 mm. According to the maximum daily data for each season, there is a noticeable variation in the total rainfall; the winter season had the highest total rainfall of 833.17 mm, followed by the spring season with 481.83 mm. The lowest quantity is recorded in the summer (79.25 mm), followed by fall (435.20 mm). According to rainfall patterns, the estimated rainwater collection potential reveals significant seasonal variability, as shown in Figure 10. Based on average daily rainfall data, the estimated seasonal rainwater collecting capacity has a more modest dispersion than the estimates derived from maximum daily rainfall. The most promising season is still winter, at approximately 373.51 m^3, followed by spring, at 211.16 m^3.

Table 1. Results of the correlation analysis between measured rainfall data and rainfall products using temporal correlation analysis

		Actual	CHIRPS	CFSR	ERA5	ERA5-AG	ERA5-LAND	MERRA2	TerraClimate
Actual	Pearson Correlation	1	.961**	.965**	.990**	.990**	.982**	.960**	.979**
	Sig. (2-tailed)		.000	.000	.000	.000	.000	.000	.000
CHIRPS	Pearson Correlation		1	.985**	.943**	.951**	.933**	.948**	.962**
	Sig. (2-tailed)			.000	.000	.000	.000	.000	.000
CFSR	Pearson Correlation			1	.952**	.962**	.943**	.963**	.963**
	Sig. (2-tailed)				.000	.000	.000	.000	.000
ERA5	Pearson Correlation				1	.998**	.997**	.945**	.961**
	Sig. (2-tailed)					.000	.000	.000	.000
ERA5-AG	Pearson Correlation					1	.997**	.950**	.967**
	Sig. (2-tailed)						.000	.000	.000
ERA5-LAND	Pearson Correlation						1	.930**	.953**
	Sig. (2-tailed)							.000	.000
MERRA2	Pearson Correlation							1	.978**
	Sig. (2-tailed)								.000
Terra Climate	Pearson Correlation								1
	Sig. (2-tailed)								
**. Correlation is significant at the 0.01 level (2-tailed).									

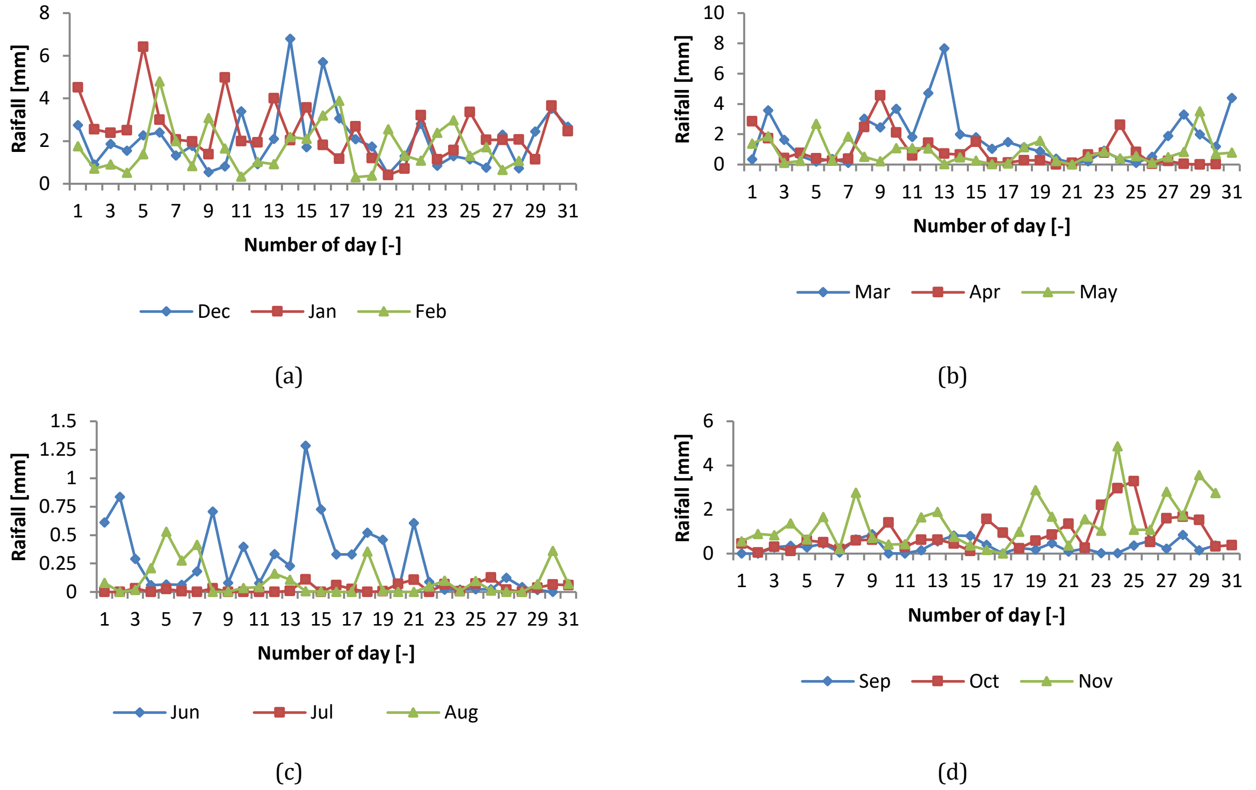

Figure 8. Average daily rainfall data during the period of 2015-2023: (a) Winter, (b) Spring, (c) Summer and (d) Fall

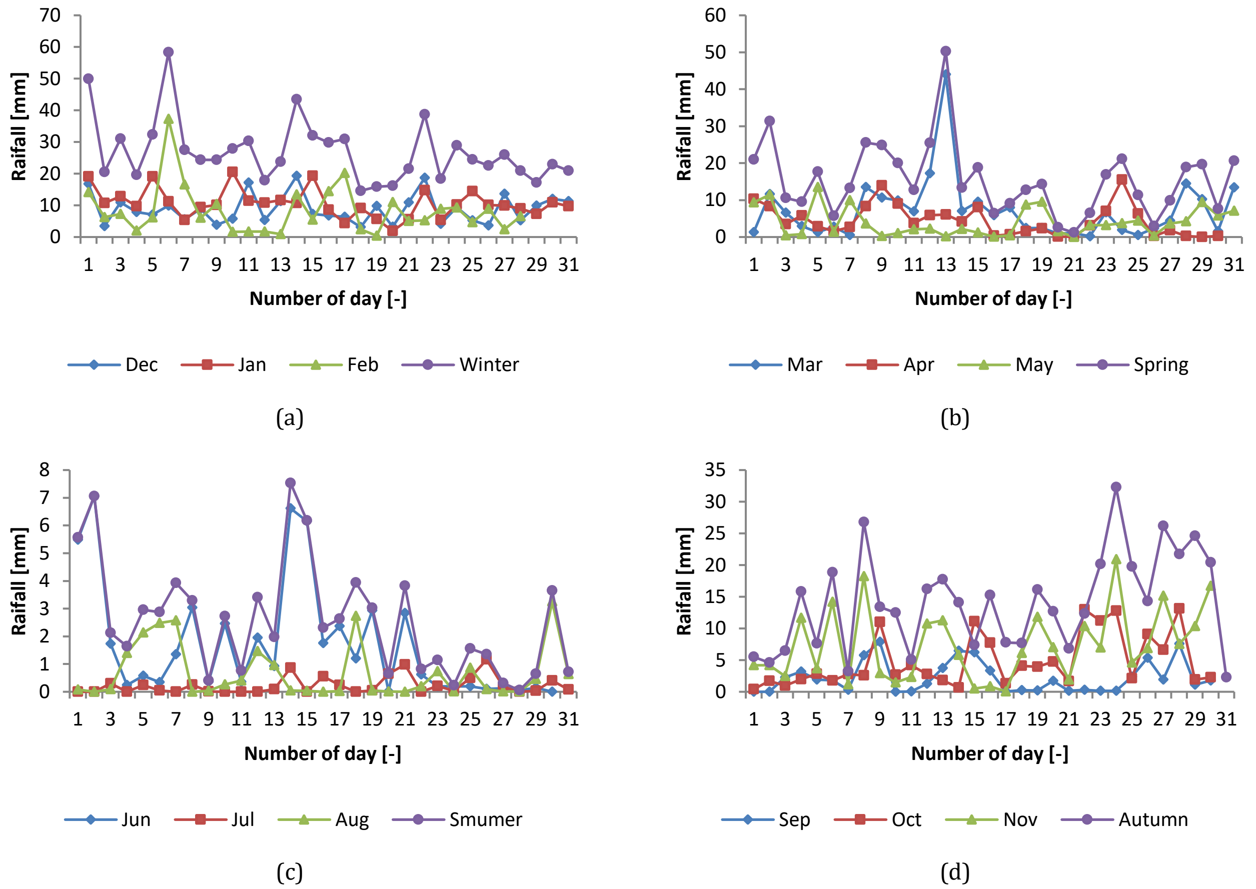

Figure 9. Maximum daily rainfall data during the period of 2015-2023: (a) Winter, (b) Spring, (c) Summer and (d) Fall

Besides, fall contributes 157.08 m^3, whereas summer has the lowest potential at only 25.04 m^3. The maximum daily rainfall statistics show that winter has the most potential, with approximately 1665.12 m^3 of harvestable rainwater, indicating its rank as the wettest season. The mildest season is fall (869.77 m^3), followed by spring (962.96 m^3). Furthermore, summer has the lowest potential (158.39 m^3).

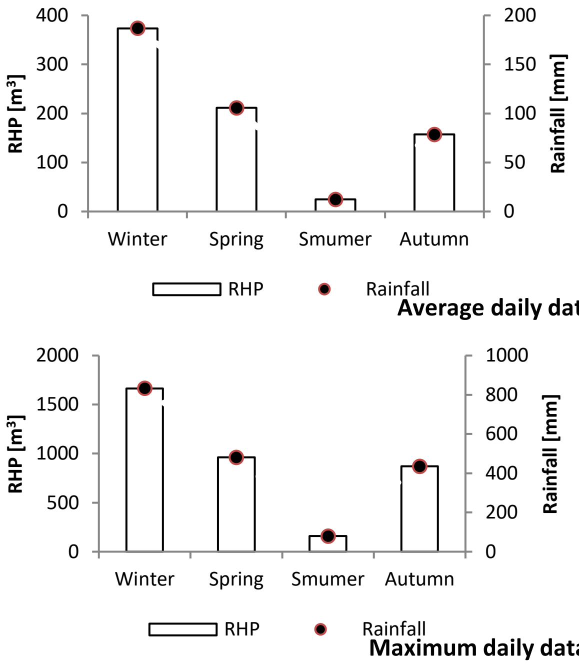

Figure 10. Total amount of RHP and rainfall during the period of 2015-2023

3.3 Technical Sustainability

The term "technical sustainability" in engineering describes features of products that impact effectiveness and performance. For the proposed 430 kW solar system, JKM585N-72HL4-V, manufactured by Jinko Solar Company, with an efficiency of 22.65% was selected as an efficient PV module. Also, two units of central inverters with a capacity of 250 kW and an efficiency of 98% were utilized. For the selected location, the energy production (EP) by a fixed solar tracking mode and capacity factor (CF) with various orientation angles was evaluated to find the optimal orientation that ensures maximum energy output, as shown in Figure 11. The results of the study demonstrate the significant energy production potential of the proposed hybrid rainwater and solar harvesting system. At a slope angle of 30° toward the north, the system may generate roughly 734.09 MWh annually with a capacity factor of 19.49% followed closely by 731.69 MWh with a capacity factor of 19.43% at a slope angle of 40° (also facing north). This design yields the best performance across all the situations that were analyzed.

Based on the above, the proposed system's monthly global irradiation on a tilted surface, energy production, and capacity factor were evaluated for a range of tilt degrees from 30° to 40°, in steps of 2°, to determine the optimal tilt angle for maximum energy output (Figure 12). The results indicated that the highest annual solar radiation, 2277.45 kWh/m^2, was produced at a tilt angle of 34°. At this optimal angle, the system's maximum energy production of approximately 735,316.3 kWh, or a capacity factor of 19.52%, was achieved as shown in Figure 12.

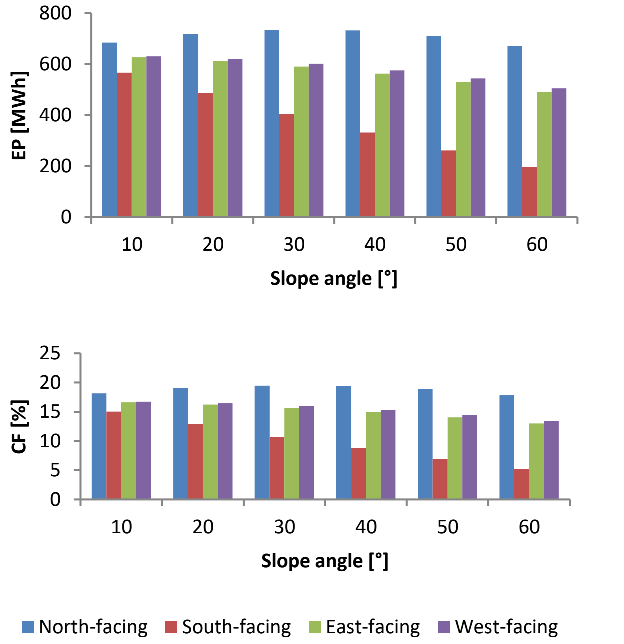

Figure 11. Annual energy production and capacity factors of the proposed system with various orientation angles

Based on the results obtained by [50-52], the proposed system is technically feasible to construct and run a solar photovoltaic system in the chosen location, based on the solar system's technical viability due to the values obtained, as the annual energy production and its capacity factor are compatible with the acceptable values.

3.4 Economic sustainability and emission reduction analysis

To determine whether a solar photovoltaic project will be sustainable and profitable, an economic analysis is a crucial step in the development process. For the economic analysis, the developed system would initially cost 525,822 USD and 1,006,656 USD based on the size of the tank, which is estimated based on average and maximum daily rainfall data, respectively. This includes the cost of 737 solar panels, which cost 175.50 USD each; the central inverter of the system costs 64,496.25 USD; crucial parts such as channels (4,167.45 USD) and pipes (500 USD), as well as the cost of the concrete rainwater storage tank, which is 150 USD/m^3. Additionally, the basic infrastructure was supplemented with other indirect expenses to facilitate an accurate evaluation. Those are as follows: 8.6% for installation and spare parts; 0.6% for engineering, development, and feasibility study costs; and 3% for miscellaneous/contingency funds. Moreover, the financial evaluation was assumed based on the literature. The operation and maintenance (O&M) cost was estimated to be 1% of the annual total investment, accounting for regular maintenance and system dependability. A 25-year system lifespan was assumed based on the expected lifetime of solar components. The electricity tariff was assumed to be 0.1 USD/kWh. An 8% inflation rate and a 6% discount rate were used in financial computations to account for macroeconomic factors. The proposed system's Levelized Cost of Energy (LCOE) and Simple Payback Period (SPP) could be accurately calculated thanks to these parameters. In this study, the LCOE and the SPP were used to assess the proposed system's performance.

Figure 13 depicts the SPP, which is the amount of time needed to recover the project's initial investment in the chosen region. It is found that the proposed system in the selected location has the longest payback period when the slope angle is 40°; when the slope angle is 34°, the system has the shortest payback period.

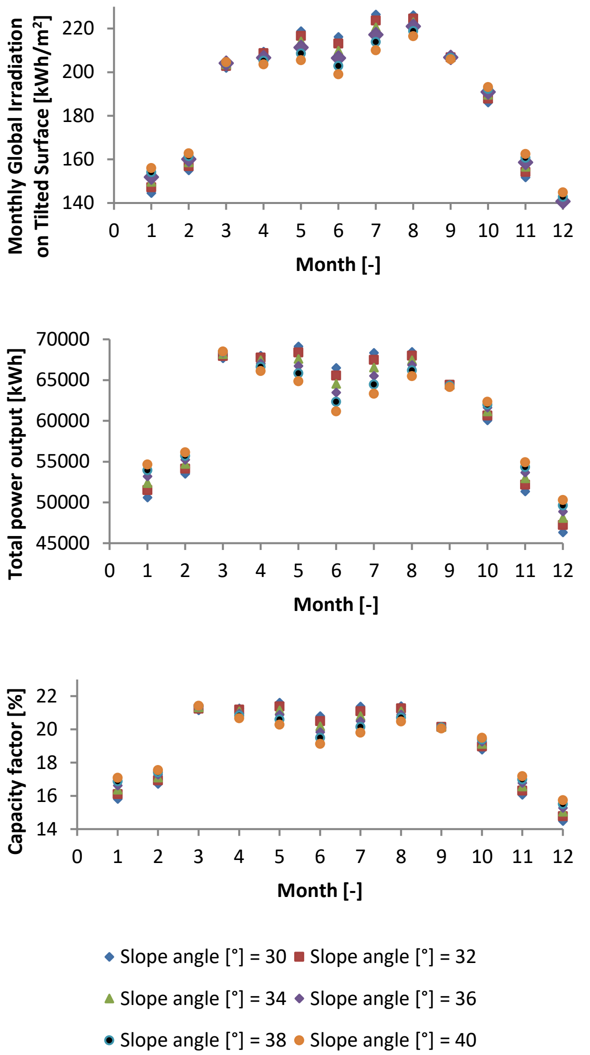

Figure 12. Monthly value of global irradiation on a tilted surface, energy production, and capacity factor with various slopes

Moreover, the findings demonstrate that LCOE is within the range of 5.476-5.503 cents/kWh and 2.860-2.875 cents/kWh depending on the slope angle and data used, as shown in Figure 14. Besides the economic viability, it would be interesting to calculate the ecological benefits of constructing the proposed system in terms of the tons of greenhouse gas (GHG) emissions that would be prevented. As mentioned previously, fossil fuels are the main source of power for Northern Cyprus's electrical grid. According to regional energy estimates and literature, the average CO_2 emission factor for Northern Cyprus's grid electricity is approximately 0.77 kg CO_2/kWh. Therefore, the total annual reduction in CO_2 emissions in the chosen case study is displayed in Figure 15. According to the results, implementing the suggested PV project into action in the chosen area can prevent a sizable quantity of CO_2. As illustrated in Figure 15, the system with the largest reductions in CO_2 emissions has a slope angle of 34°.

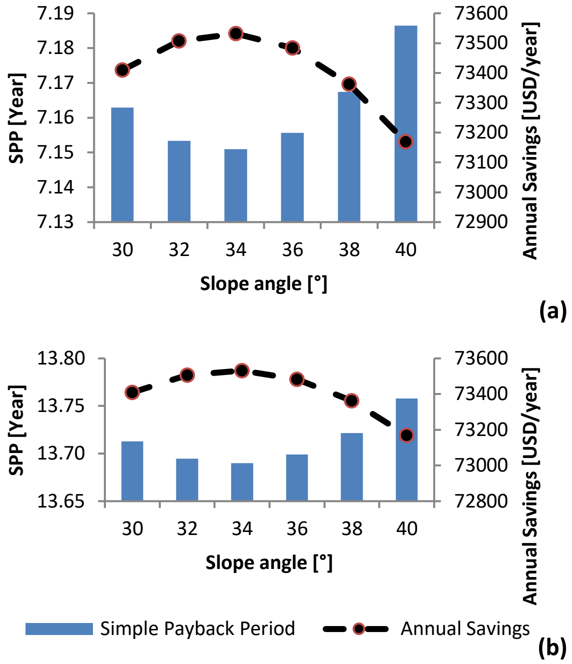

Figure 13. The estimated SPP for various slope angles: (a) based on the average daily rainfall data, and (b) based on the maximum daily rainfall data

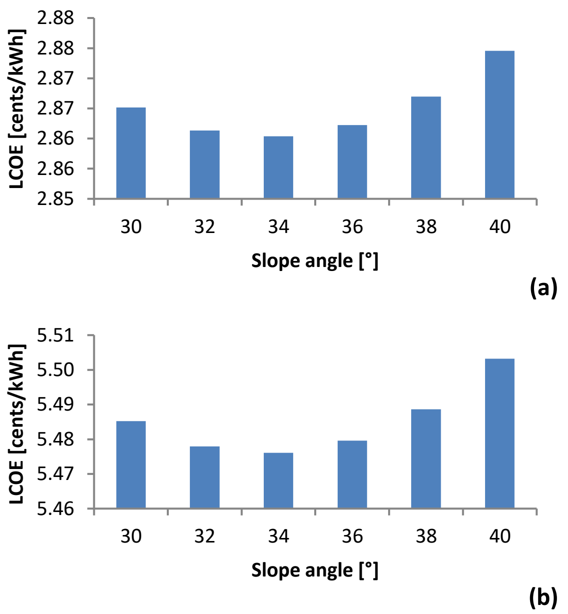

Figure 14. The estimated LCOE for various slope angles: (a) based on the average daily rainfall data, and (b) based on the maximum daily rainfall data

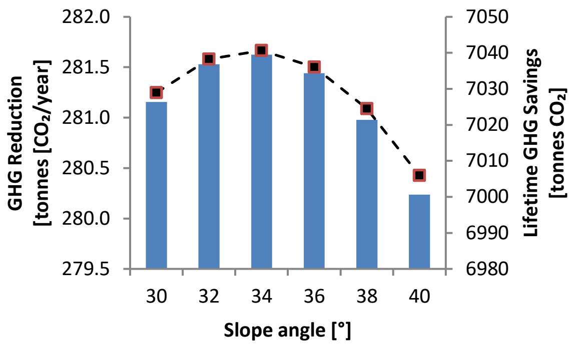

Figure 15. The estimated GHG reduction and lifetime GHG savings for various slope angles

4. Conclusion

This study aimed to develop and assess a hybrid rooftop system that integrates solar energy generation and rainwater collection to promote the use of renewable energy sources, conserve water, and promote the environment at the Grand Library at Near East University. Besides, the performance of the systems was analyzed from technical, hydrological, environmental, and economic perspectives. The potential for rainwater collection was evaluated using information on the average and maximum daily precipitation. In the research area, ERA5-AG is the most reliable dataset for rainfall estimation. It showed the lowest values of RMSE and MAE and the highest accuracy based on the R-squared value compared to several satellite rainfall datasets with ground observations. According to the seasonal distribution, winter also offered the highest harvesting potential, with an estimated 1,665.12 m^3 based on maximum values and 373.51 m^3 based on averages. Moreover, a variety of orientation angles were tested to identify the optimum orientation angle for maximizing solar energy output. A slope angle of 34° (north-facing) produced the largest energy output, 735,316.3 kWh annually, with a capacity factor of 19.52%, according to the analysis. The developed system in the selected location has the shortest SPP with a slope angle of 34°. Furthermore, the results indicate that the LCOE ranges from 5.476 to 5.503 cents/kWh and from 2.860 to 2.875 cents/kWh, respectively, depending on the data used and slope angle. In terms of the environment, the PV system significantly reduces CO_2 emissions; the largest reduction is seen in the 34° tilt design. In the end, the proposed system is a good choice for sustainable infrastructure in urban academic settings because it is not only environmentally and technically sound but also offers long-term financial benefits .Despite the encouraging results, this study has several limitations. The accuracy of estimations of the amount of rainwater that can be collected, particularly at the local level, may be impacted by the uncertainties that remain in satellite-derived rainfall statistics, despite their testing. Additionally, the AI-powered solar panel cleaning system's long-term performance, dependability, and maintenance requirements were not fully discussed. Besides, economic assumptions, such as equipment costs and payback periods, might vary depending on local and market conditions. Therefore, in future studies, more comprehensive rainfall prediction using machine learning approaches and high-resolution, localized data may improve the accuracy of rainwater harvesting estimates. Also, an experimental study is necessary to assess the AI-based cleaning system's resilience. Additionally, combining advanced techno-economic simulations with Life Cycle Assessment (LCA) utilizing tools such as HOMER software would result in a more comprehensive evaluation. Adding IoT for real-time optimization and expanding the system to many climates could further increase scalability and performance.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the authors.

Conflict of interest

The authors declare no potential conflict of interest.

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