Static Structural Simulation and Economic Feasibility of Hybrid Solar–Rainwater Rooftop Systems: A Case Study from Beirut, Lebanon

Youssef Kassem
Department of Mechanical Engineering, Faculty of Engineering, Near East University, Nicosia (via Mersin 10, Turkiye), Cyprus | Energy, Environment, and Water Research Center, Near East University, Nicosia (via Mersin 10, Turkiye), Cyprus
yousseuf.kassem@neu.edu.tr (corresponding author)

Huseyin Camur
Department of Mechanical Engineering, Faculty of Engineering, Near East University, Nicosia (via Mersin 10, Turkiye), Cyprus
huseyin.camur@neu.edu.tr

Osama Abed Al Halim
Department of Mechanical Engineering, Faculty of Engineering, Near East University, Nicosia (via Mersin 10, Turkiye), Cyprus
20244582@std.neu.edu.tr

Received: 10 December 2025 | Revised: 6 January 2026 | Accepted: 12 January 2026

ABSTRACT

Lebanon's energy and water crises, which include electrical shortages, comparatively high electricity prices, and water scarcity, are significant challenges. This study investigates the techno-economic and structural feasibility of a rooftop Photovoltaic (PV) and Rainwater (RW) collection system for a residential building in Beirut, considering the water and electricity crises. Accordingly, the feasibility of a 14.4 kW grid-connected PV system with and without battery storage was determined under average and extreme rainfall conditions. Structural feasibility showed a 35-degree angle of inclination, along with a relatively higher Factor of Safety (FOS) and lower weight, while the mechanical properties of galvanized steel and e-glass fiber were similar. The results demonstrate that Rainwater Harvesting (RWH) potential varied between 198 m³ in the average rainfall scenario and 1,558 m³ in the Maximum (Max.) rainfall case, constituting a valuable supplemental water supply. Additionally, the results indicate that the annual PV production was always considerably higher than demand, yielding substantial surplus energy, while around 60% of consumption falls at night, supporting the integration of modest battery storage. An economic evaluation showed a Levelized Energy Cost (LEC) of 0.244–0.271 USD/kWh for grid-connected operation with batteries, which yields favorable payback periods and strong life-cycle savings, even under Beirut's moderate solar irradiation. Consequently, this PV-RWH system is a dependable, financially feasible, and ecologically beneficial system for Lebanon that helps mitigate the shortages of electricity and water resources while promoting sustainable management.

Keywords-Lebanon; rooftop; PV-rainwater collection system; techno-economic

I. INTRODUCTION

The most significant global challenges that demonstrate the rapidly accelerating impacts of climate change involve freshwater scarcity, environmental concerns, and an increasing demand for energy [1]. The increased temperatures and altered Precipitation (P) patterns have further raised the severity and frequency of droughts and floods, hence presenting new challenges to water governance and underpinning the need for robust, sustainable water management techniques [2]. At the same time, the global energy industry has growing pressure to reduce greenhouse gas emissions and to advance low-carbon renewable energy systems [3]. These energy and water challenges are of growing importance, as integrated alternative solutions have to meet the difficulties presented by climate change.

RWH has emerged as a decentralized, sustainable water resource, particularly in semi-arid and water-stressed metropolitan regions [4]. By collecting, storing, and utilizing P from rooftops and other impermeable surfaces, RWH systems significantly decrease stormwater flow [5], improve municipal water supplies [6], and assist in groundwater recharge [7]. In line with this, authors in [8, 9] stated that RW collection systems are especially crucial in areas with little or extremely variable rainfall because they may lessen the detrimental effects of hydrological changes brought on by climate change. Rooftop solar PV systems are also very popular today in many countries across the world owing to their ease of availability, cleanliness, and renewability [10]. In this regard, authors in [11-13] noted that a large number of residential, commercial, and institutional buildings offer unused rooftop space suitable for PV installation, which converts abundant solar radiation into clean electricity. Accordingly, the development and implementation of a hybrid system that could incorporate RW collection with solar systems could be of prime importance for the achievement of sustainable development goals. However, few existing studies have developed a hybrid wind/solar–RWH system [14–19]. For instance, authors in [15] developed a 3-in-1 rooftop configuration that utilized wind, solar, and RW collection; it included a guide vane which enhanced the wind turbines' performance by 73.2% at low wind speeds due to its aerodynamic enhancement capabilities. Additionally, a new development featured a V-shaped eco-roof capable of combining solar collection, wind power, and RW collection with natural ventilation and skylights, proving that architectural optimization would further enhance the energy performance and indoor comfort of buildings [16]. Furthermore, authors in [17] presented a V-shaped roof and guide vane structure capable of balancing building energy demand, highlighting the potential of multi-functional rooftops. Authors in [18] developed small-scale hybrid rain–wind harvesters using piezoelectric and electromagnetic mechanisms that are capable of enabling continuous sensing applications in variable weather conditions. Authors in [19] also introduced a dual-use rooftop solar–RWH system for households and agriculture, aimed at improving clean energy and water availability in low-rainfall areas.

Based on the above, integrated PV-RWH systems are promising dual-resource solutions for mitigating water scarcity and supporting the energy transition in developing countries, including Lebanon. The current study presents environmental and infrastructural challenges facing Lebanon, including electricity shortages [20], rising energy costs [21], and increasing pressure on freshwater resources [22]. The country's current reliance on diesel generators, the rapid deterioration of grid stability, and the widespread pollution of its groundwater have created an urgent need for decentralized and sustainable energy and water solutions [21]. In this context, the rooftop solar PV system proposed in this work offers a practical and scalable pathway for alleviating energy scarcity and water insecurity at the individual household level, particularly in densely populated urban areas such as Beirut. Consequently, the aim of the current study is to evaluate the technical and financial performance of an on-grid rooftop solar system, with and without battery storage, integrated with an RWH configuration for a residential building in Beirut. To identify a lightweight, robust, and high-performance configuration, a variety of solar-RWH structural designs were developed, employing various materials and tilt angles. The average and Max. rainfall values, which have a direct impact on the tank capacity and related expenses, were used to examine the techno-economic viability of the proposed system.

II. MATERIALS AND METHODS

A. Site Details

The residential building in Beirut, Lebanon, was used as the framework for the study's site. It is located on the southeast Mediterranean Sea at a latitude of 33.8938°N and a longitude of 35.5018°E. Beirut is powered by Electricity of Lebanon (EL), which owns over 90% of the industry. However, despite large expenditures over the years, the corporation is plagued by corruption, poor management, and a severe financial crisis, which leads to expensive private generators and frequent blackouts. The study's location was a 200 m² residential structure with about 150 m² of rooftop area. The selected region has a hot-summer Mediterranean climate, which results in hot, dry summers and warm, humid winters. Moreover, the Average Daily Electricity Consumption (ADEC) of the selected building is presented in Figure 1 and estimated using:

$$DEC = \sum N \times T \times P \times t \qquad (1)$$

where N is the number of the electrical load, T is the type of electrical load, P is the power rating of the electrical load, and t is the average operating hour.

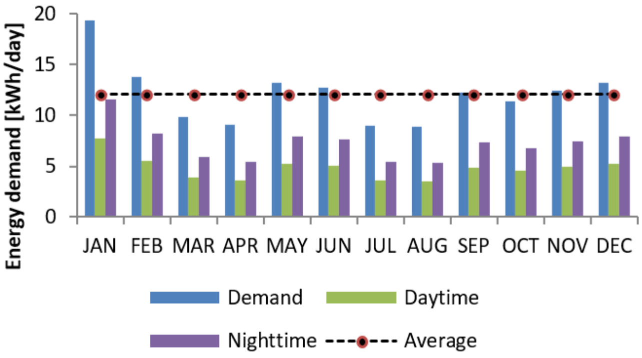

Fig. 1. Monthly variation of the average energy demand of the selected building.

B. Climate Data

Monthly climate data for the period from 1982 to 2024 were collected from the NASA POWER database. Table I lists the annual and average values of the selected climate parameters, including Solar Radiance (SR) and P. Figure 2 illustrates the monthly variation of the climate data. NASA POWER meteorological data were selected based on previous studies [23, 24], which conclude that the former are useful for environmental, agricultural, and climatological analyses. Specifically, authors in [23, 24] found that the dataset is appropriate for long-term climate assessment, evapotranspiration calculation, and crop or livestock modeling, as it performs exceptionally well compared to ground meteorological observations, particularly for temperature variables. However, P estimates are less reliable and may require local calibration or validation before being used in hydrological studies, whereas temperature data consistently perform satisfactorily. Moreover, authors in [25] highlighted NASA POWER's capacity to support climatological research, PV system planning, and solar energy resource evaluation. Additionally, the P data utilized for the study were sourced from the NASA POWER dataset (satellite-based rainfall data). This implies that the Rainwater Harvesting Potential (RHP) presented also reflects satellite estimates for either average or Max. rainfall conditions. Satellite-based rainfall data are applied widely in the literature to estimate the potential of rainfall harvesting system [26-28].

TABLE I. ANNUAL AND AVERAGE VALUES OF WEATHER PARAMETERS

Parameter	Unit	Annual	Average
SR	kWh/m^2	1702*	142
P	mm	431	36
RH	%	-	64
AT	℃	-	19
Tmax	℃	-	28
Tmin	℃	-	12
MWS	m/s	-	3
MaxWs	m/s	-	10
MinWS	m/s	-	0

C. System Description

The proposed system is an innovative hybrid rooftop design intended for residential areas to address the shortages of electricity and water. It combines high-efficiency PV power generation with an RWH network on one structural platform, enabling sustainable resource management, as shown in Figure 3. Six independent structures, each spanning 3× 3 m, compose the system. With six solar panels (Table II) installed in each structure, the system has a total capacity of 14.4 kW. It is designed to meet the mean household's consumption of 12 kWh/day (Fig. 1), after accounting for all operational and environmental losses. Once the residence's battery system is fully charged, any extra energy produced can be fed into the local utility grid, providing grid support and financial gain. The battery system is designed to supply only the nighttime electricity demand. During the day, the PV system directly supplies the load and charges the battery up to its full capacity. The battery sizing was based on a $LiFePO_4$ battery at nominal capacity of 200 Ah at 48 V, assuming 90% round-trip efficiency and an 80% Max. DoD. Given the long cycle life of $LiFePO_4$ technology, the battery lifetime is assumed to be 30 years.

In addition, three single-phase hybrid solar inverters (VT-6607105) with a capacity of 5 kW and an efficiency of 97.6% are utilized in this study due to their availability in the market. The PV modules are mounted on a durable black steel structural frame. These sections are linked by gray connection plates, which also act as structural connectors and RW collection channels. Each channel is 2 m wide and 3 m high, with an inner water path of 10 cm wide and 7 cm deep. All solar modules and their connection plates are installed at a fixed tilt of 35°, a value that maximizes the amount of solar radiation absorbed, ensures that structural loads remain within acceptable limits, and allows collected RW to flow efficiently by gravity. Moreover, RW falling on the PV surfaces runs into the connecting plates, which in turn channel it into the PVC secondary drainage system embedded in the structural frame. This network comprises approximately 42 m of piping, leading the water to a vertical downpipe at the corner of the building. Finally, the system discharges into a storage tank at ground level, either a 10 m³ plastic tank suitable for moderate residential use or a 50 m³ reinforced concrete tank for large-scale application. Such captured water could be utilized for irrigation and landscaping purposes, reducing reliance on municipal supplies and contributing to better water management. This multi-functional rooftop system converts unused roof space into a compact, energy-efficient, and water-conserving infrastructure. Furthermore, the roof of the main residential building is also designed to supply the RWH network. It is also covered with a water-repellent, smooth coating material, such as elastomeric waterproof paint a polyurethane-based reflective coating, which has extensive applications in architectural and environmental design. Both materials have smooth surface finishes to minimize water loss through surface roughness or absorption and to optimize the effectiveness of collecting rainfall runoff. Additionally, they reflect sunlight and lower the temperature of the roof's surface, which lowers the need for inside cooling and enhances the building's overall energy efficiency. By combining PV power generation and RW collection into a single integrated design, the system decreases environmental impact and improves resource self-sufficiency, supporting the construction of resilient and environmentally friendly buildings. It thereby advances contemporary sustainability objectives, such as producing renewable electricity, saving drinkable water, reducing residential utility bills, and facilitating energy sales to the grid.

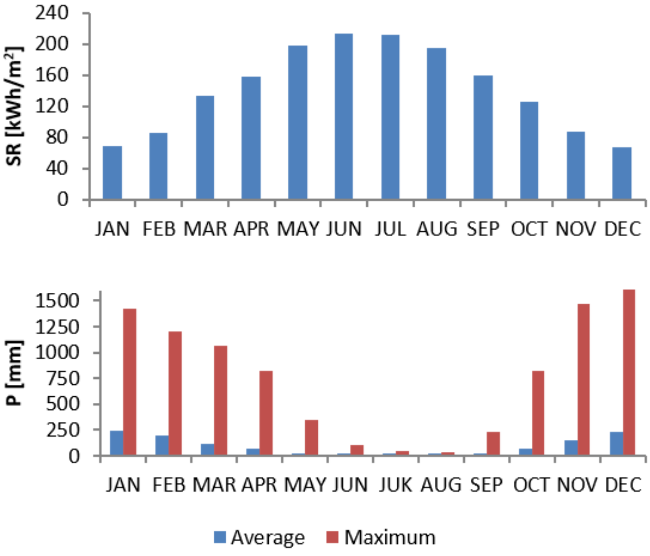

Fig. 2. Monthly variation of climate data.

Fig. 3. Schematic view of the proposed system.

TABLE II. SPECIFICATION OF THE SELECTED PANEL

Parameter	Unit	Value
Model	-	SPR-MAX3-400COM
Nominal Power	W	400
Panel Efficiency	%	22.6
Rated Voltage	V	66.0
Rated Current	A	6.07
Open-Circuit Voltage	V	75.4
Short-Circuit Current	A	6.57
Power Temp.Coef.	%/°C	–0.27
Voltage Temp.Coef.	%/°C	–0.236
Current Temp.Coef. .	%/°C	0.058
Weight	kg	19
Cost	USD/W	2.01
Temp.Coef. : Temperature coefficient		

D. PV Structure Design and Analysis

For the development of hybrid PV–RW modules, a lightweight and structurally efficient rooftop support system has been developed. Twelve materials, including galvanized steel, AISI 1045 (cold drawn steel), AISI 4340 (normalized steel), AISI 4130, steel normalized at 870 °C, aluminum alloy (1060), aluminum alloy (2024), aluminum alloy (3003), aluminum alloy (6061), zinc alloy (AG40A), AISI 304 (stainless steel), AISI 1020 (low carbon steel), and e-glass fiber, are comparatively evaluated. To guide the material selection and geometric refinement, a comprehensive FEA methodology was adopted through SolidWorks Simulation. In the literature, several studies have evaluated the PV structure utilizing SolidWorks Simulation, COSMOS and ANSYS [29-33]. The static simulations are carried out under realistic loading conditions such as self-weight (gravity), wind suction and pressure, and localized service loads, considering roof anchorage points modeled as the primary boundary supports. A tetrahedral mesh with local refinement was applied at stress-sensitive regions such as joints and transitions. Mesh convergence studies were conducted to ensure numerical stability. The structural response was evaluated in terms of von Mises stress and FOS.

E. RETScreen Software for the Techno-Economic Feasibility of the Project

Software tools for solar PV analysis are widely used for predictive and real-time research. Among the most common are RETScreen, PVSyst, Hybrid, and Homer. RETScreen is a robust software program developed for the evaluation and management of renewable energy projects [34] and has been extensively used to assess the financial feasibility of both on- and off- grid PV systems of various scales. It was developed by the Canmet Energy Diversification Research Laboratory (CEDRL) of Natural Resources Canada in collaboration with the Global Environment Facility (GEF), the National Aeronautics and Space Administration (NASA), the United Nations Environment Programme (UNEP), and the Renewable Energy and Energy Efficiency Partnership (REEEP). RETScreen allows users to develop energy-efficient project models as well as generate a five-step analysis report that includes the project's energy usage, cost, emissions, financial benefits, and risk [35].

TABLE III. ECONOMIC AND FINANCIAL PARAMETERS USED IN THIS STUDY

Parameter	Unit	Value
The lifetime of the PV module	Year	25
Cost of tank	$/m^3	120
Support structure for solar panel	$/kW	150
RW collection channel	$/m^2	25
Miscellaneous/contingency fund	% of the total initial cost	3
Installation and spare parts	% of the total initial cost	8.6
The lifetime of the inverter	Year	10
Feasibility study, development, and engineering cost	% of the total initial cost	0.6
Inflation rate	%	6
Discount rate	%	10
Project life	Year	25
Energy cost increase rate	%	5
Reinvestment rate	%	9
Debt ratio	%	60
Debt interest rate	%	9
Debt term	Year	10

In this study, RETScreen is used for three purposes: to calculate the energy generation and Capacity Factor (CF); to estimate the GHG emission reduction of a possible project; and to calculate the economic feasibility metrics. The financial criteria used to estimate these indicators (Table III) are collected from earlier research. Table III also displays the cost of the developed system. It should be highlighted that the system's financial and economic features are grounded in current market data and align with cost prices documented in the literature. Furthermore, it is employed to estimate the net present value, LEC, Simple Payback (SP), Equity Payback

(EP), annual life cycle savings, and other economic feasibility indicators. These economic feasibility metrics were calculated in order to evaluate the prospective PV project's profitability and investment benefits.

F. Estimating Rainwater Harvesting Potential

According to [36], the RHP can be determined by:

$$HP = R_A \times A_C \times R_c \qquad (2)$$

where R_A is the amount of rainfall annually [m], A_C is the catchment area [m^2], and $R_c$is the runoff coefficient, which is assumed to be 0.85 for tilted solar panels (smooth glass surface).

III. RESULTS

A. Results of Static Structural Simulation and Optimal Design Selection

A variety of PV structural configurations were assessed over five slope angles (30°, 35°, 40°, 45°, and 50°) and multiple frame geometries to determine the lightest structure that could safely support the PV modules under combined gravitational and wind loads. Among these changes, the design with a 35° inclination consistently demonstrated superior structural performance in terms of reduced mass, improved load distribution, and less internal stress. The 35° tilt not only reduced load eccentricity and achieved favorable axial force alignment, but also maintained adequate drainage capacity for the integrated rainfall collection channels. The final step involved a comparative material assessment utilizing a static FEA to determine the most suitable material for constructing the selected structure. The calculated FOS and Von Mises stress, including Minimum (Min.) and Maximum (Max.) values, were used to assess these simulation results. The results showed that while the Max. stresses of all materials were within acceptable structural boundaries, the corresponding FOS values varied significantly due to distinct strength-to-weight relationships.

As shown in Table IV, steel typically provides a high FOS; however, aluminum alloys' lower yield strength results in generally modest FOS values despite their relatively low stresses. AISI 4340 (FOS ≈ 442.09), AISI 1045 (FOS ≈ 320.04), and e-glass fiber (FOS = 848.99) had the highest FOS due to their high yield strength. However, building with composites usually requires more specialized techniques, which might increase production costs and make rooftop assembly more difficult. Galvanized steel and stainless steel, with their FOS values of 125.86 and 127.65, respectively, and established manufacturing compatibility, are suitable for large-scale, dependable, and practical use. The optimized 35° design also resulted in a significantly lower total structural mass compared to the other angles, which is essential for reduced rooftop loads and easier installation. Displacement levels were far within allowable serviceability limits, and the few locations of stress concentration showed mechanical integrity under the worst-case simulated loads. Based on integrated criteria of structural safety, manufacturability, load-bearing efficiency, and mass optimization, the 35° arrangement was confirmed as the optimal design. Galvanized steel and high-strength alloy choices were identified as suitable fabrication materials, depending on cost and corrosion needs. A comparison of the mechanical performance, structural weight, and total structural cost of the selected materials revealed notable variations, as depicted in Figure 4. E-glass fiber outperformed all metallic alternatives with the highest FOS (≈849) and the lowest structural mass. Because of its high safety margin and lightweight properties, which reduce load transfer to the slab and simplify installation logistics, e-glass fiber is a popular choice for rooftop applications. Galvanized steel provides an excellent balance between material cost and manufacturing feasibility. Despite being heavier than composite alternatives, galvanized steel offered an appropriate FOS (>125), a comparable cost, outstanding corrosion resistance, and ease of manufacturing. Furthermore, the most often used structural material in Lebanon is galvanized steel, which has a reliable supply chain and established construction methods. Therefore, the results indicate that e-glass fiber can be proposed when lightweight design and Max. safety are priorities, whereas galvanized steel is the most cost-effective and regionally feasible option, making it a solid and dependable choice for wider adoption.

TABLE IV. MAX. AND MIN. VALUE OF VON MISES STRESS AS WELL AS FOS FOR ALL PROPOSED STRUCTURES

Materials	**Von Mises stress**		**FOS**
	Max.	**Min.**	
Galvanized steel	1.620×10^6	1.717×10^2	125.86
Cold Drawn steel (AISI 1045)	1.656×10^6	2.181×10^2	320.04
Normalized steel (AISI 4340)	1.606×10^6	1.618×10^2	442.09
AISI 4130 (normalized at 870°C)	1.622×10^6	1.741×10^2	283.6
Stainless steel (AISI 304)	1.620×10^6	1.717×10^2	127.65
Low-carbon steel (AISI 1020)	1.620×10^6	1.717×10^2	217.04
E-Glass fiber	1.649×10^6	1.094×10^2	848.99
Aluminum 1060	1.601×10^6	1.602×10^2	17.22
Aluminum 2024	1.781×10^6	2.184×10^2	42.57
Aluminum 3003	1.601×10^6	1.602×10^2	25.83
Aluminum 6061	1.601×10^6	1.602×10^2	34.45
Zinc alloy (AG 40A, Zamak 3)	1.616×10^6	1.674×10^2	136.76

B. Rainfall Characteristics and Rainwater Harvesting Potential Value

Figure 5 displays the monthly variation of average and Max. rainfall for the selected site. It was found that the average monthly rainfall ranges from 0.18 to 30.68 mm. The Max. value is recorded in the winter season. Besides, the winter and summer seasons experienced the highest and lowest values, respectively, with 209.65 mm and 2.20 mm, according to the Max. rainfall data.

Figure 6 presents the results, showing a strong correlation between the RHP and the annual rainfall values. The findings indicate a significant discrepancy between the average and Max. rainfall conditions and the RHP. Under a typical annual rainfall (≈1164.5 mm), the anticipated RHP for the rooftop area under consideration is around 198 m^3 per year. However, under Max. rainfall conditions (≈9164.2 mm), the RHP increases significantly to nearly 1558 m^3 per year – roughly eight times higher than average. This proportional increase in collected volume demonstrates the sensitivity of water harvesting to changes in yearly P. The relationship shows that while ordinary rainfall produces moderate amounts, high P years can create significant water reserves and lessen reliance on municipal supply. This demonstrates that when rainfall-triggered storage systems are built to withstand periods of high collection, rooftop RW collecting can be a dependable additional water source.

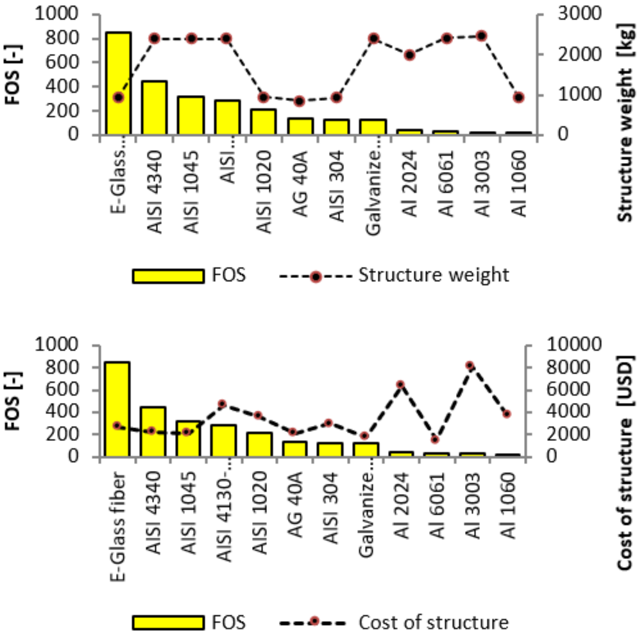

Fig. 4. Comparison of FOS, structural weight, and cost for the selected materials.

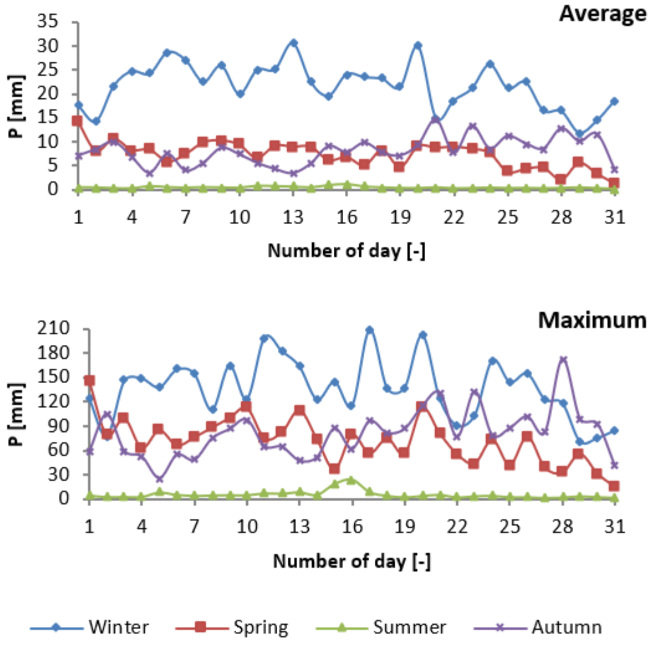

Fig. 5. Monthly variation of average and Max. rainfall for selected site.

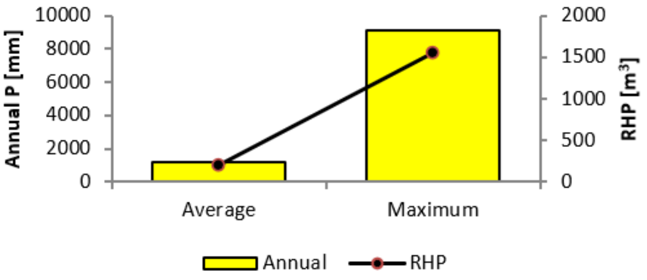

Fig. 6. Annual rainfall and RHP value based on average and Max. rainfall data.

C. *Technical Sustainability of the Proposed System*

Energy balance analysis for the installed 14.4 kW rooftop PV system shows that the monthly PV generation surpasses the household electricity demand throughout the year. The results, presented in Figure 7, indicate that the average monthly energy production varies from 1108 kWh in January to 2039 kWh in July, while the domestic demand for electricity remains much lower, varying between 275 and 410 kWh per month.

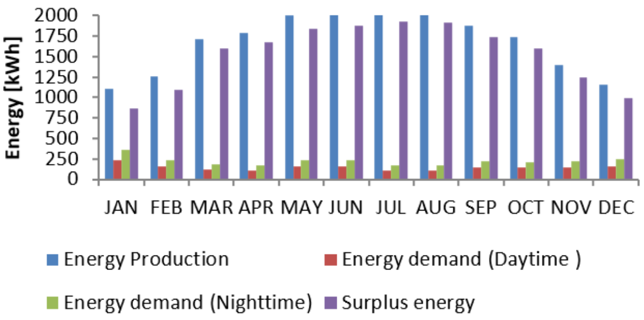

Fig. 7. Monthly variation of energy.

When consumption is divided into daytime and nighttime, it is found that nighttime demand constitutes a considerable portion of total consumption, usually accounting for 55–65% of residential electricity consumption. This, on the one hand, reflects the behavioral and occupancy patterns of urban households, where most of the energy-consuming activities fall under the evening hours. The results indicate that daily nighttime use varies from approximately 5.3 kWh/day in August to 11.6 kWh/day in January. Based on these different requirements and given plausible battery depth-of-discharge and round-trip efficiency limitations, the nominal battery capacity required to fully serve nighttime loads for one, two, and three nights of autonomy has been computed. The worst-case sizing demand takes place during the month of January and results in nominal battery storage requirements of approximately 16.1 kWh, 32.3 kWh, and 48.4 kWh for one, two, and three-night autonomy, respectively. Seasonal variations in battery sizing are due to differences in monthly nighttime demand, given that daytime PV production is always high enough to fully recharge the batteries even during winter. This means that a single night of autonomy could be considered nominally adequate (~16–18 kWh nominal for the residence under study) to meet operational needs without failure, while striking a balance between cost and performance. In practice, this design choice also allows the system to utilize abundant daytime surpluses to top up its battery charge, maximizing household self-consumption and minimizing grid dependence.

D. Results of Economic Viability of Grid-Connected System without Battery Storage

The effects of rainfall availability factors, export tariffs, and structural material selection were taken into consideration during the evaluation of the economic performance of the proposed hybrid solar-RWH system, which operates in a grid-connected mode without battery storage. Given that Beirut has a relatively modest annual solar radiation compared to other regions of the MENA climate zone, the achievable energy yield is constrained; hence, grid connection allows for the sale of surplus energy and the supply of nighttime deficits without relying on cost-intensive storage systems. This operational model offers significant improvements in financial feasibility. The results in Figures 8 and 9 indicate that as the electricity export rate increases from 0.1 to 0.3 USD/kWh, the SP and EP periods were reduced significantly for both structural material alternatives. This reduction is more pronounced between 0.1 and 0.2 USD/kWh, demonstrating the high sensitivity of return on investment to export tariffs. For Max. rainfall conditions, which maximize water-harvesting benefits and thus permit a larger tank volume, SP was reduced to roughly 6–7 years at the highest export rate of 0.3 USD/kWh and remained below 12 years at even a modest rate of 0.15 USD/kWh. Under average rainfall data, SP and EP values increased slightly because only a smaller tank is economically viable, reducing overall annual revenues from water reuse but leaving solar generation unaffected. Nevertheless, Beirut's seasonal rainfall pattern still supports worthwhile water recovery during most of the year.

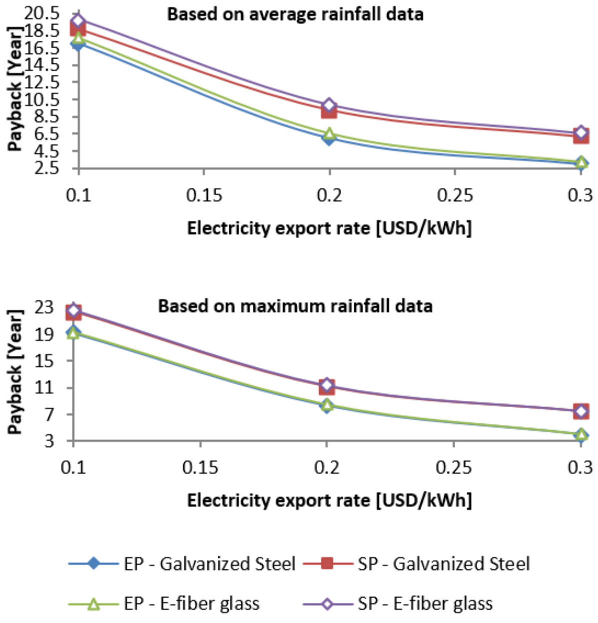

Fig. 8. Payback versus electricity export rate with various scales of rainfall data.

The two candidate structural materials considered (galvanized steel and e-glass fiber) have relatively small economic distinctions. At Max. rainfall, the computed cost of electricity production is 0.157 USD/kWh for galvanized steel and 0.158 USD/kWh for e-glass fiber, reflecting nearly identical generation cost performance. At average rainfall, galvanized steel performs somewhat better (0.131 USD/kWh versus 0.139 USD/kWh), primarily because its fixed structural cost dominates under reduced water yields. This reflects the marginal advantage of galvanized steel in the Beirut context due to its lower material cost and wide market availability. Meanwhile, E-glass fiber, with a higher initial cost, would yield slightly lower payback under Max. rainfall due to lower mass loading and extended durability. These findings are further supported by the Net Present Value (NPV) results. For export rates of 0.2 and 0.3 USD/kWh, the NPVs for both materials are very favorable, reaching over 100,000 USD in the case of Max. rainfall and approaching that value in the case of average rainfall. The Annual Life Cycle Savings (ALCS) are the highest for the rate of 0.3 USD/kWh and decline almost linearly with decreasing export rates.

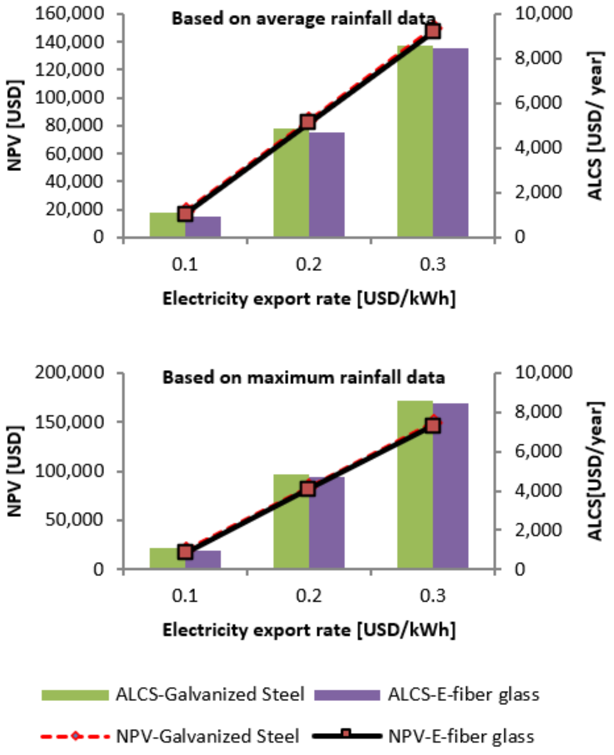

Fig. 9. NPV and ALCS versus electricity export rate with various scales of rainfall data.

E. Results of the Economic Viability of the Grid-Connected System with Battery Storage

The financial evaluation of the hybrid solar–RWH system under grid-connected conditions with nighttime battery storage demonstrates strong economic viability under all considered electricity export tariffs and the various rainfall scenarios. With battery storage, surplus daytime PV energy can be used at night, thereby reducing grid dependence and increasing self-consumption efficiency. This is particularly beneficial in Lebanon due to poor grid stability and uncertain pricing of electricity. As shown in Figure 10, for both galvanized steel and e-glass structures, SP and EP decrease significantly with increasing export rates. For lower export tariffs in the range of 0.1–0.2 USD/kWh, SP remains relatively high due to the limited financial return from the sale of surplus energy. When the export tariff exceeds 0.3 USD/kWh, a significant reduction in SP occurs, falling below 10 years at 0.4 USD/kWh and reaching approximately 7–8 years at 0.5 USD/kWh under Max. rainfall.

Under average rainfall, SP values were slightly higher due to reduced harvested water benefits and a smaller economically justified tank size. Still, economic feasibility was attainable consistently under all conditions tested. The economic benefit of the battery storage is further accentuated as represented by the NPV and ALCS results in Figure 11. NPVs grow almost linearly with the export rate, crossing 150,000 USD at 0.4 USD/kWh in the case of Max. rainfall, drawing near to similar values in the average rainfall case. The ALCS was increased from approximately 2,000 USD/year at 0.1 USD/kWh to 13,000-15,000 USD/year at 0.5 USD/kWh, confirming that nighttime battery utilization significantly enhances long-term financial returns owing to saving electricity purchase from the grid.

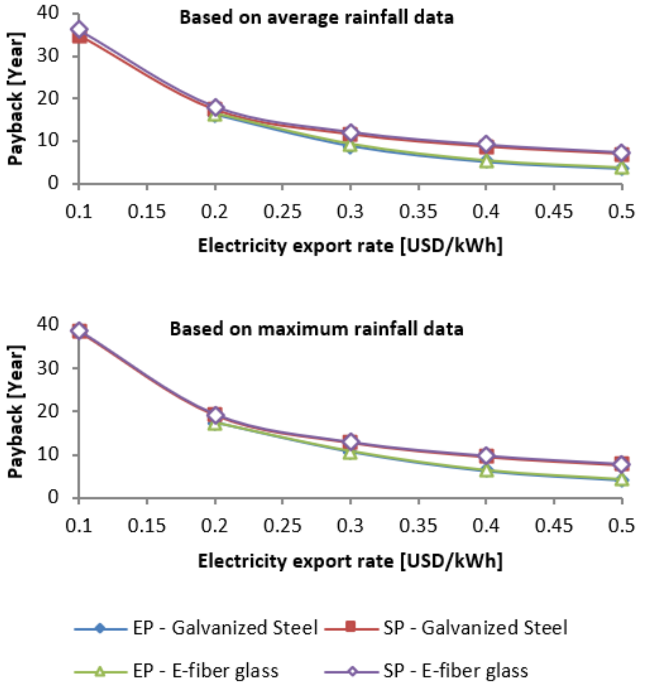

Fig. 10. Payback versus electricity export rate with various scales of rainfall data.

Regarding material selection, the key economic differences between the galvanized steel and E-glass structures remain modest but meaningful. After correction with regard to the LEC value, both materials perform almost identically under Max. rainfall conditions—0.270 USD/kWh in the case of galvanized steel versus 0.271 USD/kWh for e-glass. Under average rainfall, however, galvanized steel becomes slightly more economically favorable at 0.244 USD/kWh compared to 0.252 USD/kWh for e-glass. This behavior arises from the structural material, affecting capital investment, installation logistics, and maintenance implications: on the one hand, galvanized steel benefits from a lower market cost due to its common use in Lebanon; on the other hand, E-glass fiber ensures lightweight structural behavior with excellent safety performance. Thus, galvanized steel generally holds a slight cost advantage under average rainfall, whereas E-glass becomes attractive as the tank size increases, together with the increase in water yield under Max. rainfall.

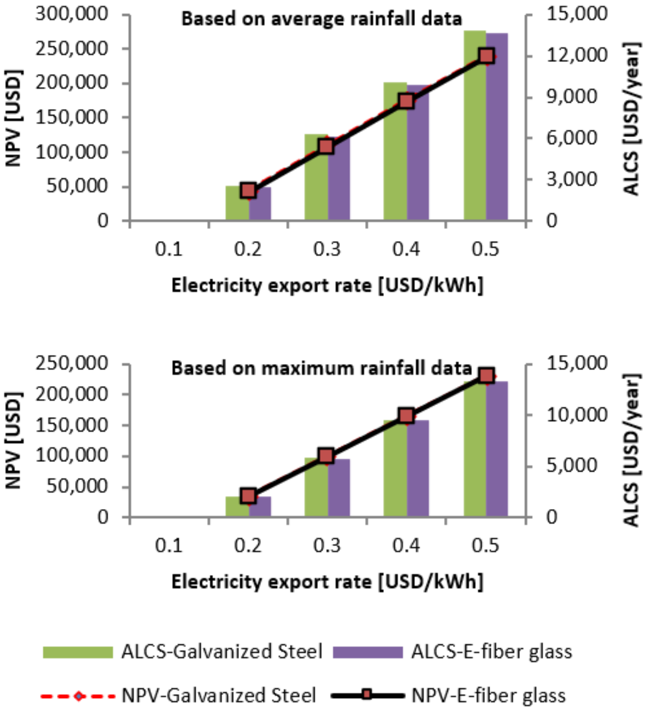

Fig. 11. NPV and ALCS versus electricity export rate with various scales of rainfall data.

IV. DISCUSSION

A combined solar-RWH system provides a self-sufficient water and power solution by utilizing solar energy for power and using the panel structures to channel RW into storage. The study's findings demonstrate that the proposed rooftop hybrid solar-RWH system is a technically feasible and financially viable solution for residential sustainability in Beirut. In comparison to other Middle Eastern regions, Lebanon receives only modest solar irradiation, according to [37] and the International Renewable Energy Agency (IRENA). Therefore, the designed 14.4 kW rooftop PV system generated considerable annual surpluses, with monthly energy generation ranging from 1108 kWh in January to 2039 kWh in July. These values exceed the energy needs of the household throughout the year, verifying that rooftop PV installations can meet residential demands very reliably even in areas with limited solar resources and offer excess energy that could be exported to the grid. These findings support those of [23, 24]. For Mediterranean climates with moderate irradiance, authors in [23, 24] showed that NASA-POWER solar data are dependable and highly productive in coastal regions. Further techno-economic analyses reveal that integration with battery storage improves economic feasibility by a great margin, reducing SP, increasing EP, and yielding very substantial NPV and ALCS. The estimated LEC ranges from 0.244 to 0.271 USD/kWh depending on material selection and rainfall scenario. These fall within or below the range reported in [38-40]. The structure analysis verified that the 35° tilt is optimal, minimizing mechanical stress and weight while retaining high FOS. A simulation comparison of the materials confirmed that both galvanized steel and e-glass fiber produced structurally safe and manufacturable systems. E-glass offered better safety margins because of its favorable strength-to-weight characteristics, while galvanized steel had lower initial costs and a familiar supply chain. These findings are consistent with previous structural optimization research, which highlighted low weight and good manufacturability as two crucial parameters for rooftop PV structures [41]. Furthermore, the high FOS obtained in the present study was consistent with the findings of [42], where an initial FOS of over 200 was reported for the structure to mount a solar panel. Additionally, authors in [39] showed that after substantial weight optimization, the system had a FOS greater than 70 while retaining appropriate structural integrity, confirming that high FOS values are both common and acceptable for preliminary conservative PV mounting designs. Moreover, the RW results emphasize the substantial hydrological significance that the system would contribute under both average and Max. rainfall conditions. Calculated annual RHP varied from 198 m^3/year under average rainfall to 1558 m^3/year under Max. rainfall. Taking into consideration the deteriorating status of Lebanon's groundwater reserves, surface water pollution, and growing reliance on expensive tanker supply—major discussion issues within national hydrogeological assessments—these results demonstrate that PV-RWH systems can offer considerable local water security.

V. CONCLUSIONS

The technical and financial feasibility of an integrated Photovoltaic – Rainwater Harvesting (PV–RWH) system on the roofs of residential buildings in Beirut was reaffirmed as a decentralized approach to addressing Lebanon's water and energy crisis. The main outcomes of the study are: (1) the structural optimization process indicated that a 35-degree tilt angle was optimal and that galvanized steel and e-glass fiber performed similarly, with a low Levelized Energy Cost (LEC) ranging between US$0.131 and US$0.158/kWh; (2) the Rainwater Harvesting Potential (RHP) was estimated at between 198 and 1,558 m^3 annually, which would greatly reduce municipal water needs; (3) annual PV production has consistently been significantly higher than demand, producing a huge energy surplus; and (4) financially, systems without backup batteries were the most viable, achieving a payback period of no more than 6-7 years even with an export cost of US$0.30/kWh, while battery-supported systems had a payback period of 7-8 years with higher export rates and annual lifecycle cost savings of between US$13,000 and US$15,000.

Future studies should focus on (a) optimizing the size of PV batteries and water storage for the detailed demand curves, (b) evaluating the system's resilience under potential climate change scenarios affecting solar resources and rainfall patterns, and (c) implementing the system at the local community deployment scale to strengthen sustainability in urban settlements.

REFERENCES

[1] M. Khondoker, S. Mandal, R. Gurav, and S. Hwang, "Freshwater Shortage, Salinity Increase, and Global Food Production: A Need for Sustainable Irrigation Water Desalination—A Scoping Review," *Earth*, vol. 4, no. 2, pp. 223–240, 2023, https://doi.org/10.3390/earth4020012.

[2] S. Soomro *et al.*, "Drought management for long-term water sustainability and resilience," *Marine & Freshwater Research*, vol. 76, no. 5, Mar. 2025, Art. no. MF24210, https://doi.org/10.1071/MF24210.

[3] S. Chen, P. Liu, and Z. Li, "Low carbon transition pathway of power sector with high penetration of renewable energy," *Renewable and Sustainable Energy Reviews*, vol. 130, Sept. 2020, Art. no. 109985, https://doi.org/10.1016/j.rser.2020.109985.

[4] A. Das and S. Mishra, "Smart and sustainable water management: policy, technology, and innovation pathways for resource resilience," *Green Technology, Resilience, and Sustainability*, vol. 5, no. 1, Oct. 2025, Art. no. 5, https://doi.org/10.1007/s44173-025-00022-8.

[5] W. D. Xu, M. J. Burns, F. Cherqui, S. Duchesne, G. Pelletier, and T. D. Fletcher, "Real-time controlled rainwater harvesting systems can improve the performance of stormwater networks," *Journal of Hydrology*, vol. 614, Nov. 2022, Art. no. 128503, https://doi.org/10.1016/j.jhydrol.2022.128503.

[6] S. R. Ghimire, J. M. Johnston, W. W. Ingwersen, and S. Sojka, "Life cycle assessment of a commercial rainwater harvesting system compared with a municipal water supply system," *Journal of Cleaner Production*, vol. 151, pp. 74–86, May 2017, https://doi.org/10.1016/j.jclepro.2017.02.025.

[7] A. R. Noori and S. K. Singh, "Rainfall Assessment and Water Harvesting Potential in an Urban area for Artificial Groundwater Recharge with Land Use and Land Cover Approach," *Water Resources Management*, vol. 37, no. 13, pp. 5215–5234, 2023, https://doi.org/10.1007/s11269-023-03602-0.

[8] A. Adham, J. G. Wesseling, R. Abed, M. Riksen, M. Ouessar, and C. J. Ritsema, "Assessing the impact of climate change on rainwater harvesting in the Oum Zessar watershed in Southeastern Tunisia," *Agricultural Water Management*, vol. 221, pp. 131–140, July 2019, https://doi.org/10.1016/j.agwat.2019.05.006.

[9] K. Wartalska *et al.*, "The Potential of RainWater Harvesting Systems in Europe – Current State of Art and Future Perspectives," *Water Resources Management*, vol. 38, no. 12, pp. 4657–4683, 2024, https://doi.org/10.1007/s11269-024-03882-0.

[10] S. Joshi, S. Mittal, P. Holloway, P. R. Shukla, B. Ó Gallachóir, and J. Glynn, "High resolution global spatiotemporal assessment of rooftop solar photovoltaics potential for renewable electricity generation," *Nature Communications*, vol. 12, no. 1, 2021, Art. no. 5738, https://doi.org/10.1038/s41467-021-25720-2.

[11] M. Asif, R. Sharieff, M. Olawale, and M. I. Khan, "Unlocking the potential of unregulated rooftops for solar PV on residential buildings: Identifying and addressing key challenges," *Energy Nexus*, vol. 18, June 2025, Art. no. 100447, https://doi.org/10.1016/j.nexus.2025.100447.

[12] B. Ranjgar and A. Niccolai, "Large-Scale Rooftop Solar Photovoltaic Power Production Potential Assessment: A Case Study for Tehran Metropolitan Area, Iran," *Energies*, vol. 16, no. 20, 2023, Art. no. 7111, https://doi.org/10.3390/en16207111.

[13] D. Bernasconi and G. Guariso, "Rooftop PV: Potential and Impacts in a Complex Territory," *Energies*, vol. 14, no. 12, 2021, Art. no. 3687, https://doi.org/10.3390/en14123687.

[14] W. T. Chong, M. S. Naghavi, S. C. Poh, T. M. I. Mahlia, and K. C. Pan, "Techno-economic analysis of a wind–solar hybrid renewable energy system with rainwater collection feature for urban high-rise application," *Applied Energy*, vol. 88, no. 11, pp. 4067–4077, Nov. 2011, https://doi.org/10.1016/j.apenergy.2011.04.042.

[15] W. T. Chong, A. Fazlizan, S. C. Poh, K. C. Pan, and H. W. Ping, "Early development of an innovative building integrated wind, solar and rain water harvester for urban high rise application," *Energy and Buildings*, vol. 47, pp. 201–207, Apr. 2012, https://doi.org/10.1016/j.enbuild.2011.11.041.

[16] W. T. Chong *et al.*, "Performance assessment of a hybrid solar-wind-rain eco-roof system for buildings," *Energy and Buildings*, vol. 127, pp. 1028–1042, Sept. 2016, https://doi.org/10.1016/j.enbuild.2016.06.065.

[17] X. Wang *et al.*, "Preliminary Techno–Environment–Economic Evaluation of an Innovative Hybrid Renewable Energy Harvester System for Residential Application," *Energies*, vol. 12, no. 8, 2019, Art. no. 1496, https://doi.org/10.3390/en12081496.

[18] H. Cao, X. Zeng, L. Wu, X. Wu, and Z. Zhang, "A hybrid wind and rainwater energy harvesting system for applications in sea-crossing bridges," *Ocean Engineering*, vol. 234, Aug. 2021, Art. no. 109267, https://doi.org/10.1016/j.oceaneng.2021.109267.

[19] Y. Kassem, H. Gökçekuş, A. Kiraz, and A. H. A. Abdelnaby, "Integrating Rainwater Harvesting and Solar Energy Systems for Sustainable Water and Energy Management in Low Rainfall Agricultural Region: A Case Study from Gönyeli, Northern Cyprus," *Sustainability*, vol. 17, no. 18, 2025, Art. no. 8508, https://doi.org/10.3390/su17188508.

[20] N. Subuh, R. Ballout, I. Toufeili, I. I. Kassem, and S. A. Kharroubi, "Beliefs, Practices, and Knowledge of Household Food Handlers Regarding the Impact of Electricity Outages on Food Safety: Findings from a National Cross-Sectional Study in Lebanon," *Foods*, vol. 14, no. 5, 2025, Art. no. 855, https://doi.org/10.3390/foods14050855.

[21] Y. Kassem, H. Gokcekus, I. A. A. Albakoush, and K. S. B. Abdullah, "Solar-Powered Solutions for the Water and Energy Shortage Problem: The Case Study of Nahr El Bared, Lebanon," *Engineering, Technology & Applied Science Research*, vol. 13, no. 3, pp. 10861–10869, June 2023, https://doi.org/10.48084/etasr.5858.

[22] Gregory B. Yared, "Water Scarcity In Lebanon: The Edge Of Collapse," BA thesis, Environmental Studies, Fordham University, Bronx, New York City, United States, 2023.

[23] G. C. Rodrigues and R. P. Braga, "Evaluation of NASA POWER Reanalysis Products to Estimate Daily Weather Variables in a Hot Summer Mediterranean Climate," *Agronomy*, vol. 11, no. 6, 2021, Art. no. 1207, https://doi.org/10.3390/agronomy11061207.

[24] A. H. Halimi, C. Karaca, and D. Büyüktaş, "Evaluation of NASA POWER Climatic Data against Ground-Based Observations in The Mediterranean and Continental Regions of Turkey," *Journal of TekirdagAgricultural Faculty*, vol. 20, no. 1, pp. 104–114, Jan. 2023, https://doi.org/10.33462/jotaf.1073903.

[25] A. D. Quansah *et al.*, "Site adaptation of NASA-POWER reanalysis solar radiation products for tropical climates in Ghana using bias correction for clean energy application," 2024, https://doi.org/10.21203/rs.3.rs-4571887/v1.

[26] S. Aziz, M. Y. S. Dasti, M. Abrar, F. Mumtaz, and A. Tariq, "Satellite-based rainwater harvesting sites assessment for Dera Ghazi Khan, Punjab, Pakistan," *Environmental Science and Pollution Research*, vol. 31, no. 32, pp. 45399–45413, 2024, https://doi.org/10.1007/s11356-024-34195-9.

[27] Y. Prihanto, R. H. Koestoer, and D. Sutjiningsih, "Re-assessing Rainwater Harvesting Volume by CHIRPS Satellite in Semarang Settlement Area," IOP Conference *Series: Earth and Environmental Science*, vol. 98, no. 1, 2017, Art. no. 012004, https://doi.org/10.1088/1755-1315/98/1/012004.

[28] Y. P. K. Suni, J. Sujono, and Istiarto, "Identifying potential sites for rainwater harvesting ponds (embung) in Indonesia's semi-arid region using GIS-based MCA techniques and satellite rainfall data," *PLOS ONE*, vol. 18, no. 6, 2023, Art. no. e0286061, https://doi.org/10.1371/journal.pone.0286061.

[29] C. Bayram and E. Köse, "Structural and topology optimization of steel construction profiles in solar energy systems," *European Mechanical Science*, vol. 7, no. 4, pp. 285–295, Dec. 2023, https://doi.org/10.26701/ems.1388159.

[30] G. Kamela, T. Zeundjua, and M. Oduetse, "Wind load analysis and cost assessment of a dual-axis stand-alone photovoltaic structure," *Engineering Research Express*, vol. 6, no. 1, 2024, Art. no. 015514, https://doi.org/10.1088/2631-8695/ad2b25.

[31] S. Gautam, D. B. Das, and A. K. Saxena, "Impact of solar panel spacing on wind load in an elevated solar panel structure," *Discover Mechanical Engineering*, vol. 3, no. 1, 2024, Art. no. 50, https://doi.org/10.1007/s44245-024-00081-4.

[32] A. Pellja, O. Liivapuu, and J. Olt, "Design and Optimization of a Welded Structure for a Mobile Power Station with Complex Configuration," *Environmental and Climate Technologies*, vol. 29, no. 1, pp. 471–482, 2025, https://doi.org/10.2478/rtuect-2025-0032.

[33] J. Macedo, J. Molina, Y. S. Vidal, A. Mendoza, J. Canazas, and C. Diaz, "Static analysis and topological optimization of photovoltaic panel support using recycled polymeric plastic," *Advances in Science and Technology. Research Journal*, vol. 19, no. 6, pp. 167–180, 2025, https://doi.org/10.12913/22998624/203079.

[34] P. Singh and H. K. Channi, "Comparative feasibility analysis of PV plant with energy effective measures in Chandigarh University using RETscreen," in *Mechatronics: Concepts, Tools, Applications, and New Trend*, Ajay Kumar, Parveen Kumar, Sarita Rathee, Brijesh Kumar, Ed., 1st ed., Boca Raton, USA: CRC Press, 2025, ch. 8, pp. 141–163.

[35] H. T. Paradongan *et al.*, "Techno-economic feasibility study of solar photovoltaic power plant using RETScreen to achieve Indonesia energy transition," *Heliyon*, vol. 10, no. 7, Apr. 2024, Art. no. e27680, https://doi.org/10.1016/j.heliyon.2024.e27680.

[36] R. Villar-Navascués, A. Pérez-Morales, and S. Gil-Guirado, "Assessment of Rainwater Harvesting Potential from Roof Catchments through Clustering Analysis," *Water*, vol. 12, no. 9, 2020, Art. no. 2623, https://doi.org/10.3390/w12092623.

[37] M. Hasanzadeh and K. V. Kamran, "Harnessing Solar Energy: Mapping the Potential and Performance of Middle Eastern Countries," in *9th Advanced Engineering Days (AED)*, Tabriz, Iran, 9–10 July 2024.

[38] S. Bhakta, V. Mukherjee, "Techno-economic viability analysis of fixed-tilt and two axis tracking stand-alone photovoltaic power system for Indian bio-climatic classification zones," *Journal of Renewable and Sustainable Energy*, vol. 9, no. 1, 2017, Art. no. 015902, https://doi.org/10.1063/1.4976119.

[39] A. Bahrami, C. O. Okoye, and U. Atikol, "Technical and economic assessment of fixed, single and dual-axis tracking PV panels in low latitude countries," *Renewable Energy*, vol. 113, pp. 563–579, Dec. 2017, https://doi.org/10.1016/j.renene.2017.05.095.

[40] B. Hammad, A. Al-Sardeah, M. Al-Abed, S. Nijmeh, and A. Al-Ghandoor, "Performance and economic comparison of fixed and tracking photovoltaic systems in Jordan," *Renewable and Sustainable Energy Reviews*, vol. 80, pp. 827–839, Dec. 2017, https://doi.org/10.1016/j.rser.2017.05.241.

[41] L. A. Iturralde Carrera *et al.*, "Advances in Mounting Structures for Photovoltaic Systems: Sustainable Materials and Efficient Design," *Technologies*, vol. 13, no. 5, 2025, Art. no. 204, https://doi.org/10.3390/technologies13050204.

[42] G. Drobyshev, "Design of the solar panel mounting system," BA thesis, Mechanical and Sustainable Engineering, Arcada University of Applied Sciences, Helsinki, Finland, 2025.