A Techno-Economic Comparative Study of a Grid-Connected Residential Rooftop PV Panel

The Case Study of Nahr El-Bared, Lebanon

Hüseyin Çamur
Department of Mechanical Engineering
Engineering Faculty
Near East University
Nicosia, Cyprus
huseyin.camur@neu.edu.tr

Youssef Kassem
Department of Mechanical Engineering
Engineering Faculty
Near East University
Nicosia, Cyprus
yousseuf.kassem@neu.edu.tr

Ebaa Alessi
Department of Mechanical Engineering
Engineering Faculty
Near East University
Nicosia Cyprus
ibaa_a88@hotmail.com

Abstract—Lebanon suffers from daily electricity shortages. The country has paid much attention to renewable energy sources, particularly solar, to gradually replace conventional energy. Installing a photovoltaic (PV) system becomes increasingly attractive for residential consumers due to the rising electricity tariff rates while it reduces the dependency on domestic power generators. No known study has dealt with the investigation of potential grid-connected rooftop PV systems with various sun-tracking modes and PV technologies in Nahr El-Bared, Lebanon. Consequently, the main objective of the current paper is to investigate the feasibility of a 5kW grid-connected PV system of various technologies (mono-crystalline silicon and poly-crystalline silicon) and sun-tracking modes including fixed tilt and 2-axis systems for rooftop households in Lebanon. The Nahr El-Bared camp was the case study was of the paper. RETScreen Expert software was used to evaluate the techno-economic performance of the proposed systems. The results show that the annual electrical energy from a fixed 5kW PV panel tilted at an optimal angle ranged from 8564.47kWh to 8776.81kWh, while the annual electrical energy from the PV tracking system was within the range of 11511.67-12100.92kWh. This amount of energy output would contribute significantly to reduce the energy shortage in the country. A typical household was selected to establish a load profile and load supply during both grid availability and outage periods. The highest energy consumption that can be covered by the PV systems was recorded during the spring and summer seasons. Also, the average energy production cost ranged from 0.0239 to 0.0243$/kWh for all the proposed systems. It was concluded that a 5kW grid-connected rooftop PV system could be economically justifiable. Finally, this study tried to increase the awareness about utilizing PV sun-tracking systems and the feasibility of small-scale grid-connected rooftop PV systems in the selected regions. The results of this research can help investors in the energy and building sectors.

Corresponding author: Youssef Kassem

I. INTRODUCTION

Energy is an indispensable need, which, until quite recently, was met with the consumption of conventional fossil fuels. However, the use of fossil fuels has polluted the environment and led to climate change mainly due to greenhouse gas emissions [1]. The environmental problems resulting from the increasing consumption of fossil fuels have encouraged scientific researchers to search for alternative sources of energy that would affect less the environment [2, 3]. Many researchers found that renewable energy sources, like solar and wind, play a significant role in reducing Greenhouse Gas (GHG) emissions. For instance, authors in [4] concluded that the utilizing of solar thermal energy provided an important step towards sustainable zero-emission production in the industry. Authors in [5] found that renewable energy sources have a high potential for providing an increasing share of future energy growth without increasing GHG emissions. Authors in [6] reported that the production of electricity with the use of solar systems can protect the environment. Recently, solar power has been considered as a potential, economically viable, and environment friendly energy source. Authors in [7] evaluated the solar energy potential in Pakistan based on data from 58 meteorological stations covering the whole country. The results indicated that in an area of $100m^2$, 45 MW to 83 MW power per month may be generated in the southern Punjab, Sindh, and Balochistan regions. Authors in [8] compared the potential of utilizing wind energy and solar energy as power sources for a small household in three urban regions in Northern Cyprus. The results showed that the selected regions have huge solar

potential compared to the wind energy potential. Authors in [9] studied the feasibility of a 12MW grid-connected wind/PV project in two regions of Northern Cyprus. The results indicated that the selected regions have a high potential compared to wind energy. Authors in [10] evaluated a techno-economic analysis of a 50MW wind/PV system in various locations in Libya. The results showed that a solar PV plant project was more economical than a wind farm. Authors in [11] reported that the production of electricity using solar systems would have a great material impact on the lives of low-income households as compared to their high-income counterparts in United States. Authors in [12] investigated the feasibility of a 10MW grid-connected PV system at different locations in Libya. The results indicated that the proposed system offered the best solution for generating electricity in Libya.

Lebanon suffers from problems in the electricity sector. Generally, electricity cuts range from 3 to 13 hours per day, depending on the area. As a result, families are forced to pay two electricity bills: one to the Electricity Provider of Lebanon (Electricite du Liban-EDL) for the energy it provides, and another for generators, in which many families have to invest in order to ensure continuous access to electricity. Moreover, the electric rationing, has returned at a high rate due. Presently, the demand is estimated to be more than 3458MW, while the current capacity is around 2000MW. Besides, the cost of generating electricity is high. With peak time electricity demand of about 3458MW, which is probably less than its real size, the EDL only provides a part of this demand, and the remaining demand is met through private diesel generators, illegally connected to low voltage distribution networks. Most of the households depend on this source despite its very high prices and its low capacity. The potential for utilizing wind and solar energy in Lebanon has been investigated in [13-22]. Authors in [13] investigated the feasibility of 100MW grid-connected wind/solar systems in the Rayak region. The results indicated that wind power was more efficient than solar power in the selected region. Authors in [17] investigated the potential of wind energy at 3 coastal regions of Lebanon. The results showed that small-scale wind turbines offered high wind potential when compared to other types of wind turbines. Similar results were found in [18, 19]. Furthermore, according to the solar atlas map, the Global Horizontal Irradiation (GHI) and Direct Normal Irradiation (DNI) values vary from 1600kWh/m^2 to 2000kWh/m^2 and 1700W/m^2 to 2200W/m^2, respectively. Based on the values of GHI and DNI, it is concluded that the country has high solar resources, being categorized as good, excellent, or outstanding according to solar potential classes [23]. The coastal regions have lesser values of GHI and DNI compared to other regions based on the solar atlas map. According to the wind atlas map, the mean wind speed and wind power density are within the range of 2.5-3m/s and 25-75W/m^2, respectively at a height of 10m in coastal regions. Therefore, it can be concluded that the country has a huge solar energy potential compared to wind energy. The conclusions after reviewing the previous studies are:

- Lebanon has a huge solar energy potential when compared to wind energy.

- Solar power systems can reduce fossil fuel consumption and CO_2 emissions.

- No scientific studies proposed small-scale grid-connected rooftop PV solar power systems to meet the electricity demand of households in Nahr El-Bared.

- To the best of our knowledge, no studies investigated the economic feasibility of small-scale PV systems with various sun-tracking systems (fixed-tilt and two-axis tracking systems) in Lebanon.

Thus, there is a of literature discussing the performance of rooftop PV systems in Lebanon. Also, according to [13], citizens rely on domestic power generators or small home generators during the periods of power outage, adding financial burdens to the citizens. Furthermore, none of the reviewed studies addresses the case of Nahr El-Bared in Lebanon. According to United Nations Relief and Works Agency in 2018, the total energy generated from the generators in the Nahr El-Bared is found to be about 80MWh/day. Therefore, grid-connected PV systems can be an attractive solution to reduce electricity consumption, dependence on utility power, and increase electricity generation from renewable energy sources for residential electricity users. Furthermore, household rooftop PV systems will create significant savings in the cost of electricity bills. Additionally, such systems can help the EDL to reduce fossil fuel consumption and make electricity available throughout the day. Consequently, the study aims to investigate the techno-economic and environmental sustainability of rooftop PV systems in Nahr El-Bared. To achieve this, the NASA's database has been utilized as a source of meteorological information. Sun-tracking systems, including fixed tilt and 2-axis systems, are investigated in this study. Moreover, numerous economic indices including net present value, payback period, annual life cycle savings, internal rate of return, and the Levelized Cost of Energy have been taken into consideration as measure of performance indicators for the proposed projects. To this aim, RETScreen software was used in the present study. The proposed system can provide valuable inputs for the development of new policies and innovative solutions for the PV market growth in the country.

II. MATERIALS AND METHODS

The solar energy potential in the selected region in the Northern part of Lebanon is discussed based on NASA's average monthly global solar radiation and air temperature. Besides, the grid-connected rooftop PV system is investigated as a solution for the electricity crisis with the use of the RETScreen software. Figure 1 shows the methodology used in this study.

A. Study Area and Data

Nahr El-Bared camp is one of the largest Palestinian camps in the northern part of Lebanon, located near Tripoli and near the Mediterranean Sea at 34°30'28.19"N latitude and 35°57'23.99"E longitude. From a topographic perspective, the highest and lowest average elevation reach 27m and 12m above the sea level respectively. The area of the old camp is estimated to be about 2km². According to United Nations Relief and Works Agency (2018), Nahr El-Bared camp is divided in two

camps, the old camp with an average apartment area of 78m^2 and total built residential area of 360000m^2 and the new camp with an average household area of 150m^2 and total built area of 300000m^2. Several studies evaluated the solar energy potential in different locations using the NASA database [24, 25].

Moreover, the NASA database showed good agreement with the measured data of global solar irradiation of previous studies [25-27]. Therefore, the monthly NASA database is utilized in the current study to investigate the potential of solar energy in the selected region.
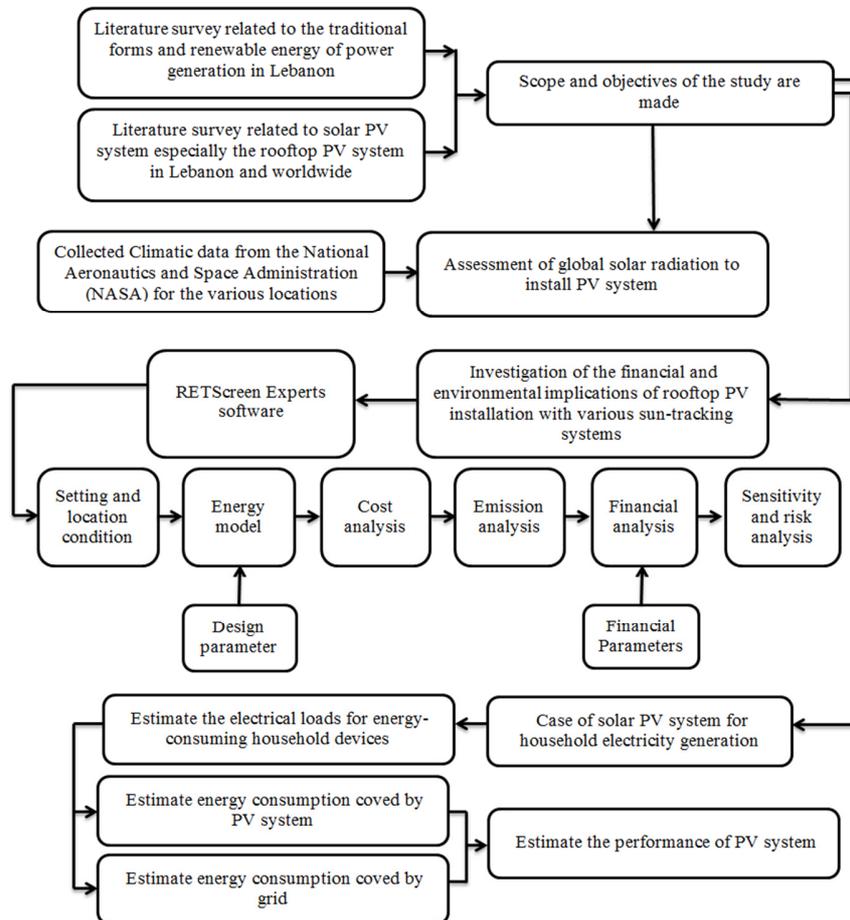

Fig. 1.   The flowchart of the analysis steps of the current study.

B. Design of the PV Power System

For the proposed small-scale grid-connected PV system, mono-Si-CS6X-300M and poly-Si - CS6X-310P were selected which are manufactured by Canadian Solar. Table I summarizes the specifications of the selected modules. The total number of modules and the area required for the proposed system are 17 modules and 33m^2. The description method of designing a solar PV system is available in [10, 13, 25].

Power generating factor (PGF):

$$PGF = \frac{SI \times SH}{STCI} \quad (1)$$

Energy demand (ED):

$$ED = ECAL \quad (2)$$

Solar PV Energy Required (SPVER):

$$SPCER = PER \times ELS \quad (3)$$

PV Module Sizing:

$$TWPR = \frac{SPVER}{PGF} \quad (4)$$

$$PVMS = \frac{TWPR}{PVOPR} \quad (5)$$

Inverter Sizing (IS:)

$$IS = PER \times FS \quad (6)$$

where *SI* is solar irradiance, *SH* is the sunshine hours, *STCI* is standard test condition irradiance, *ECAL* is the energy consumption of all loads, *TWPR* is total Watt peak rating, *PGF* is panel generation factor, *PVMS* is PV module size, *PVOPR* is PV output power rating, *FS* is the factor of safety, *PER* is peak energy requirements, *ELS* is energy lost in the system and the factor of safety is 1.3. Moreover, one inverter with 6kW capacity and 97.9% efficiency is used to convert the DC into AC and feed it directly to the grid (Table II).

TABLE I.   PV MODULE SPECIFICATION

Item	Specification	
Module technology	Mono-Si	Poly-Si
Manufacturer	Canadian Solar	
Model	mono-Si - CS6X-300M	poly-Si - CS6X-310P
Nominal power [W]	300	310
Open-circuit voltage [V]	45	44.9
Short-circuit current [A]	8.74	9.08
Voltage at point of maximum power [V]	36.5	36.4
Current at point of maximum power [A]	8.22	8.52
Module area [m2]	1.919	1.918
Efficiency [%]	15.63	16.16
Warranty [year]	25	25
Cost [USD/Wdc]	0.83	0.8

TABLE II.   SPECIFICATIONS OF THE SELECTED INVERTOR

Input DC parameters	Value
MPP voltage range V_{DC} (at 25°C / at 50°C)	850V-1425V/1275V
Min. input voltage $V_{DC,min}$ / start voltage $V_{DC,Start}$	778V/878V
Max. input voltage $V_{DC, max}$	1500V
Max. input current $I_{DC, max}$ (at 25°C / at 50°C)	3000A / 2700A
Max. short-circuit current rating	4300A
Output DC parameters	**Value**
Nominal AC power at $\cos\varphi = 1$ (at 25°C / at 40°C / at 50°C)	2500kVA/2350kVA/2250kVA
Nominal AC power at $\cos\varphi = 0.8$ (at 25°C / at 40°C / at 50°C)	2000kW/1880kW/1800kW
Nominal AC IAC, nom = Max. output current $I_{AC, max}$	2624A

C. Economic Analysis

Software like RETScreen and HOMER are used to estimate the economic indicators for financial analysis. Several researchers have utilized RETScreen to investigate the feasibility of a grid-connected PV system [8, 10]. In the present study, 6 economic indicators, namely NPV, LCOE, IRR, SP, EP, and ALCS are estimated using RETScreen. Also, the GHG emission reduction, energy production, and the Capacity Factor (CF) for the proposed systems are determined using RETScreen.

Net Present Value (NPV):

$$NPV = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n} \quad (7)$$

Levelized Cost Of Energy (LCOE):

$$LCOE = \frac{sum\ of\ cost\ over\ lifetime}{s\ of\ electricity\ generated\ over\ the\ lifetime} \quad (8)$$

Internal Rate of Return (IRR):

$$O = \sum_{n=0}^{N} \frac{C_n}{(1+IRR)^n} \quad (9)$$

Simple Payback (SP):

$$SP = \frac{C - IG}{(C_{ener} + C_{capa} + C_{RE} + C_{GHG}) - (C_{o\&M} + C_{fuel})} \quad (10)$$

Equity Payback (EP):

$$EP = \sum_{n=0}^{N} C_n \quad (11)$$

Annual Life Cycle Savings (ALCS):

$$ALCS = \frac{NPV}{\frac{1}{r}\left(1 - \frac{1}{(1+r)^N}\right)} \quad (12)$$

GHG Reduction Cost (GRC):

$$GRC = \frac{ALCS}{\Delta_{GHG}} \quad (13)$$

Benefit-Cost ratio (B-C):

$$B - C = \frac{NPV + (1-f_d)C}{(1-f_d)FDC} \quad (14)$$

Capacity Factor (CF)):

$$CF = \frac{P_{out}}{P \times 8760} \quad (15)$$

where P_{out} is the energy generated per year, P is the installed capacity, N is the project life in years, C_n is the after-tax cash flow in year n, r is the discount rate, C is the total initial cost of the project, f_d is the debt ratio, B is the total benefit of the project, IG is the incentives and grants, C_{enter} is the annual energy savings or income, C_{appa} is the annual capacity savings or income, C_{RE} is the annual Renewable Energy (RE) production credit income, C_{GHG} is the GHG reduction income, $C_{o\&M}$ is the yearly operation and maintenance costs incurred by the clean energy project, C_{ruel} is the annual cost of fuel, which is zero for renewable projects, and Δ_{GHG} is the annual GHG emission reduction.

III.   RESULTS AND DISCUSSION

A. Monthly Solar Radiation

It is well known that the performance of PV modules is influenced by several climate parameters including the meteorological factors of the specific location, and solar irradiance is one of the most essential among them. Several studies utilized various simulation tools to assess the performance simulation of small-scale grid-connected rooftop PV systems. Authors in [28] assessed the feasibility of a 6.4kW grid-connected rooftop PV system in Ujjain, India by using 4 simulation tools. The results indicated that PV*SOL is an easy, fast, and reliable software tool for the simulation of the solar PV system in the selected region. Authors in [29] investigated the performance of a 1MW grid-connected rooftop PV system in an educational institute in India using 3 simulation tools and the actual data and the PVGIS has the lowest average mean bias error and average normalized mean bias error compared to the other two tools (PVSyst and PVWatt). In this paper, the performance of the developed PV systems is estimated by 2 simulation tools, PVGIS and RETScreen. With the PVGIS (Figure 2), the highest solar radiation was recorded in July with a value of 246.892kWh/m^2 while the minimum was obtained in December with a value of 76.211kWh/m^2. In the RETScreen simulation tool, the highest value of solar radiation was recorded in July (250.48kWh/m^2) as shown in Figure 2. Moreover, it was found the annual solar radiation is 1941 kWh/m^2 and 2010kWh/m^2, given by PVGIS and RETScreen

respectively. It is noticed that the PVGIS and RETScreen almost give the same annual value of solar radiation. Authors in [25] found that the estimated values of solar radiation, obtained from PVGIS and RETScreen, are close to the actual data. Based on the value of solar radiation at the selected location, it was found that the solar source of Nahr El-Bared is categorized as excellent (class 5) according to [23]. Therefore, this region is suitable for installing a PV system.
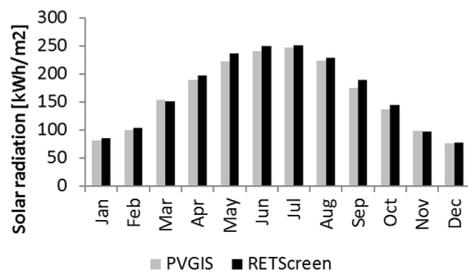
Fig. 2.   Average monthly solar radiation at the studied location.

B. Electricity Generation and Capacity Factor

The optimum slope angle and azimuth angle for the fixed-tilt system are estimated with the Photovoltaic Geographical Information System (PVGIS) simulation tool. Several scientific studies have used PVGIS to find the slope angle and azimuth angle for PV systems [30, 31]. Generally, the PVGIS provides the optimum slop and azimuth angles that give the maximum annual global solar radiation for a specific location. The slop and azimuth angles for the selected study were estimated to be 30° and -3° respectively. The economic feasibility of the developed system is investigated with RETScreen. According to [32, 33], solar radiation and the number of clear sunny days are important factors that affect the annual energy exported to the grid by the panel and the Capacity Factor (CF). Table III shows the monthly and annual Electricity Generation (EG) and CF of the proposed systems. For the fixed-tilt system, it is found that the total annual value of EG is 8564.47kWh for mono-Si and 8776.81kWh for poly-Si. The total annual EG for the two-axis tracking system is within the range of 11511.67kWh (mono-SI) to 12100.92kWh (poly-Si). The maximum value of EG is recorded in July for all the proposed systems. It can be concluded that the amount of output power could be increased from 34% to 37% by a two-axis tracking system. Furthermore, it is found that the CF values of both systems vary from 19.01% to 26.43% for the fixed-tilt and two-axis sun-tracking systems. These observations can be supported by the findings of other researchers who analyzed the feasibility of grid-connected PV systems. For instance, authors in [34] found that the CF of the proposed PV system in Oman was within the range of 16-23%. Authors in [35] found that the value of CF of grid-connected PV systems with different sun-tracking modes was within the range of 17.54-27.42%. Authors in [35, 36] concluded that the use of the two-axis instead of the fixed-tilt option significantly increases the generated electricity. Therefore, it can be concluded that the value gotten from the present study for the selected location is compatible with the acceptable values. Consequently, it is technically sustainable to build a grid-connected rooftop PV system in Nahr El-Bared.

TABLE III.   ELECTRICITY GENERATION IN KWH AND CAPACITY FACTOR FOR THE DEVELOPED SYSTEMS

Month	Fixed-tilt axis		Two-axis	
	Mono-Si	Poly-Si	Mono-Si	Poly-Si
Jan.	514.14	526.89	663.81	680.27
Feb.	549.70	563.33	663.81	700.90
Mar.	726.28	744.29	663.81	963.47
Apr.	778.32	797.61	1015.02	1040.19
May	861.40	882.76	1261.22	1292.49
Jun.	853.38	874.54	1293.29	1325.35
Jul.	864.42	885.85	1296.47	1328.61
Aug.	852.87	874.02	1246.95	1277.86
Sep.	805.77	825.75	1083.05	1109.90
Oct.	718.62	736.43	970.07	994.12
Nov.	562.21	576.15	730.92	749.05
Dec.	477.36	489.19	623.25	638.70
Annual [kWh]	8564.47	8776.81	11511.67	12100.92
CF [%]	19.17	19.01	26.43	26.21

C. Performance of the Proposed Systems

The performance of the aforementioned sun-tracking systems was evaluated by the estimation of the economic and environmental factors for each system. In this study, the financial parameters (Table IV) inflation rate, discount rate, reinvestment rate, debt ratio, debt interest rate, were considered as input variables for the estimated economic indicators assumed based on [10, 13, 25, 35, 37-40]. In the present study, the system cost is around $5261 and $5243 for mono-Si and poly-Si fixed-tilt and $7365 and $7347 for mono-Si and poly-Si two-axis tracking systems which are estimated based on recent market data in the country and are consistent with the cost prices available in the literature. In general, the net present value of any investment project can be defined as the difference between the present value of cash inflows and outflows of the project [41]. Therefore, it is clear that in order to calculate the net present value, there must be a discount rate based on which the cash flows associated with the investment are deducted [42, 43]. Therefore, it can be concluded that the difficulty in determining the discount rate that is used as a basis for calculating the net present value has an impact on the investment decision. Additionally, the average credit interest rate can be used as the discount rate, or the interest rate on project loans can be considered as the discount rate [44]. There is an inverse relationship between the discount rate and the current value of the project, which means that choosing a discount rate is very important [45]. The debt ratio is the financial ratio used to assess and measure the leverage of an entity over the relationship between total debt (long-term debt and short-term debt) and total assets [46]. If the ratio is higher than 1, this means that the total liabilities are higher than the total assets, which means that the facility's leverage is high and it faces more financial risks. If the ratio is less than 1, then this means that the total liabilities are less than the assets, which means that the facility is financially sound. Besides, high-interest rates lead to an increase in the future value of the project as the period of investment leads to a future value increase. The results regarding the economic performance of the 5kW grid-connected rooftop PV system for all the developed PV systems are summarized in Table V. The obtained results show that the value of NPV for the proposed systems is positive and makes the project to be financially and

economically feasible [24, 35]. Also, it is found that the proposed projects in the selected location are economically acceptable based on the internal rate of return, which is a measure of a project's profitability [24, 47]. It is observed that the developed PV project has the longest value of EP of 3.2 years for mono-Si and the lowest one for poly-Si system with a value of 3.1 years. For the fixed-tilt system, the SP values are 6.14 years and 5.97 years for mono-Si and poly-Si respectively. For the two-axis tracking modes, the SP values are 6.24 and 6.07 years respectively for mono-Si and poly-Si. The results indicate that the PV projects in the region make financial sense.

TABLE IV.   FINANCIAL PARAMETERS

Factor	Unit	Value
Inflation rate	%	2.5
Discount rate	%	0
Reinvestment rate	%	9
Project life	year	25
Debt ratio	%	50
Debt interest rate	%	0
Debt term	year	20
Electricity export escalation rate	%	5

TABLE V.   ECONOMIC PERFORMANCE –CURRENT STUDY

Parameters	Fixed-tilt axis		Two-axis	
	Mono-Si	Poly-Si	Mono-Si	Poly-Si
IRR [%]	15.99	16.14	15.92	16.05
SP [year]	6.14	5.97	6.24	6.07
EP [year]	3.21	3.12	3.26	3.17
NPV [$]	37658.51	38740.63	51809.73	53294.87
ALCS p$/year]	1506.34	1549.63	2072.39	2131.79
NPV [$]	-248.79	-249.75	-248.26	-249.20
LCOE [$/kWh]	0.0246	0.0239	0.0249	0.0243
Performance [%]	82.63	81.90	91.62	93.16

TABLE VI.   ECONOMIC PERFORMANCE COMPARISON

Ref.	Country	Size/ load	Tracking mode	LCOE [$/kWh]
[8]a	Northern Cyprus	6.4kW	Fixed Tilt	0.0194-0.0199
[10]a	Libya	5kW	Fixed Tilt	0.0307-0.0270
[38]a	Norway	2.07kW	Fixed Tilt	0.149-11.632
[48]b	India	6kW	Fixed Tilt	2.944
			Two-axis adjustment tracking	3.165
[49]c	Nigeria	1kW	Two-axis continuous tracking	0.299
[50]a	Jordan	7.98kW	Fixed Tilt	0.097
			Two-axis continuous tracking	0.122
[51]b	India	5.19 kWh/d	Fixed Tilt	0.226-0.287
			Two-axis continuous tracking	0.523-0.732
[52]a	Spain	1kW	Fixed Tilt	0.075
			Two-axis continuous tracking	0.109
[53]c	Iraq	4kW	Fixed Tilt	0.09
[54]a	Europe	4kW	Fixed Tilt	0.120-0.390
[55]a	Indonesia	3kWp	Fixed Tilt	0.09
[56]a	Iraq	5kW	Fixed Tilt	0.078
CS	Lebanon	5kW	Fixed Tilt	0.0239-0.0246
			Two-axis continuous tracking	0.0243-0.0246

CS: Current Study, a: grid-connected PV system, b: stand-alone PV with micro WT hybrid power system, c: Stand-alone PV system

The lowest value of LCOE is found for poly-Si systems as shown in Table V. The LCOE value of the proposed projects is compared with the existing value of small-scale PV systems in the literature. Table VI summarizes the economic analysis of solar projects with various tracking modes in different countries. It is found that the LCOE values of the proposed systems are within the range of the maximum (3.165$/kWh) and minimum (0.0199$/kWh) of LCOE values obtained from the literature. It is noticed that the value of LCOE is slightly increased by 4.23% when the two-axis system is used. This increment of LCOE is primarily due to the high cost of the two-axis system. The developed systems provide a very good insight into the economic viability of the project for all regions. Additionally, the obtained results demonstrated that the development of the proposed 5kW PV power system is economically acceptable due to the obtained favorable economic results.

D. The Case of a Solar PV System for Household Electricity Generation

This section aims to evaluate the techno-economic performance of 5kW grid-connected PV systems for rooftop PV systems. Designing the electrical load is an essential part of this section. The energy demand (E_{load}) of the considering household can be estimated by [57]:

$$E_{load} = \sum_{j=1}^{N_{category}} P_j n_j T_j \quad (16)$$

where P_j is the rated power of the j-th kind of household appliance (kW), n_j is the number of the j-th kind of household appliances, T_j is the used hours per day of the j-th kind of household appliance (h/day) and $N_{category}$ is the category number of household appliances.

According to [58, 59], lighting, TV, air conditioning, refrigerator, electric cooker, washing machine, water heater, and small power appliances are the most important energy-consuming household devices. In this case, the chosen house is equipped with efficient appliances. The characteristics of this house are:

- Room number: three rooms.

- Lighting: rooms, kitchen, toilet, bathroom, courtyard, and corridor.

- Appliances: refrigerator, TV, water heater, computer, laptop, washing machine, air conditioner, and fan.

The total energy consumption for the chosen house is estimated as 20kWh/day. As mentioned previously, the total annual energy generating from both PV systems is varied from 8564.47kWh to 8776.81kWh and 11511.67kWh to 12100.92kWh for fixed-tilt and two-axis tracking systems, respectively.

Figure 3 shows the energy consumption covered by the proposed PV systems and grid for each month. It is observed that around 13% out of the total energy consumption is covered by the grid and the remaining is supplied by a fixed-tilt PV system, which is about 87% for the winter season. This is due to a heavy electrical load connected in the system like a water heater. For the rest of the year, the PV systems could cover all

the energy consumption. Also, due to the length of the day that depends on sun altitude, the geographical latitude of the location, declination angle of the sun, and hour angle, the amount of energy production from the PV system will be increased.
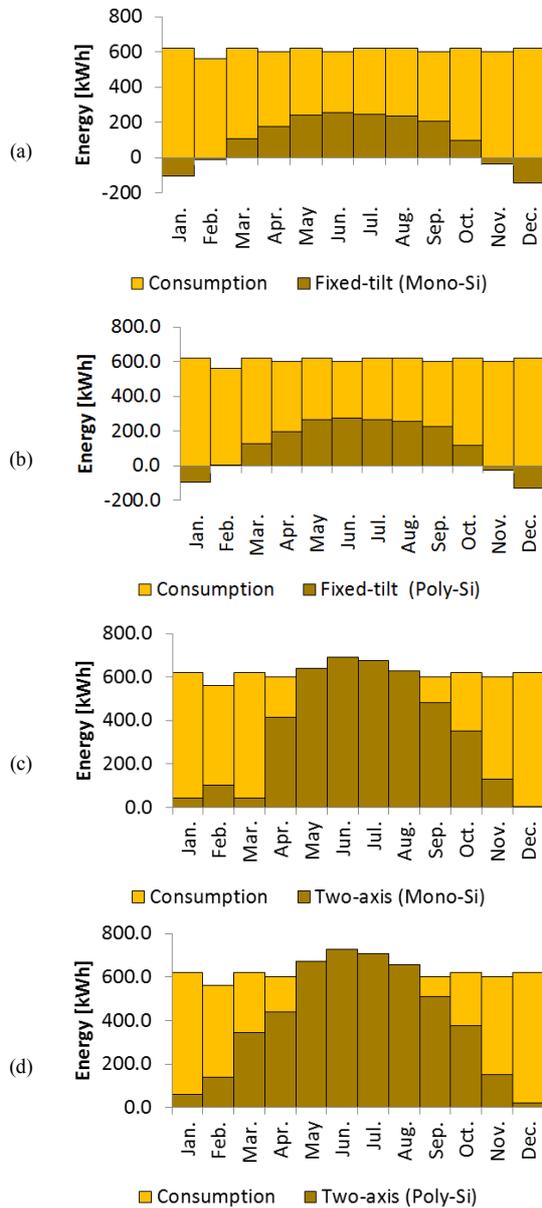

Fig. 3.   Monthly variation of energy generation and energy consumption.

IV.   LIMITATIONS AND CONCLUSIONS

Due to rising electricity tariff rates and the potential reduction of the dependency on domestic power generators in Lebanon, installing PV systems has become increasingly attractive for residential consumers, a trend that is supported by the reviewed studies. Before starting the main conclusions in the present study, it is essential to acknowledge the limitations

of this work. First, the financial parameters were assumed based on historical values in the literature. Second, the influence of various parameters such as dust, irradiation intensity, air temperature, and relative humidity were neglected due to limitations of the RETScreen software. Third, the cost of the proposed projects was estimated based on the existing costs in the literature. The findings from the present study showed that the annual value of solar radiation for the selected region is $2010 kWh/m^2$. Based on annual global solar irradiation, the analysis indicates that the selected region in Lebanon has a potential for the distribution of PV power systems in residential applications. Moreover, the annual energy output showed that the 5kW grid-connected PV system in Nahr El-Bared was within the range of 8564.47-8776.81kWh and 11511.67-12100.92kWh respectively when fixed tilt and two-tracking systems have been used. Based on this analysis, it was found that the highest energy consumption that can be covered by PV systems is recorded in spring and summer seasons.

The average energy production cost ranged in 0.0239-0.0249$/kWh for all the proposed systems. The electricity price depends on the amount of energy consumption, i.e. the energy cost calculation starts from 0.025$/kWh for energy consumption of 0-100kWh, 0.04$/kWh for 100-300kWh, 0.0584$/kWh for 300-400kWh, 0.0875$/kWh for 400-500kWh, and 0.146$/kWh over 500kWh. Therefore, the energy production cost of the proposed systems is competitive with the electricity tariffs. Furthermore, it was found that the difference between the energy production cost from a fixed-tilt system and from a two-axis tracking system is lower than 2%. It can be concluded that a 5kW grid-connected PV tracking system is economically justifiable.

The results of this paper demonstrate that a small-scale grid-connected rooftop PV system in the Nahr El-Bared has the potential to solve the electricity issue in the area, reduce the consumption of fossil fuels and environmental pollution by minimizing the emissions of CO_2. The present study tried to increase the awareness about utilizing PV sun-tracking systems and the feasibility of small-scale grid-connected rooftop PV systems in the studied region. The results of this research can help the investors in the energy and building sectors and accelerate an informed transition towards a more sustainable future.

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