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Economic-Environmental-Energetic (3E) analysis of Photovoltaic Solar Energy Systems: Case Study of Mechanical & Renewable Energy Engineering Departments at Wadi AlShatti University

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ABSTRACT

This research aims to prove the technical, economic and environmental feasibility of a PV solar energy system to cover the basic electrical load in an academic institutional building - the Departments of Mechanical and Renewable Energy Engineering at Wadi Alshatti University, Libya. The present research comes in line with the aspirations of the Libyan state to shift towards renewable and clean energies in compliance with the Paris Climate Change Treaty, and also in line with the university's mission to achieve sustainability and preserve the environment in the local community. The present study discussed the economic, environmental and energy impacts of the PV solar system size by estimating the energy costs (LCOE), the power supply reliability (PSR), the amount of load that can be covered using solar energy, and the extent of the system's success in alleviating the carbon footprint on society by calculating the social cost and the amount of CO2 that was prevented from emission to the atmosphere.

التحليل الاقتصادي- البيئي- الطاقوي لمنظومات الطاقة الشمسية الكهروضوئية: دراسة لقسم الهندسة الميكانيكية والطاقات المتجددة بجامعة وادي الشاطئ

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الكلمات المفتاحية:

ليبيا
منظومة الخلايا الكهروضوئية الشمسية
الجدوى الاقتصادية والبيئية والتقنية
الحمل الكهربائي
مباني المؤسسات التعليمية

الملخص

يهدف هذا البحث لاثبات الجدوى الاقتصادية والبيئية والتقنية لمنظومات الخلايا الفوتوضوئية في تغطية الاحمال الكهربائية لقسم الهندسة الميكانيكية والطاقات المتجددة بجامعة وادي اشاطئ. ويأتي هذا البحث متسقا مع تطلعات الدولة الليبية في التحول نحو الطاقات المتجددة والنظيفة وذلك لتحفيف التزاماتها الدولية تجاه اتفاقية باريس للتغير المناخي، كضلك متسقا م رسالة جامعة وادي الشاطئ لتحقيق الاستدامة والحفاظ لى البئة المحلية. عرضت الدراسة الحالية تأثير حجم المنظومة الشمسية على الاداء الاقتصادي والبيئي والطاقوي للمنظومة وذلك عن طريق حساب عدة مؤشرات اقتصادية وبيئية مثل، تكلفة انتاج وحدة الطاقة (LCOE)، واعتمادية مصدر الطاقة (PSR)، والحمل الكهربائي الذي يمكن تطيته بالطاقة الشمسية، ونجاعة المنظومة الشمسية في تلطيف البصمة الكربونية وذلك عن طريق حساب الضرر البيئي الناجم من انبعاث CO2 والذي منع من الانبعاث في الهواء الجوي.

Introduction

Driven by concerns about climate change and global warming, the global installed capacity of solar PV has grown continuously since 2000. In 2023, the global installed capacity of solar photovoltaic energy will reach 1,177 GW. This growth in the solar photovoltaic market reflects a global shift towards renewable and sustainable energy technologies. China and the United States lead the global PV market, with 307 and 122 GW of installed solar PV capacity, respectively. On the other hand, Chile and Honduras had the highest share of photovoltaic energy mix in total energy produced in 2023 [1].

Solar energy is one of the cleanest and most abundant renewable energy sources in the world, and plays a vital role in achieving environmental and economic sustainability. Libya is located in the "solar belt" of North Africa, with a population of 6.735 million in 2021 and a land area of 1.8 million square kilometers. It receives approximately 3500 hours of sunlight annually and around 2300 kWh/m² of annual global horizontal solar radiation (Fig. 1) [2]. This work aims to design and estimate the cost of a PV solar energy system for an administrative building for the Mechanical and Renewable Energy Engineering Department, at Wadi Alshatti University, with an emphasis on the

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potential economic and environmental benefits. The current study is consistent with the Libyan government's trends in shifting towards generating electrical energy from renewable and environmentally friendly energies, and it aspires for the contribution of renewable energies to reach 10% by the year 2025 and more than half of the total energy production by 2050 [3]. PV solar system design process requires a careful assessment of the building's energy needs, as well as a study of environmental and climatic factors that affect the system's efficiency. The costs associated with installing and maintaining the system must also be estimated to ensure the project is economically feasible. Studies indicate that the use of solar energy can reduce the energy shortage and mitigate carbon footprint [3]. Researches indicated that designing an effective solar energy system requires taking into account several factors, including selecting appropriate solar panels [4], determining the optimum tilt and orientation panels' angles [5], allocating ideal location for their installation faraway from any sources of shadows [6], and estimating initial and operational expenditures [7].

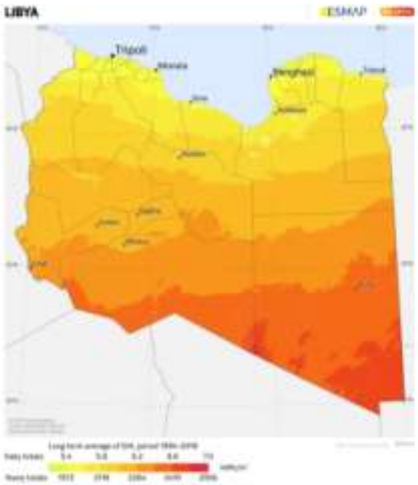


Fig.1: Annual average global horizontal irradiation in Libya
[Source: https://solargis.com/maps-and-gis-data/download/Libya]

Numerous studies have examined the design and cost estimation of solar energy systems, particularly in the context of administrative buildings. These investigations aim to provide a comprehensive understanding of the factors that influence the design and financial assessment of solar energy systems, thereby facilitating informed decision-making regarding project implementation. The following is a review of significant prior research in this domain.

Nassar and others revealed the potential of rooftop solar cells to cover the energy demand in Gaza Stripe-Palestine. They concluded that it is possible to build PV solar fields installed on the roofs of government, residential, educational and mosque buildings with a capacity of 555 MW, which are capable of generating 923,742 MWh at a levelized cost ranges 0.07-0.11 $/kWh. The propsed project requires an investment of 800 million $US and will be backed within 3.2 years [9].

In Sydney, Australia, a large scale one axis tracking photovoltaic system has been designed to cover 42% of the electricity load of Macquarie University. With the currently available 71,000 square meters of usable space, it is able to generate about 12,850,000 kWh /year. The project would cost upward of $70,000,000 and produce electricity at a cost of approximately $0.26 per kWh. with a 16 year payback period [10].

In Assuit, Egypt, a study carried by Awad et al., conducted optimum design and economic feasibility of rooftop PV solar energy system for Assuit University. The objective of the optimization is determining the lowest cost to fulfill the load (34 MW) requirement entirely. The project needs 228,287 m^2 of Mono-Crystalline PV solar modules with an efficiency of 17.2%, and 32 inverters. The proposed project would cost M$29.28 and produce electricity at a cost of $0.583 per kWh [11].

In his exploration of solar energy utilization in Libya [9], Maka et al., underscored the necessity of analyzing the current landscape and the challenges associated with the implementation of solar energy projects. The findings indicated substantial potential for the adoption of solar energy in administrative buildings, highlighting the importance of tailoring system designs to meet the specific energy requirements of these structures. Furthermore, the results demonstrated that solar energy can be economically viable for both public and private institutions, particularly when systems are designed with efficacy in mind. This assertion is further supported by an economic feasibility study of solar energy projects in Libya, which emphasizes the estimation of installation and maintenance costs, alongside an analysis of potential returns on investment [10].

Several studies presented the impact of the climatic conditions on PV solar system efficiency [7], [11], [12]. Moreover, some studies have focused on the application of innovative technologies in the design of solar systems, such as the utilization of advanced software for modeling energy performance. These methodologies were implemented in an office building located in a hot climate, resulting in notable improvements in system efficiency and reductions in costs [12]. The influence of government policies on the development of solar energy projects in Libya has also been explored in other studies, which analyze how governmental support and legislation impact project costs, thereby offering valuable insights for designers and investors [14].

Key climatic data of the site

The study site is located on the campus of the College of Engineering at Wadi Shatti University in Brack, Libya (27° 32' N, 14° 17' E). An aerial photograph of the study location is provided in Figure 2. This site was carefully selected to ensure compatibility with the prevailing terrain and climatic conditions, thereby facilitating the investigation of various available resources for the generation of 100% clean and sustainable energy, in accordance with the study's hypothesis. The site is situated near a mountain, at an elevation of approximately 450 meters above sea level [7].

Methodology

The study will be executed through the following steps:

Data Collection: Data is considered as the first step of any study. The required data for the present analysis including: meteorological data (solar irradiance, air temperature), energetic data (electrical load requirements), economic data (costs of the project), technical data (dimensions of the building's roof, electrical characteristics of the PV solar panels) and environmental data (CO_2 emission factor, footprint).

Data analysis: This phase involves the analysis of the building's energy consumption data, preparation of detailed schedules to estimate the total technical requirements and identification of an optimal size and location for the installation of solar panels.

Results presentation: In this part, the key findings of the research will be presented in their academic form using graphical representation tools in the form of graphs, Figures, and Tables.

According to local researches, the suitable PV module type is Stion SN-115 (thin film technology) and the ideal inverter is AEG Power Solutions: Protect MPV. 150.01 480V (CEC2013). Table 1 illustrated the technical, economic and environmental characteristics of the Stion SN-115 PV module.

Table 1: Economic, environmental [18] and electrical characteristics of **PV solar module type Stion SN-115**

η; %	P_{max}; W	V_{mp}; Volt	I_{mp}; Amp	Bp; %/°C	Bv; Volt/°C	βI; Amp/°C	Capital Cost; $/kW	O&M cost, $/kW/year	Lifespan; year	CO_2 LCA; $kgCO_2/kWh$
11.40	125	41.0	3.0	-0.004	-0.360	0.007	870	21	30	0.052

[Source: https://www.principalsolarinstitute.org/psi_ratings_query_stion/]

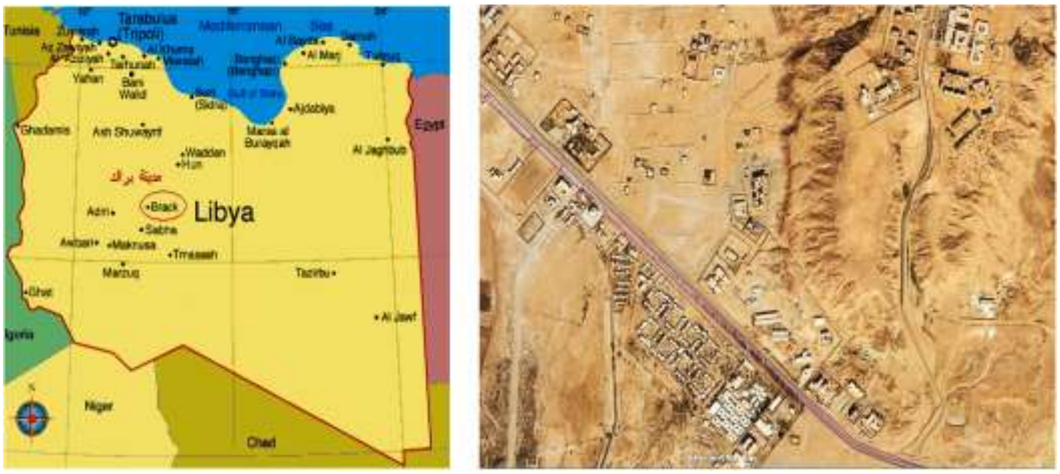


Fig.2: The Libyan map and aerial view of the targeted community [7].

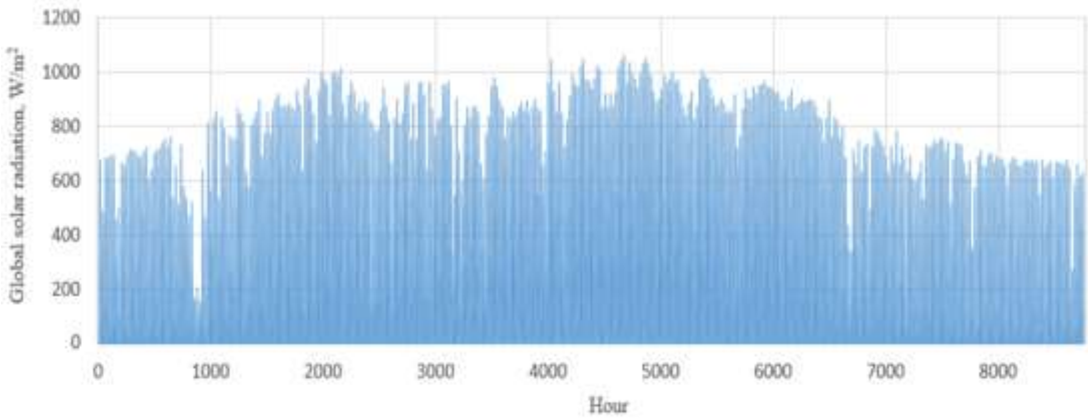


Fig.3: Hourly global horizontal solar irradiation (GHI)

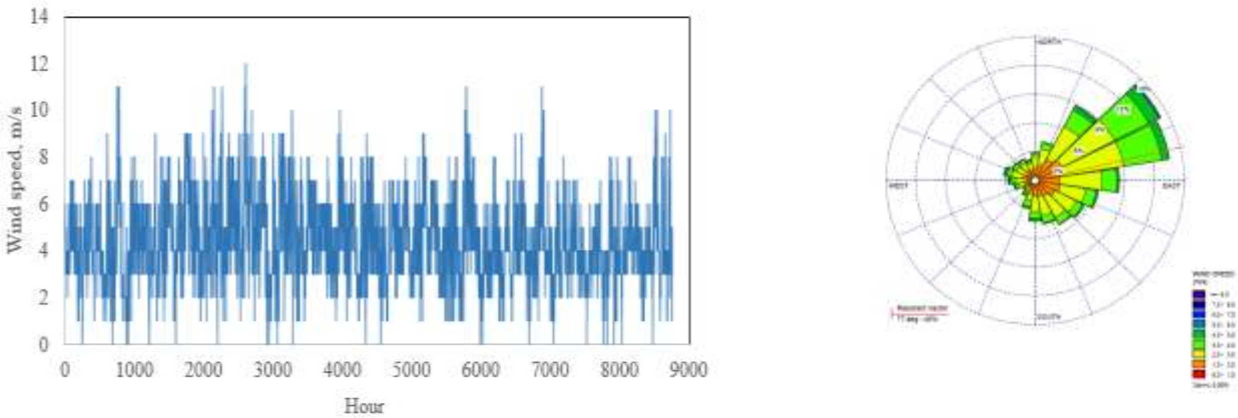


Fig.4: Hourly wind speed and wind-rose

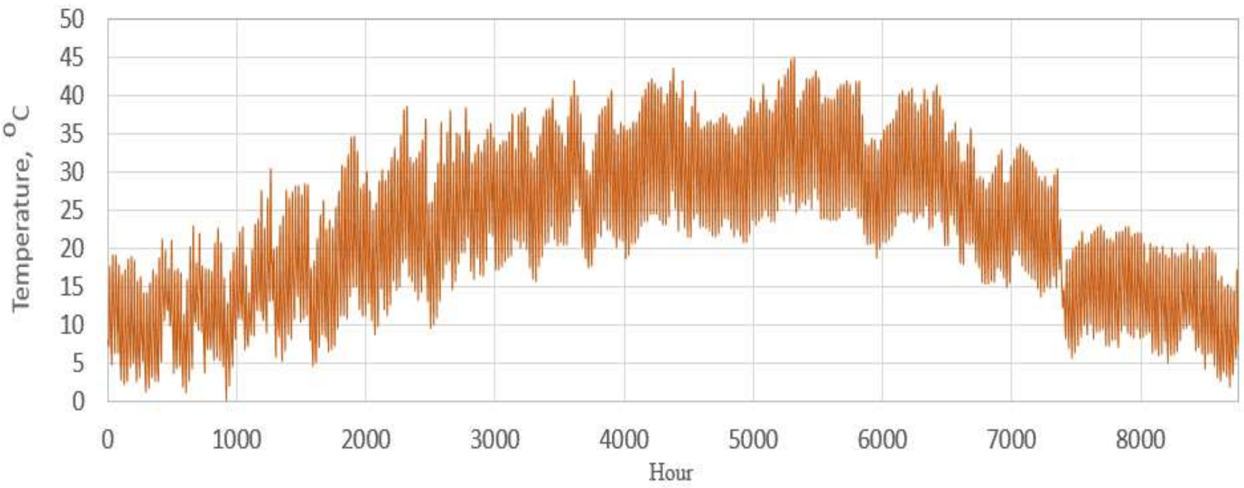


Fig.5: Hourly ambient air temperature

Hypotheses, limitations and uncertainties of the results

The following hypotheses are adopted in the current work:

1. No losses due to connections and links.
2. The optimum tilt angles of the PV solar modules were estimated according to [18].
3. Isotropic sky diffuse and ground reflected transposition model has been used for estimating the global inclined solar irradiation [19], [20].
4. The total losses due to soil, shadow etc, 12% [15].
5. Constant inverter efficiency (0.95) [22].

The key limitation of the proposed approach is that it does not provide sensitivity analysis related to the impact of various weather parameters on the behavior of a PV solar module and inverter. The major sources of uncertainty are the data availability, model selection and the price of the facilities. Nassar and Alsadi reported a variation in the price of PV modules that exceeded 360% [20].

Energy modelling of PV solar system

The real power (P_{PV}) of the PV panel under real operation and climatic conditions is [23]

$$P_{PV} = P_{STC}\left[1 + \beta_p(T_{cell} - T_{STC})\right]\frac{H_t}{H_{STC}} \quad (1)$$

Where: T_{STC} and T_{cell} are the celll's surface temperature at Standard Test Condition, β_p is the power temperature coefficient. The challenge that researchers will face is to find an empirical equation to determine the cell surface temperature T_{cell} [24].

$$T_{cell} = T_{\infty} + 7.8 \times 10^{-2} H_t \quad (2)$$

The proposed PV solar system has to be secure and sustain energy supply independently. As, the solar energy is the only source for fulfilling the load requirement of the site under concern. Therefore, the objective function (14) is subjected to the power supply reliability (PSR) operational constraint [26].

$$PSR = \frac{\sum_{t=1}^{8760}[E_{Load}(t) - P_{PV}(t)]}{\sum_{t=1}^{8760} E_{Load}(t)} \leq \varepsilon_L \quad (3)$$

Where: $E_{Load}(t)$, $P_{PV}(t)$ are instantaneous load and PV powers respectively. t is the optimization time span and equals 8760 hours. PSL has a value that varies from 0 to 1.0. 0.0 indicates full fulfilment of the load, while PSL equals to one indicating sizing deficiency.

Economic and environmental analysis

The cost of energy (LCOE) and the payback time money (PBTM) are estimated with considering the cost of environmental damage (C_{CO2}) as [26]:

$$LCOE = \frac{\left(\frac{r(1+r)^n}{(1+r)^n - 1}\right) \times C_{PV} + C_{O\&M} - C_{CO2}}{E_{PV}} \quad (4)$$

$$PBTM = \frac{C_{PV}}{I_{PV}} \quad (5)$$

Where: C_{PV} the capital cost of the system in \$, $C_{O\&M}$ denotes the cost of operation and maintenance (\$/year), E_{PV} is annual energy produced by the system (kWh/year), n is the device lifetime (30 years), r the annual inflation rate, I_{PV} is the income from the PV system.

The cost of environmental damage (C_{CO2}) caused by CO_2 gas can be calculated by the following equation [27].

$$C_{CO2} = EF_{CO2} \times E_t \times \emptyset_{CO2} \quad (6)$$

where: EF_{CO2} represents the CO_2 emission factor of the electric power generation system (1.037 kg CO_2/kWh) [28], [29] $\emptyset_{CO2}$ represents the carbon social cost (\$/ton CO_2), which may be considered as \$ 70/ton CO_2 [30].

System load calculation

We count the AC loads, capacity and number of weekly operating hours in order to obtain the weekly consumption for each device as shown in Table (2). We add all the watt-hours for each week to determine the total weekly consumption (E) [31].

1. By multiplying the total weekly consumption by 1.15 in order to compensate for the losses in inverter, we obtain the real consumption per week
2. AC to DC frequency converter voltage: usually 12 or 24V. This will be the DC system voltage.
3. We obtain the ampere-hours per week by dividing the actual consumption per week by the system voltage.
4. The total daily ampere-hour rate is calculated by dividing the ampere-hour for each week by 7 days.
5. The daily load, taking into account the losses in the process of charging and discharging the batteries, is calculated by multiplying the total daily ampere-hour
6. By dividing the daily load considering losses by the number of hours of solar shine in the area (n), we obtain

the total ampere-hour required from the solar cells.
7. The optimal amperage and voltage for solar panels are derived from the specifications provided in the solar panel characteristics, as detailed in Table 1.
8. Corrections for temperature and solar radiation intensity are applied to the power, as represented in Equation 1.
9. The number of solar panels is calculated by dividing the total power requirement from the PVs by the nominal power of one panel.

Results and discussion

Table 3 tabulated the devices, rated power and the operating hour.

Figure 6 illustrated the estimated hourly electrical load characteristic of the Mechanical and Renewable Energy Engineering Department during the year of 2023. The department's load curve is characterized by three regions. The zero-load region is the vacation period, which extends throughout the entire month of August. The low load period includes the winter and spring seasons (5 months) and extends from the beginning of November to the end of March, in where the hourly load is about 6.8 kWh. While the maximum load period (23.3 KWh) extends throughout the summer and fall seasons (6 months).

Figure 7 depicted the PV solar productivity of 1kW power under the real climatic conditions.

The Power supply reliability is roughly defined as the number of power outage hours over a period of time hours, (in our case 8760 hours). Figure 8 illustrated the relationship between the PSR and the PV solar field capacity.

Table 3: Inventory of electrical devises and instrumentations and average monthly operating hours in the Mechanical and Renewable Energy Department

No	A/C	Lambs	Comp.	Fridge	Kettle
Quantity	20	100	20	1	1
Power; W	825	20	200	75	800
Average hourly operating regime					
January	0	8	8	12	1
February	0	8	8	12	1
March	0	8	8	12	1
April	8	8	8	24	1
May	8	8	8	24	1
June	8	8	8	24	1
July	8	8	8	24	1
August	0	0	0	0	0
September	8	8	8	24	1
October	8	8	8	24	1
November	0	8	8	12	1
December	0	8	8	12	1

Table 2: Approach to calculate the electrical load requirements

Description of pregnancy	Device capacity	×	Number of weekly operating hours	=	Weekly consumption
			Total weekly consumption of alternating loads		

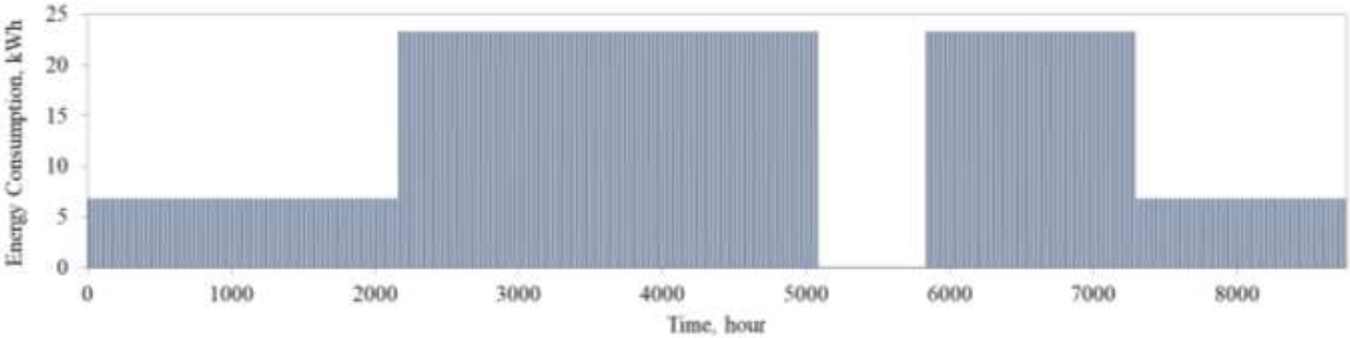


Fig. 6: Hourly electrical load of the Mechanical and Renewable Energy Engineering Department

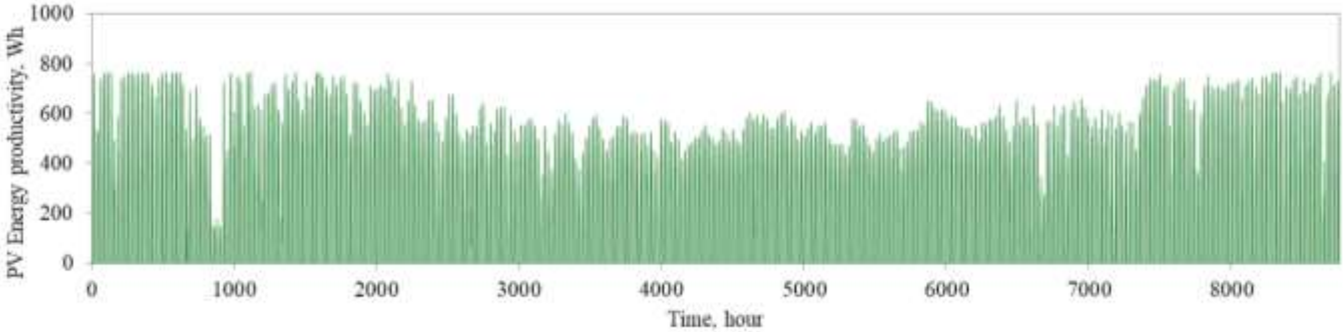


Fig. 7: Productivity of 1kW PV solar field capacity

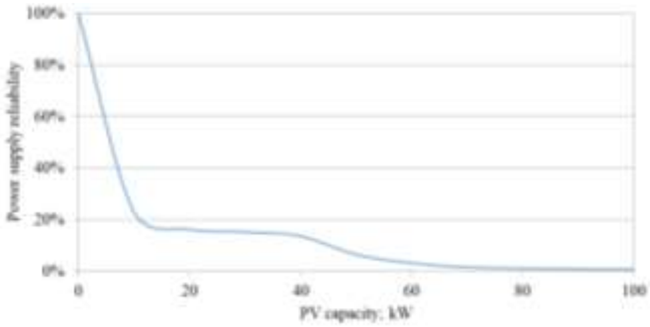


Fig. 8: The PSR as a relation to the PV capacity

It is clear from Figure 8 that the value of zero is not reachable and the very low value of PSR is significantly costly the system. PSR of 1% means that the load disruption is around 87.6 hours over a whole year. The acceptable value for the system under consideration is determined by economic optimization.

Figure 9 illustrated the impact of the PV solar field capacity on the annual load covered and the corresponding percentage of the load covering by the PV solar system.

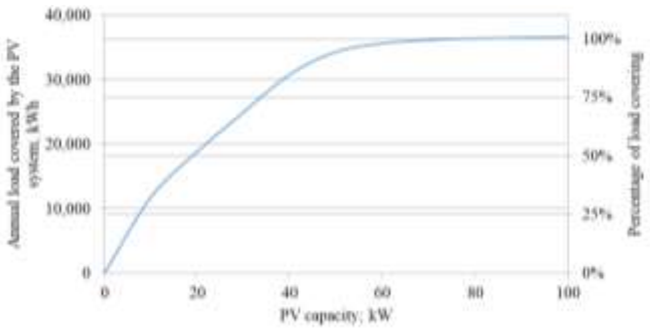


Fig. 9: The relationship between the annual load covered by the PV solar system and the PV solar system capacity

It is obvious from the Figure 9 that the effect of the size of the solar system has a large impact when the size of the system is less than 50 kW, and the effect gradually decreases after 60 kW until it almost disappears at 80 kW, and it never reaches 100%, no matter how large the solar system increases. The reason for this may be due to the presence of clouds on a specific day, and therefore there will be no solar energy on that day, and thus we will never reach the load coverage for that hour, no matter how large the system is. This represents one of the disadvantages of solar systems isolated from the grid and without an energy storage system.

Figure 10 represented a comparative economic analysis of LCOE with different approaches. The LCOE calculated by three different concepts: without considering the social cost of the CO_2 (SC), with including the CO_2 social cost, and the last involving the CO_2 life cycle assessment of the PV system (52 ton CO_2/kWh) in additional to the CO_2 social cost. As it appears from the figure, the environmental impact in the economic analysis reduces the LCOE, which gives a fair opportunity for clean energies to compete in the energy market.

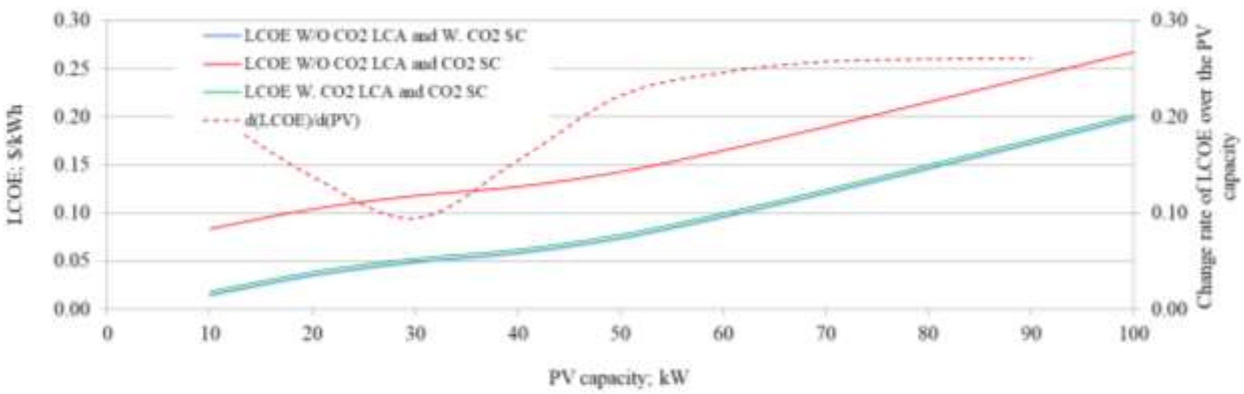
As it is clear from Figure 10, there is no explicit optimum point for the given objective function, however, if considering the weight of the PV system size on the LCOE by including the changing rate of the LCOE with the PV solar system size, the optimum point is obviously appears at 30 kW, which represents the maximum impact of the PV solar field size on the LCOE. However, this will not solved the problem and another constraint should be involved, we suggest that, the amount of investment allocated to this project could have the final decision in this issue.

Due to the system's operating schedule, it is possible to get economic benefits by buying the surplus production of the solar system to the public electricity grid, thus achieving an additional profit from it and also helping to reduce the deficit and increase the robust of the electricity system in the country. Figure 11 demonstrates the relation between the PV solar capacity and the surplus electrical energy that can be exported to the grid.

Figure 12 embodies the relation between the environment and the economy aspects. The real social cost of CO2 resulted from electricity generation using fossil fuel in additional to the CO_2 quantity that emitted due to manufacturing PV solar energy system equipment and devices. Figure 12 demonstrates the real annual savings of CO_2 emissions due to energy production of PV solar system and the energy required to produce the PV solar system equiepments and devices and the social cost related to the PV solar energy size.

Conclusions

Previous research underscores the significance of designing and estimating the costs associated with solar energy systems for the engineering department building at Wadi Al-Shatti University. These systems are pivotal in enhancing energy efficiency and reducing operational expenditures. The findings reveal substantial potential for the implementation of solar energy systems in Libya, which could significantly bolster the adoption of renewable energy in the future.



Fig, 10: A comparison of LCOE with different approaches and the change rate of the LCOE with respect to the PV system size.

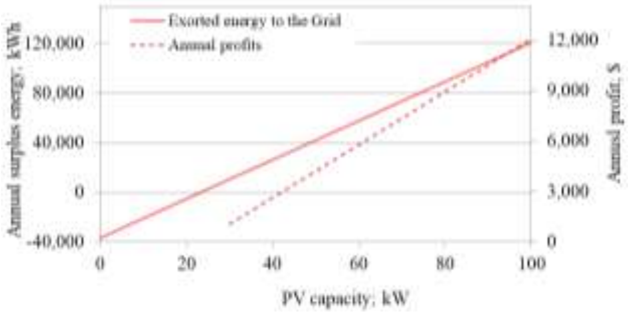


Fig. 11: The annual energy injected to the grid and the associated profits related to the PV solar system size

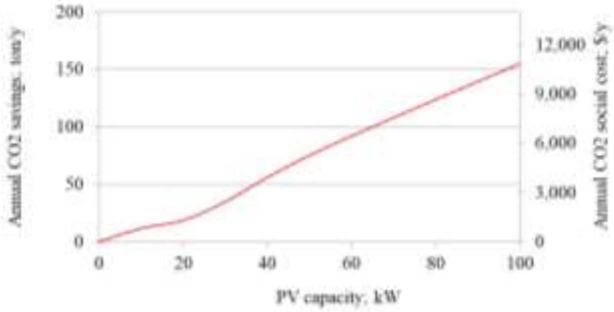


Fig. 12: The annual savings of CO2 emissions and Social cost related to the PV solar energy size

Given the current challenges posed by the deterioration of the public electricity infrastructure and the prevailing political instability in Libya, we conclude that solar energy systems present a viable solution to the issue of power outages. However, the high initial costs associated with these systems pose a significant barrier to widespread adoption, particularly among low-income populations. Furthermore, the considerable load requirements necessitate a large number of solar panels, which in turn demand extensive areas for installation.

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