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Techno-economic feasibility analysis of Benban solar Park

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Abstract By 2035, Egypt pursues to generate 22% of the total electricity from photovoltaic power plants to meet the national spreading demand for electricity. The Egyptian government has implemented feed-in tariffs (FiT) support program to provide the economic incentives to invest in the PV power plants. The present study is carried out to evaluate the techno-economic feasibility of a large-scale grid-connected photovoltaic (LS GCPV) of the Benban Solar Park with a total capacity of 1600 MW AC producing annual electricity of 3.8 TWh. The characteristics of PV panels considering the meteorological data of Benban Solar Park are evaluated. Additionally, the reduction of greenhouse gas (GHG) emissions due to constructing Benban Solar Park is assessed. As well, the influences of annual operation and maintenance cost and the interest rate on the electricity cost and the payback period are evaluated. The results indicate that the electricity cost is about 8.1 US¿/kWh with 10.1 years payback period, which is indeed economically feasible with an interest rate of 12%. Furthermore, the Benban Solar Park will avoid annually almost 1.2 million tons of greenhouse gas. Finally, based on the techno-economic analysis, the improvement directions for the feasibility analysis based on agrivoltaic systems are proposed.

1. Introduction

Rapidly growing of the global population and improving people's level of life must be faced with increasing the power generation. However, utilizing fossil fuels in power generation has adverse impacts on the environment leading to drastic weather changes such as the depletion of the ozone layer and global warming, causing ice melting at both south and north poles [1]. Additionally, using a water cooling system in thermal power plants results in critical environmental thermal pollution. On the other hand, another area of major interest is well utilization of renewable energy resources. Sustainable clean energy resources such as hydro, wind, or solar photovoltaic have no unsatisfactory effect on the environment compared with non-renewable resources, hence reducing the CO_2 emissions [2–4]. Particularly, the photovoltaic power plant is

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Nomenclature

i	interest rate
n	project lifetime
G	solar irradiance (W/m^2)
P	present capital cost
P	power (W)
V	voltage (V)
S	salvage value
T	temperature (°C)

Subscript

m	maximum
s	surface

Acronyms

AC	alternative current
AOMC	annual operation and maintenance cost
ASV	annual salvage value
BOO	build-own-operate
CPM	cost per Megawatt hour
CRF	capital recovery factor
DC	direct current
FAC	fixed annual cost
FiT	feed-in tariffs
GCPV	grid-connected photovoltaic
GHG	greenhouse gas
IEA	International Energy Agency
MENA	Middle East and North Africa
MERE	Ministry of Electricity and Renewable Energy
PV	photovoltaic
SFF	sinking fund factor

designed with diverse techniques and improvements to convert solar energy into electricity [5–7]. Recently, optimizing the utilizing of renewable energy measures to fulfill the owner-specified reduction in energy consumption with minimizing the desired upgrade costs is a crucial issue [8].

Several studies were achieved to study the economic feasibility of the grid-connected photovoltaic (GCPV) systems, which introduce the guiding solution to the investors to invest in this area of energy. The environmental, technical as well as economic impacts are important to evaluate the cost-efficient methodology of the GCPV power plant that is appropriate to each country for distinctive operating and geographic conditions [9]. The essential costs attendant with the GCPV power plant are the capital costs of individual components such as PV modules, structures, DC and AC cables, inverters, in addition to the operation and maintenance costs (OMC) [10]. The associated benefits with this type of power plant are the export of electrical energy to the national grid electricity as well as its simplicity and comparatively low OMC. The optimal values of the tilt and azimuth angles of photovoltaic panels to maintain the maximum system performance as well as to minimize the cost of electricity were studied by Akdemir et al. [11].

Buonomano et al. [12] achieved a thermo-economic analysis of a trigeneration system using the solar energy for cooling, heating, and electrical energies requirements in Naples, Italy. The results indicated that the payback period was around 12 years without any national funding. Agyekum [13] conducted a techno-economic study of a solar PV with a 20 MW capacity for different power plants *i.e.* PV-only and PV with battery using the System Advisor Model (SAM). The results revealed that PV-only and PV with battery systems integrated by a fixed-axis tracking technology (FT) produced the same annual energy of 31 GWh. Al-saqlawi et al. [14] presented a mathematical model describing the techno-economic characteristics for four systems *i.e.*, solar panel DC, grid-connected sub-system, economic sub-system, and grid-independent sub-system. The implementation was achieved over 20 years. The results indicated that the GCPV system was not feasible compared with other systems while for high price of electricity, the grid-independent systems with a low battery cost were economically feasible.

Kazem et al. [15] investigated numerically the techno-economic feasibility of 1 MW GCPV. The system cost is economically feasible for an annual system yield factor of 1875.1 kW h/kW p with a capacity factor of 21.7%. Al-Badi et al. [16] analyzed the solar radiation, electrical energy production, and its cost for a 5 MW GCPV power plant for different locations around Oman. The results demonstrated that the electricity cost was varied from 210 to 304 US$/MWh depending on the location. Oloya et al. [17] analyzed the techno-economic implementation of a solar PV plant with a capacity of 10 MW located in Soroti, Uganda. Based on the feed-in tariff (FiT) mechanism, the evaluated payback period, internal rate of return, and profitability index were 9.28 years, 10.55%, and 1.51, respectively showing that it was economically viable. As well, the 0.1087 US$/kWh cost of energy was in the range for analogous projects.

Ameur et al. [18] assessed the performance of various PV types such as polycrystalline, monocrystalline, and amorphous silicon (Si) systems. The results revealed that the polycrystalline-Si technology had superior performance compared with those for amorphous-Si and monocrystalline-Si technologies. In addition, the economic analysis indicated that the polycrystalline-Si had the most effective cost with 0.10 USD/kWh levelized cost of energy (LCOE). A two-stage stochastic model to optimize the design and operation of residential PV systems was employed by Zheng et al. [19]. The influences of essential factors such as FiT, profiles and levels of tariff, and unit costs, were evaluated to supply stakeholders with key findings.

Celik [20] designed a 300 kW GCPV power system and assessed its techno-economic feasibility in Ankara, Turkey. The results indicated that the cost of electricity with battery storage systems was 3–4 times greater than that of the GCPV; moreover, it was reduced by lowering the taxes and increasing government subsidies. Zubair et al. [21] estimated the photovoltaic (PV) capabilities in an urban environment based on the optimization of the PV placement distance and the cooling load of buildings provided by PV modules. The results showed that the net present value (NPV) of the system for a small cooling load was 41,250 USD with the real and nominal values of LCOE of 2.99 and 4.31 cents USD/kWh, respectively. In addition, the real value of the LCOE of the project was 80% lower than the cost of energy from the national grid. Furthermore, the capital cost and the payback period of the project with an installed capacity of 14.7 kW were 17,916 USD and 4.1 years, respectively.

Castillo-Calzadilla et al. [22] studied the advantages and disadvantages, technical parameters, quality of electrical supply, reliability, and economic and environmental issues of three DC microgrids to the service building. The results showed that for the best case, the accuracy of the measurements and the average voltage applied to the load were about 99.45%, and 24.54 V, respectively. In addition, the developed systems showed a potential of greenhouse gas (GHG) recovery of almost 35.05 tCO_2/year, with 7 years and 3 years return investment for the renewable-based microgrid and traditional microgrid, respectively. Laajimi and Go [23] studied the techno-economic performance of a LS GCPV with a capacity of 30 MW employing an energy storage system. Conducting the economic analysis for two states, Perak and Pahang showed the same costs for the same project scales and the large-scale system with energy storage was profitable. Edoo and King [24] assessed the economics of a solar PV power plant with battery (PVB) using a System Advisor Model (SAM). The influences of inverter loading ratio (ILR), battery size, and tracking type on LCOE were implemented. The results revealed that the tracking increased the clipping losses and its benefits on reducing the LCOE decreased as the ILR increased. As well, the sensitivity analyses indicated that the battery costs had a significant influence on the LCOE.

Edalati et al. [25] studied experimentally and theoretically the performance of major parts of a 10 MW GCPV system. The technical and economic feasibility of the PV power plant and the profit expectations for different cities were investigated. The results showed that the LCOE was equal 19.92 and 38.38 US¢kWh in the southeastern and northern parts, respectively. Further, the high selling electricity prices achieved the lowest value of LCOE. Khalid and Junaidi [26] evaluated the feasibility of 10 MW PV power plant for eight locations in Pakistan. The results demonstrated that the examined plant reduced the yearly production of carbon dioxide (CO_2) by 17,938 tons. Moreover, using one-axis tracking system generated the cheapest electricity at Quetta. While, the high initial cost led to the infeasibility of the system even for high solar irradiance regions. Finally, the summary of previous economic studies of solar PV power systems including the location, capacity, electricity cost, and payback period is presented in Table 1.

It is noticed from the above discussion that there is a lack of economic studies for large-scale grid-connected photovoltaic (LS GCPV). Therefore, the aim of the current study is to assess the economic feasibility of LS GCPV for Benban Solar Park with a 1600 MW power capacity, subdivided into 32 subsystems. This paper utilizes the real collected field data taking into consideration the national economic situation of power generation and its strategies to study the technical-economic feasibility of a LS GCPV of the Benban Solar Park in Aswan, Egypt. In the present study, the influences of the interest rate on the cost of electricity production and the payback period are evaluated. In addition, reducing the GHG emissions due to the construction of the Benban Solar Park compared with that of the fossil fuel power plant are assessed. Finally, a technical assessment that evaluates the characteristics of PV panels considering the meteorological data of Benban Solar Park is introduced to propose the available improvement of the system's economic feasibility based on the agrivoltaic system.

2. Current situation of energy sector in Egypt

Up-to-date, the electric power generation in Egypt depends essentially on non-renewable energy resources, particularly oil and natural gas, which contribute by about 95% of the total energy demand. The period next to 2011, the Arab Republic of Egypt faced a critical economical restriction due to the shortage of fuel supply to the thermal power plants. The developments in Egypt of the power plants infrastructure are approached such as constructing three combined power plants with 14,400 MW total capacity. The Arab Republic of Egypt has limited reserves from non-renewable sources due to the growing demand and the high extraction cost. Therefore, Egypt confronts difficulty in covering its electricity demands from these resources. The balance between the petroleum production and the energy consumption can be achieved when the economic difficulties facing the oil and gas sector are managed. So, a renewable resource such as solar energy is the best possible solution for the sustainable energy supply. Additionally, the solar photovoltaic power generation system, among technologies of renewable energy, is one of the potential choices to fulfill the growing nation's electricity demand. Solar energy that is a clean resource of energy has magnificent potential principally in high solar irradiation regions like Egypt.

3. Economic support mechanisms in Egypt

There is a set of mechanisms for establishing renewable energy projects in Egypt for demand and production, as shown in Fig. 1, including the following:

- Commercial projects: the establishment of plants to produce electricity from the solar PV power systems with supplying the electricity directly to the consumers.
- Competitive tenders: Egyptian Electricity Transmission Company will put the projects in the public tenders between the qualified investors in the system of building, ownership and operation or build-own-operate (BOO) and sign a contract to purchase the electricity produced for 20 years.
- Net metering: the solar PV projects are implemented by the private sector to feed its loads connected to the national grid electricity with a capacity of 20 MW, with a comparison between the electricity consumed from the national grid and electricity produced from PV power plant.
- A feed-in tariffs (FiT): a mechanism to encourage electricity production from solar PV power systems. In this system, the electricity companies buy the electricity from their producers at a pre-announced price that achieves an attractive return on investment through a long-term energy purchase agreement for the project lifetime [19,29,30]. These agree-

Table 1 Summary of previous economic studies of various solar photovoltaic power systems.

Ref.	Year	Study	Location	System	Capacity	Lifetime (years)	payback period (years)	Tracker system	Cost of electricity (US$/kWh)	Main findings
[12]	2014	Thermo-economic	Naples, Italy	Dependes on the operation	800 kW	One-year study	15	N.A	Variable	• The economic system performance was enhanced by increasing the solar radiation capacity.The system performance was low in winter and high in summer.The capital cost of the system is nearly 3.6 M$, maintaining 14 years of simple pay back.
[13]	2021	Thermo-economic	Three locations of Wa, Sunyani, and Nsawam in Ghana	PV-only and PV-battery	20 MW	25	N.A	single-axis and double-axis	0.067 – 0.076	• The systems maintained a capacity factor between 16% and 18%.All locations achieved negative NPV.The sensitivity analysis indicated that using a tracking system, had a considerable influence on techno-economic system performance.
[14]	2018	Techno-economic	Muscat, Oman	Solar panel, grid-independent, grid-connected, economic system	N.A	20	10	Employed	N.A	• The grid-independent system was economics for high battery cost and low electricity prices.Operating PV with maximum efficiency had a little effect on the system cost.Increasing the size of the grid-independent system made it infeasible.
[15]	2017	Techno-economic	Adam, Oman	Grid-connected	1 MW	25	10	Employed	0.2258	• The optimum inverter size was 800 kW.The system was feasible for the operating conditions of the examined city.
[16]	2011	Economic	25 locations in Oman	Grid-connected	5 MW	25	N.A	Constant tilt angle	0.21 – 0.304	• The capacity factor of the solar plant varied between 20% and 14%.The plant at the best location was competitive to the diesel plant.
[17]	2021	Techno-economic	Soroti City, Uganda	grid-connected	10 MW	20	9.28	Fixed tilt angle of 10°	0.1087	• The estimated payback period, profitability index, and internal rate of return indicated the economic viability.The capacity factor of the installation was 19.07%.
[20]	2006	Techno-economic	Ankara, Turkey	Grid-connected	300 kW	25	N.A	Constant tilt angle of 40°	0.44	• The battery cost increased the cost of PV system considerably.
[23]	2021	Techno-economic	Pahang and Perak, Malaysia.	Grid-connected	30 MW	25	5.42	N.A	0.057	• The project had the cheapest electricity with US$/kWh while increasing the energy storage output resulted in the increase of LCOE over 0.11 US$/kWh.
[24]	2021	Techno-economic	Solitude, Mauritius	Grid-connected	15 MW	20	N.A	Fixed and one axis	0.188	• The availability of the solar PV power plant with battery to overcome the evening peak was high.
[25]	2016	Techno-economic	Iran	Grid-connected	10 MW	20	Dependent on annual inflation rate	Employed	0.199 – 0.384	• Discount rate in Iran was 20%/year, causing LCOE for GCPV plants was greater than the average electricity price.
[26]	2013	Economic	Quetta - Pakistan	Grid-connected	10 MW	30	18.5	One axis tracking system	0.157	• The price of PV modules and electric power tariff in Pakistan had a considerable effect of the feasibility of the plant.
[27]	2012	Techno-economic	Three locations in Oman	Grid- independent	Variable according to the location	20	6	N.A	0.327	• Increasing the PV temperature decreased the efficiency, which increased the plant cost.
[28]	2021	Techno-economic	Andhra Pradesh, India	Grid-connected	50 MW	N.A	4.16 – 4.58	Fixed tilt angle of 10°	0.0536	• The payback period was increased due to the curtailment from 4.16 years to 4.58 years.

N.A: not applicable or value not directly available; **Ref.**: references number.

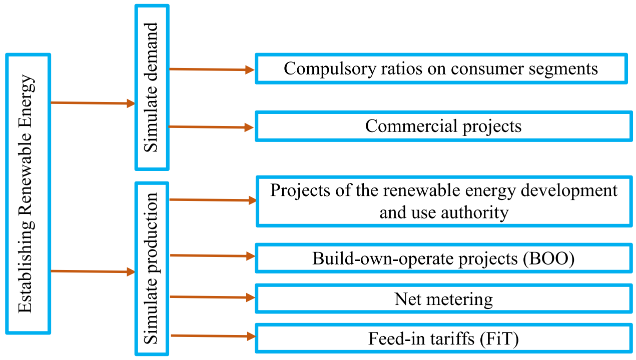

Fig. 1 Mechanisms for promoting the renewable energy in Egypt.

Table 2 The FiT prices for solar PV power systems in Egypt [32].

PV system capacity	FiT price
Household	0.848 LE/kWh
Smaller than 200 kW	0.901 LE/kWh
200–500 kW	0.973 LE/kWh
500–20 MW	0.136 US$/kWh
20–50 MW	0.1434 US$/kWh

LE: Local currency (Egyptian Pound).

ments are varied according to the technology used, the capacity and the location of the solar PV plant. Table 2 illustrates the FiT prices for various solar PV power systems in Egypt. These prices are constant during the contract period.

4. Solar PV power growth

Fig. 2 presents the annual cumulative installations of solar PV power systems established over the world during the last two decades from 2010 to 2030 [31]. The total electric power generated by the solar PV power systems increased inconsiderable during the first decade in the 21th century while it increased from almost 50 GW in 2010 to more than 650 GW in 2020. Furthermore, the production of electric power in the European Union from the solar PV power systems in 2015 was nearly 90 GW, with an increase of about 100% compared to its value in 2010. In addition, the period from 2015 to 2020 recorded a sharp rise in the electrical power generation from photovoltaic power plants by nearly two times. This reveals that there is a massive development of solar PV power projects in recent years.

In 2020, the most five producers of global electricity generation from the solar PV power systems of 627 GW are China, European Union, USA, Japan, and India with an electricity production of 204.7, 131.3, 75.9, 63, and 42.8 GW, respectively. As well, there are some major markets contributed considerably all over the world such as Vietnam by almost 4,8 GW, Australia by 3,7 GW, Korea by 3,1 GW, Brazil by 2,0 GW, United Arab Emirates by 2,0 GW, Egypt by 1,7 GW, Taiwan by 1,4 GW, Israel by 1,1 GW, Mexico by 1,0 GW, and followed by the decline Turkish market by 0,9 GW [31]. The establishment of solar PV power plants in the above-mentioned countries represents 88% of all systems established all over the world. This implies that the widespread installation of the solar PV power systems is still concentrated in a limited number of countries. The attention of large countries to expand the construction of solar PV power plants will increase the number of investors in this field. However, the regions with the highest solar radiation and the extended number of solar brightness hours, such as those in the Middle East and Africa, represent limited participants of the solar PV power systems. This requires making great efforts to take the advantages of this sustainable potential energy.

Egypt is one of the solar belt area countries that is characterized by its geographical location. The average direct annual solar radiation intensity in Egypt is 2500 kWh/m^2 with a maximum value of 3200 kWh/m^2 that is maintained in Upper Egypt, by an average of daily sunshine period from 9 to 12 h. In Egypt, utilizing solar energy to produce electricity did not flourish during the last two decades of the previous century due to the raised capital cost of PV modules and inverters. Therefore, it was limited to particular applications such as grid-independent remote areas and rural electrification. Recently, the Egyptian government paid great attention to renewable energy resources, especially the solar PV power applications. In turn, the Ministry of Electricity and Renewable Energy (MERE) issued the Solar Atlas of Egypt to support the solar power development in all phases such as site selection and pre-feasibility evaluation as well as to identify the principal climate data that ensure the PV solar power generation [32].

5. Benban solar Park

Solar energy is the most important resource of energy on Earth. Egypt is geographically located between latitudes of 22^{O} N and 31.5^{O} N and longitudes of 24^{O} E and 37^{O} E, thus it is situated in the central position of the global solar belt, as shown in Fig. 3. Egypt has established the largest solar power plant in the world in Benban village, Aswan. The Benban village is located in the western desert at the latitude of 24.26^{O} N and the longitude of 32.43^{O} E at 40 km north of Aswan and 650 km south of Cairo, as shown in Fig. 4. The location of the Benban solar power plant is selected in accordance with the studies and reports by NASA and a number of international scientific institutions which emphasize that the project site is one of the most sun brightest regions around the world [33].

5.1. Description of Benban solar Park

The Benban Solar Park is designed with a total capacity of 1600 MW covering an area of 37.2 square kilometers and it is divided into 32 sub-systems. Egypt planned to extend the total capacity of Benban Solar Park to 2000 MW gained from 40 sub-systems. The sub-systems are divided into four groups titled plant-1, 2, 3, and 4 and each plant consists of eight sub-systems with almost 50 MW AC electrical power capacity as represented in Fig. 5. The four solar PV power plants are connected to the Egyptian high voltage network through four transformer stations titled Benban-1, Benban-2, Benban-3,

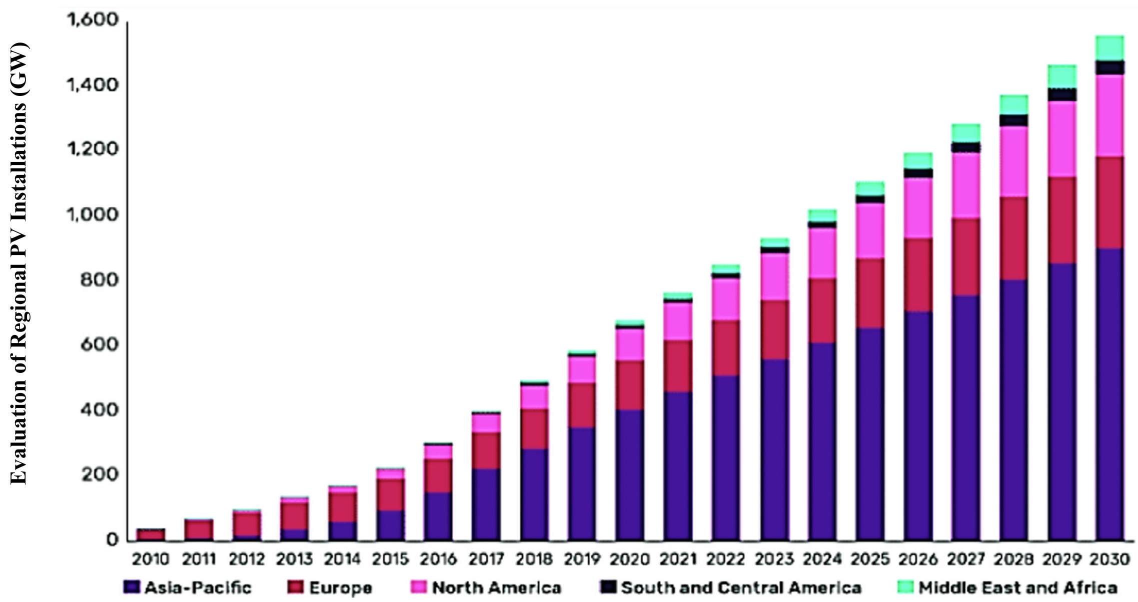

Fig. 2 Worldwide cumulative installations of solar PV power systems [31].

and Benban-4 which are constructed by MERE. Benban Solar Park, as a part of the Egyptian FiT program, is the most immense national energy project in renewable resources. A 25-years contract is signed with the MERE to purchase the electricity by 14.34 US¿/kWh [34].

Fig. 6 shows a recent satellite photo of the Benban Solar Park representing the geographical locations such as latitudes and longitudes. Each sub-system with a capacity of 50 MW AC that is constructed on an area of 1600*600 m^2 is divided into 12 blocks; each one contains a number of trackers and two models of inverter *i.e.*, Growatt CP2000 Station-S and Growatt CP2520 Station-S. The main components for each 50 MW AC sub-system are shown in Table 3. The sub-system contains approximately 192,510 PV modules and 24 inverters to convert the direct current (DC) output of the solar photovoltaic modules into alternative current (AC) that is connected to the national grid electricity transmission system. Table 4 presents the specifications of the utilized inverters *i.e.*, Growatt CP2000 Station-S and Growatt CP2520 Station-S. All PV modules are connected to tracking systems to maximize the electrical power generation during the diurnal hours.

Fig. 7 shows the schematic diagram of the tracker system in a 50 MW sub-system that is divided into three strings, where

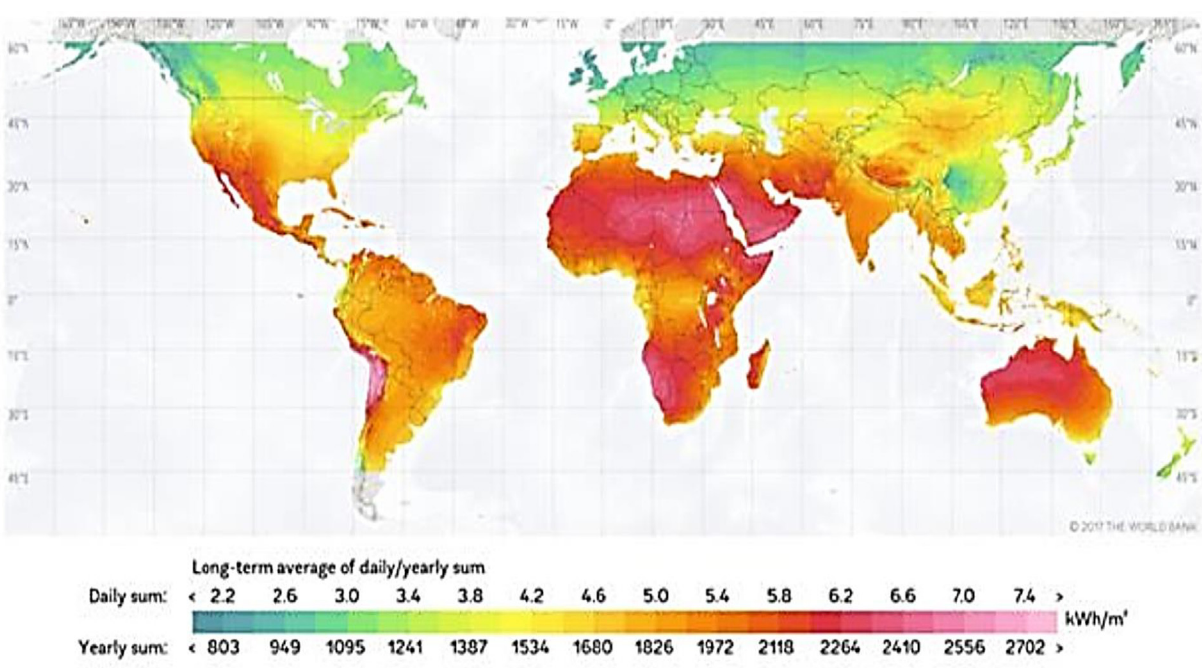

Fig. 3 Global horizontal irradiation [31].

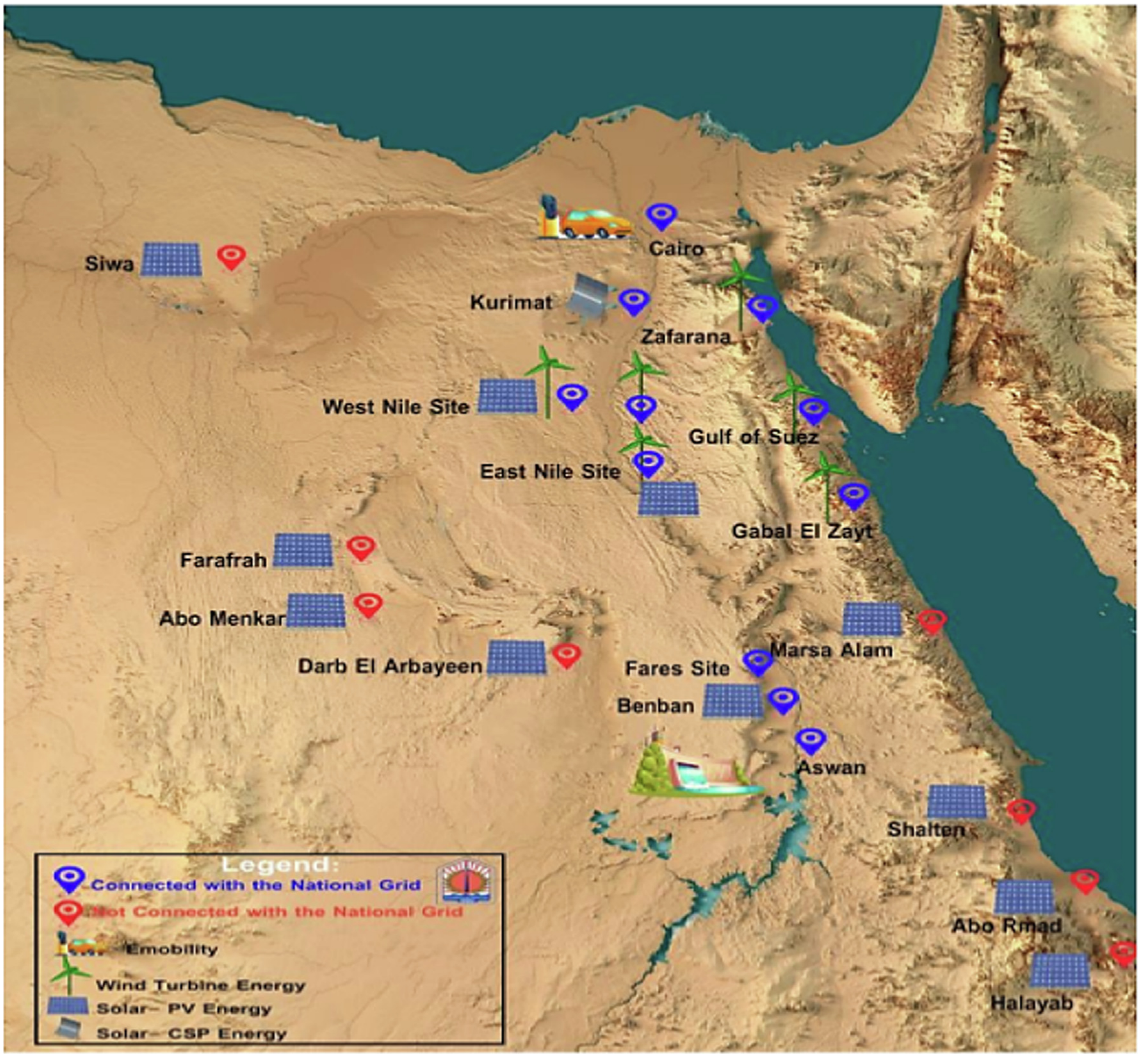

Fig. 4 Location of Benban Solar Park.

each one contains 31 PV modules connected in series. Then, the combiner collects the direct current and the voltage output from the strings. The designed inverters have specified features to maintain the required adaption to use in the Benban Solar Park such as automatic synchronization, high conversion efficiency, anti-islanding protection, and maximum power point tracker. In the present project, the power point tracker efficiency that is defined as the ratio between the ideal power supply to the inverter and the power converted by the inverter is maximized.

6. Technical evaluation

6.1. Meteorological data of Benban solar Park

The economic feasibility study of the Benban Solar Park requires some necessary parameters such as the total solar irradiation, ambient temperature, and wind velocity. Over the past few decades, the climate change impacts on the energy systems have increased substantially [35]. The climate modeling is a valuable tool for investigating the future climate changes such as environmental temperature, solar intensity, and wind velocity in the system productivity. These models are utilized to decide the required procedures for ensuring the market flexibility and the continuous technological development to overcome any potential risk coming from the climate-driven changes in the techno-economic feasibility of the system [36]. In the present study, the impact of the climate variables on the productivity of PVs in the Benban Solar Park is limited during the project lifetime so it will be ignored [37].

Fig. 8 shows the average values of the solar irradiation for different months during 2021. The results indicate that June and July recorded the highest solar irradiation during the year with an average value of about 272 kWh/m^2 while January and December record the average lowest values of solar irradiation, which are 161 kWh/m^2 and 151 kWh/m^2, respectively. The distributions of the average ambient temperature, relative humidity, and wind speed are illustrated in Fig. 9. The average highest values of ambient air temperature during June, July, and August are 36.1, 36.2, and 35.8 °C, respectively. While the average lowest values are maintained during January, February, and December are 16.5, 18.9, and 18.2 °C, respectively. On the other side, the average lowest value of the relative humidity obtained during June equals 17.7% while the

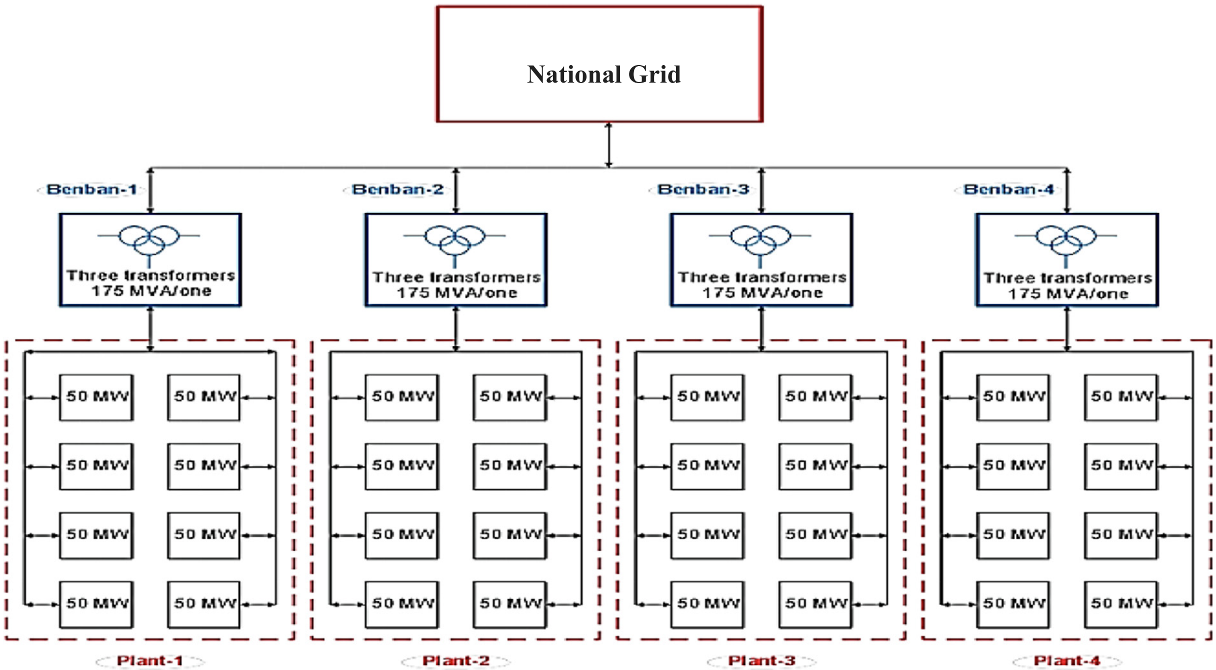

Fig. 5 Schematic diagram of a 32 sub-systems of Benban Solar Park.

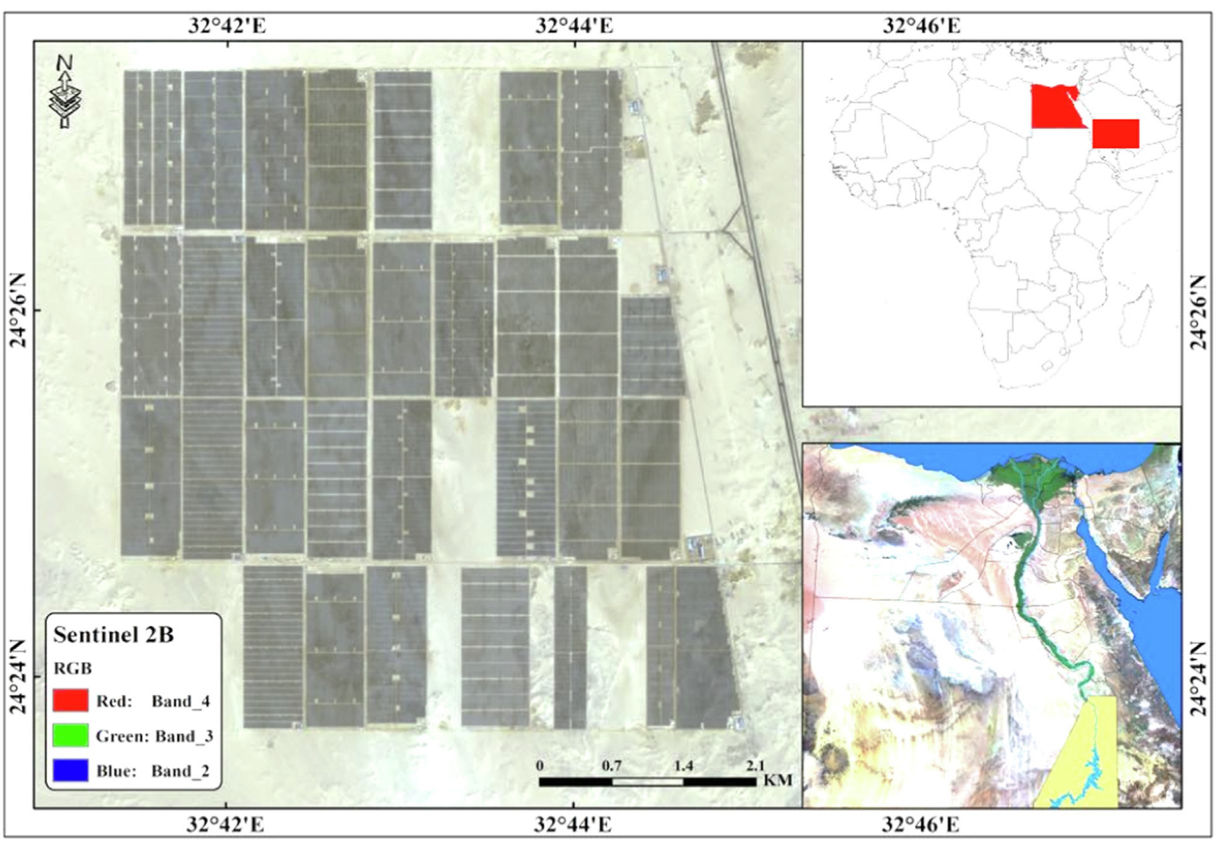

Fig. 6 Satellite photo of Benban Solar Park.

Table 3 The main components for each 50 MW sub-system.

No. of block	No. of trackers	No. of PV modules	Inverters	
			No.	Model
1	147	13,671	2	Growatt CP2000
2	193	17,949	2	Growatt CP2520
3	197	18,321	2	Growatt CP2520
4	147	13,671	2	Growatt CP2000
5	196	18,228	2	Growatt CP2520
6	150	13,950	2	Growatt CP2000
7	147	13,671	2	Growatt CP2000
8	200	18,600	2	Growatt CP2520
9	199	18,507	2	Growatt CP2520
10	150	13,950	2	Growatt CP2000
11	147	13,671	2	Growatt CP2000
12	197	18,321	2	Growatt CP2520
Total	**2070**	**192,510**	**24**	

Table 4 The specifications of employed inverters.

	Value/Inverter model	
	Growatt CP2000	Growatt CP2520
Maximum DC power (kW)	2300	2900
Maximum DC voltage (V)	1000	1000
Maximum input current (A)	3640	3600
Number of DC inputs	40	32
Max AC power (< 45 ℃ ambient) (kVA)	2200	2760
Rated AC power (kVA)	2000	2520
Maximum efficiency (%)	98.7	98.7

average highest values of the relative humidity recorded during January and December are 43 and 42.5%, respectively. Additionally, the average value of the wind speed during the year in Benban Solar Park is almost equal to 4.4 m/s.

6.2. Characteristics of PV modules

Table 5 introduces the specifications of the utilized PV module. In addition, each 50 MW AC sub-system has four weather monitoring stations to record the solar irradiation, ambient temperature, and wind speed. During the night hours, the electrical consuming devices are supplied with electricity from the National Grid Electricity. Each entire sub-system is linked to a control system that is followed up by specialized engineers and technicians.

Based on the collected data from the station, Fig. 10. illustrates the power-voltage characteristics curve of the employed PV module under different surface temperatures of the PV modules (T_s). The voltage and power are studied and analyzed to assess the characteristics of the PV modules during the summer months in which the temperature of the module is increased considerably that has a negative effect on the electrical performance of modules. Increasing the surface temperature from 50 to 70 °C reduces the maximum power output of the PV panels by 10.7 and 10.6% at solar irradiation of 1000 and 1100 W/m^2, respectively.

7. Economic evaluation

The solar GCPV power plants have a number of economic advantages such as a low-level infrastructure and simple design, installation, operation, and maintenance. The economic feasibility study of the GCPV power system is important to evaluate the actual cost of electricity production and to determine the payback period for reducing the risk of installation. The cost analysis of the GCPV power plants depends on several factors such as the initial investment cost, interest rate, annual electricity generated, operating and maintenance cost, project lifetime, cost of the electricity generated, selling price of a kilowatt-hour, and salvage value of the project. In addition, the cost analysis of the GCPV power plants is controlled by the weather meteorological data such as the ambient air temperature, solar intensity, and relative humidity [38].

The first sub-system of Benban Solar Park with a capacity of 50 MW AC electricity was connected to the national grid electricity transmission system in March 2018. A number of funding agencies and international banks fund the immense investment of the largest solar power plant all over the world in the Benban Solar Park. International Finance Corporation

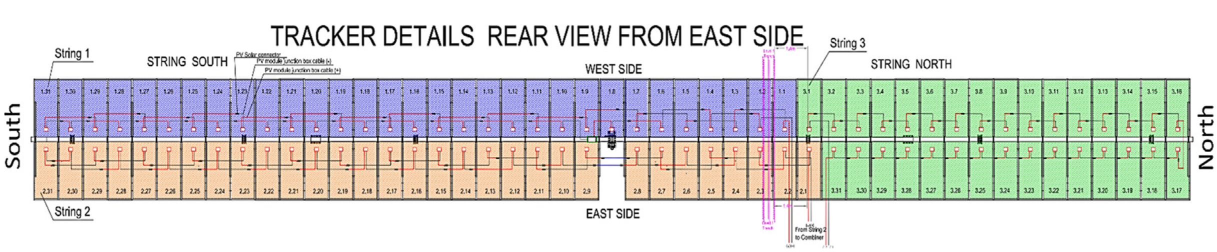

Fig. 7 Schematic diagram of the tracker system of 50 MW sub-system.

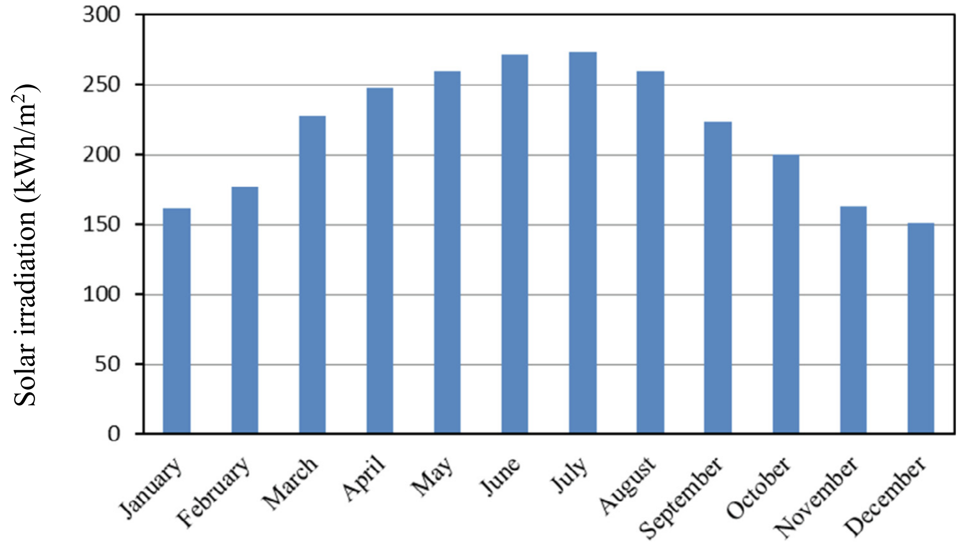

Fig. 8 Average solar irradiation in Benban Solar Park for different months during 2021.

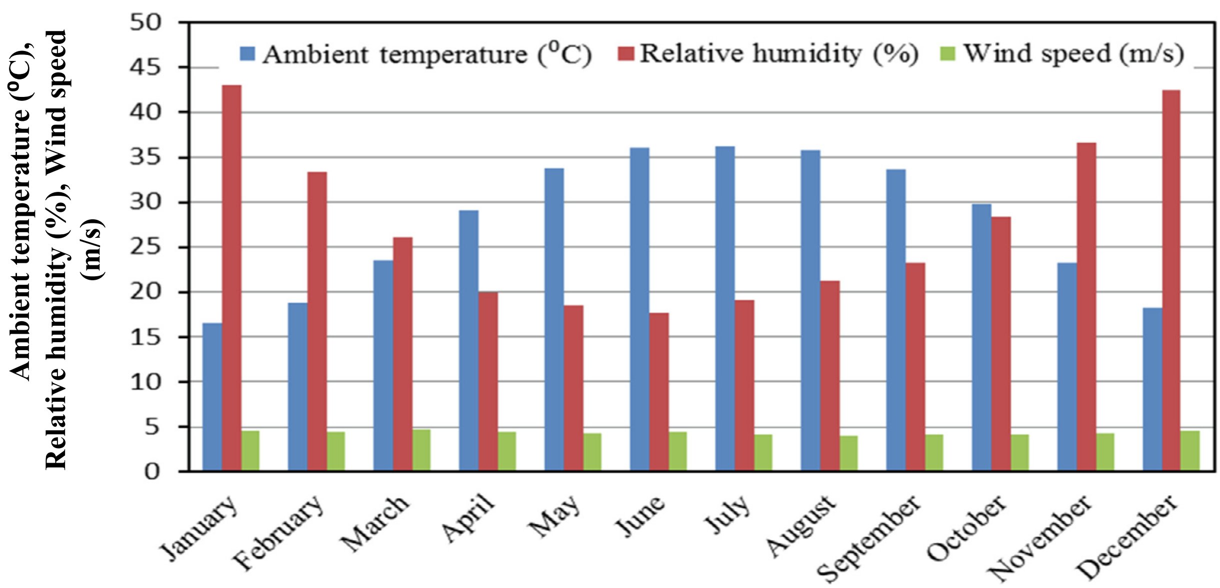

Fig. 9 Average values of ambient temperature, relative humidity, and wind speed in Benban Solar Park for different months during 2021.

Table 5 The specifications of PV module.

Parameter	Value
Solar module type	JKM330PP-72-V
Maximum power (W)	330
Power tolerance (%)	0–3
Maximum power voltage (V)	37.8
Maximum power current (A)	8.74
Open circuit voltage (*V*)	46.9
Short circuit current (*A*)	9.14
Nominal operating temperature (^{O}C)	45 ± 2
Operating temperature (^{o}C)	from − 40 to + 85
Dimensions (mm)	1956*992*40

(IFC), European Bank for Reconstruction and Development (EBRD), African Development Bank (ADB), Arab European Bank (AEB), Dutch Development Bank (DDB), and other private sector participations collaborate funding the Benban Solar Park. Therefore, it is considered the largest private consortium to fund a solar photovoltaic power plant in the Middle East and North Africa (MENA).

7.1. Cost analysis

The cost of constructing LS GCPV of Benban Solar Park depends fundamentally on the initial cost and interest rate. The effect of the operation and maintenance cost on the economic feasibility of LS GCPV power plants is low, as it

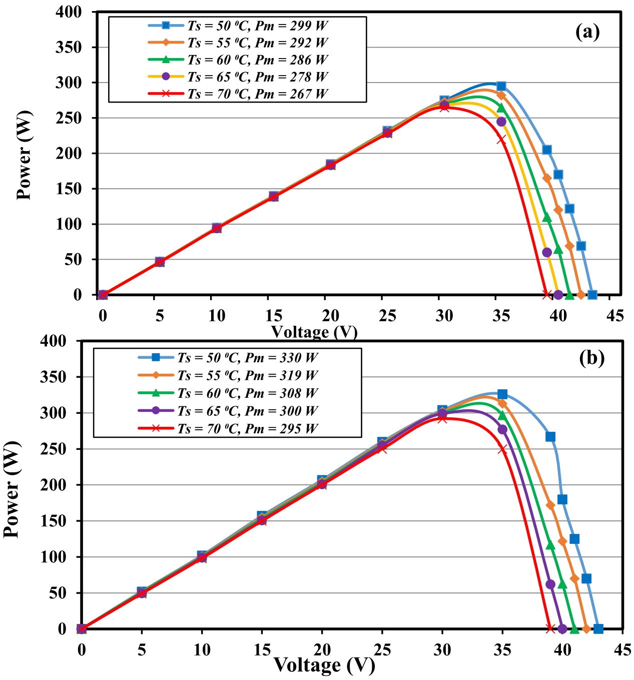

Fig. 10 P-V characteristics curve under different surface temperatures at solar irradiance (G) of (a) 1000 W/m^2 and (b) 1100 W/m^2.

requires only labor and maintenance for cleaning the PV modules and the inspection of the main components. Therefore, it is found that the cost of establishing the Benban Solar Park project is summarized in main points including PV modules, inverters, installation, structure, DC and AC cables, and transportation.

The governing equations of the economic analysis of solar GCPV power system are presented below to compute the main parameters such as the capital recovery factor; CRF, (Eqn. (1)), fixed annual cost; FAC, (Eqn. (2)), sinking fund factor; SFF, (Eqn. (3)), annual salvage value; ASV, (Eqn. (5)) and annual operation and maintenance cost; AOMC, (Eqn. (6)) [39]. The annual cost that is symbolized by AC, can be obtained from Eqn. (7). Finally, the cost per Megawatt hour; CPM, can be calculated by dividing the project annual cost; AC, by the annual average yield of Megawatt hour; M, as expressed in Eqn. (8).

$$\mathrm{CRF} = \frac{i(1+\mathrm{i})^n}{[(1+i)^n - 1]} \tag{1}$$

$$FAC = P(CRF) \tag{2}$$

$$\mathrm{SFF} = \frac{i}{[(1+i)^n - 1]} \tag{3}$$

$$S = 0.15(P) \tag{4}$$

$$ASV = S(SFF) \tag{5}$$

$$AOMC = 0.02(FAC) \tag{6}$$

$$AC = FAC + AOMC - ASV \tag{7}$$

$$CPM = \frac{AC}{M} \tag{8}$$

where P is the present capital cost of GCPV power system; S is the project salvage value; $\boldsymbol{i}$ is the interest rate, which is assumed to be varied from 1 to 14%; and n is the project lifetime, which equals 25 years in the present study according to the signed contract.

8. Economic results

8.1. Cost evaluation of electricity generation

The Egyptian government represented by the MERE affords all required facilities to secure the success of the Benban Solar Park project, starting with the selection of the project location that is near to the main highway roads and the national grid electricity transmission system. In addition, MERE awarded the land usufruct throughout the project lifetime, and finally MERE signed a contract to purchase the generated electricity during the project lifetime. In the present implementation, the data collection is based on a number of visits to the project site and interviewing the design and operating engineers, installation, operation and maintenance companies. The initial costs of the main components of the for one 50 MW sub-system of the Benban Solar Park project are illustrated in Table 6.

For installations of PV, the module efficiency is reduced by almost 10 – 25% due to the module dust soiling and losses in the wiring and inverters [40]. The dust deposition on PV modules is a complex phenomenon and it is mainly impacted by a number of factors such as environmental and weather conditions [41]. In order to mitigate the influence of the dust accumulation on the PV modules, regular cleaning methods for the dry climate in the western desert of Egypt of Benban Solar Park have been applied effectively.

In the present study, the generated electrical power output is assumed constant in the operational lifetime of the solar GCPV systems. However, the output power of PV modules is annually degraded by 0.5–1%, where a 12.5–25% reduction in power output is acquired at the last year of the project lifetime [42,43]. The solar GCPV modules absorb the solar energy transferring a limited part of it directly into electrical energy [18,44]. A limited wavelength of the incident irradiation on PV cells is transformed into electricity with an efficiency of about 15–20%; however, the remaining part of incident solar energy is wasted as thermal energy resulting in a crucial issue of heating the PV modules itself, consequently rising surface temperature of PV modules and hence, reducing the electrical efficiency [7,45]. Where, the electrical output power decreases by 0.65% per every degree Celsius of temperature increment

Table 6 Initial costs of main components for each 50 MW sub-system.

Sections	Cost US$	Cost ratio
Modules	31,311,913	45.4%
Inverters	15,573,121	22.5%
Installations	7,289,545	10.6%
Land	none	0%
Structure	7,897,009	11.4%
DC and AC cables	3,727,609	5.4%
Transportation	3,230,595	4.7%
Total	**69,029,792 (1.38/W)**	**100%**

up to 80 °C [6]. So the effect of temperature on the PV modules is taken into consideration to make the results more responsible [46,47]. Therefore, the real cost of the electricity generation is calculated based on the average output power of each sub-system of 50 MW AC while the designed electrical capacity of the project is 63.5 MW DC.

The present study is conducted to evaluate the economic analysis of the solar GCPV power system to supply electricity to the national grid under a number of assumptions such as the annual average output power during the project lifetime is constant and it equals 50 MW AC for each sub-system. In addition, the AOMC is constant at 2% of the fixed annual cost [14,48], and the cost of electricity is based on variable interest rate in the range of $1\% \leq \boldsymbol{i} \leq 14\%$ depending on the national economic stability.

There are a number of factors affect the interest rate during the project lifetime such as political short-term gain, alternative investments, exchange rate, risks of investment, taxes, consumer confidence, and type of loan program. So, through the present economic study the interest rate ranges from 1 to 14% while according to a number of financial variables, the interest rate in Egypt is around 12%. Fig. 11 shows the effect of the interest rate on the electricity cost. It can be concluded that the cost per kilowatt-hour increases linearly with increasing the interest rate. Moreover, increasing the interest rate from 1 to 14% increases the electricity cost drastically and steadily by almost two times and a half.

The influence of the interest rate on the payback period is represented in Fig. 12. It is noticed that increasing the interest rate up to 7% has a slight effect on the payback period by an increment of 30% while further increasing the interest rate up to 14% increased the payback period significantly by almost 80%. Moreover, it can be noticed that the actual cost of electricity production from the Benban sub-system equals 8.1 US¿/kWh at an interest rate of 12%. As the MERE signed a contract to purchase the electricity generated from the project by 14.34 US¿/kWh during the project lifetime, the project is expected to recover its expenses within 10 years. Furthermore, Fig. 13 presents the impact of AOMC on the payback period and the cost of electricity production. In the present study, the AOMC is presented as a percentage of the fixed annual cost. It is observed that increasing the AOMC from 2 to 20% increases the cost of electricity production and the payback period by 17.8 and 30.4%, respectively.

8.2. Solar PV power and environment

The LS GCPV of Benban Solar Park depends on utilizing the PV modules that have zero GHG emissions. The electric power generated by the solar PV power system can replace a part of electric power generated by the thermal power plants using fossil fuels; therefore, the solar renewable energy will reduce the CO_2 emissions [49,50]. The Benban Solar Park with a capacity of 1600 MW will contribute significantly to preserving the environment by avoiding 1.2 million tons of GHG emissions annually, which is equivalent to 694,000 cars off the road or planting 813,000 trees each year [31].

9. Policies for economic improvements of GCPV system

In the near future, the cost of electricity production of GCPV system will be reduced significantly ensuring its economic feasibility through several measures such as the advancement in the material and technology of photovoltaic and trackers, increasing the electrical efficiency, optimizing the system technology, growing the mass production, reducing the costs of operation and maintenance. However, there are a number of aspects that have a considerable influence on the economic feasibility of the GCPV system, that are not related to the PV modules themselves such as raw material prices, financial cost, taxes cost, and transportation cost, etc.

9.1. Improvement based on agrivoltaic system

Previous research [37] clarified the effect of the surface temperature of the solar PV panel on the electrical energy output. The working conditions of the previous study [6] which aimed to improve the performance of solar panels using cooling water are similar to the Benban solar Park. This study showed that

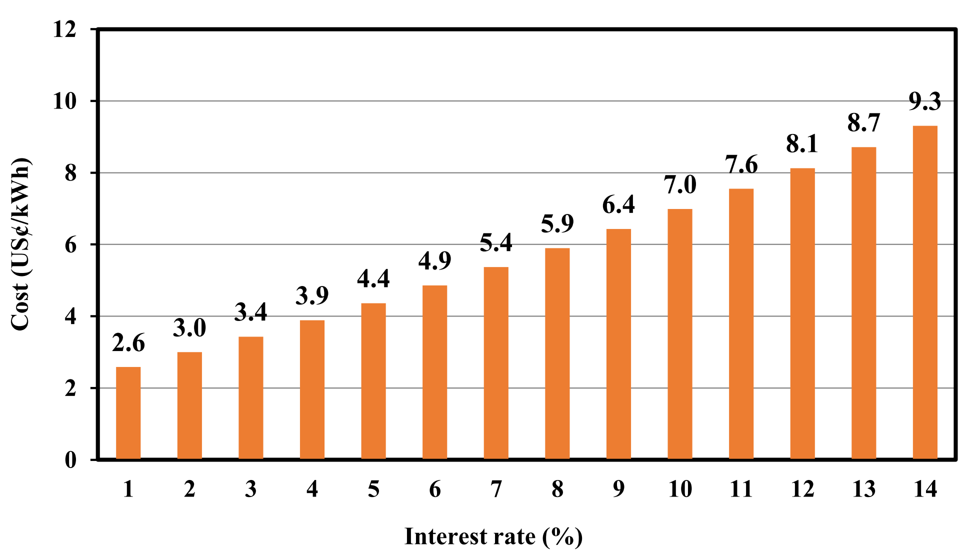

Fig. 11 Influence of the interest rate on the electricity cost.

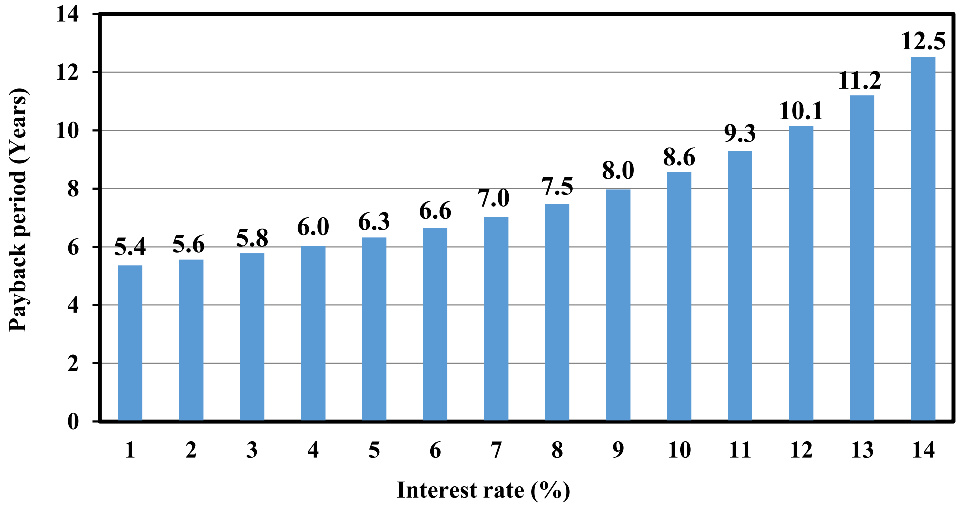

Fig. 12 Influence of the interest rate on the payback period.

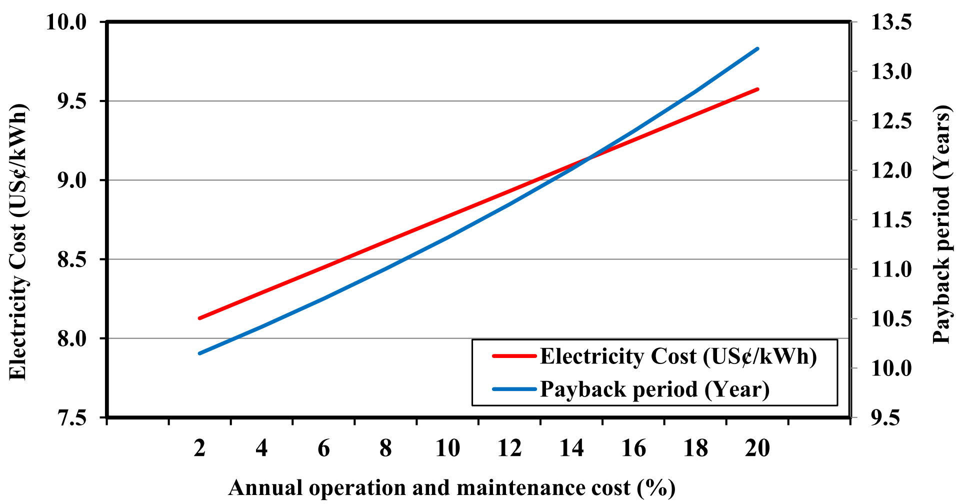

Fig. 13 Influence of AOMC on the payback period and electricity cost.

utilizing of water cooling for solar panels leads to an increase in the electrical energy output by 8.2%. This attributed to maximizing the benefit when cultivating the vast land area on which the station is built, and using the irrigation water to cool the PV panels in the first, and then for the irrigation process. Thus, a double advantage can be achieved; first, an increase in the electrical energy output by 8.2% in the summer months where the panel surface temperature is high. Second, the agricultural crops as an economic value, as the solar panels are located at a height of 1.5 m from the surface of the earth. The PV solar panels are installed above the existing cultivated areas while the maintained spaces among rows of PV modules provide the necessary solar radiation for crops.

Applying water cooling technology from April to September months on the current plant leads to increasing the electricity production of the plant by almost $4.49*10^3$ megawatt-hours annually, which saves almost $646.5*10^3$ dollars annually. Cooling the solar panels based on water that is available from nearby irrigation systems makes the maintenance process easier and inexpensive, as water cleans and cools the panels and consequently reduces the operating and maintenance costs. So, the feasibility analysis for generating electricity from PV modules states that using the available territory for agricultural purposes is a sustainable solution for increasing the power generated from the Benban Solar Park. Increasing the production of electricity in addition to the annual return from agriculture makes the projects of producing electricity from the Benban solar Park have a promising future.

10. Concluding remarks

Recently, the utilization of solar energy for GCPV power plants has gained popularity all over the world to meet the requirements of drastically increasing the population and industrialization instead of depleting the non-renewable resources of fossil fuels. It is a major issue to study the acceptance economic level of these power plants as well as to evaluate the proper financing indicators, viability, feasibility, and interest rate involved with the construction of GCPV power plants. In the current study, the techno-economic feasibility of LS GCPV of Benban Solar Park in Aswan, Egypt with a total capacity of 1600 MW AC is examined using the FiT mechanism. The results of the economic feasibility show that the cost of the electricity production from the Benban Solar Park is considerably affected by the interest rate and it equals 8.1 US¿/kWh at an interest rate of 12%.

Moreover, rising the interest rate from 1 to 14% increases the cost of electricity steadily by almost two times and a half. Furthermore, elevating the interest rate from 1 to 7% increases the payback period by 30% while further raising the interest rate up to 14% increases significantly the payback period by almost 80%. In addition, increasing the annual operation and maintenance cost from 2 to 20% raises the electricity cost and the payback period by 17.8 and 30.4%, respectively. Finally, the Benban Solar Park with a total capacity of 1600 MW will avoid the dissipation of 1.2 million tons of GHG emissions annually. Increasing the surface temperature during the summer months has a negative effect on the economic analysis where it reduces the generated power by almost 10.7%. In addition, the application of agrivoltaic systems offers a number of benefits depending on the climatic and regional operating conditions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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