Site Selection of Large-Scale Grid-Connected Solar PV System in Egypt

Hamdy M. Sultan[1], Oleg N. Kuznetsov.[2], Ahmed A. Zaki Diab[3]
[1,2,3]Department of Electrical Power Systems, Moscow Power Engineering Institute "MPEI"
Moscow, Russia
[1,3]Electrical Engineering Department, Faculty of Engineering,
Minia University
Minia, Egypt
[1]hamdy.soltan@mu.edu.eg, [2]kuznetsovon@mpei.ru, [3]a.diab@mu.edu.eg

***Abstract*— Installing a photovoltaic (PV) power plant at a proper location is a critical problem for the system planners and investors. This study explored the potential of large-scale grid-connected solar PV generation in Egypt. Overall, 27 locations were assessed for their technical potential considering a 100 MW PV power plant in each site. The main analysis criteria are geographical conditions, economic profits, environmental benefits, availability of vacant lands for installation in the present and future developments, availability of water resources and the distance from transmission lines, substations, and highways. The project viability analysis has been accomplished based on RETScreen Expert package depending on electricity production, financial, and GHG emission analyses. Taking into account the other criteria beside the results obtained from RETScreen Expert, the suitable sites for the installation of the proposed power plant will be determined.**

***Keywords*—Photovoltaic; RETScreen; Site selection; Viability analysis**

I. Introduction

Egypt is a resource-rich country as it is one of the countries of the solar belt area most suitable for applications of solar energy, where the results of the Atlas of Egypt show that the average solar radiation column between 2000-3200 kWh/m^2/year [1]. The daily sunshine duration hours range between 9-11 hours/day, which provide opportunities for investment in various solar energy fields.

In the early of the last two decades, the Egyptian government noticed that conventional resources of energy would not be sufficient to cover the energy demands in the future. Egypt plans to supply 20 percent of energy demand from nonconventional sources by 2022 while providing wind energy at 12 %, Hydropower 5.8 %, and solar energy 2.2 %. It is planned to have 3.5 GW solar energy by 2027; which include 2.8 GW of photovoltaic (PV) and 700 MW from concentrated solar power (SP). Moreover, the strategy envisages the generation of 7.2 GW (12% of wind-generated electricity) by 2022. The plan foresees significant private sector participation, which will take the lead to 67 % of the plan [2-3]. The plan of the Renewable Energy sector in Egypt is to implement 51.3 GW to the present generated power. The first solar thermal power station was built in Kuraymat in 2011. The total capacity is 140 MW, with a 20 MW solar share. In the Western Sahara in the Siwa Oasis, solar plant with a capacity of 10 MW has entered service in 2015.

The Egyptian Electricity Holding Company is currently under coordination to take the executive steps to sign the agreements for the purchase of energy generated from the projects of the private sector power plants with a total capacity of 1000 MW; 250 MW wind power plant in Suez Gulf, 200 MW solar power plant in Kom Ombo – Aswan, Renewable energy project in West Nile area with a total power generated of 550 MW [4].

The adoption of photovoltaic technologies remains so sluggish, and it requires a significant support from the government. However, there is plenty of opportunity in supporting the energy access of the nation through both grid-connected and stand-alone solar PV power systems. Grid-connected systems are connected and feed power into the national grid. These systems can be either distributed type, serving a certain grid-connected customer and connected to the distribution network or centralized type, feeding power into a transmission grid [5]. Both types of these systems are potential options for countries like Egypt.

With the purpose of determining the optimum site for installing of the planned solar PV power plant, this paper presents a techno-economic and environmental investigation of implementation PV power plants of 100 MW capacity at selected promising sites in Egypt. The metrological data of 27 sites were used. The energy yield, financial study, and greenhouse gases emissions are accompanied for 27 locations with the aid of RETScreen Expert package. Besides the results obtained from RETScreen Expert, other factors are applied in this study. These factors are such as availability of vacant lands for installation in the present and future developments, availability of water resources and the distance from transmission lines, substations, and highways.

II. PV-Module Selection

Egyptian market has a large number of PV modules which have different specifications. The suitable PV-module type was selected in accordance with the ratio of the module generated power and its surface area (power/surface area). The 200 W peak Sanyo mono-Si-HIP-200BA3 PV-module consists of

Hetero-junction with Intrinsic Thin-layer (HIP) PV cells is suggested in this paper. The electrical and mechanical characteristics of the proposed module are presented in Table I[6].

TABLE I. SPECIFICATIONS OF THE SELECTED PV MODULE

Model Number:	HIP-200BA3
Electrical Specifications	
Max. Power (Pmax):	200 Watts
Max. Power Voltage (Vpm):	55.8 Volts
Max. Power Current (Ipm):	3.59 Amp
Open Circuit Voltage (Voc):	68.7 Volts
Short Circuit Current (Isc):	3.83 Amps
Minimum Power (Pmin):	180.0 Watts
Maximum System Voltage (Vsys):	600 Volts
PTC Rating:	188.7 Watts
Cell Efficiency:	19.7%
Module Efficiency:	17.0%
Mechanical Specifications	
Dimensions:	1319 X 894 x 35mm
Weight:	14kg
Module Area	1.18 m^2
Normal Operation Condition Temperature (NOCT)	44.2º C
Standard Operating Conditions (SOC)	
SOC Temperature	20 ºC–40 ºC
SOC Relative Humidity	45%–95%

III. DESCRIPTION OF THE PROPOSED PV SYSTEM

From the technical, economic and environmental point of view, this paper explores the possible locations in Egypt for the construction of 100MW photovoltaic power plants. Depending on the proposed PV panels, 500,000 units are needed to establish the proposed 100 MW power station. Consequently, an area equals to 590,000 m^2 will be covered with PV modules. RETScreen Expert includes four possible types of sun tracking system upon which the solar modules are fixed. In this work, the fixed-axis position of the modules is selected in order to reduce the initial cost of the power plant. Inverters having an efficiency of 95% were selected for integrating the power plant into the utility grid [7].

IV. SPECIFIC SITE SELECTION FACTORS

A. Climate

In principle, the total solar energy received per unit area on the horizontal surface is the most important factor that is firstly considered by developers and investors. In the period of obtaining data on solar resources, there are usually two data sources, satellite & meteorological data and ground measurements [5].

In term of digital solar resource data in Geodatabase, SOLARGIS is an organization provides the data layers in long-term yearly or monthly averages. The data layers consist of Global horizontal irradiation (GHI). Figure 1 shows GHI over the Egypt landscape.

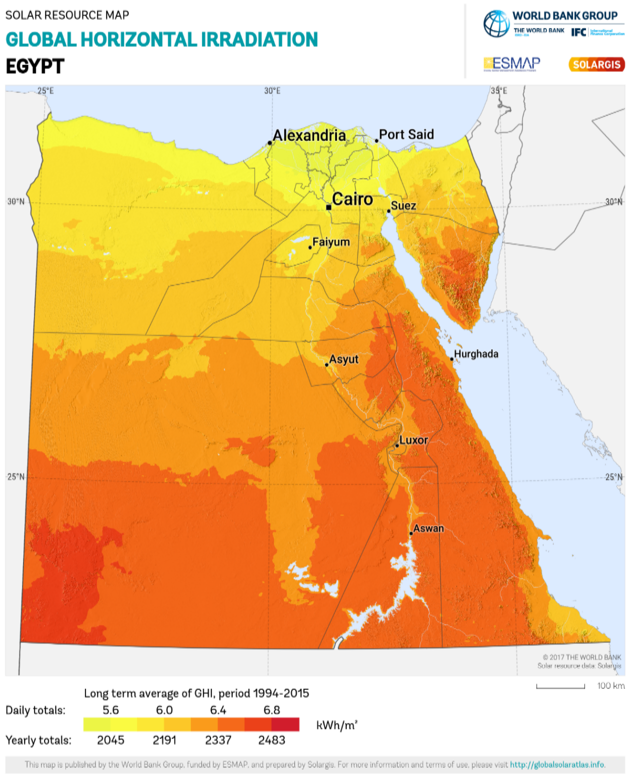


Fig.1. Global horizontal irradiation over Egypt.

B. Electrical and Transport Networks

In accordance with the need to install a solar power plant for the export of electricity depends on the availability of a distribution or transmission network [5]. The map of national freeways in Egypt is shown in Fig. 2. The proposed sites in this study for installing PV power plants also are presented in this map. The distance between the selected site and grid integration point, described by transmission lines and substations, is another important factor concerned in the selection of the power plant site. The map of high voltage and extra high voltage transmission networks with the power generation plants of Egypt published on the official website of the ministry of electricity and energy, which is given in [8]. This configuration will be useful to selection the new sites of PV power generation.

C. *Water Resource*

For cleaning the modules, the main sources of water supply, groundwater, stored water or a portable water tank for the Module should be taken into account. In addition, pure water with a low mineral content is preferred [5-9]. In some cases, adjacent Areas that represent some kind of industrial or agricultural zone that can form dust particles, they will be painted above the mirrors of the solar panels. Thus, cleaning can be the usual activity required in a solar farm.

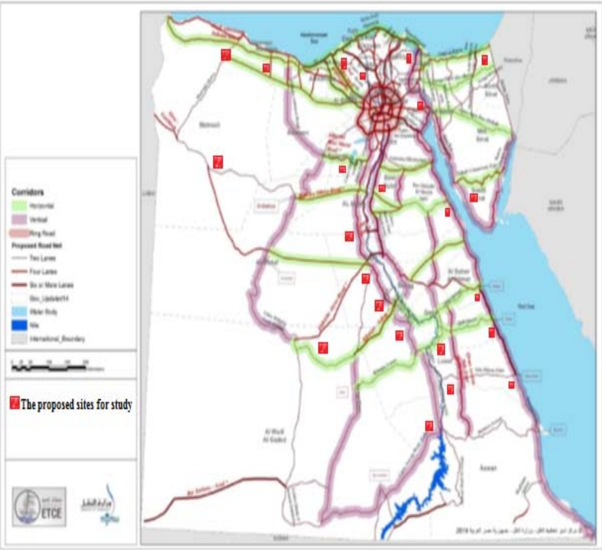


Fig.2. Map of the national freeways in Egypt.

D. Land-Use and Availability of Vacant Land

Land and proximity should be considered in accordance with the acquisition of a power line crossing the land plots of various Landowners [5]. It was recommended to consider public lands as priority areas for solar projects. In connection with the requirements of flat land, Mountains or buildings on the far horizon are also considered as causes of losses at the PV power plant . Even a land with a steep slope exposes the sun, which will be beneficial, a steep slope area has a high rate of runoff and erosion, which may affect the basement of the modules [9].

The total area of Egypt is estimated at 1.0104 million square meters, of which 78,990 square kilometers are living quarters, which is equivalent to 7.8%. However, 22% of Egypt's area is 220,319 square kilometers, that no Egyptian citizen can cross or touch. Where they were landed by mines of occupation by Germany, Great Britain and Italy in World War II. As for the shores of Red Sea, Sinai and Western Sahara, the mines prevented the cultivation of large areas of land that have the necessary water in the areas of Al-Hamam and El Alamin in the northeast of Egypt.

V. RESULTS AND DISCUSSION

A. The Behavior of Solar Radiation and Sunshine Hours

The results show that every day on the horizontal surface in Egypt, on average, a solar radiation of more than 5.0 kWh / m2 is obtained. The long-term average values over 20 years of the number of sunshine hours and horizontal solar radiation on at the proposed sites are summarized in Table II. The minimum solar radiation value is 5.38 kWh/m2 /day at Cairo Airport. Also, its maximum value is 6.64 kWh/m2 /day at Aswan. Moreover, from Table II it is shown that the higher values of global solar radiation are obtained in the southern region of Egypt in Aswan, Kossier, Edfo, Luxor etc. Furthermore, its lower values are relatively in the northern region like Matrouh, Alexandria, Sidi Barany, Ismailia, etc.

TABLE II. LONG-TERM DAILY MEAN VALUES OF SUNSHINE DURATION AND GLOBAL SOLAR RADIATION ON HORIZONTAL SURFACE.

St. No	City	Lat. (Deg)	Long. (Deg.)	Alt (m)	Solar Radiation kWh/m2/day	Sunshine Duration (h)
1	Bahria	28.7	29	118	5.88	12.125
2	Dakhla	25.5	29.3	122	6.04	12.125
3	Kossier	26.2	34.1	205	6.29	12.125
4	Safaga	26.7	33.8	267	5.85	12.108
5	Hurgada	27.2	33.6	222	5.93	12.117
6	Ras gharib	28.3	32.9	224	5.75	12.125
7	Qena	26.2	33	369	5.89	12.133
8	Edfo	25	32.8	132	6.2	12.125
9	Aswan	24.1	32.5	526	6.64	12.125
10	Luxor	25.6	32.8	156	6.06	12.117
11	Sohag	26.7	31.9	433	6.08	12.117
12	Asyut	27.4	31.3	248	5.92	12.125
13	Minia	28.1	30.5	99	5.89	12.142
14	Cairo	30.1	31.4	115	5.38	12.117
15	Fayum	29.3	30.7	12	5.79	12.125
16	Beni-suif	29	31.2	76	5.71	12.133
17	Sidi barany	31.5	25.9	62	5.42	12.117
18	Siwa	29.3	25.5	-1	5.92	12.133
19	Arish	31	33.8	108	5.45	12.125
20	Alexandria	31.1	30	-6	5.87	12.125
21	Matrouh	31.2	27.2	148	5.45	12.125
22	Ismailia	30.6	32.2	23	5.45	12.133
23	Port said	31.2	32.3	-1	5.8	12.125
24	Suez	30	32.4	64	5.69	12.117
25	Mansousa	31	31.4	5	5.5	12.125
26	El-tour	28.3	33.7	99	5.74	12.117
27	Tahrir badr	30.7	30.7	14	5.55	12.142

The variation of global solar radiation on the long term of 20 years for all months at 27 sites has been displayed in Fig. 3. Moreover, the seasonal variation of global solar radiation depending on the main values per month is given in Fig. 4. From these figures, it is clear that in summer months the solar radiation is higher than its value in the winter. A maximum of 8.078 kWh/m^2/day is received in June compared with a minimum of 3.272 kWh/m^2/day in December. The eastern-south parts of Egypt also witness high global solar radiation intensity, and then should be exploited. Thus, it would be useful to implement PV plants to cover the increased peak load necessities.

The long-term average of sunshine hours for each selected site for every month are shown in Fig. 5. Fig. 6 shows the variation of the values of sunshine duration in the four seasons over Egypt obtained by the average value of monthly mean values from 27 locations. The maximum value of the duration of sunshine hours of 13.89h received in June, while a minimum value of 10.32h is found in December. It was found that the average duration of sunlight is 12.12 hours per day and about 4423.8 hours each year. From Table II, it is evident that the values of sunshine durations ranged between a minimum of 12.108h h in Safaga (lat. 26.7, long. 33.8 and alt. 267 m above sea level) and a maximum of 12.142 in Minia (lat. 28.1, long. 30.5 and alt. 99 m above sea level). Higher values of the duration of sunshine hours are obtained in the northern and middle regions while relatively lower values in the southern areas.

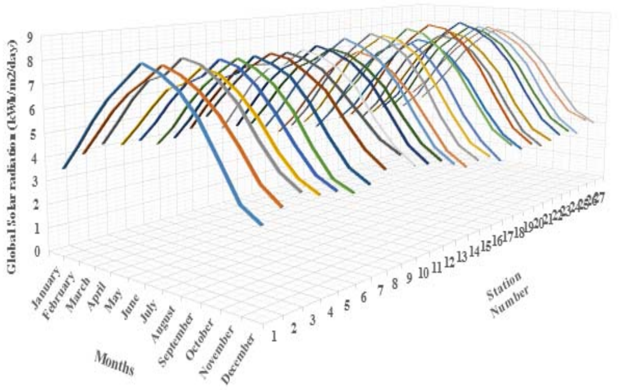


Fig.3. The average monthly solar radiation variation on the long term.

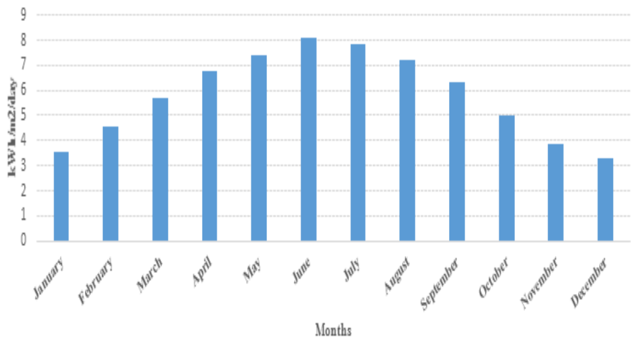


Fig.4. The seasonal variation of global solar radiation.

B. *Air Temperature and Humidity Behaviour*

To verify that the environmental conditions in Egypt are in line with the standard conditions given in Table I [6], a study of the average values of relative humidity and air temperature each month on the long term is performed depending on the data taken from NASA [10]. From Fig. 7 and 8, the air temperature and humidity for the proposed locations in Egypt are consistent with the operating standards of the PV module mono-Si-HIP-200BA3.

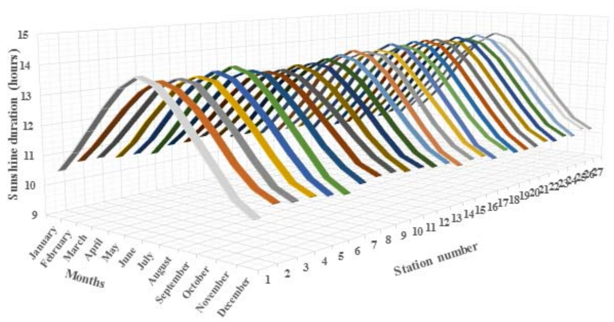


Fig.5. The monthly mean values of sunshine duration on the long term.

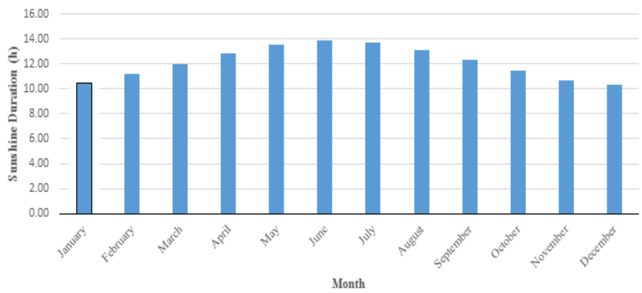


Fig.6. Seasonal mean values of sunshine duration.

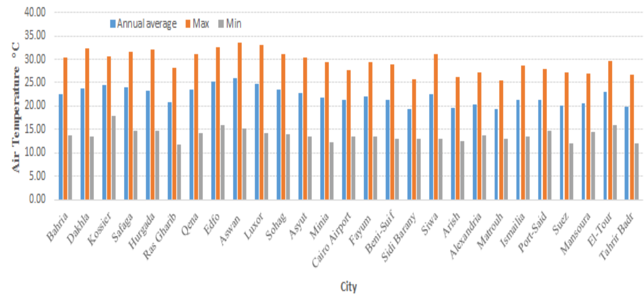


Fig.7. The averaged air temperature on the long term.

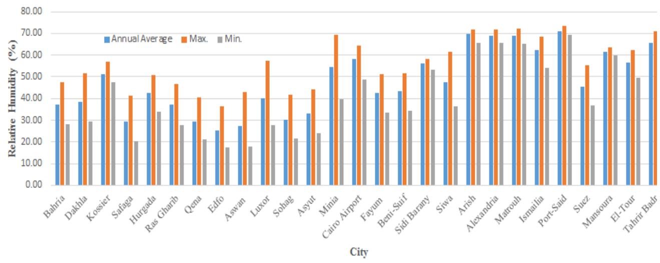


Fig.8. The averaged relative humidity (%) on the long term.

C. *Renewable Energy Production*

The inputs of RETScreen Expert are the values of average solar radiation, air temperature, and the site location. The specific energy yield, the annual energy production and the reduction in greenhouse gases are obtained as output from the program. The values of energy produced per unit area received at the selected sites are shown in Fig. 9. The maximum energy yield of 299.205 kWh/m^2 was produced at Kossier while the lowest value of 261.53 kWh/m^2 at Cairo airport. The overall average specific energy yield has been 279.616 kWh/m^2.

The supplied annual energy production (MWh) is also obtained as an output from the program. The total generated energy in a year from 100MW PV systems at the 27 selected sites has been shown in Fig. 10. The maximum annual energy generated of 176.53 GWh has been gotten from the power plant to be installed in Kossier, and at least 154.30 GWh of a power plant near Cairo airport.

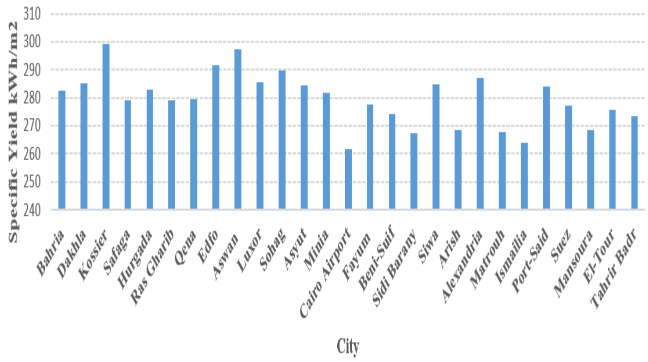


Fig.9. Specific energy yield variation with location.

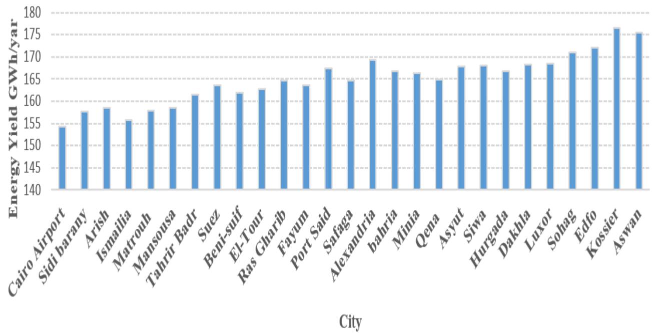


Fig.10. Annual energy production of different locations.

D. Economical Feasibility Analysis

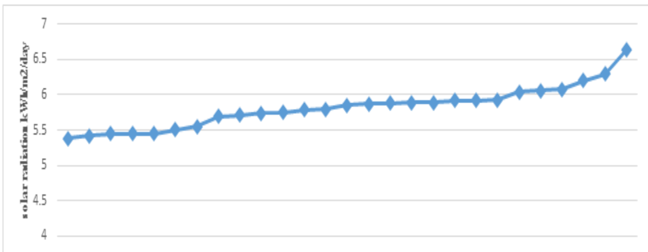
The RETScreen was used to define the internal rate of return (IRR), a simple payback period (SPP), years for positive cash flow (YPCF), annual life cycle saving (ALCS), net present value (NPV), benefit-cost ratio (BCR) and the energy production cost (EPC) per kWh of generated electricity. Economic factors, such as the rate of energy cost escalation, flow rate, as well as the costs of the main components of the photovoltaic system, are given the literature [11]. All these costs and interest rates were used as a contribution to the RetScreen software to economically analyze the feasibility of all sites.

If the IRR equals to exceed the required return rate, the study will be accepted from the financial point of view. The calculated values of IRR of all sites are shown in Fig. 11b. The maximum value of return rate of 16.7% is found at Aswan while the minimum of 10.7% at Matrouh. The value of IRR is directly proportional with the value of average solar radiation (Fig. 11a).

The program calculates the SPP, which equal to the length of time taken by the project to regain its own initial cost, out of the revenue or savings it generates. The program uses the year number and cumulative cash flows after paying taxes to calculate YPCF. The amount of YPCF is the time period that is required for the owner of such a project to return the money paid when investing the project. The simple payback period and years for positive cash flow are shown in Fig. 11c for all the studied sites. It is found that in Aswan SPP and YPCF have minimum values of 7.6 and 6.7 years, respectively. Respective maximum values of 11.9 and 10 years, were found in Minia. The average value of 9.6 and 8.2 for SPP and YPCF respectively, can be fulfilled at any location over Egypt.

When analyzing NPV, the current value of all cash tributaries and the current value of all cash gains, related to the investment project, are compared [12]. The difference between current values of these cash flows called the NPV, which determines whether the investment project normally acceptable or not. Positive values of NPV ensure that the project is potentially feasible. The program estimates the ratio of the net benefits to the project cost which is defined as the net Benefit-Cost ratio BCR. Ratios with a value greater than unity is an indicator of a profitable project. The program also calculates ALCS, which is a nominal annual saving with equalization, having the exact value of project life and NPV. Taking into account the NPV, the project lifetime and the discount rate, the value of ALCS is calculated. The variation of NPV and ALCS over the proposed locations are presented in Fig. 11d while the variation of the value of BCR is given in Fig. 11e.

Another output from the program is production cost of the generated units or EPC. This value represents the electricity export rate required in order to have a Net Present Value (NPV) equal to zero. The EPC was calculated for the entire locations and is presented in Fig. 12. The EPC has a minimum value of 14 cents/kWh at Cairo airport region and a maximum value of 18 cents/kWh in Aswan, as given in Fig. 12. Meanly, at any location in Egypt, the generated unit from PV power plants costs about 15.98 cents.



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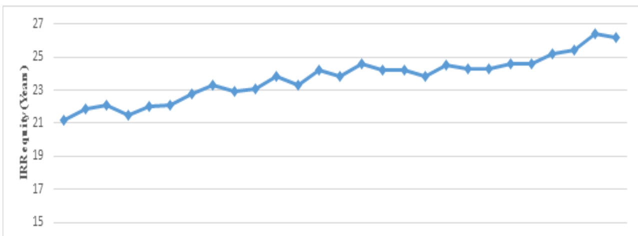
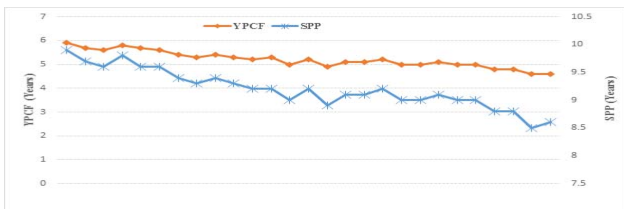


(b)



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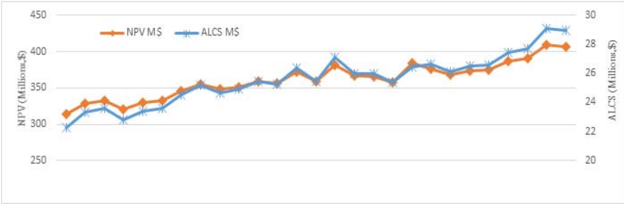

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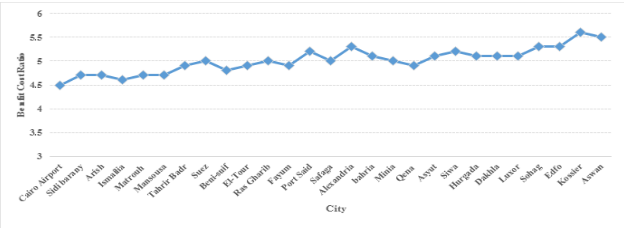

(e)

Fig.11. The variation of economical factors with the location of PV power plants.

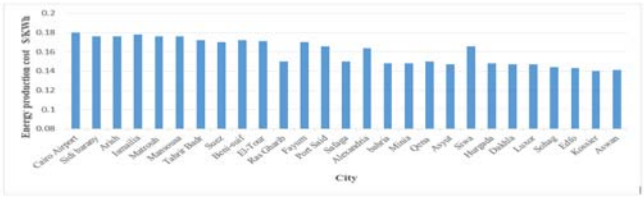

Fig.12. Energy production cost.

E. Greenhouse Gases Reduction

The amount of greenhouse gases represented as ton of carbon dioxide (CO_2), which could be prevented as a profit from the building PV solar power plants at the proposed locations are given in Fig. 13. From this study, it was noted that a total of 70,572 ton of CO_2 could be avoided at least in the local atmosphere if the power plant is established near Cairo airport. In general, 75,451.74 tonnes of CO2 per year can be avoided to reach the atmosphere from anywhere in Egypt because of the 100 MW solar power plant installed in such location.

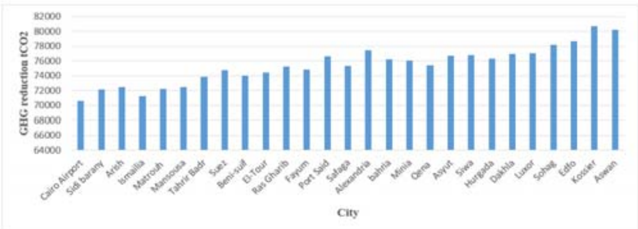

Fig.13. GHG reduction because of the use of PV power plants.

VI. CONCLUSIONS

The study highlights the following outcomes:

- The solar irradiation ranges from a minimum of 5.38 kWh/m^2/day at Cairo airport and a maximum of 6.64 kWh/m^2/day at Aswan while average value is more than 5.0 kWh/m^2/day.
- The sunshine duration varies from a minimum value of 12.108h at Minia to a maximum value of 12.142h at Safaga, while the average value over Egypt is 12.12h.
- The annual energy production from the proposed 100MW power plant varies from 154.3 GWh at Cairo airport to 176.53GWh at Kossier.

Based on these results and the results obtained from the economic feasibility analysis it is recommended that the southeastern of Egypt on the shore of the Red Sea and on the East of Nile River are the best locations for installation of large-scale PV power plants.

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