"CONSTRUCTION AND TECHNICAL PERFORMANCE OF RESIDENTIAL PHOTOVOLTAIC POWER SYSTEM"

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ABSTRACT:

Photovoltaic (PV) power system may become a competitive energy source for a single family residence with a roof top solar cell array. A proposed approach is introduced to identify and resolve engineering problems that may result from the use of residential PV systems. This approach is stated as a step-by-step to develop the construction and technical performance considering the peak power of the system, the performance of PV module used and installation site characteristics. Also, the electric system description, instruments, protection, maintenance and reliability verification are assessed.

The proposed approach is applied to a PV system of 1 kW peak power for residences at different Egyptian sites. Also, one year's solar data at the considered sites are used to show the operation performance.

Results of this work may be of significant value in regard to the construction and operation of residential PV systems in the near future in many of the world countries as well as in Egypt. Also, the proposed approach may be generalized to install residential PV system with different ratings (peak powers) at any site under various meteorological and operating conditions.

1- INTRODUCTION:

The solar energy option for energizing load demand in the regions above and below the Equator, extending from about 30° appears to be viable and worth consideration. This energy is non depletable and non polluting source. Photovoltaic power (PV) system is the main tool for conversion of solar energy into electricity. This is due to its low cost, high efficiency with respect to other alternatives, and require short time for construction [1].

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PV systems are more suitable for stand-alone operation, especially for remote applications, and can be connected to distribution or subtransmission systems. The utility power grid solves two major problems of PV generation. These are a guaranteed supply of power and the storage of excess energy generated. However, with no utility grid, a storage battery or / and back up diesel generator are commonly employed [2].

Because PV technology shows promise of commercial readiness for residential use before the end of this decade, it is incumbent upon authors to address the very practical and difficult issues before the technology is actively marketed. Some of these specific issues are:

- PV system analysis and performance verification.
- PV subsystems integration.
- PV system installation.
- Maintenance, durability and reliability.
- Residential PV system design.
- PV-utility interfacing.
- Residential PV system economics.

In 1979, the Florida Solar Energy Center began a feasibility study to determine the appropriateness and cost of designing and operating an experimental photovoltaic residence on its site at Cap Canaveral, Florida [3]. Also, a prototype PV system was built comprising the full-size PV array as would be used in a lived residence at the southwest in Las Cruces, New Maxico, by BDM Corporation [4,5].

For possible wide application of PV systems, the performance of a commercial PV module exposed to local field conditions has been investigated [6,7]. Also, residential PV system has been designed and its economy has been evaluated [8]. However, construction, subsystem integration, performance verification and maintenance of this system has not been developed. This paper presents an approach to solve the engineering problems associated with constructed and operating performance of residential PV system in Egypt.

2- PROPOSED APPROACH:

The approach introduced here is for constructing and evaluating the operating performance of a residential PV system. This approach is summarized as follows:

2.1- Construction of PV System:

The PV array size (S_v) required to identify the peak power of a PV system (P_{vp}), considering the installation site characteristics and the performance of PV module used, is given as:

$$S_v = P_{vp} / H_{tp}\, \eta_o\, f_p \qquad (1)$$

where; H_{tp} is the peak value of solar radiation received on tilted surface, η_o is the overall efficiency of PV system, and f_p is the packing factor, and η_o is given as:

$$\eta_o = \eta_m\, \eta_{pc}\, \eta_d$$

where; η_m is the module efficiency at normal operating cell temperature (NOCT), η_{pc} is the efficiency of power conditioner and η_d is the distribution and interconnection efficiency.

Corresponding to the standard area of the module used (S_{vm}) and S_v, the number of PV modules (N_m) is determined. Then, N_m is arranged in series and in parallel to produce the voltage required by the power conditioner. Also, these modules are configure into an array composed of strings and branches with by pass diodes to obtain the construction of PV array required.

2.2- Performance of PV System:

The solar data at PV installation site is used to determine the average daily solar radiation received on the PV array through the year months [9]. Then, the monthly (H_{tm}) and yearly (H_{ta}) solar radiation received on PV array are obtained as:

$$H_{tm} = \sum_{i=1}^{n} N_m S_{vm} H_{ti} \tag{2}$$

$$H_{ta} = \sum_{m=1}^{12} H_{tm} \tag{3}$$

where; H_{ti} is the average daily solar radiation received on PV array in kWh/ m^2 for month m, and n is the number of days of this month.

The monthly, $E_{vm}(DC)$, and yearly, $E_{va}(DC)$, DC energy output of the PV array constructed in section 2.1 are computed as:

$$E_{vm}(DC) = H_{tm}{*}\eta_m{*}\eta_d{*}\eta_{th}{*}f_p(1-f_s)(1-f_d) \tag{4}$$

$$E_{va}(DC) = \sum_{m=1}^{12} E_{vm}(DC) \tag{5}$$

where; f_s and f_d are the soiling and degradation factors respectively, and η_{th} is the efficiency of temperature correction factor to adjust module efficiency. The value of η_{th} is deduced monthly which is dependent on H_{ti} and the average monthly ambient temperature (T_{am}) at the considered site. It is determined as:

$$\eta_{th} = \begin{cases} 1 & \text{at } T_{cm} \le 45^\circ C \\ (1-0.004T_{om}) & \text{at } T_{cm} > 45^\circ C \end{cases} \tag{6}$$

where; T_{om} is (T_{cm} - 45) and T_{cm} is the average cell operating temperature during the month m and is given by [10]:

$$T_{cm} = T_{am} + 2.70\, H_{ti} \tag{7}$$

The monthly, $E_{vm}(AC)$, and yearly, $E_{va}(AC)$, AC energy output of the employed PV system are calculated as:

$$E_{vm}(AC) = E_{vm}(DC)\eta_{pc} \tag{8}$$

$$E_{va}(AC) = \sum_{m=1}^{12} E_{vm}(AC) \tag{9}$$

Thus, The average PV array efficiency is developed as function of H_{ta} and E_{va}. While the average PV system efficiency is deduced as a function of H_{ta} and $E_{va}(AC)$.

The PV System Capacity Factor ($C.F._{,v}$) is defined for the year months as follows:

$$C.F._{,v} = E_{vm}(AC) / P_{vp}\, n\, t_s \tag{10}$$

where; t_s is the average daily sun rise hours of the considered month.

The electrical system description, instruments, protection, maintenance, and system reliability verification and diagnostics are assessed for the proposed residential PV system as follows:

a- Electric system description: Each module utilizes a by-bass diode, and each string is isolated from the active array for current, voltage or other diagnostic measurements without disturbing the overall system operation. The control panel allows connection to inverters. Individual string currents are displayed on an ammeter panel located adjacent to the array control panel. These meters serve as gross indicators of individual string performance and facilitate module electrical degradation or failure.

b- Instruments: The instrumentation system of a PV residential facility can be classified into four subsystems. These are meteorological, DC, AC and house / array conditions. Meteorological subsystems are usually installed by Meteorological Authority (MA) over world countries. From these MAs, temperature, incident solar radiation on horizontal surface, wind speed/direction, rainfall, barometric pressure and ambient relative humidity are provided for different sites and days of the year. The DC subsystem incorporates voltage, current and energy information of the PV array. The AC power components monitored are the residential load and inverter output. A redundant energy monitoring system employing kWh meters which are used to record house usage and inverter supply energies.

c- System protection and grounding: Series blocking diodes are necessary to prevent the backed of energy from the power conditioner to the solar array. Also, the inclusion of bypass diodes across each module in the PV array minimises the effect of a module open-circuit failure on the total PV system performance, power output and efficiency.

Full-line-voltage restored and fuses are used to protect inverters. Two zink oxide resistor are connected between the positive and negative buses and grounded to absorb induced transient current. Also, full system is grounded. On the DC side of the system all metal parts associated with the array are connected to a single ground wire near the center of the array, then connected to earth ground. This grounding minimises the peak DC voltage stress to ground. The metal cabinet of power conditioner and all other metal enclosure within the building are also grounded [5]. If the inverter output to residential-AC service contains a neutral wire, it is required that the neutral be earth grounded at the residential load center. This connection establishes the AC ground.

d- Maintenance of PV array: During the system life-time, three areas of routine system maintenance are carried out. These are module failure detection, module's failure removal / replacement, and array washing [3].

Open-circuiting is the most common failure mode found with PV modules. The procedure for finding a module failure begins with disconnecting the inverter from PV array. Then, the open-circuit voltage of each string is measured during medium to high irradiance conditions. The string which has low voltage than other string has shadown module or modules. This module is identified as having open-circuit failure if it shows zero short-circuit current across the bypass diode of the module.

The second maintenance task is to replace a module or modules.

The final task of system maintenance is routine washing of PV array [5]. It is accomplished easily by a professional window washer using standard equipment and procedure.

e- System reliability verification and diagnostics: General performance and reliability is verified through the daily visual inspection of various meters. The array is also viewed to note any damaged or dirty modules.

At least once a month, detailed diagnostic checks are made on the system performance and reliability. These diagnostic checks include the power output and efficiency

3 - APPLICATION:

The proposed approach in section 2, and meteorological data are utilized to construct a 1 kW- PV system to supply residences at different sites of Egypt. These sites are Alexandria (31° 30′ N), Shebin El-Kom (30° 27′ N), Cairo (30° 5′ N) and Aswan (23° 52′ N). Polycrystalline photovoltaic modules are used here to complete the 1 kW peak roof array at the aforementioned sites. Each module has a gross area of 0.744 m^2 and a peak output of 60 watts [6]. Appendix (I) gives specifications of these modules.

The number of modules and the gross area of PV array are determined at different sites of Egypt and given as:

Site	Alexandria	Shebin El-Kom	Cairo	Aswan
No. of modules	20	20	18	16
Gross area of PV array	14.88	14.83	13.39	11.90

Figure 1 depicts the construction of the PV array at Cairo site. It consists of two parallel branches each contains 9 series modules. This construction is two parallel branches each contains 10 series modules at Alexandria and Shebin El-Kom sites, and two parallel branches each contains 8 series modules at Aswan site.

However, multi power conditioning units (PCUs) may result in lower values of lost production because only PCU portion of the field is shut down if one PCU fails [11,12], two PCUs each of them has a rated power of 500 W is used in this work. Figure 2 shows the electrical circuit of the proposed PV system for supplying residential loads. While Figure 3 illustrates the AC distribution panel and metering devices.

The hourly solar radiation and average monthly temperature at Cairo site measured by Meteorological Authority of Egypt are utilized here to develop the operating performance of the proposed PV system. Figure 4 shows the hourly solar radiation received on the array of this system [13]. This figure gives the average daily solar radiation received on unit area of PV array through the year months. The results of this figure are listed in Table 1. These results are tabulated in kWh for different year months (H_{tm}). These H_{tm} are used with Equation (4) to estimate monthly DC output of PV array study and listed in column 3 of Table 1. Column 4 of this table gives the average monthly PV array efficiency. The average monthly cells temperature is deduced by Equation (7) and given in last column of Table 1.

The monthly AC output of inverters in Figure 2 are determined, at an average inverter efficiency of 90 % [12], and listed in column 3 of Table 2. The monthly system efficiency is deduced and given in column 4 of Table 2. Equation (10) is used to estimate the monthly system capacity factor, and shown in last column of this table.

The results of operating performance of the proposed PV system at the considered site are obtained from Table 1 and 2 as:

Annual solar radiation received on PV array	: 26401	kWh
Annual DC output	: 2216	kWh
PV array average efficiency	: 8.42	%
Annual AC output	: 1996	kWh
System average efficiency	: 7.58	%
System average capacity factor	: 0.42	p.u.

Also, the operating performance of the proposed PV system is determined at other Egyptian sites study and revealed the annual AC output as 1685, 1870 and 2290 kWh at Alexandria, Shebin El-Kom and Aswan respectively.

The economical model in Ref. [14] is used here to develop the economy of the proposed PV system. This economy is deduced considering the following assumptions:

1-The capital investment of PV system (PV array, inverter, wire, etc.) is 2 $\$/W_p$.
2- The life-time of PV system is 25 years.
3- The interest rate is 8%.
4- The running cost is 2 % of the captial investment.

Figure 5 gives the unit energy cost (UEC) of the proposed PV system at the study sites of Egypt. This figure concluded the UEC as 11.1, 10.0, 9.4 and 8.2 ¢/kWh (37.4, 34.0, 31.7 and 27.9 ps/kWh) at Alexandria, Shebin El-Kom, Cairo and Aswan sites respectively.

CONCLUSIONS:

A proposed approach has been introduced in this paper to evaluate overall residential PV system construction, electric system description, instruments, protection, and maintenance. Also, the operating performance of this system is assessed considering the peak power of the system, the performance of PV module used and installation site characteristics. This approach is applied to evaluate a standard 1 kW peak PV system for residences at different sites of Egypt. The remarkable results of this application are:

1-The PV array area varies from 11.9 m^2 at Aswan site to 14.88 m^2 at Alexandria site, and the number of modules varies from 16 to 20 at the aforementioned sites.

2-PV array efficiency varies from 8.46 - 8.53 % in winter months and from 8.23 - 8.32 % in summer months.

3-PV system energy output varies from 66 - 233 kWh through the year months.

4-PV system efficiency varies from 7.41 - 7.67 % through the year months.

5-The capacity factor of the PV system varies from 0.18 - 0.52 through the year months.

6-The substrate temperature of array is approximately 6-23° C above the ambient temperature.

7- The unit energy cost varies from 8.2 -11.1 ¢/kWh.

These results which are obtained from the construction of 1 kW peak residential PV system is invaluable and widely applicable to the design and construction of other PV system of comparable size. The operating performance obtained is also invaluable.

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APPENDIX (I)

The specification of polycrystalline PV module at an insolation of 1 kW/ m^2 and 45° C [6]:

Peak power, watt	: 60
Voltage at peak power, volt	: 17.1
Current at peak power, ampere	: 3.51
Gross area, m^2	: 0.744

Table (1): The Operating Performance of PV Array Study at Cairo site.

PV Array Data / *Month*	*Solar Radiation Received on PV Array, kWh*	*PV Array DC Output, kWh*	*PV Array Efficiency, %*	*Average Ambient Temperature at Noon, °C*	*PV Array Cell Temperature at Noon, °C*
January	869	74	8.51	14	19.9
February	1790	152	8.49	16	29.7
March	2631	223	8.48	20	38.7
April	2620	222	8.47	24	43.9
May	3116	258	8.28	27	50.3
June	2942	242	8.23	29	52.0
July	2650	220	8.30	30	50.0
August	2766	230	8.32	29	49.5
September	2148	182	8.47	27	43.0
October	2211	187	8.46	26	41.0
November	1732	147	8.49	21	33.0
December	926	79	8.53	16	22.2

Table (2): The Operating Performance of PV System Study at Cairo site.

PV Array Data / *Month*	*Solar Radiation Received on PV Array, kWh*	*PV Array AC Output, kWh*	*PV System Efficiency, %*	*System Capacity Factor, p.u.*
January	869	66	7.60	0.18
February	1790	137	7.65	0.41
March	2631	201	7.67	0.54
April	2620	200	7.63	0.48
May	3116	233	7.48	0.54
June	2942	218	7.41	0.52
July	2650	198	7.47	0.46
August	2766	207	7.48	0.48
September	2148	164	7.64	0.42
October	2211	169	7.64	0.45
November	1732	132	7.62	0.40
December	926	71	7.67	0.21

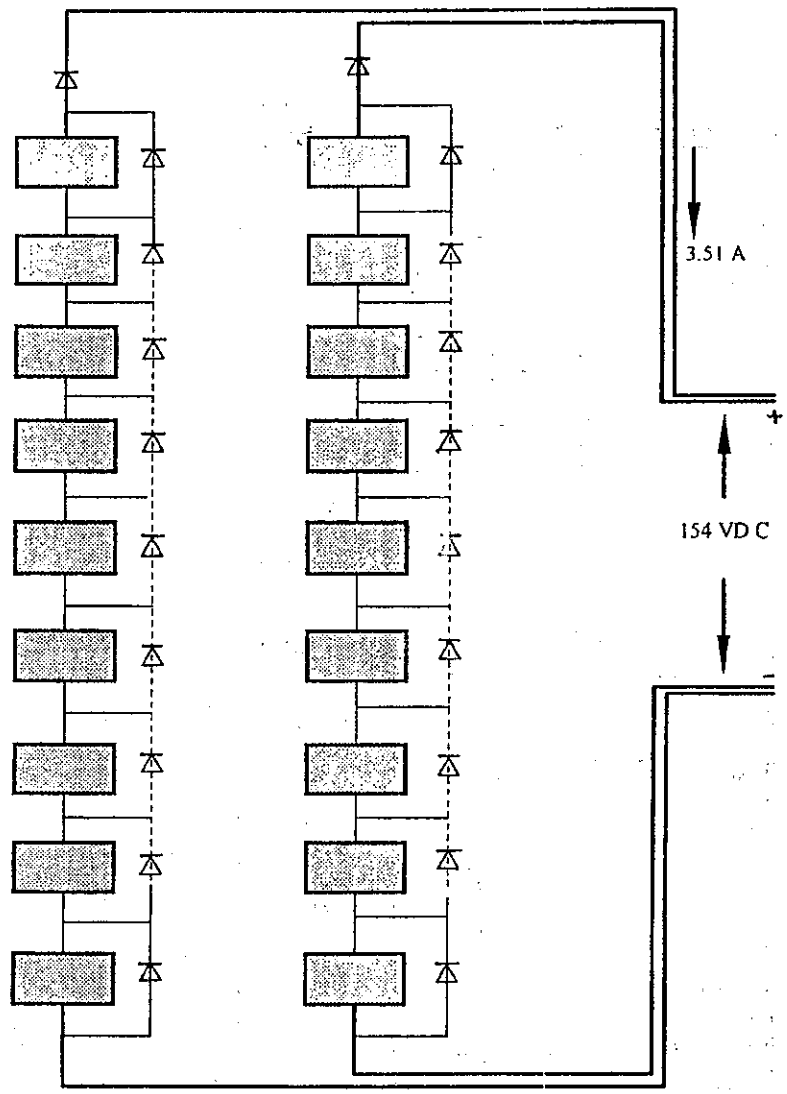

Figure (1): PV array construction at Cairo site.

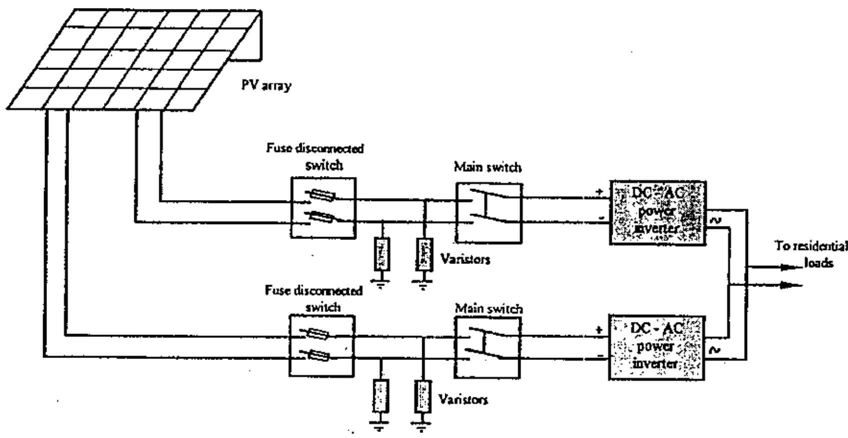

Figure (2) : Electrical circuit of the PV system study.

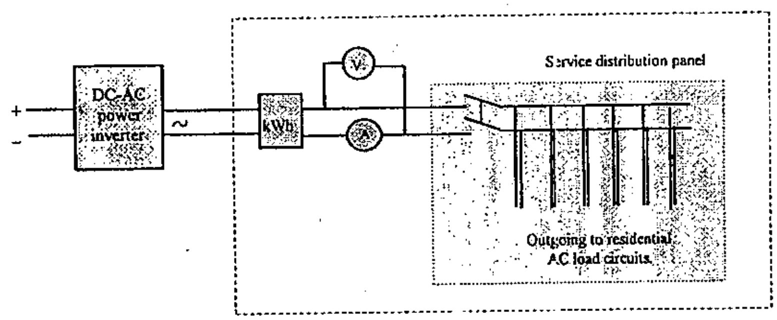

Figure (3): The line diagram of AC distribution panel and metering devices.

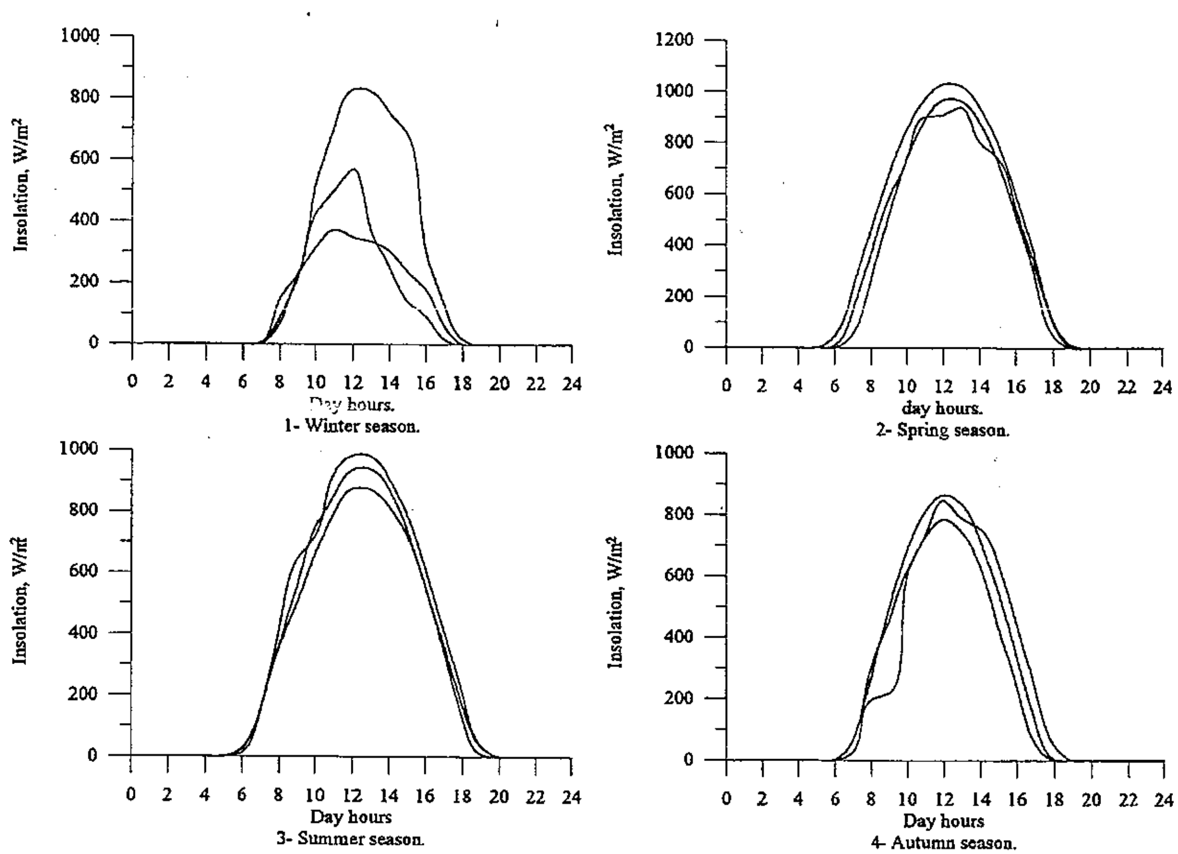

Figure. (4): The solar radiation received on unit area of PV array installed at Cairo site for different year months, [13].

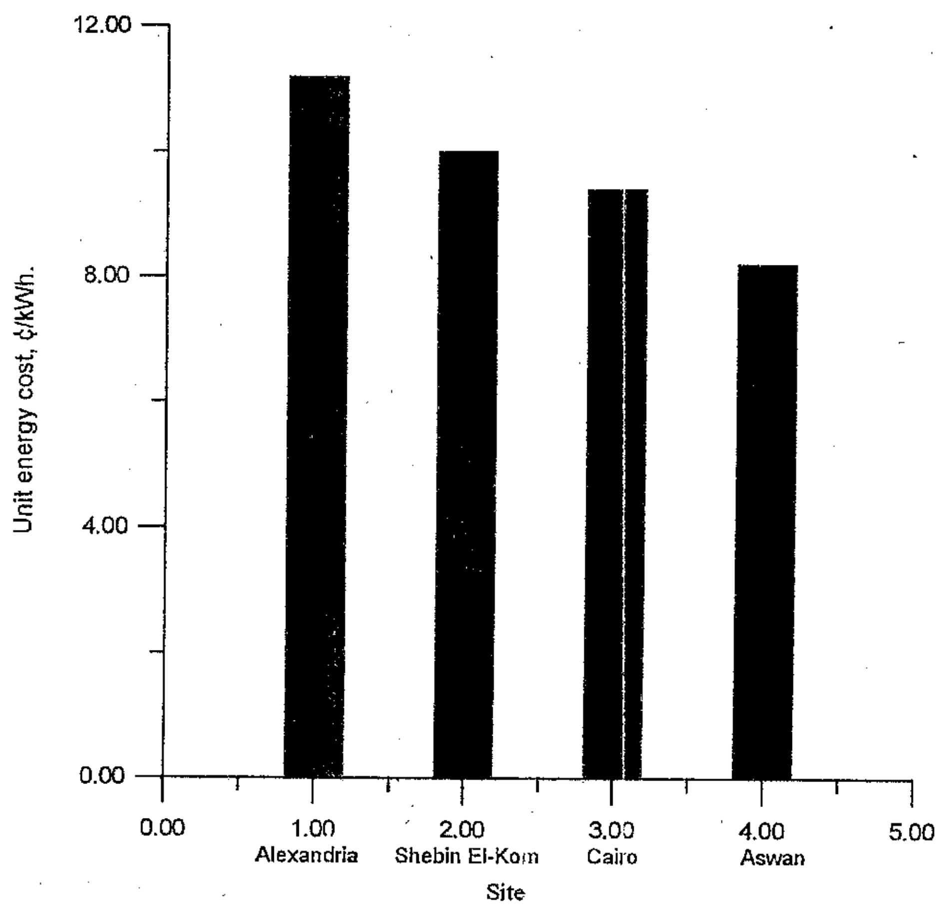

Figure (5): The unit energy cost of the PV system study at different sites of Egypt.

بسم الله الرحمن الرحيم

"الخواص الفنيه والتركيب لمنظومة القوى الفوتوفولتيه المستخدمه لتغذية الأحمال المنزليه"

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الملخص العربى:

اقترح فى هذا البحث طريقه لأيجاد الحلول الهندسيه للمشاكل الناتجه من تركيب منظومات القوى الفوتوفولتيه لتغذية الأحمال المنزليه. وقد اشتملت هذه الطريقه على خطوات تركيب المنظومه الفوتوفولتيه وايجاد الخواص الفنيه لهذه المنظومه اعتمادا على أقصى قدره، خواص الموديل الشمسى المستخدم وخصائص الموقع المراد اقامة المنظومه الفوتوفولتيه فيه. كما تم ايضاح الدوائر الكهربيه، أجهزة القياس والحمايه وطرق الصيانه اللازمه لهذه المنظومه لتحقيق الوثوق (Reliability) فى تشغيلها لتغذية الأحمال المنزليه.

وقد تم تطبيق الطريقه المقترحه لتركيب منظومه قوى فوتوفولتيه ذات قدره ١ ك. وات فى مناطق مختلفه من مصر، كما تم ايجاد خواص التشغيل لهذه المنظومه خلال عام. وقد أوضحت النتائج فائدة الطريقه المقترحه لتركيب منظومه القوى الفوتوفولتيه لتغذية الأحمال المنزليه، حيث أوضحت خواص التشغيل التى تم الحصول عليها امكانية التوسع فى تشغيل منظومات القوى الفوتوفولتيه لتغذية الأحمال المنزليه فى المواقع المختلفه من مصر.