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NEW INVESTIGATION ON THE APPLICATIONS AND COMPUTER SIMULATION OF PHOTOVOLTAIC CELLS AND STORAGE SYSTEMS

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ABSTRACT

A complete model is proposed as a tool to simulate and optimize photovoltaic cells and storage systems. The normalized form of the equations with respect to the battery capacity allows us to generalize its use for any type and size of batteries. The validity of this model to represent the battery voltage evolution during charge, overcharge and discharge processes and to predict the performance of solar systems under different operational conditions is analyzed. Moreover, the battery efficiency losses are presented as a function of the upper regulation thresholds of the charge controllers and the size of the array and storage systems in a domestic application in the climate of Egypt.

KEYWORDS: Photovoltaic cells, storage systems**,** battery efficiency**,** overcharge and discharge processes.

INTRODUCTION

People generally find it more difficult to accept solar energy merely as a means of reducing fuel consumption than as a complete alternative to the conventional utility electric sources. One reason to day may be that providing a 100 % solar energy to a project usually results in costly a system to be practical. Secondly, assurances for proper functioning of the solar system in providing and storing solar energy in cloudy and no-sun conditions, for- several days, are questionable. The greatly increased cost of fuel (Fig. 1a), however, is changing the economics of applying solar systems [1-3]. The possible rate of growth of the solar energy supply is suggested by the curves in Fig. (1b), where the growth in the market fraction commanded by a given energy source is plotted for both conventional and the newer alternative energy sources [4].

Distribution of Solar Energy All Over the World

It is common knowledge that solar radiation is unevenly distributed, and that it varies in intensity from one geographic location to another depending upon the latitude, season, and time of day [5, 6]. Until recently, valid records for solar radiation have been very scanty in the vast majority of the developing countries. In the absence of such useful information as a guide for the proper exploitation of solar energy, only general hints can be offered regarding the geographic areas with favorable conditions for solar energy applications. For convenience and simplicity, the geographic distribution of total solar radiation on a global scale is divided in terms of intensity into four broad belts around the earth. These are shown in Fig. (2), and also described briefly hereunder with respect to the northern hemisphere, with the under- standing that the same conditions apply to the corresponding belts in the southern hemisphere:
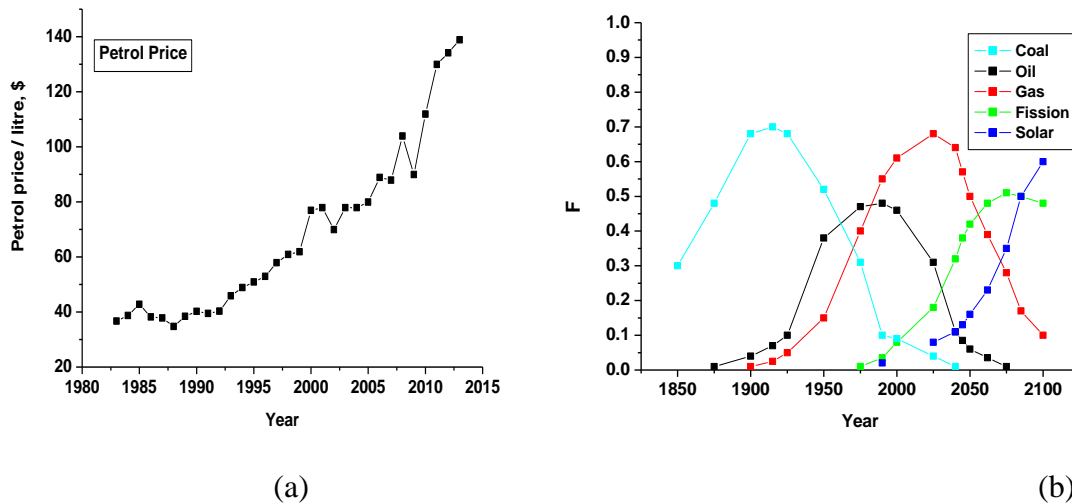
(a) (b)

Fig. (1) : Petrol price increase during the period 1980-2013 (a), and history and projection
of energy sources for the world (b), plotted versus year ("F" is a fraction of the
of the total market supplied by a given energy source).

Most favorable belt: This belt embraces the regions that are naturally endowed with the most favorable conditions for solar energy applications. These semi-arid regions are characterized by having the greatest amount of solar radiation, more than 90 % of which comes as direct radiation because of the limited cloud coverage and rainfall. Moreover, there is usually over 3,000 hours of sunshine per year.

Moderately favorable belt: This belt is the next most favorable, because the humidity is high, and cloud cover is frequent, the proportion of scattered radiation is quite high. There is a total of about 2,500 hours of sunshine per year.

Less favorable belt: In this belt, the average solar intensity is roughly about the same as for the other two belts, but there are marked seasonal variations in both radiation intensity and daylight hours. During the winter months solar radiation is relatively lower than in the rest of the year.

Least favorable belt: Here, about half of the total radiation is diffuse radiation, with a higher proportion in winter than in summer, primarily because of the rather frequent and extensive cloud coverage.
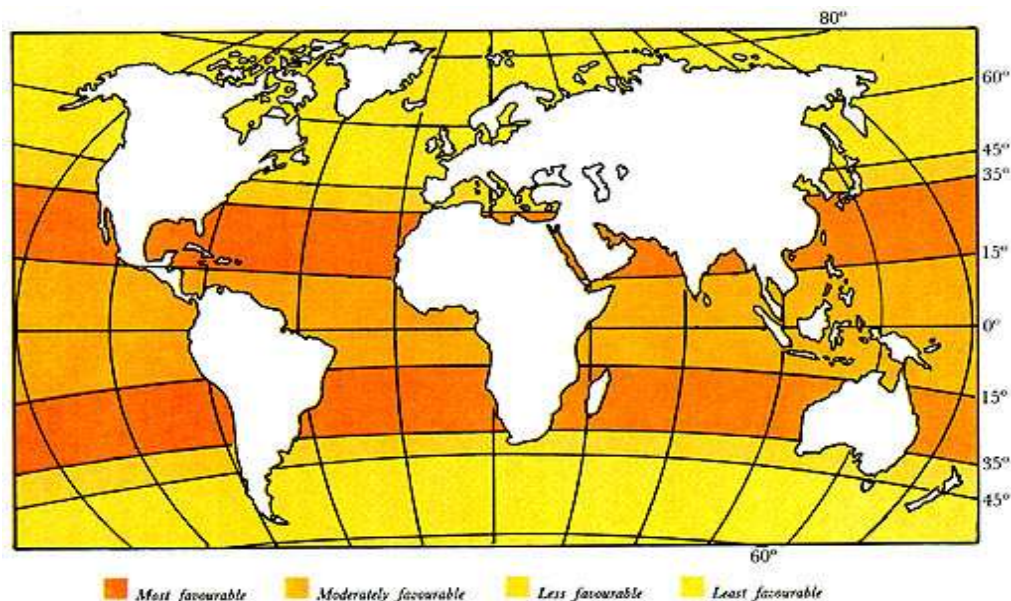

Fig. (2) : Worldwide distribution of solar radiation into belts indicating feasibility
of solar applications.

Atmospheric Effects on Solar Radiation

The Earth receives 174 petawatts (PW) of incoming solar radiation (insolation) at the upper atmosphere. Approximately 30 % is reflected back to space while the rest is absorbed by clouds, oceans and land masses (Fig. 3). The spectrum of solar light at the Earth's surface is mostly spread across the visible and near-infrared ranges with a small part in the near-ultraviolet.

Earth's land surface, oceans and atmosphere absorb solar radiation, and this raises their temperature. Warm air containing evaporated water from the oceans rises, causing atmospheric circulation or convection. When the air reaches a high altitude, where the temperature is low, water vapor condenses into clouds, which rain onto the Earth's surface, completing the water cycle. Finally, the total solar energy absorbed by Earth's atmosphere, oceans and land masses is approximately 3,850,000 exajoules (EJ) per year. In 2002, this was more energy in one hour than the world used in one year. Photosynthesis captures approximately 3,000 EJ per year in biomass. The technical potential available from biomass is from 100–300 EJ/year. The amount of solar energy reaching the surface of the planet is so vast that in one year it is about twice as much as will ever be obtained from all of the Earth's non-renewable resources of coal, oil, natural gas, and mined uranium combined.

The Solar Constant

The radiation intensity on the surface of the sun is approximately 6.33×10^7 W/m^2. Since radiation spreads out as the distance squared, by the time it travels to the earth (1.496×10^{11} m or 1 AU is the average earth-sun distance), the radiant energy falling on 1.0 m^2 of surface area is reduced to 1367 W as depicted in Fig. (4).
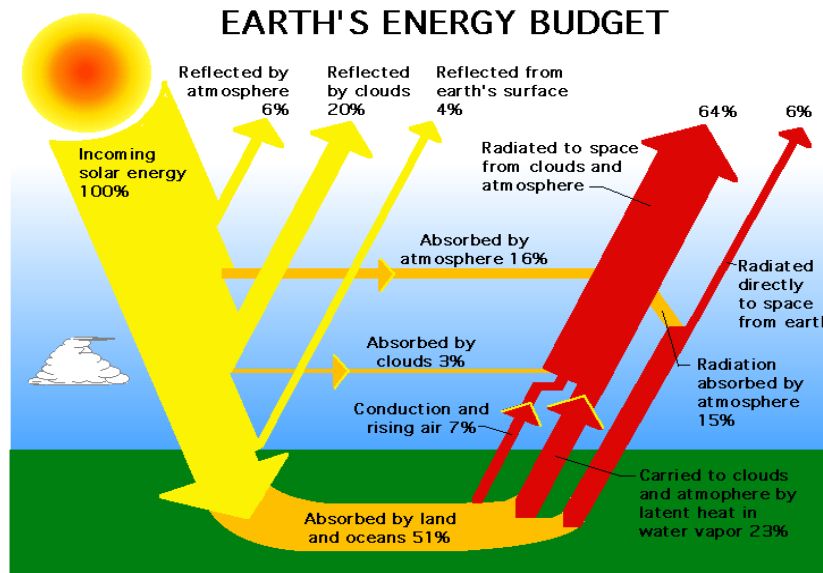

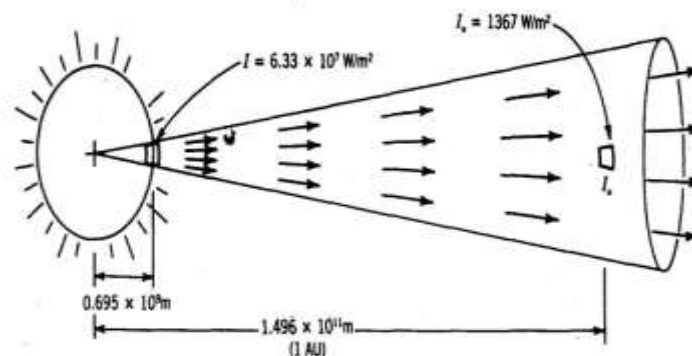*Fig. (3) : Typical absorption and scattering of incident solar energy.*

Fig. (4) : Divergence of energy from the sun to the earth.

Market Size and Distribution

The market for photovoltaic (PV) modules has grown at an average annual rate of over 15 % for the last decade to a present size (in 1993) of approximately 65 MW$_{peak}$ per year **[7].** With increased involvement of utilities and

lending in situations, such as the World Bank, this rate is expected to approach 20 % by the end of the decade. Of particular interest is the strong differential growth rate in rural consumer segment, which now accounts for nearly half of the total PV market, versus slightly over 25 % at the start of the decade. The second largest market segment, comprising slightly over 30 % of the present market, is for industrial applications. This market will remain a significant portion of the total business through the remainder of the decade (Fig. 5).
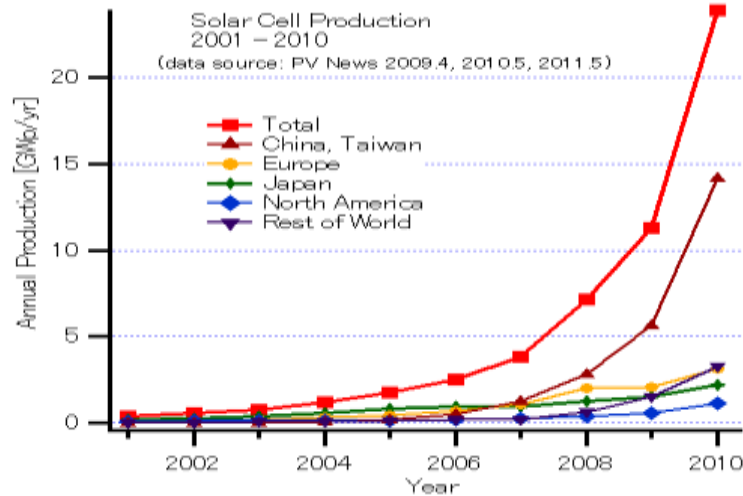

Fig. (5): Solar cell production within the period 2001-2010.

By 2015, installed solar capacity will grow another 347 % to over 72.0 gigawatts as utilities worldwide are incentivized and forced to adopt sustainable production assets, and as solar energy reaches price parity in a growing number of markets (Fig.6). In order for those forecasts to hold true, improved policy is going to have to do battle with current economic conditions.
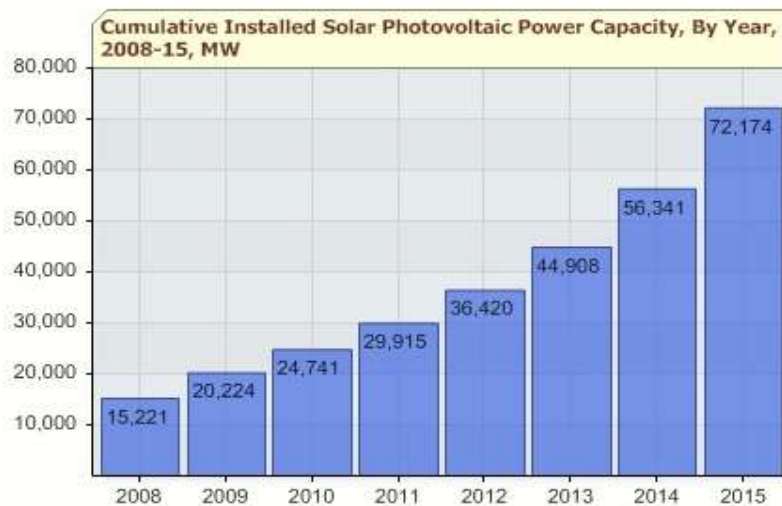

Fig. (6): Cumulative installed solar photovoltaic power capacity, by year 2015, MW.

Solar Radiation Intensity at Egypt
Solar radiation intensity at Egypt was measured [7, 8] to be with a maximum value of 135000 lux at summer, while its value at winter decays to about 50 % of the maximum value. The sunshine duration at Cairo, Egypt reaches on the average 13.0 hours in summer and 10.0 hours in winter. All over the day time, the light intensity is quite sufficient to drive the solar system into its maximum output voltage which in turn is quite convenient for storing energy using batteries. From that, it is clear that we ought to move to the solar energy which is an infinite source, where many attracting applications, either simple or complex, are proved.

Advanced Photovoltaic Cells

Some new versions of passivated emitter and rear locally diffused (PERL) cells demonstrated open circuit voltage of 709 mV with a one-sun efficiency of 23.50 % [9], the highest ever for silicon. Besides, the PERL cell (passivated emitter and rear cell) have recently demonstrated improved cell performance owing to the high quality surface passivation and high bulk carrier lifetimes [10]. Noting that, a maximum solar-to-electrical power conversion efficiency of just over 37.7 % is achievable by harvesting UV to near IR photons up to 1.10 eV. dye-sensitized solar cells [11]. Where, it is announced, at Dec., 2012, that Sharp corporation has achieved the world's highest solar cell conversion efficiency of 37.7 % using a triple-junction compound solar cell in which three photo-absorption layers are stacked together (Fig. 7). Sharp achieved this latest breakthrough as a result of a research and development initiative promoted by Japan's New Energy and Industrial Technology Development Organization (NEDO) on the theme of "R&D on Innovative Solar Cells." Measurement of the value of 37.7%, which sets a new record for the world's highest conversion efficiency, was confirmed at the National Institute of Advanced Industrial Science and Technology (AIST).
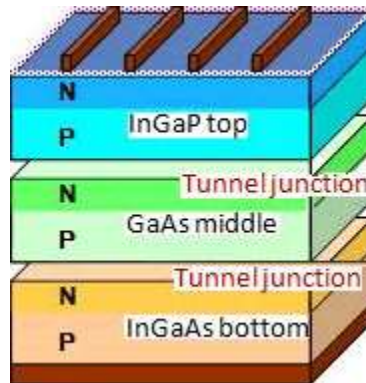

Fig. (7): Structure of triple-junction compound solar cell.

COST ANALYSES FOR PHOTOVOLTAIC POWER

The dependence of the level and the cost of PV power upon the characteristics of the application and the user are of the most part intuitively clear. The cost falls as the cost per watt of the solar cell modules drops, and the cost increases with increasing recurring costs of operating and maintaining the system. If the array efficiency decreases, because of aging or is otherwise reduced, by under utilization during some months when the load is light, this will increase the effective cost of the power produced and consumed. These dependencies are expressed as:

$$E = 10^5 \, (C.F)/U.S + OM \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

In this equation E, the cost in \$/kWh, is levelized, i.e., it is the ratio of the total costs incurred throughout the life of the system, divided by the number of peak kilowatt hours of energy the system produces in its useful life. C is the installation cost of the system in $\$/W_{pk}$. S is the ratio of the energy in kWh generated annually to the power rating of the system in kW_{Pk}; under ideal conditions. S equals the number of hours in a year divided by the daily average to peak insolation. The utilization factor U, accounting for factors that tend to reduce system output or its value. OM is the operation and maintenance cost, cent/kWh. Finally, F is the fixed-charge rate that represents the cost of financing the system. It equals the sum of the annual capital-related charges divided by the initial installed cost of the equipment.

Issues of Energy Storage

Only the storage of electrical energy is considered here (Fig. 8), because some PV systems also generate thermal energy, but the storage of thermal energy is well covered. In general, there is a need for energy storage in a PV systems that is not connected to a utility grid.
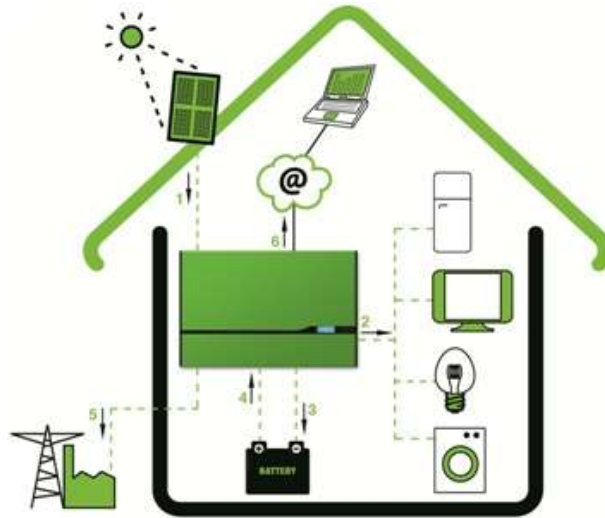
Fig. (8): Solar energy system with built-in battery storage.

Solar Battery Storage

The solar battery is the perfect solution to utilize self-generated solar power. For those small and medium-sized systems, the lead-acid battery is currently the only practical means of storage. These batteries can last more than 2100 deep discharge-charge cycles at a reasonable premium in price. Lead in the lead-acid battery accounts for both the large weight and the high cost of the battery. Advanced batteries avoid the use of expensive materials, from which, are those shown in Table (1), which lists some of the most intensely pursued developmental batteries [12].

Table 1: Some Advanced Batteries.

Battery Type	Cycles to 80 % discharge	Normal Life span	Price per kWh for life of battery	Price per kWh including maintenance, & installation
Marine/RV Battery	150	1 year	$ 0.75	$ 1.00
Deka Golf Cart Battery	500	5 to 6 years	$ 0.26	$ 0.34
L16P (regular)	700	4 to 8 years	$ 0.22	$ 0.30
Trojan T105 RE	1000	10 to 12 years	$ 0.16	$ 0.22
Hup Solar-One	2100+	18 to 24 years	$ 0.14	$ 0.16

Advanced Lithium Polymer Battery with Nano

The new and unique design that Exergonix [13, 14] is introducing is a novel technology to be used for future grid storage systems in a vast array of applications (Fig. 9). The use of nano materials allows the battery to have significant increases in power, energy, and cycle life. Now energy storage systems can be systematically built to obtain the 10+ year calendar life needed in the real world [15].
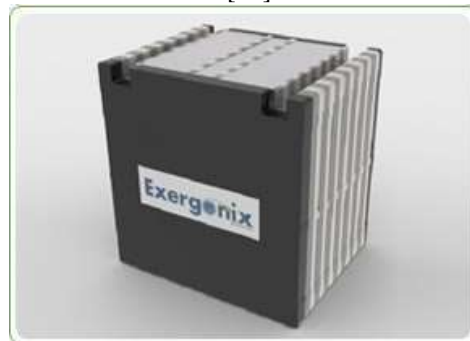

Fig. (9): Lithium Polymer Battery with Nano.

Exergonix has designed a community scale energy storage system for smart grid applications (Fig. 10). This system uses nano based cells with 30kWhr battery, and is capable of peak delivery exceeding 200 kW when coupled with an appropriate power conversion system. Using the nano based cell technology, Exergonix utilizes its state of the art battery design to manufacture the Battery Energy Storage System (BESS) for smart grid and other applications. The 1.0 MW system is manufactured using a segmented 500 KWh structure where there are two separate units that are each independently controlled by proven power control electronics. The BESS is contained in a fully independent seismic rated enclosure that is approximately 45 feet long where the storage system, bidirectional converter, power controls, system voltage controls, and fire suppression are all included. Depending on the mode of operation the system can be installed in a building or a smaller enclosure where walk-in access is not critical.
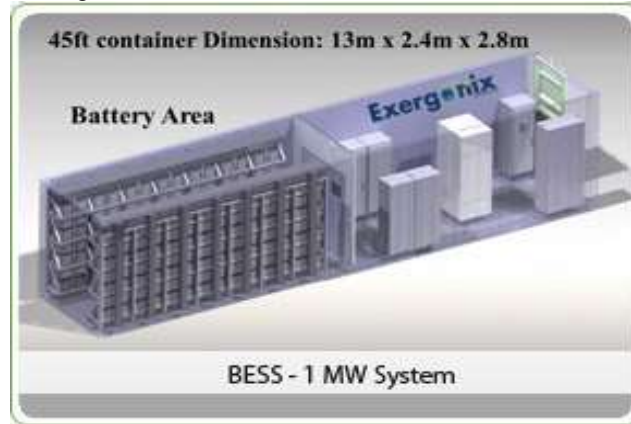

Fig. (10): storage system for smart grid applications.

COMPUTER MODELING AND ENERGY BALANCE SYSTEMS

Energy balance condition and the system analysis considered in this investigation could be understood as the total energy available from the solar arrays which would be divided into the energy required for charging the battery system, energy consumed by the load and also any other equipment and losses. However, if utility back up is easily provided, the investigated model for energy balance will be met even for a long period of cloudy or no-sun conditions. In this work computer evaluations of solar system, sizes of storage and solar-array for any load demand regarding the deficit and surplus are also presented. The model includes and discusses the minimum cost conditions for the system under various load demand to properly evaluate the right system for a certain application.

The model begins with the array size of the solar system and ends with the energy supplied to the load. Regarding the total energy received in different months [7], climate data plays an important role in this analysis [16-19]. It also affects to a large extent the design of the storage capacity of batteries employed. In order to show this, consider Fig. (11a) which illustrates the block diagram of the system in which the surplus and deficit situations are shown. This would be directly translated into cost. It is seen from Fig. (11b) that the received energy is not enough to supply the load and batteries simultaneously and may not 'be enough, in some cases, to supply the load only. In such case this received energy is used to complete the charge of the batteries utilized to their prescribed level in order to sustain further working hours if a utility backup is available, otherwise, the load operation may not be met. This amount of energy in which the system fails to supply the load demand is named as deficit (Fig. 11c). However the surplus means that the received energy is not only enough to supply the load but also to provide enough charge for the battery to maximum capacity and excess energy would be still available. Consider the circuit of Fig. (11a), in which the following quantities are defined as:

Ep : energy from PV solar arrays taking into account climate conditions for each month (in
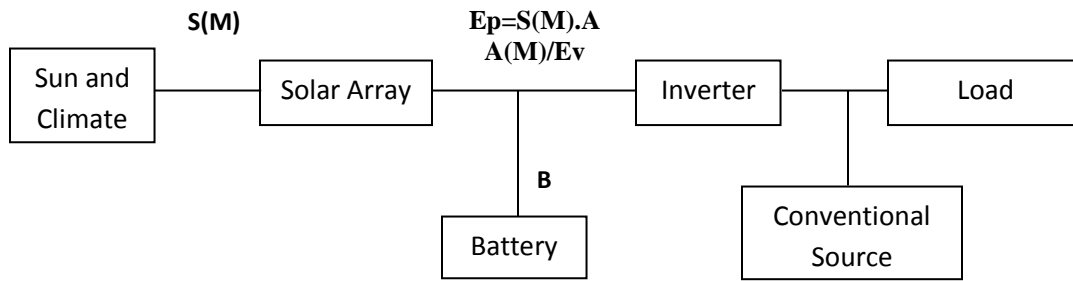   average), which is considered with the optimum tilt angle [19].

Al : PV array size.

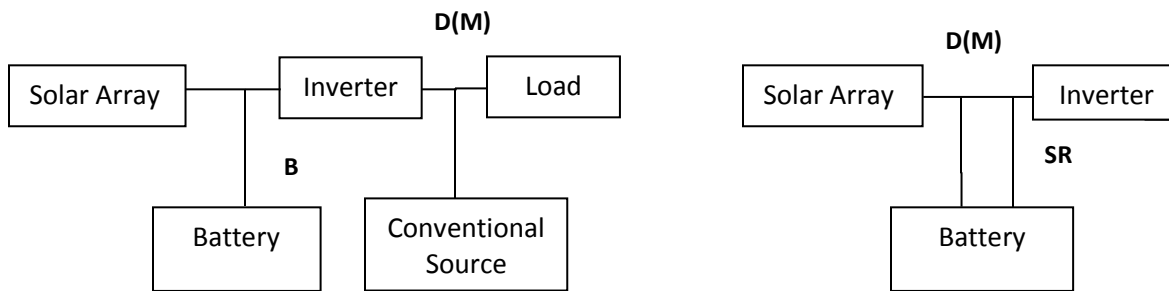CB : recent capacity of batteries (in kWh).

EB : battery efficiency.

Cre : recovery capacity required for batteries to raise the capacity from C_r to C_{MAX} (in kWh).

D   : load demand during the day.

N_1 : energy drawn from the batteries to the load.

(a) Block Diagram of Photovoltaic System.

(b) Deficit   *(c) Surplus*

Fig. (11): Block diagram of the solar system (a) in which, the deficit (b) and surplus, and (c) situations were shown.

S_r : surplus energy in excess to be stored because the batteries are fully charged.

C_{MAX}: maximum capacity of batteries which is (in kWh) Calculated according to day and night load demand

N_C : number of days required to reach the maximum charge.

N_A : number of days in the month at which batteries reach minimum state of charge.

N_D : number of days required for recovery.

S_B : battery storage capability.

C_{MIN}: minimum capacity of batteries in kWh.

E_V : inverter efficiency; if it exists in the system.

The energy entering the batteries during the day is given as:
$$A = E_P - D.E_V \ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..\dots..(2)$$
if $A > 0$, energy is applied to the battery, and if $A < 0$, energy is extracted from it. So, according to the state of charge in the batteries, capacity changes may amount to d_{CB}, where:
$$dC_{BA} = A * E_B \quad \textbf{if A > 0} \ \dots\dots\dots\dots\dots\dots\dots\dots.\dots\dots\dots\dots\dots\dots\dots..\dots\dots\dots(3)$$
$$dC_{BA} = A / E_B \quad \textbf{if A < 0} \ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots...(4)$$
During the night, battery discharges and supplies the nightly load demand "N" and the resulting change in battery state of charge is thus dC_{BN}, where:
$$dC_{BN} = - N / E_B \ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..\dots\dots\dots..(5)$$
The battery state of charge is given by summing up dC_{BN} to the previous charge value, C_B. However C_B must remain within the limit:
$$C_{MINI} < CB < C_{MAX} \ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..\dots\dots\dots\dots(6)$$
If the lower limit is reached, the "deficit" would be given as :
$$E_D = D + N \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..\dots(7)$$

Reaching the lower limit of storage in batteries, the load may be backed up by the conventional utility or the load-demand would not be met such as in the case of remote areas or in cloudy or no-sun conditions. In this case the low energy collected by the PV arrays is provided to the batteries. This is done only to keep the battery charge above its lower limit in order not to reduce the battery service life, then:

$$dC_{BA} = E_P * E_B \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots......(8)$$
$$dC_{BN} = 0 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(9)$$

This situation remains unchanged till the prescribed state of charge C_{re} has been restored. The system then switches back to the normal mode of supplying the load and storage together. If the battery reaches the upper limit, and still a generated energy supplied to the load, a surplus is reached, where:

$$E_S = E_p - D. E_V \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. (10)$$

The energy balance is easily performed daily with the help of a computer. The battery storage capability can be conventionally expressed in terms of the number of days through which the battery could feed the load. This amount of energy stored would provide energy to the system in cloudy days or no sun conditions or during a performed maintenance without the support of energy collected by solar array. This energy stored in the batteries is given as:

$$S_B = (C_{MAX} - C_{MINI}) E_V . E_B / (D+N) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(11)$$

Monthly Calculations

The average energy per month could be used in the calculation. The load demand is given also in monthly average values and is considered to be constant in the illustrative example given, which is 2.0 kWh consumption rate. The flow chart of the computer program developed in this investigation includes the above procedures (Fig. 12), in which the year divides into 12 months each is of 30.4 days on the average. Each month is characterized by the index M, running from 1 to 12. Within each month the day number is running from 1 to 30.4. A set of input data are read considering the optimum tilt angle which is equal to the latitude angle of Egypt, namely 30.1 degree. Quantities represent the solar arrays namely Al and C are provided. At this point the program sets up the battery charges C_l, C_{re} and C_B to a suitable initial values (C_B = C in the given example). At the end of each month, quantities such as energy balance, battery state of charge, "surplus and deficit" are calculated.

Optimum Cost Conditions

Different situations obtained by performing the energy balance of the system for different PV array size and batteries of different sizes are collected. These results are displayed into a map as shown in Fig. (12). The battery storage capability covers more days of load demand, the PV array size is smaller and the deficit of the system is reduced. Inversely, the smaller is the battery size the higher is the deficit and PV array size [20-22].

The cost of energy generated by any energy system that does not require fuel is solely due to the amortization of the capital and operation and maintenance, if taxes and insurance charges are neglected. This cost can be expressed as [23]:

$$X = \{[(r (1+r)^n) / ((l+r)^n -1)] + m\} . (p/87.6 k) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.(12)$$

where:

X : generation cost per kWh.

k : annual average production factor.

m : fraction of the capital cost needed per year for operation and maintenance of the system.

n : amortization period in year.

p : capital cost per kW.

r : annual interest rate per system.

Knowledge of the above cost allow to define a curve for the cost of the system element as a function of the PV array size with-constant deficit as shown in Fig. (13b). Such a curve obtained from curve in Fig. (13a) by considering horizontal lines of constant deficit and consequently defines the corresponding PV array size. Considering also, that the cost of each deficit value has a condition, for a given PV size and corresponding optimum number of days required for storage. The minimum value of each curve is considered to be the optimum balanced condition among the battery size, PV array size and corresponding cost.

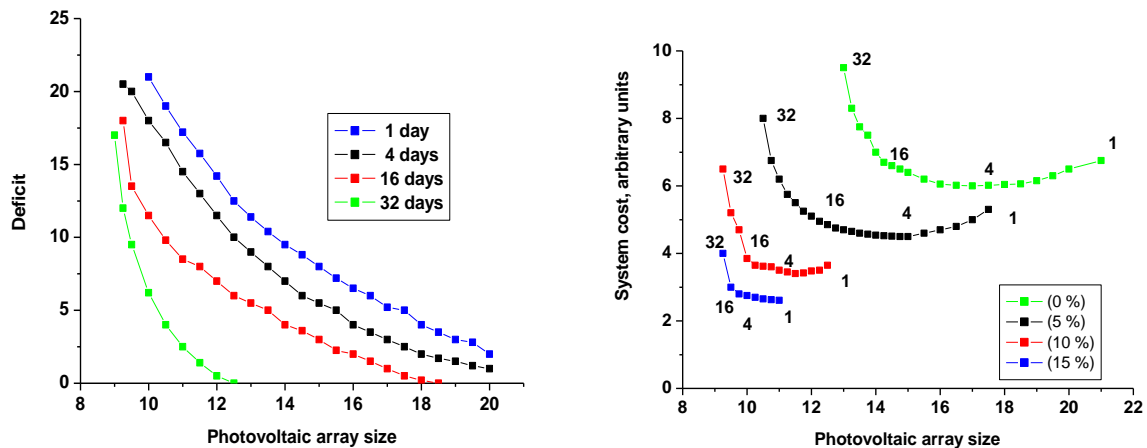*Fig. (12): Flow chart of the developed computer program.*
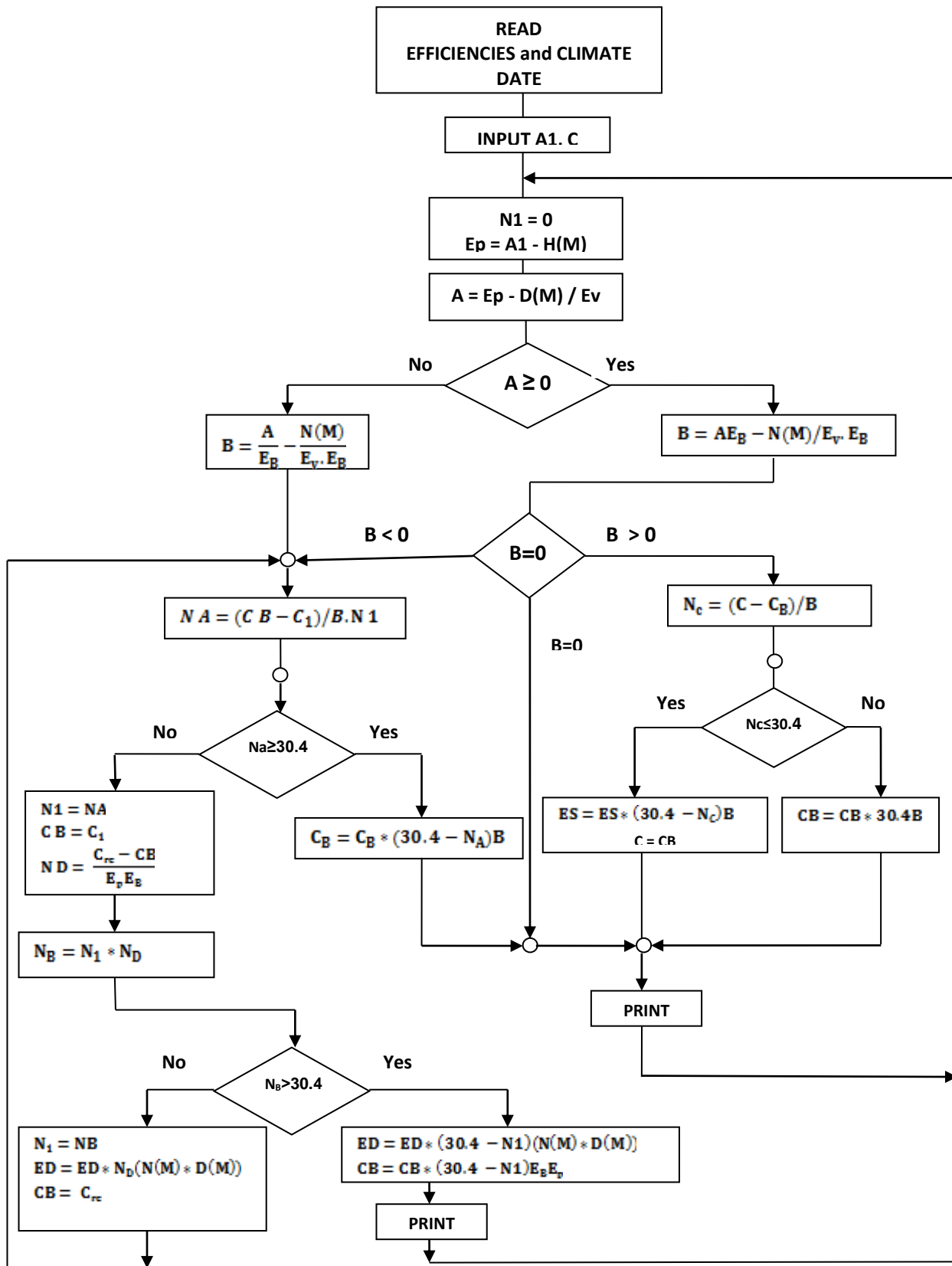
Fig.13: (a) The obtained situations by performing the energy balance of the system for different PV array and batteries sizes, and (b) cost of the system element as a function of PV array size with constant deficit.

CONCLUSION

The proposed procedure can be followed in order to analyze a solar system from points of view of "deficit" and "surplus" conditions. The map of cost versus PV array-size gives the minimum cost condition for each allowable "deficit" of a certain considered system. For each load the map of cost can be setup in the same way according to the model of the employed system.

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