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Design and Power Quality Improvement of Photovoltaic Power System

Springer

Chapter 1
Introduction and Background of PV Systems

1.1 Concept of Research Work

Increasing environmental concerns regarding the inefficient use of energy, climate change, acid rain, stratospheric ozone depletion, and global dependence on electricity have directed attention to the importance of generating electric power in a sustainable manner with low emissions of GHGs, particularly CO_2. In Egypt, total GHG emissions were estimated at 137.11 Mt of CO_2 equivalent, out of which more than 70 % was emitted from energy sector including about 35 % attributed to the electricity sector [1]. In the context of addressing environmental issues and climate change phenomena, Egypt signed Kyoto Protocol in 1997 and approved it in 2005. According to the Kyoto Protocol, the developed and industrialized countries are obliged to reduce their GHG emissions by 5.2 % in the period of 2008–2012 [2]. To achieve this, many industrialized countries seek to decarbonize electricity generation by replacing conventional coal and fossil fuel fired plants with renewable technology alternatives [3].

Due to the shortage of inexhaustible resources and environmental problems caused by the emissions, the traditional power generations, which are based on fossil fuel are generally considered to be unsustainable in the long term. As a result, many efforts are made worldwide and lots of countries have being introducing more renewable energies, such as wind power, solar photovoltaic (PV) power, hydropower, biomass power, and ocean power, etc. into their electric grids [4]. Currently, a significant portion of electricity is generated from fossil fuels, especially coal due to its low prices. However, the increasing use of fossil fuels accounts for a large amount of environmental pollution and GHG emissions, which are considered the main reason behind the global warming. For example, the emissions of carbon dioxide and mercury are expected to increase by 35 % and 8 %, respectively, by the

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year 2020 due to the expected increase in electricity generation. Furthermore, possible depletion of fossil fuel reserves and unstable price of oil are two main concerns for industrialized countries [5].

While the prices for fossil fuels are skyrocketing and the public acceptance of these sources of energy is declining, PV technology has become a truly sensible alternative. Solar energy plays a major role since it is globally available, flexible with regard to the system size and because it can fulfill the needs of different countries since it offers on-grid and off-grid solutions [6]. The boundless supply of sunlight and wind and their zero emission power generation become a driving force in the fast growth of PV and Wind systems technology. Unlike the dynamic wind turbine, PV installation is static, does not need strong high towers, produces no vibration, and does not need cooling systems. In addition, it is environmentally friendly, safe, and has no gas emissions [6]. The use of PV systems in electricity generation started in the seventies of the twentieth century and today is currently growing rapidly around worldwide in spite of high capital cost [5].

PV systems convert the sun's energy directly into electricity using semiconductor materials. They differ in complexity, some are called "stand-alone or off-grid" PV systems, which signifies they are the sole source of power to supply building loads. Further complicating the design of PV systems is the possibility to connect the PV system generation to the utility "grid connected or on-grid" PV systems, where electrical power can either be drawn from grid to supplement system loads when insufficient power is generated or can be sold back to the utility company when an energy surplus is generated [7, 8]. Based on prior arguments, grid-connected, or utility-interactive systems appear to be the most practical application for buildings where the available surface is both scarce and expensive. Grid-connected PV systems currently dominate the PV market, especially in Europe, Japan, and USA. With utility interactive systems, the public electricity grid acts as an energy store, supplying electricity when the PV system cannot. The performance of a PV system largely depends on solar radiation, temperature and conversion efficiency. Although, PV systems have many advantages, they suffered from changing of system performance due to weather variations, high installation cost, and low efficiency that is hardly up to 20 % for module [9]. An interesting problem associated with PV systems is the optimal computation of their size. The sizing optimization of stand-alone or grid connected PV systems is a convoluted optimization problem which anticipates to obtain acceptable energy and economic cost for the consumer [10].

The main aim of this chapter is to present the introduction and concept of research work done in this book. First, the chapter studies the energy situation in Egypt and discusses Egypt goals and policies regarding their Renewable Energy Sources (RESs) especially solar energy resource. Secondly, solar PV energy applications share in Egypt are demonstrated and development of rooftop PV technologies are discussed. Then, an overview of PV systems are presented. Finally, the research motivation, objectives, and book outlines are introduced.

1.2 Energy Situation in Egypt

Energy plays a significant role in any nation's development, and securing energy is one of the most important challenges facing any developmental plans. While Egypt has limited fossil fuels, their RESs abound. Nevertheless, RESs currently represent just a small fraction of the energy mix. They appears to be great potential for the utilization of Egypt's renewable resources to generate electricity, thereby boosting exports and economic development [11]. Recently, Egypt has adopted an ambitious plan to cover 20 % of the generated electricity by RESs by 2022, including 12 % contribution from wind energy, translating more than 7200 MW grid-connected wind farms. The plan includes also a 100 MW Solar thermal energy concentrated solar power with parabolic trough technology in Kom Ombo city, and two PV plants in Hurgada and Kom Ombo with a total installed capacity 20 MW each [2]. In order for Egypt to achieve these goals, policies must be aimed at localizing the Renewable Energy (RE) supply chain and strengthening technological capabilities at various levels. Egypt is also still in the developmental phase of legislation supporting the use of RE. A proposed electricity law is currently under construction and development. It would include some legislation supporting RE in terms of obligations or commitments on both energy consumers and producers to assign a part of their production capacity and/or consumption to be from RESs.

The long-term security requirement of Egypt is to reduce the dependence on imported oil and natural gas and move toward the use of RESs. Egypt's current captive-market electricity structure, with the government being a sole buyer, is not conducive to the rise of a new RE regime. However, a new proposed electricity law, now in the process of being approved. The anticipated new electricity law tackles the issue by providing market incentives for private investors, along with those in RE. Competitive bidding for a determined share of the Egyptian network from RE is supposed to build a guaranteed market demand for renewable bulk-energy producers. Additionally, based on decentralization trend, anticipated new law and market structure, it seems likely that electricity prices will rise considerably, including peak-demand figures. Subsidies, as a policy tool, will be used selectively, especially for low-income and low-consumption residential consumers.

1.3 Solar Energy Resource in Egypt

Favorable climate conditions of Upper Egypt and recent legislation for utilizing RES provide a substantial incentive for installation of PV systems in Egypt. Egypt possesses very abundant solar energy resources with sunshine duration ranging from 9 to 11 h/day with few cloudy days over the year or ranging between 3285 and 4000 h/year. Egypt lies among the Sun Belt countries with annual global solar

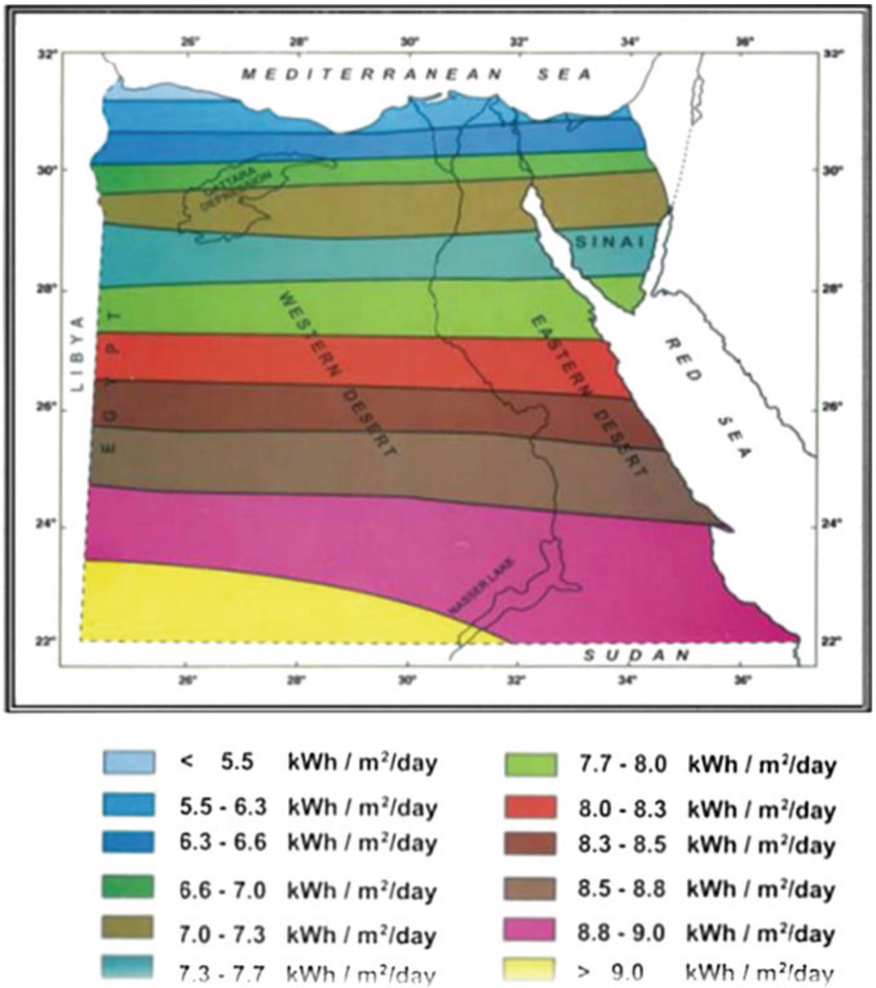


Fig. 1.1 Solar atlas of Egypt (annual average direct solar radiation) [1]

insolation, as shown in Fig. 1.1 ranging from 1750 to 2680 kWh/m^2/year from North to South and annual direct normal solar irradiance ranging from 1970 to 3200 kWh/m^2/year also from North to South with relatively steady daily profile and small variations making it very favorable for utilization [1].

El-Minia has a high solar energy potential, where the daily average of solar radiation intensity on horizontal surface is 5.4 kWh/m^2, while the total annual sunshine hours amounts to about 3000. These figures are very encouraging to use PV generators for electrification of the faculty as it has been worldwide success fully used.

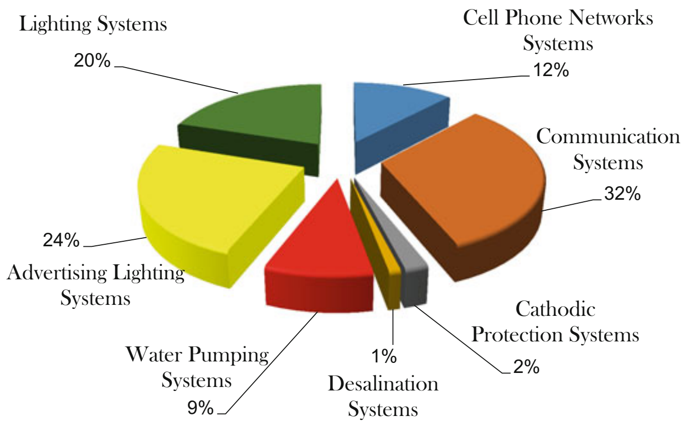


Fig. 1.2 PV applications share in Egypt [1]

1.3.1 Photovoltaic Applications in Egypt

Most of solar PV energy applications share in Egypt were demonstrated in Fig. 1.2, including water pumping, desalination, refrigeration, village electrification, lighting, telecommunication, and other solar PV applications. It is estimated that the solar PV systems installed capacity is presently more than 5.2 MW peak with around 32 % of that capacity is in telecommunications sector due to the rapid expansion of mobile telephones repeater stations where the desert represents more than 90 % of Egypt's area [1].

1.4 Rooftop Photovoltaic System Technology

In the next years, there will be an explosion of solar PV rooftops across the world, big and small. Fifteen or 20 years from now, a "bare" rooftop will seem very strange to us, and most new construction will include PV as routine practice. This will lead to a parallel explosion in micro-grids (both residential and commercial), community-scale power systems, and autonomous-home systems. The grid will become a much more complex hybrid of centralized and distributed power, with a much greater variety of contractual models between suppliers and consumers [4].

Development of rooftop PV technologies has received much attention and introduction of a subsidy for the system cost and energy production especially in Germany and Japan has encouraged the demand for rooftop PV systems [12], where German PV market is the largest market in the world, and Germany is a leading country in terms of installed PV capacity. One of the most suitable policies for introducing rooftop PV systems to the market is Feed-in Tariff mechanism. According to this approach, eligible renewable power producers will receive a set price from their utility for all the electricity they generate and deliver to the grid, where grid interactive PV systems derive their value from retail or displacement of electrical energy generated. The power output of a PV system depends on the irradiance of Sun, efficiency and effective area of PV cells conducted. Therefore, it is compulsory to choose the optimal size of PV system according to the application.

Egypt has abundant solar energy resource, which is extensively applied to buildings. Therefore, solar energy utilization in buildings has become one of the most important issues to help Egypt optimize the energy proportion, increasing energy efficiency, and protecting the environment. Solar PV system can easily be installed on the rooftop of education, governmental as well as on the wall of commercial buildings as grid-connected solar PV energy application. Energy efficiency design strategies and RE are keys to reduce building energy demand. Rooftop solar PV energy systems installed on buildings have been the fastest growing market in the PV industry. The integration of solar PV within both domestic and commercial roofs offers the largest potential market for PV especially in the developed world [12].

1.5 Photovoltaic Systems Overview

Photovoltaic systems can be grouped into stand-alone systems and grid-connected systems as illustrated in Fig. 1.3. In stand-alone systems the solar energy yield is matched to the energy demand. Since the solar energy yield often does not coincide

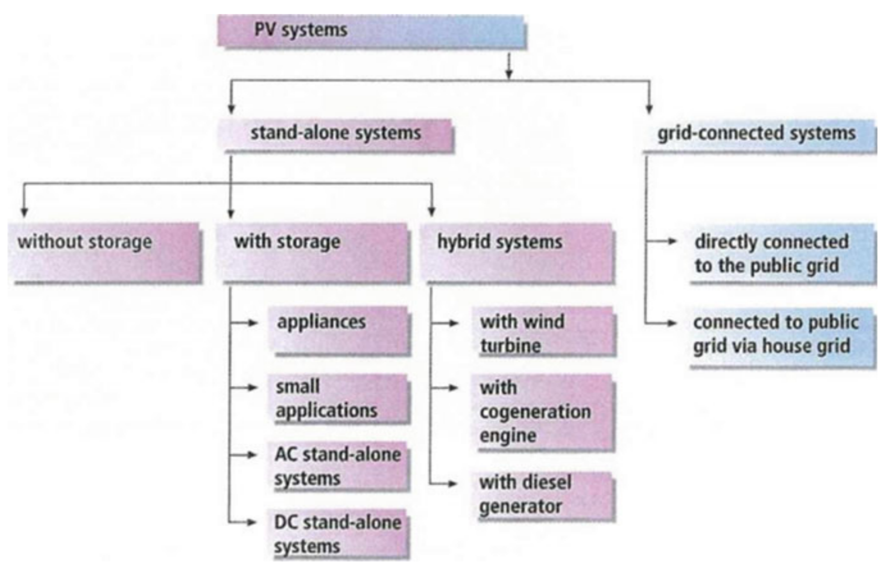


Fig. 1.3 PV systems classifications [13]

in time with the energy demand from the connected loads, additional storage systems (batteries) are generally used. If the PV system is supported by an additional power source, for example, a wind or diesel generator this is known as a PV hybrid system. In grid-connected systems the public electricity grid functions as an energy store [13].

1.5.1 Stand-alone Systems

The first cost-effective applications for photovoltaics were stand-alone systems. Wherever it was not possible to install an electricity supply from the mains utility grid (UG). The range of applications is constantly growing. There is great potential for using stand-alone systems in developing countries where vast areas are still frequently not supplied by an electrical grid. These systems can be seen as a well-established and reliable economic source of electricity in rural areas, especially where the grid power supply is not fully extended [14]. Solar power is also on the advance when it comes to mini-applications: pocket calculators, clocks, battery chargers, flashlights, solar radios, etc., are well-known examples of the successful use of solar cells in stand-alone applications.

Stand-alone PV systems generally require an energy storage system because the energy generated is not usually required at the same time as it is generated (i.e., solar energy is available during the day, but the lights in a stand-alone solar lighting system are used at night). Rechargeable batteries are used to store the electricity. However, with batteries, in order to protect them and achieve higher availability and a longer service life it is essential that a suitable charge controller is also used as a power management unit. Hence, a typical stand-alone system comprises the following main components [13]:

1. PV modules, usually connected in parallel or series-parallel;
2. Charge controller;
3. Battery or battery bank;
4. Loads;
5. Inverter (i.e., in systems providing AC power).

1.5.2 Grid-Connected Photovoltaic Systems

The basic building blocks of a grid-connected PV system are shown in Fig. 1.4. The system is mainly composed of a matrix of PV arrays, which converts the sunlight to DC power, and a power conditioning unit (PCU) that converts the DC power to an AC power. The generated AC power is injected into the UG and/or utilized by the local loads. In some cases, storage devices are used to improve the

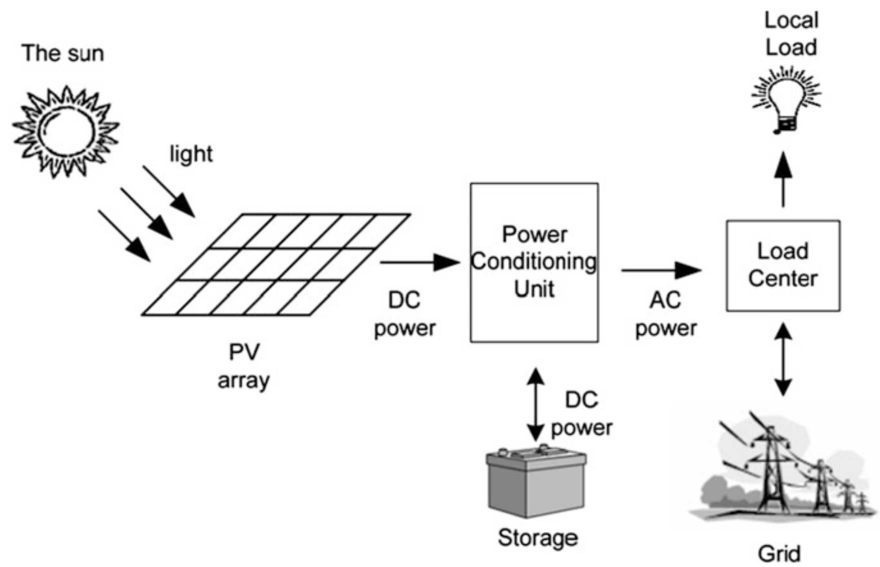


Fig. 1.4 Main components of grid-connected PV systems [5]

availability of the power generated by the PV system. In the following subsections, more details about different components of the PV system are presented.

A grid connected PV system eliminates the need for a battery storage bank resulting in considerable reduction of the initial cost and maintenance cost. The PV system, instead, uses grid as a bank where the excess electric power can be deposited to and when necessary also withdrawn from. When the PV system is applied in buildings, the PV modules usually are mounted on rooftop, which can reduce the size of mounting structure and land requirements.

1.5.3 The Photovoltaic Cell/Module/Array

The PV cell is the smallest constituent in a PV system. A PV cell is a specially designed P-N junction, mainly silicon-based semiconductor and the power input is made possible by a phenomenon called the photoelectric effect. The characteristic of photoelectric effect was discovered by the French scientist, Edmund Bequerel, in 1839, when he showed that some materials produce electricity when exposed to sunlight. The photons in the light are absorbed by the material and electrons are released, which again creates a current and an electric field because of charge transfer. The nature of light and the photoelectric effect has been examined by several scientists the last century, for instance Albert Einstein, which has led to the development of the solar cell as it is today [15].

In most practical situations the output from a single PV cell is smaller than the desired output. To get the adequate output voltage, the cells are connected in series into a PV module. When making a module, there are a couple of things that need to be considered.

- No or partly illumination of the module
  During the night, when none of the modules are illuminated, an energy storage (like a battery) connected directly in series with the modules makes the cells forward biased. This might lead to a discharge of the energy storage. To prevent this from happening a blocking diode can be connected in series with the module. But during normal illumination level this diode represents a significant power loss.
- Shading of individual cells
  If any of the cells in a module is shaded, this particular cell might be forward biased if other unshaded parts are connected in parallel. This can lead to heating of the shaded cell and premature failure. To protect the system against this kind of failure, the modules contain bypass diodes which will bypass any current that cannot pass through any of the cells in the module.

If the output voltage and current from a single module is smaller than desired, the modules can be connected into arrays. The connection method depends on which variable that needs to be increased. For a higher output voltage the modules must be connected in series, while connecting them in parallel in turn gives higher currents. It is important to know the rating of each module when creating an array. The highest efficiency of the system is achieved when the MPP of each of the modules occurs at the same voltage level. Figure 1.5 shows the relation between the PV cell, a module and an array.

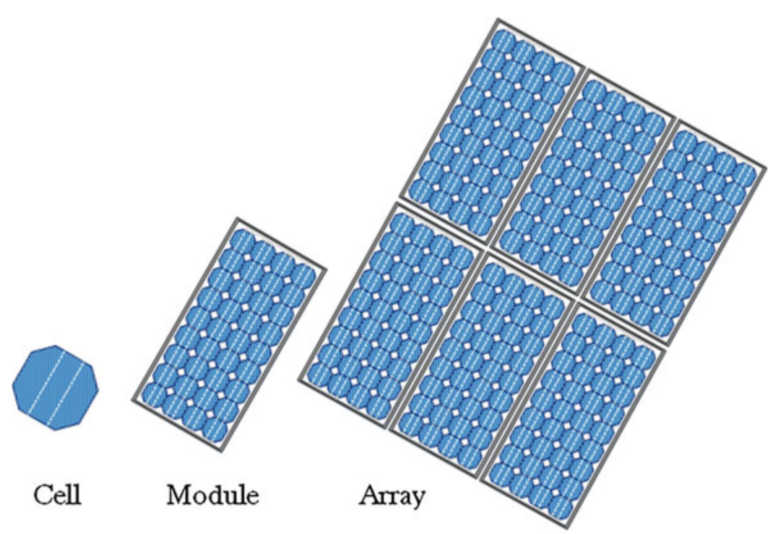


Fig. 1.5 Relation between the PV cell, a module and an array

1.5.4 Power Conditioning Units

Power conditioning units are used to control the DC power produced from the PV arrays and to convert this power to high-quality AC power before injecting it into the UG. PV systems are categorized based on the number of power stages. The past technology used single-stage centralized inverter configurations. The present and future technology focus predominantly on the two-stage inverters, where a DC–DC converter is connected in between the PV modules and the DC–AC inverter as shown in Fig. 1.6.

In single-stage systems, an inverter is used to perform all the required control tasks. But, in the two-stage system, a DC–DC converter precedes the inverter and the control tasks are divided among the two converters. Two-stage systems provide higher flexibility in control as compared to single-stage systems, but at the expense of additional cost and reduction in the reliability of the system [16]. During the last decade, a large number of inverter and DC–DC converter topologies for PV systems were proposed [16, 17], In general, PCUs have to perform the following tasks:

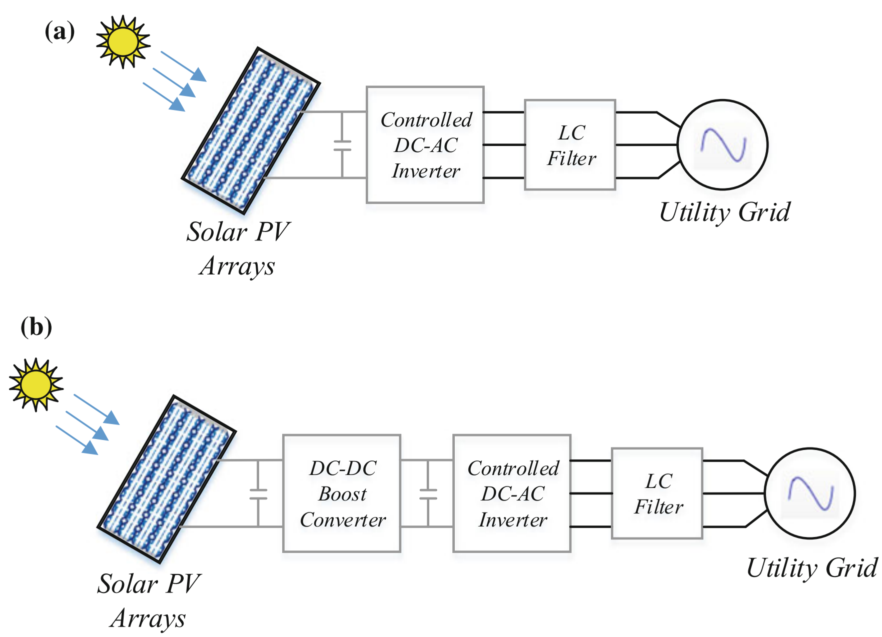


Fig. 1.6 Classification of system configurations **a** single stage **b** two stages

1.5.4.1 Maximum Power Point Tracking (MPPT)

One of the main tasks of PCUs is to control the output voltage or current of the PV array to generate maximum possible power at a certain irradiance and temperature. There are many techniques that can be used for this purpose [17–20] with the Perturb-and-Observe (P&O) and Incremental Conductance (IC) techniques being the most popular ones [7].

1.5.4.2 Control of the Injected Current

Power Conditioning Units should control the sinusoidal current injected into the grid to have the same frequency as the grid and a phase shift with the voltage at the point of connection within the permissible limits. Moreover, the harmonic contents of the current should be within the limits specified in the standards. The research in this field is mainly concerned with applying advanced control techniques to control the quality of injected power and the power factor at the grid interface [21–23].

1.5.4.3 Voltage Amplification

Usually, the voltage level of PV systems requires to be boosted to match the grid voltage and to decrease the power losses. This task can be performed using step-up DC–DC converters or MLIs. 3L-VSIs can be used for this purpose as they provide a good tradeoff between performance and cost in high voltage and high-power systems [24].

1.5.4.4 Islanding Detection and Protection

Islanding is defined as a condition in which a portion of the utility system containing both loads and distributed resources remains energized while isolated from the rest of the utility system [25].

1.5.4.5 Additional Functions

The control of PCUs can be designed to perform additional tasks such as power factor correction [26], harmonics filtering [27], reactive power control [28], and operating with an energy storage device and/or a dispatchable energy source such as diesel generator as an uninterruptible power supply [29].

1.6 Connection Topologies of Photovoltaic Systems

PV systems have different topologies according to the connection of the PV modules with the PCU. Some of the common topologies are discussed below.

1.6.1 Centralized Topology

This is one of the well-established topologies. It is usually used for large PV systems with high-power output of up to several megawatts. In this topology [16, 30], a single inverter is connected to the PV array as illustrated in Fig. 1.7. The main advantage of the centralized topology is its low cost as compared to other topologies as well as the ease of maintenance of the inverter. However, this topology has low reliability as the failure of the inverter will stop the PV system from operating. Moreover, there is significant power loss in the cases of mismatch between the modules and partial shading, due to the use of one inverter for tracking the maximum power point. Since the maximum power point of each module varies depending on the solar radiation (changing with tracking, shading, cloud cover, etc.), module material, etc. Thus, a local maximum power point of a module may not correspond with the global maximum power point of the whole system resulting in under-operation of some PV modules.

1.6.2 Master–Slave Topology

This topology aims to improve the reliability of the centralized topology [31]. In this case as shown in Fig. 1.8, a number of parallel inverters are connected to the array and the number of operating inverters is chosen such that if one inverter fails, the other inverters can deliver the whole PV power. The main advantage of this

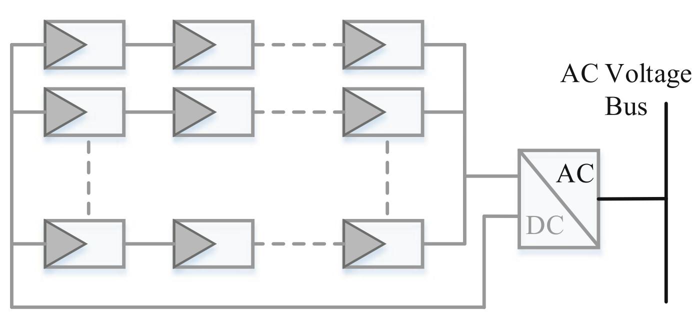


Fig. 1.7 Central inverter configuration of PV systems

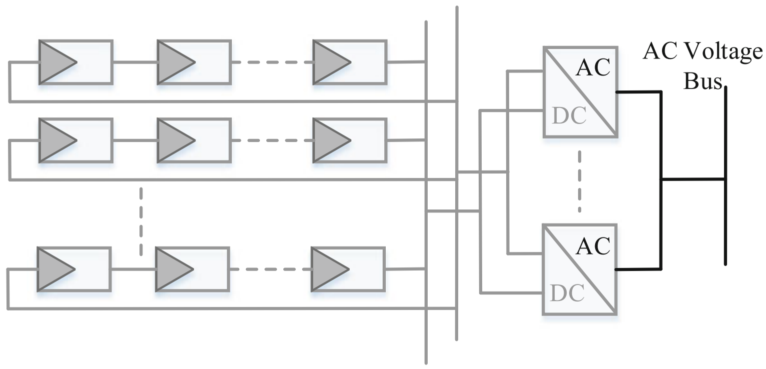


Fig. 1.8 Master–slave configuration of PV systems

topology is the increase in the reliability of the system. Moreover, the inverters can be designed to operate according to the irradiance level, where for low irradiance level some of the inverters are shut down. This technique of operation extends the lifetime of inverters and overall operating efficiency. However, the cost of this topology is higher than that of the centralized topology and the power loss due to module mismatch and partial shading is still a problem with this topology.

1.6.3 String Topology

In the string topology, each string is connected to one inverter as depicted in Fig. 1.9; hence, the reliability of the system is enhanced [16, 30, 32]. Moreover, the

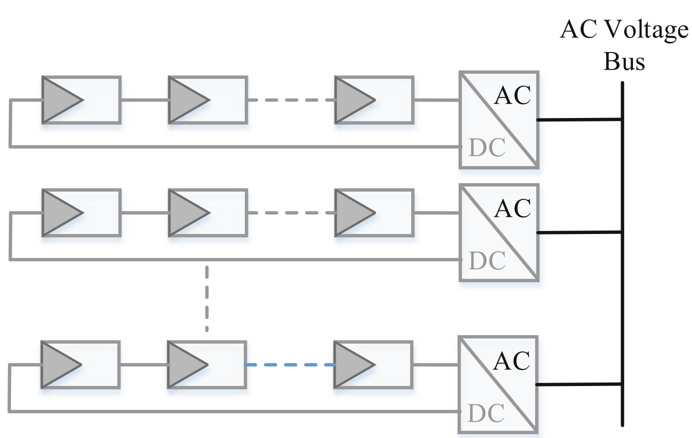


Fig. 1.9 String inverter configuration of PV systems

losses due to partial shading are reduced because each string can operate at its own maximum power point. The string topology increases the flexibility in the design of the PV system as new strings can be easily added to the system to increase its power rating. Usually, each string can have a power rating of up to 2–3 kW. The main disadvantage of this topology is the increased cost due to the increase in the number of inverters.

1.6.4 Team Concept Topology

This topology is used for large PV systems; it combines the string technology with the master–slave concept as shown in Fig. 1.10. At low irradiance levels, the complete PV array is connected to one inverter only. As the irradiance level increases, the PV array is divided into smaller string units until every string inverter operates at close to its rated power. In this mode, every string operates independently with its own MPP tracking controller [33].

1.6.5 Multi-String Topology

In this topology, every string is connected to a DC–DC converter for tracking the MPP and voltage amplification [16, 32]. All the DC–DC converters are then connected to a single inverter via a DC bus as shown in Fig. 1.11. This topology combines the advantages of string and centralized topologies as it increases the energy output due to separate tracking of the MPP while using a central inverter for reduced cost. However, the reliability of the system decreases as compared to string

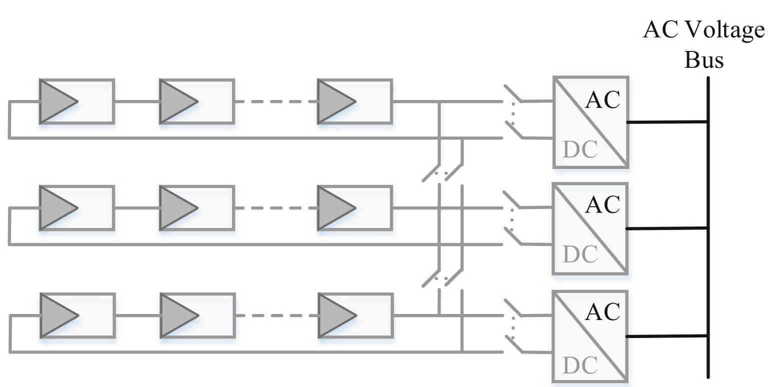


Fig. 1.10 Team concept configuration of PV systems

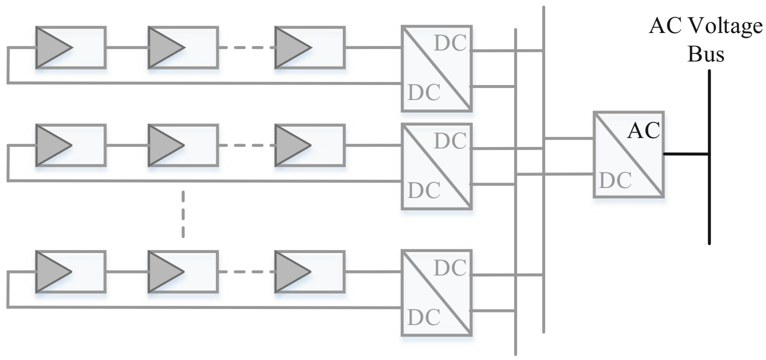


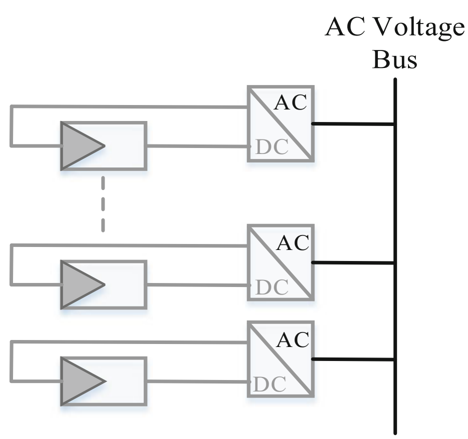
Fig. 1.11 Multi-inverter configuration of PV systems

topology and the losses due to the DC–DC converters are added to the losses of the system.

1.6.6 Modular Topology

This is the most recent topology. It is also referred to as "AC modules," because an inverter is embedded in each module as described in Fig. 1.12. It has many advantages such as reduction of losses due to partial shading, better monitoring for module failure, and flexibility of array design [16, 32]. However, this topology is suitable only for low power applications (up to 500 W) and its cost is relatively high. Moreover, the lifetime of the inverter is reduced because it is installed in the open air with the PV module, thus increasing its thermal stress.

Fig. 1.12 Module inverter configuration of PV systems



Chapter 3
Optimum Design of Rooftop Grid-Connected PV System

3.1 Introduction

Egypt is experiencing one of its most considerable energy crises for decades. Power cuts in Egypt have been escalated in recent years due to the shortage of fuel necessary to run power plants—due to the rapid depletion of fossil fuels and continual instability of their prices—and overconsumption of loads especially in summer season, which negatively affected various levels of social and economic activities. On the other hand, Egypt has some of the highest GHG emissions in the world. To solve problems of power cuts and emissions, Egypt is taking impressive steps to rationalize consumption and optimize the use of electricity in addition to develop and encourage PV system projects that can be deployed on rooftop of institutional and governmental buildings. As a result, Egypt government intends to implement about one thousand of grid-connected PV systems on the roof of governmental buildings. As a case study, this book presents a new approach for optimum design of 100 kW rooftop grid-connected PV system for Faculty of Engineering buildings. In order to ensure acceptable operation at minimum cost, it is necessary to determine the correct size of rooftop grid-connected PV system taking into account meteorological data, solar radiation, and exact load profile of consumers over long periods. The next limitation to consider is the area available for mounting the array. For the majority of grid-connected PV systems, this area is the roof of the house or any other building.

This chapter presents a new approach for optimum design of rooftop grid-connected PV system installation on an institutional building at Minia University, Egypt as a case study. The new approach proposed in this chapter is based on optimal configuration of PV modules and inverters according to not only MPP voltage range but also maximum DC input currents of the inverter. The system can be installed on the roof of Faculty of Engineering buildings' B and C. The study presented in this chapter includes two scenarios using different brands of commercially available PV modules and inverters. The first scenario includes four

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types of PV modules and three types of inverters while the second scenario includes five types of PV modules and inverters. Many different configurations of rooftop grid-connected PV systems have been investigated and a comparative study between these configurations has been carried out taking into account PV modules and inverters specifications. Energy production capabilities, COE, SPBT, and GHG emissions have been estimated for each configuration using proposed MATLAB computer program.

3.2 Site Description

Faculty of engineering which located in Upper Egypt was established in the late of 1976s. It is comprised of three buildings A, B, and C, with approximately 200 staff, 3500 undergraduate students, and 400 employees. Location is selected as it has many of the typical attributes of an education building, since it contains classrooms, offices, computer laboratories, and engineering laboratories. An important limitation to consider in the design of rooftop PV system is the area available for mounting the arrays on the buildings. To determine the amount of space available for the system, a site survey was performed leading to net roof areas available of 2100 and 3100 m^2 for buildings B and C, respectively. Coordinate of selected site is 28.1014 (28° 6′ 5″) $^{\circ}N$, 30.7294 (30° 43′ 46″) $^{\circ}W$. Electrification of faculty of engineering is often realized through an electric distribution network via three transformers with rated 1000, 500, and 500 kVA from Middle Egypt for Electricity Distribution Company (MEEDCo.). There are three energy meters M_1, M_2, and M_3 with numbers 16947, 59310007, and 59310857, respectively, put on each transformer to indicate the total energy consumed by faculty loads. Figure 3.1 shows a Google Earth™ image of the selected site.

3.2.1 Load Data

First, the load demand of faculty of engineering has been gathered. The main electrical loads for faculty are represented in lighting, fans, Lab devices, air-conditioners, and computers with accessories. Table 3.1 provides most electrical appliances used in the faculty, while Table 3.2 provides energy consumption and their bills values for the faculty of engineering during a recent year, 2013 which have been taken from MEEDCo. These values actually have been gotten from electricity bills paid by the university, where university is the largest customer of its energy supplier. It can be seen that the yearly energy consumption reaches 980.33 MWh during 2013 year. According to energy bills, it was noticed that energy consumed continues to increase due to the increasing loads that faculty added during the recent period. Also it was found that the faculty pays 25 piaster/kWh (3.57 cent/kWh) up to 2012 year as an energy tariff, it is considered as power

Fig. 3.1 Google Earth™ image of faculty of engineering buildings' layout

Table 3.1 Typical electrical appliances

Floor		Load type			Total power/floor
		Lights (40 W)	Fans (80 W)	Air-conditions (3 HP)	
No. of units	Ground	565	36	4	34,432
	First	510	37	11	47,978
	Second	435	33	3	26,754
	Third	426	32	4	28,552
	Fourth	416	20	2	22,716
	Sum	2352	158	24	–
Total power		94,080 W	12,640 W	53,712 W	160,432 W

service on low voltage according to the tariff structure of the Egyptian Electricity Holding Company. Starting from January 2013, the energy tariff increased by about 13.8 % to be 29 piaster/kWh (4.14 cent/kWh). It is expected that tariff structure continues to increase to reduce governmental subsides.

Table 3.2 Typical energy consumption in the faculty for a recent year (2013)

Month	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Energy (MWh)	71.88	54.78	50.04	67.44	62.04	76.26	80.40	97.44	110.278	98.46	113.76	105.04
Bills (EGP)	20,845	15,886	14,512	18,494	17,992	22,115	23,316	28,258	29,806	28,553	32,990	30,462

3.2.2 Climate Data

Strength of solar radiation is the primary consideration in selecting location for PV installation. The generated output power of a PV array is directly proportioned to the input solar radiation. So, to get an optimum design of rooftop PV system, it is important to collect the meteorological data for site under consideration. Hourly data of solar direct irradiance and ambient temperature are available for 1 year. Table 3.3 shows monthly average radiation on the horizontal surface which has been obtained from Egyptian Metrological Authority for El-Minia site, Egypt. El-Minia and Upper Egypt region have an average daily direct insolation between 7.7 and 8.3 kWh/m^2/day [1, 75].

It is clear from Table 3.3 that solar energy in this region is very high during summer months, where it exceeds 8 kWh/m^2/day, while the lowest average intensity is during December with a value of 3.69 kWh/m^2/day and the actual sunshine duration is about 11 h/day. So, solar energy application is more and more considered in El-Minia and Upper Egypt as an RES compared to conventional energy sources. Figure 3.2 shows the hourly solar radiation over the year seasons as a sample data.

3.3 Methodology

3.3.1 Radiation on Tilted Surfaces

Solar irradiance data provide information on how much of the sun's energy strikes a surface at a location on the earth during a particular period of time. Due to lack of measured data of irradiance on tilted surfaces, mathematical models have been developed to calculate irradiance on tilted surfaces.

3.3.1.1 Estimation of Monthly Best Tilt Angle

The new approach is presented based on monthly best tilt angle tracking. Hourly solar radiation incident upon a horizontal surface is available for many locations. However, solar radiation data on tilted surfaces are generally not available [76]. The monthly best tilt angle, β (degrees) can be calculated according to the following equations [76]:

$$\beta = \emptyset - \delta \tag{3.1}$$

Table 3.3 Monthly average climate data (kW/m^2/day) for El-Minia, Egypt

Month	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Radiation (kWh/m^2)	4.7	5.78	6.58	7.87	8.03	8.25	7.9	7.70	7.20	6.50	5.59	4.77
Temp. T (^{o}C)	14.3	16.9	17.95	34.3	23.7	30.15	33.3	30.6	31.1	26.7	21.55	18.2

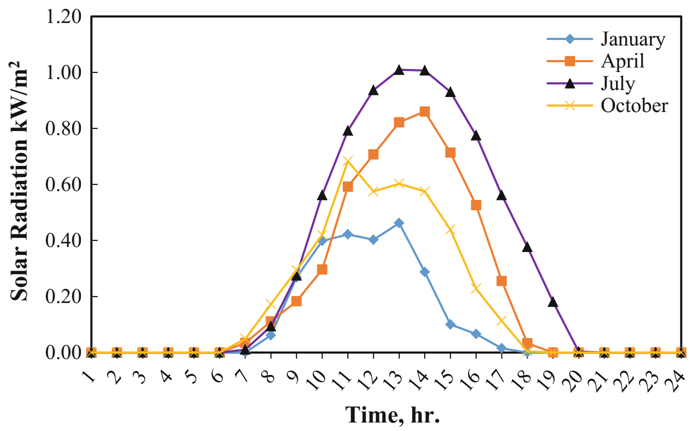

Fig. 3.2 Hourly solar radiation on horizontal surfaces at El-Minia site

Table 3.4 Number of the average day for every month and its value [77]

For the average day of the month			
Month	*n*, for the *i* day of the month	Recommended date	*n*, Recommended day per year
Jan.	*i*	17/1	17
Feb.	31 + *i*	16/2	47
March	59 + *i*	16/3	75
April	90 + *i*	15/4	105
May	120 + *i*	15/5	135
June	151 + *i*	11/6	162
July	181 + *i*	17/7	198
Aug.	212 + *i*	16/8	228
Sept.	243 + *i*	15/9	258
Oct.	273 + *i*	15/10	288
Nov.	304 + *i*	14/11	318
Dec.	334 + *i*	10/12	344

If calculations are made based on monthly average variables, it is recommended to use the average number of days for each month and the number n of the day presented in Table 3.4.

The declination angle can be calculated for the Northern hemisphere in terms of an integer representing the recommended day of the year, n, by

$$\delta = 23.45^\circ * \sin\left[360 * \frac{(284+n)}{365}\right] \tag{3.2}$$

3.3.1.2 Calculation of Radiation on Tilted Surfaces

Average daily solar radiation on horizontal surface, $\overline{H}$ for each calendar month can be expressed by defining, $\overline{K}_T$ the fraction of the mean daily extraterrestrial radiation, $\overline{H}_o$ as [76]

$$\overline{K}_{\mathrm{T}} = \frac{\overline{H}}{\overline{H}_{\mathrm{o}}} \tag{3.3}$$

The average daily radiation on the tilted surface, $\overline{H}_T$, can be expressed as follows:

$$\overline{H}_{\mathrm{T}} = \overline{R} * \overline{H} = \overline{R} * \overline{K}_{\mathrm{T}} * \overline{H}_{\mathrm{o}}, \tag{3.4}$$

where $\overline{R}$ is the ratio between radiation on tilted surfaces to radiation on horizontal surfaces. $\overline{R}$ can be estimated individually by considering the beam, diffuse, and reflected components of the radiation incident on the tilted surfaces toward the equator. Assuming diffuse and reflected radiation can be isotropic then $\overline{R}$ can be expressed as follows [76]:

$$\overline{R} = \frac{\overline{H}_{\mathrm{T}}}{\overline{H}} = \left(1 - \left(\frac{\overline{H}_{\mathrm{d}}}{\overline{H}}\right)\right) * \overline{R}_{\mathrm{b}} + \left(\frac{\overline{H}_{\mathrm{d}}}{\overline{H}}\right)\left(\frac{(1 + \cos(S))}{2}\right) + \rho * \left(\frac{(1 - \cos(S))}{2}\right) \tag{3.5}$$

$$\frac{\overline{H}_{\mathrm{d}}}{\overline{H}} = 1.39 - 4.027 * \overline{K}_{\mathrm{T}} + 5.531 * \left(\overline{K}_{\mathrm{T}}\right)^2 - 3.108 * \left(\overline{K}_{\mathrm{T}}\right)^3, \tag{3.6}$$

where $\overline{H}_{\mathrm{d}}$ is the monthly average daily diffuse radiation. However, $\overline{R}_{\mathrm{b}}$ can be estimated to be the ratio of the extraterrestrial radiation on the tilted surface to that on horizontal surface for the month, thus [76]:

$$\overline{R}_{\mathrm{b}} = \frac{\sin(\delta)\sin(\emptyset - \delta)(\pi/180)\omega_{\mathrm{s}}' + \cos\delta\,\cos(\emptyset - \delta)\sin\left(\omega_{\mathrm{s}}'\right)}{\sin(\delta)\sin(\emptyset)(\pi/180) + \cos(\delta)\cos(\emptyset)\sin(\omega_{\mathrm{s}})}, \tag{3.7}$$

where

$$\omega_{\mathrm{s}} = \cos^{-1}(-\tan(\emptyset)\tan(\delta)) \tag{3.8}$$

$$\omega_{\mathrm{s}}' = \min\left[\omega_{\mathrm{s}}, \cos^{-1}(-\tan(\emptyset - S))\tan(\delta)\right] \tag{3.9}$$

3.3.2 Mathematical Modeling of PV Module/Array

Most studies related to the performance of PV systems require the use of a model to convert the irradiance received by the PV array and ambient temperature into the corresponding maximum DC power output of the PV array. The performance of PV system is best described using single-diode model [78−81] or two-diode model [82]. These models are used to establish I-V and P-V characteristic curves of PV module/array to obtain an accurate design, optimum operation, and discover the causes of degradation of PV performance. The models recorded in the literature [78−81] vary in accuracy and complexity, and thus, appropriateness for different studies. PV cells essentially consist of an interface between P and N doped silicon. Therefore, they can be mathematically evaluated in a manner akin to that employed when dealing with basic P-N junctions. The single-diode model, shown in Fig. 3.3, is one of the most popular physical models used in the analysis to represent the electric characteristics of a single PV cell [83].

The mathematical equation describing the IV characteristics of a PV solar cells array is given by the following equations where the output current can be found by

$$I(t) = I_{ph}(t) - I_o(t)\left[\exp\left(\frac{q(V(t) - I(t) * R_s)}{AKT(t)}\right) - 1\right] - \frac{V(t) + I(t) * R_s}{R_{sh}} \quad (3.10)$$

The hourly reverse saturation current, $I_o(t)$ varies with temperature as follows:

$$I_o(t) = I_{or}\left(\frac{T(t)}{T_r}\right)^3 * \exp\left[q * E_{go}/K_i\left(\frac{1}{T_r} - \frac{1}{T(t)}\right)\right] \quad (3.11)$$

The hourly generated current of solar cells module, $I_{ph}(t)$ varies with temperature according to the following equation:

$$I_{ph}(t) = (I_{sc} + K_i(T(t) - 298)) * \frac{\overline{H}_T(t)}{100} \quad (3.12)$$

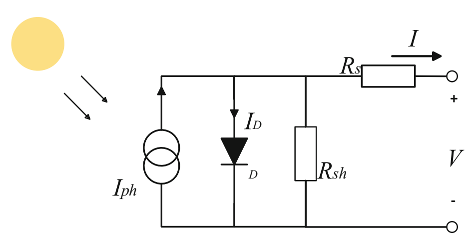

Fig. 3.3 Equivalent circuit of a PV module

The output power of a PV module can be calculated by the following equation:

$$P_{\text{pv,out}}(t) = V(t) * I(t) \tag{3.13}$$

3.3.3 Calculation of Optimal Number of PV Modules

The number of subsystems, N_{sub} depends on the inverter rating, P_{inverter} and size of PV system, P_{system}. To determine the number of subsystems, inverter rating and module data must be known.

$$N_{\text{sub}} = \frac{P_{\text{system}}}{P_{\text{inverter}}} \tag{3.14}$$

Series and parallel combination of each PV subsystem can be adjusted according to not only the MPP voltage range but also maximum DC input current of the inverter. Estimation of the initial total number of PV modules for each subsystem can be calculated as follows:

$$N_{\text{PV\_sub\_i}} = \frac{P_{\text{inverter}}}{P_{\max}} \tag{3.15}$$

Most manufacturers of inverters for PV systems make a wide range between the maximum and minimum values of MPP voltage range $\left(V_{\text{mpp\_max}}, V_{\text{mpp\_min}}\right)$, where inverters act properly and have no problem to find the maximum power point in where the module is working. Minimum and the maximum number of PV modules that can be connected in series in each branch, $N_{\text{s\_min}}$ and $N_{\text{s\_max}}$, respectively, are calculated according to the MPP voltage range as follows:

$$N_{\text{s\_min}} = ceil\left(\frac{V_{\text{mpp\_min}}}{V_{\text{mpp}}}\right) \tag{3.16}$$

$$N_{\text{s\_max}} = ceil\left(\frac{V_{\text{mpp\_max}}}{V_{\text{mpp}}}\right), \tag{3.17}$$

where V_{mpp} is the maximum power point of PV module. The optimal number of series modules, $N_{\text{s\_sub}}$ is located in the range of

$$N_{\text{s\_min}} < N_{\text{s\_sub}} < N_{\text{s\_max}}$$

Minimum and the maximum number of PV modules that can be connected in parallel in each subsystem, $N_{\text{p\_min}}$ and $N_{\text{p\_max}}$, respectively, are calculated as follows:

$$N_{\text{p\_min}} = ceil\left(\frac{N_{\text{PV\_sub\_i}}}{N_{\text{s\_max}}}\right) \tag{3.18}$$

$$N_{p\_\max} = ceil\left(\frac{N_{PV\_sub\_i}}{N_{s\_\min}}\right), \tag{3.19}$$

where optimal number of parallel modules $N_{\text{p\_sub}}$ is located in the range of

$$N_{\text{p\_min}} < N_{\text{p\_sub}} < N_{\text{p\_max}}$$

Number of PV modules connected in parallel $N_{\text{p\_sub}}$ may be set to $N_{\text{p\_min}}$ but cannot be set to $N_{\text{p\_max}}$, because the DC current results from all parallel strings may be higher than the maximum DC input of the inverter which may damage the inverter. For each number of series modules, $N_{\text{s\_sub}}$ in the series range calculated previously, estimation of the corresponding parallel modules for each subsystem can be calculated as follows:

$$N_{\text{p\_sub}} = ceil\left(\frac{N_{\text{PV\_sub\_i}}}{N_{\text{s\_sub}}}\right) \tag{3.20}$$

Then, recalculate the total number of PV module, $N_{\text{PV\_sub}}$ according to each resulted series and parallel combination

$$N_{\text{PV\_sub}} = N_{\text{s\_sub}} \cdot N_{\text{p\_sub}} \tag{3.21}$$

Assuming that inverter is operating in the MPP voltage range, the operating input voltage and current of the inverter $\left(V_{\text{mpp\_sub}}, I_{\text{mpp\_sub}}\right)$ can be calculated as follows:

$$V_{\text{mpp\_sub}} = N_{\text{s\_sub}} \cdot V_{\text{mpp}} \tag{3.22}$$

$$I_{\text{mpp\_sub}} = N_{\text{p\_sub}} \cdot I_{\text{mpp}} \tag{3.23}$$

From previous calculations, a database containing probable series and parallel combinations, PV modules, DC input voltage and current for each subsystem is formed. Optimal total number of PV modules for each subsystem is selected according to minimum number of PV modules which satisfies not only the MPP voltage range but also the maximum DC input current of the inverter. The total number of PV modules, N_{PV} for the selected site can be calculated from the following:

$$N_{\text{PV}} = N_{\text{sub}} \cdot N_{\text{PV\_sub}} \tag{3.24}$$

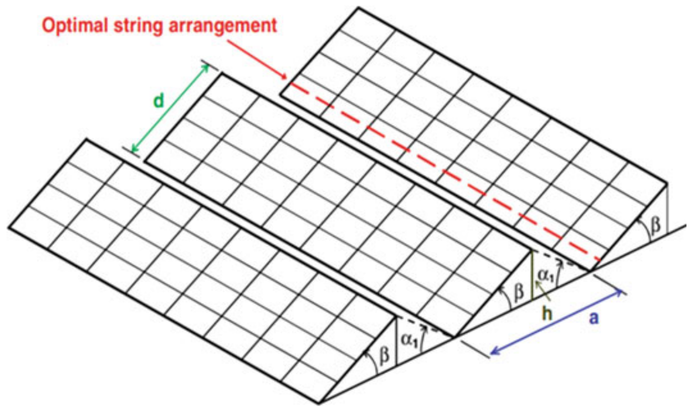

Fig. 3.4 PV modules with several stacked arrays [84]

3.3.4 Optimal Orientation and Arrangement of PV Modules

Photovoltaic arrays are usually tilted to maximize the energy production of the system by maximizing the direct irradiance that can be received. Optimal placement of PV array is often somewhat elevated, which reduces not only direct beam radiation in the winter, but also to some extent diffuse radiation all year round. In cases of single-row PV system, this loss of diffuse radiation is partially offset by additional reflected radiation from the building. But in most cases, PV array is installed in multiple rows or in stacks, which reduce the impact of reflected radiation. So, to increase output capture power from PV array, the clearance distance as shown in Fig. 3.4 between the rows of the various arrays can be calculated as follows [84]:

$$a = d\ \cos\beta + h\ \cot\alpha_1 = d(\cos\beta + \sin\beta\ \cot\alpha_1) \tag{3.25}$$

PV arrays are usually tilted to maximize the energy production of the system by maximizing the direct irradiance that can be received. Horizon elevation angle can be determined as follows [84]:

$$\alpha_1 = 66.5^\circ - \emptyset$$

3.3.5 Economic Feasibility Study

The most critical factors in determining the value of energy generated by PV system are the initial cost of the hardware and installation, and the amount of energy produced annually [85]. Commonly calculated quantities are SPBT and COE.

A grid-connected PV system is economically feasible only if its overall earnings exceed its overall costs within a time period up to the lifetime of the system. The time at which earnings equal cost is called the payback time and can be evaluated according to SPBT.

3.3.5.1 Cost of Electricity (COE)

The economical aspect is crucial for PV systems because of their high cost, which is reflected on price of kWh generated by them. COE is a measure of economic feasibility, and when it is compared to the price of energy from other sources (primarily the utility company) or to the price for which that energy can be sold, it gives an indication of feasibility [86]. Initial capital investment cost is the sum of the investment cost of parts of PV system, i.e., PV array, DC/AC inverter, and miscellaneous cost (wiring, conduit, connectors, PV array support, and grid interconnection)

$$C_{\text{cap}} = C_{\text{PV}} + C_{\text{inverter}} + C_{\text{m}} \tag{3.27}$$

Miscellaneous cost, C_m can be determined as follows:

$$C_{\text{m}} = C_{\text{labor}} + C_{\text{wiring}} + C_{\text{racks}} + C_{\text{grid}} \tag{3.28}$$

The COE ($/kWh) is primarily driven by the installed cost and annual energy production of system which can be calculated form the following equation:

$$COE = \frac{C_{\text{cap}} + C_{\text{main}}}{AEP} \tag{3.29}$$

Economic parameters considered in the proposed rooftop grid-connected PV system are shown in Table 3.5.

Table 3.5 Economic parameters considered for the proposed system

Description	Value	Notes
Installation labor cost ($/h) [87]	16.66	0.43 h/unit
Installation Materials cost [wiring, conduit, connectors] ($/module) [87]	3.60	
Mounting structure cost ($/Wp) [88]	0.080	
O&M costs, ($/year) [89]	425.60	
Grid Interconnect cost ($) [87]	2,000	
Life time, N (years)	25	
Tracking system	Monthly	

3.3.5.2 Simple Payback Time (SPBT)

A PV system is economically feasible only if its overall earnings exceed its overall costs within a time period up to the lifetime of the system. The time at which earnings equal cost is called the payback time. In general a short payback is preferred and a payback of 5–7 years is often acceptable. SPBT provides a preliminary judgment of economic feasibility, where SPBT calculation includes the value of money, borrowed or lost interest, and annual operation and maintenance costs can be calculated as follows [85]:

$$SPBT = \frac{C_{\text{cap}}}{AEP * P - C_{\text{cap}} * i - C_{\text{main}}} \tag{3.30}$$

3.3.6 *GHG Emissions Analysis*

Concerning to the environmental effects that can be avoided using PV systems. CO_2 emission is the main cause of greenhouse effect, so that the total amount of CO_2 at the atmosphere must be minimized in order to reduce the global warming. Amount of tCO_2 can be calculated according to the following equation:

$$CO_{2(\text{emission})} = F_E * AEP * N \tag{3.31}$$

3.4 Applications and Results

A new computer program has been developed based on proposed methodology for design and economic analysis of rooftop grid-connected PV system. The total load demand of the faculty is about 160.432 kW as shown from Table 3.1. However, these loads do not work all at one time, on the contrary working for a short time. Assuming demand load of 60 % of the total load demand, so a capacity of 100 kW rooftop grid-connected PV system is proposed. According to the Egyptian legalization, the feed-in rates vary depending on usage. Households will receive 84.8 piaster/kWh, commercial producers will receive 90.1 piaster/kWh (under 200 kW) and 97.3 piaster/kWh for producers of 200−500 kW [90]. Rooftop PV system operational lifetime period has been set to 25 years, which is equal to guaranteed operational lifetime period of PV module. According to Ref. [89], an hourly salary of $26.60 for a facility services engineer to maintain the system is considered. The projected maintenance costs will be 16 h/year ($425.60) for a medium system (less than 100 kW). Also to mount the panels on the roof, a solar panel rail kit is applied. The rail kit is sized based on the assumption that PV modules will be mounted on the roof inclined with monthly best tilt angle to optimize the energy output. The proposed computer program includes two scenarios using different brands of commercially available PV modules and inverters.

3.4.1 Scenario No. 1

Four different types of PV modules with three different types of inverters have been used in this scenario. Many different configurations have been investigated and a comparative study among these configurations has been carried out taking into account PV modules and inverters specifications. Flowchart of proposed MATLAB computer program is shown in Fig. 3.5.

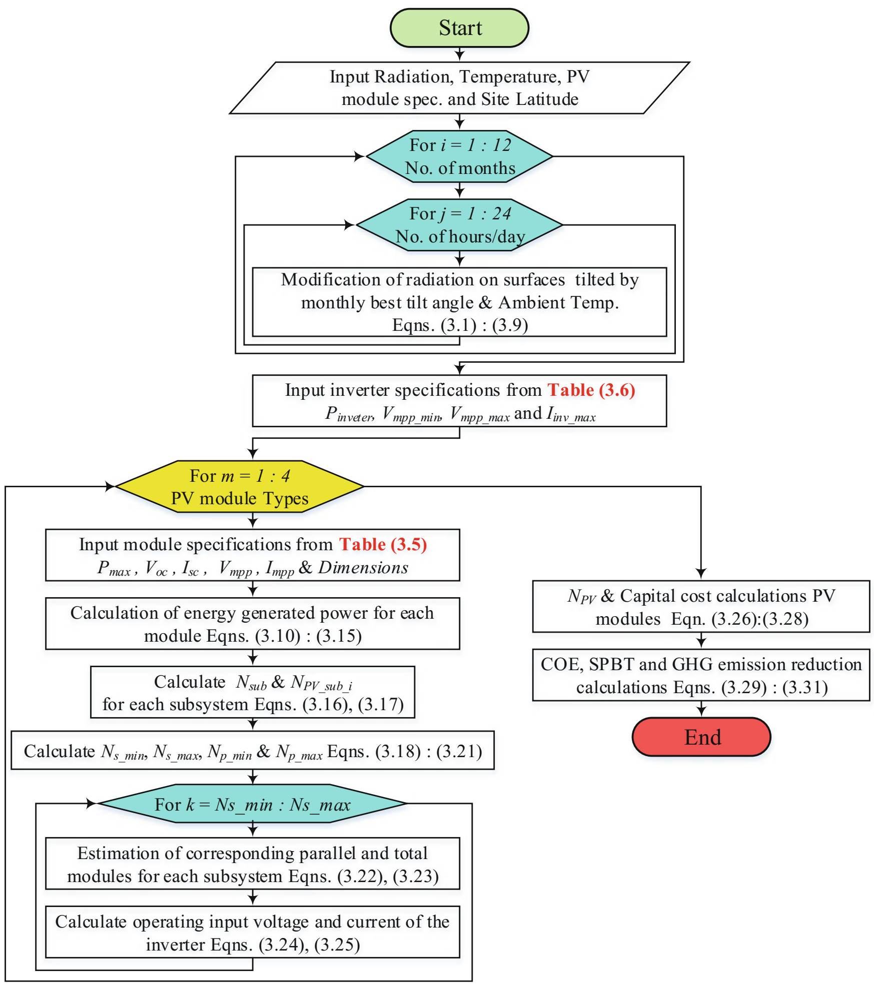

Fig. 3.5 Flowchart of proposed computer program in scenario no. 1

Table 3.6 Technical characteristics of selected PV modules in scenario no. 1

Item	Module			
	Mitsubishi PV-UD190MF5	Suntech STP270S-24/Vb	ET-P672305WB/WW	1Sol Tech 1STH-350-WH
P_{max} (W)	**190**	**270**	**305**	**350**
V_{OC}(V)	**30.8**	**44.8**	**45.12**	**51.5**
I_{sc}(A)	**8.23**	**8.14**	**8.78**	**8.93**
V_{mpp}(V)	**24.7**	**35.0**	**37.18**	**43.0**
I_{mpp}(A)	**7.71**	**7.71**	**8.21**	**8.13**
Dimensions, m	1.658 * 0.834	1.956 * 0.992	1.956 * 0.992	1.652 * 1.306
Efficiency (%)	13.7	15	15.72	16.2
Number of cells	50 cell	72 cell	72 cell	80 cell
Cell type (Silicon)	Polycrystalline	Monocrystalline	Polycrystalline	Monocrystalline
Price/unit	$340	$753	$305	$525

3.4.1.1 Selected PV Modules in Scenario No. 1

Depending on the manufacturing process, most of PV modules can be of three types: Monocrystalline Silicon, Polycrystalline Silicon, and Amorphous Silicon. Two different Silicon solar cell technologies (Monocrystalline and Polycrystalline) with four different selected types of commercially available PV modules (i.e., 190, 270, 305, and 350 W) have been used in the first scenario as illustrated in Table 3.6.

3.4.1.2 Inverter Selection in Scenario No. 1

Inverters are a necessary component in a PV system generation used to convert direct current output of a PV array into an alternating current that can be utilized by electrical loads. There are two categories of inverters, the first category is synchronous or line-tied inverters which are used with utility connected PV systems. While the second category is stand alone or static inverters which are designed for independent utility-free power systems and are appropriate for remote PV installation. Three different types of commercially available line-tied inverters (i.e., 20, 50, and 100 kW) have been used associated with capital costs as revealed in Table 3.7.

Table 3.7 Characteristics of different inverters used in scenario no. 1

Specification	Inverter		
	Sunny Tripower 20000TL	HS50K3	HS100K3
Manufacturer	SMA Solar Technology	Han's Inverter & Grid Tech. co. Ltd.	Han's Inverter & Grid Tech. co. Ltd.
$P_{inverter}$ (kW)	**20.45**	**55**	**110**
Max. DC current (A)	**36**	**122**	**245**
MPP voltage range (**V**)	**580–800**	**450–800**	**450–820**
Max. AC power (kW)	20	50	100
Max. AC current (A)	29	80	160
Frequency (Hz)	50	50	50
Price/unit	$3870	$8060	$14,500

3.4.1.3 Configurations of PV Modules for Each Subsystem in Scenario No. 1

The configuration details for each subsystem in scenario no. 1 are shown in Table 3.8, while AEP resulting from proposed PV system is calculated in Table 3.9. The optimal configuration with two subsystems (HS50K3 inverter) consists of 182 Polycrystalline silicon PV modules (ET-P672305WB). The PV modules are arranged in 14 parallel strings, with 13 series modules in each. From this table, although, the combination of ET-P672305WB PV module and HS100K3 inverter has the minimum price for kWh generated (0.6725 $/kW), this is not the best combination due to system reliability. Also, it can be seen that the maximum generated energy from HS50K3 with two subsystem is equal to 208.83 MWh, meanwhile the optimal system configuration consists of ET-P672305WB PV module and HS50K3 inverter based on lowest cost of kWh generated (0.6792 $/kWh) and system reliability. Figure 3.6 shows the rooftop grid-connected PV system layout proposed in scenario no. 1

The electric characteristics of a PV module depend mainly on the irradiance received by the module and the module temperature. Figures 3.7 and 3.8 demonstrate the electrical characteristics of optimal PV module in scenario no. 1 at specific hour over the day at different levels of irradiance and constant temperature for 2 days, one during a day in March and the other during a day in December. The amount of energy generated by the solar PV panel depends on peak sun hours available where peak sun hours vary throughout the year. It can be seen that the peak power generation during a day in March is about 298.57 W which occurs between 12:00 and 1:00 p.m., while that for a day in December is about 222.13 W and occurs between 1:00 and 2:00 p.m. The difference depends on the intensity of

Table 3.8 Specifications for each subsystem in scenario no. 1

Inverter type		Details	Module			
			Mitsubishi PV-UD190MF5	Suntech STP270S-24/Vb	ET-P672305WB/WW	1Sol Tech 1STH-350-WH
Sunny Tripower 20000TL	5 subsystem	N_{s_sub}	27	19	17	15
		N_{p_sub}	4	4	4	4
		N_{PV_sub}	108	76	68	60
		V_{sub}(V)	666.9	665.0	632.06	645.0
		I_{sub}(A)	30.84	30.84	32.84	32.52
HS50K3	2 subsystem	N_{s_sub}	29	17	**13**	16
		N_{p_sub}	10	12	**14**	10
		N_{PV_sub}	290	204	**182**	160
		V_{sub}(V)	716.3	595.0	**483.34**	688.0
		I_{sub}(A)	77.1	92.52	**114.94**	81.30
HS100K3	1 subsystem	N_{s_sub}	20	17	19	15
		N_{p_sub}	29	24	19	21
		N_{PV_sub}	580	408	361	315
		V_{sub}(V)	494.0	595.0	706.42	645.0
		I_{sub}(A)	223.59	185.04	155.99	170.73

Table 3.9 AEP and COE results in scenario no. 1

Parameter	Inverter	Module			
		Mitsubishi PV-UD190MF5	Suntech STP270S-24/Vb	ET-P672305WB/WW	1Sol Tech 1STH-350-WH
AEP (MWh/yr.)	Sunny Tripower 20000TL	228.8893	228.5928	195.0641	238.2875
	HS50K3	245.8443	245.4365	**208.8333**	254.1732
	HS100K3	245.8443	245.4365	207.1121	250.2018
COE ($/kWh)	Sunny Tripower 20000TL	0.9565	1.3988	0.7017	0.7984
	HS50K3	0.9370	1.3793	**0.6792**	0.7804
	HS100K3	0.9304	1.3727	0.6725	0.7756

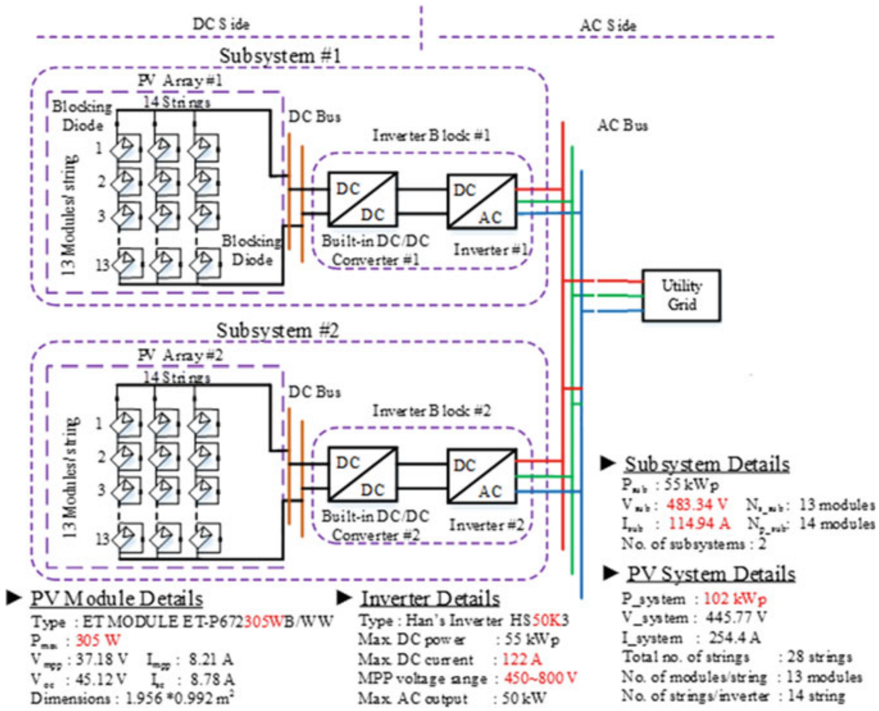

Fig. 3.6 Rooftop grid-connected PV system layout proposed in scenario no. 1

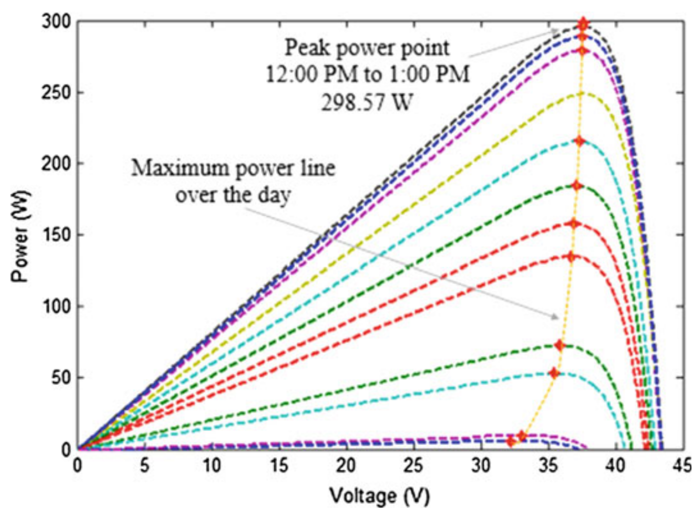

Fig. 3.7 P-V characteristics of ET−305 W PV module during a day in March

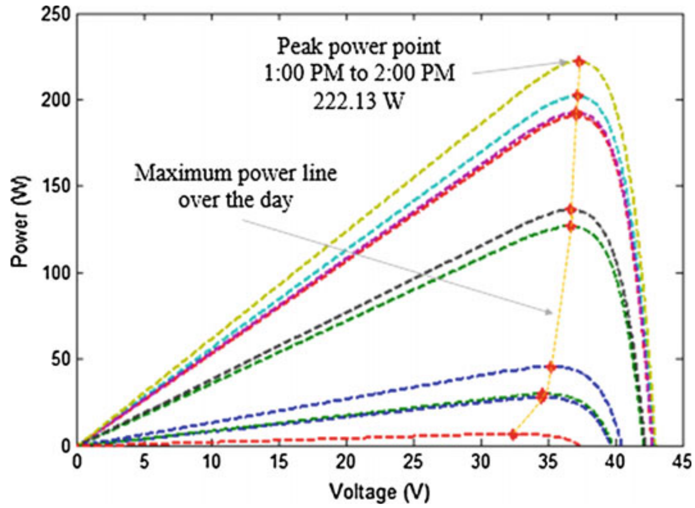

Fig. 3.8 P-V characteristics of ET−305 W PV module during a day in December

sun radiation incident on the PV modules. Also, noticed that, the characteristics of PV module appear every hour in March due to the presence of irradiance, unlike in December due to the weather clouds that occasionally scatter some of the sun's energy preventing it from reaching the ground. Clearly, the change in irradiance has a strong effect on the output power of the module, but negligible effect on the open-circuit voltage.

The annual energy production is estimated to be 208.83 MWh with $0.6792 for each kWh generated. Also, the scenario estimates that, 145.97 tons of $CO_{2\text{-eq}}$ annually will be avoided as the rooftop grid-connected PV system replaces the need of some electricity from the existing UG. Table 3.10 shows the generated output power during each month for optimal PV module (ET-P672305WB/WW) selected in scenario no. 1.

3.4.2 Scenario No. 2

Five different brands of commercially available PV modules and inverters have been conducted in this scenario as shown in Tables 3.11 and 3.12. Many different configurations of rooftop grid-connected PV systems have been investigated and a comparative study among these configurations has been carried out taking into account PV modules and inverters specifications. Flowchart of proposed MATLAB computer methodology, used in scenario no. 2, is shown in Fig. 3.9. From the proposed computer program, it can be seen that the ST25000TL inverter is not suitable for those selected PV modules in this scenario due to its low DC input

Table 3.10 Generated output power for one module of ET-P672305WB/WW

Hour	Month											
	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
01:00 AM	0	0	0	0	0	0	0	0	0	0	0	0
02:00 AM	0	0	0	0	0	0	0	0	0	0	0	0
03:00 AM	0	0	0	0	0	0	0	0	0	0	0	0
04:00 AM	0	0	0	0	0	0	0	0	0	0	0	0
05:00 AM	0	0	0	0	0	0	0	0	0	0	0	0
06:00 AM	0	0	0	0	0	0	0	0	0	0	0	0
07:00 AM	0.2418	11.7741	4.6065	7.2977	8.2353	0	2.0918	2.0996	0.4404	13.1777	3.3355	0
08:00 AM	24.4655	61.7912	59.6002	25.1291	52.1722	11.0664	20.8252	35.5297	24.4066	49.3103	49.4647	22.5759
09:00 AM	83.3111	94.8623	129.7234	42.4925	99.8702	54.4898	64.2239	86.8332	83.8088	85.8805	114.7261	104.4056
10:00 AM	151.1045	131.9372	177.3813	70.2066	111.4648	111.0428	135.1924	140.7313	142.979	124.2075	187.6101	157.0487
11:00 AM	186.4208	201.4572	230.0969	144.1673	138.5558	167.9091	192.6576	175.3098	180.5782	**205.6089**	235.2146	166.5365
12:00 AM	218.6747	**250.9574**	**246.0327**	173.1991	190.371	204.7407	228.9464	218.5693	224.7353	172.0633	**250.0235**	158.7423
01:00 PM	**229.8822**	244.2047	243.6301	202.309	**230.5426**	222.8717	**247.1432**	**234.6135**	**249.6875**	180.6353	237.6825	**183.0456**
02:00 PM	218.6747	247.9235	238.1043	**212.0242**	221.455	228.2437	246.5853	**234.6135**	243.3155	172.0633	207.3271	112.1367
03:00 PM	193.1365	244.9876	151.6879	174.8146	207.4793	**229.2902**	227.3432	211.5964	219.5043	130.0866	149.0073	37.4054
04:00 PM	124.5951	178.9874	110.8437	127.5986	163.1074	215.9664	188.4135	187.5583	177.0993	65.8824	71.0328	24.2797
05:00 PM	39.607	111.8641	43.5743	60.2103	143.349	185.9995	135.1924	143.3647	122.221	31.6332	10.6772	5.1297
06:00 PM	0.3278	36.3876	7.7319	6.9857	92.4348	145.5496	89.282	86.2857	60.5862	0.9847	0	0
07:00 PM	0	0.5885	0	0	34.1938	95.7708	41.5669	31.425	7.6333	0	0	0
08:00 PM	0	0	0	0	3.0698	42.6708	0.5901	1.6933	0	0	0	0
09:00 PM	0	0	0	0	0	6.2578	0	0	0	0	0	0
10:00 PM	0	0	0	0	0	0	0	0	0	0	0	0
11:00 PM	0	0	0	0	0	0	0	0	0	0	0	0
12:00 PM	0	0	0	0	0	0	0	0	0	0	0	0

Table 3.11 Technical characteristics of the selected PV modules in scenario no. 2

Item	Module				
	Mitsubishi PV-UD190MF5	Suntech STP270S-24/Vb	ET-P672305WB/WW	1Sol Tech 1STH-350-WH	Solar panel Heliene 96 M 420
P_{max}(W)	**190**	**270**	**305**	**350**	**420**
V_{OC}(V)	30.8	44.8	45.12	51.5	60.55
I_{sc}(A)	8.23	8.14	8.78	8.93	9.0
V_{mpp}(V)	**24.7**	**35.0**	**37.18**	**43.0**	**49.53**
I_{mpp}(A)	**7.71**	**7.71**	**8.21**	**8.13**	**8.48**
Dimensions, m	1.658 * 0.834	1.956 * 0.992	1.956 * 0.992	1.652 * 1.306	1.967 * 1.310
Efficiency (%)	13.7	15	15.72	16.2	16.4
Number of cells	50 cell	72 cell	72 cell	80 cell	96 cell
Cell type (Silicon)	Polycrystalline	Monocrystalline	Polycrystalline	Monocrystalline	Monocrystalline
Price/unit	$340	$753	$305	$525	$420

Table 3.12 Characteristics of the different inverter ratings used in scenario no. 2

Specification	Inverter				
	GCI-10 k-LV	Sunny Tripower 20000TL	ST25000TL	HS50K3	HS100K3
Manufacturer	B&B Power co. Ltd.	SMA Solar Technology	B&B Power co. Ltd.	Han's Inverter & Grid Tech. co. Ltd.	Han's Inverter & Grid Tech. co. Ltd.
$P_{inverter}$ (kW)	**10.2**	**20.45**	**26.5**	**55**	**110**
Max. DC current (A)	**30**	**36**	**32**	**122**	**245**
MPP voltage range (V)	**150–500**	**580–800**	**450–800**	**450–800**	**450–820**
Max. AC power (kW)	10	20	25	50	100
Max. AC current (A)	25	29	40	80	160
Frequency (Hz)	50/60	50	50/60	50	50
Price/unit	$1500	$3870	$2650	$8060	$14,500

current, where the common feature of selected PV modules is that, they have a high current at different voltage level to supply a high power with a minimum installation area.

3.4.2.1 Configurations of PV Modules for Each Subsystem in Scenario No. 2

The configuration details of PV modules for each subsystem in this scenario are shown in Table 3.13. From this table, it can be seen that the outputs of the proposed MATLAB computer program are the optimum total number of PV modules for each subsystem, N_{PV_sub}, number of modules per strings N_{s_sub}, number of strings, N_{p_sub}, and finally the output voltage and current of each subsystem.

Figure 3.10 displays the electrical characteristics of selected PV module (Heliene 96M 420) at different levels of irradiance and constant temperature over a day in July. The amount of energy generated by the solar PV panel depends on peak sun hours available where peak sun hours vary throughout the year. It is clear that the change in irradiance has a strong effect on the output power of the module, but negligible effect on the open-circuit voltage. Also, it can be seen that the maximum power generated during a day in July occurs at 1:00–2:00 p.m. Table 3.14 shows the generated output power for optimal PV modules (Heliene 96 M 420) selected in scenario no. 2.

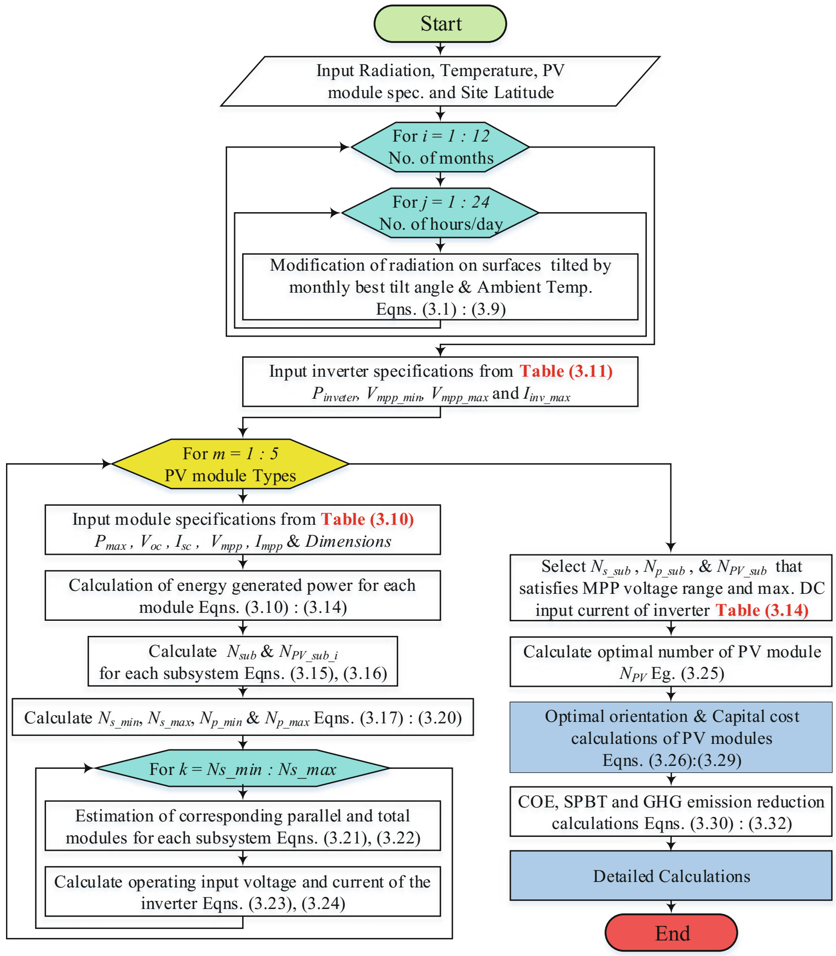

Fig. 3.9 Flowchart of proposed computer program in scenario no. 2

3.4.2.2 Optimal Configuration as a Detailed Calculation in Scenario No. 2

Many calculations have been done for many subsystems. A database containing probable series and parallel combinations, PV modules for each subsystem, and DC input voltage and current is formed. Detailed calculations for optimal configuration of selected module (Heliene 96 M 420) and inverter (GCI-10 k-LV) based on minimum price of kWh generated can be done as follows. Input data are given in Tables 3.5, 3.11, and 3.12.

Table 3.13 Specifications for each subsystem in scenario no. 2

Inverter Type/sub systems		Type Details	Mitsubishi PV-UD190MF5	Suntech STP270S-24/Vb	ET-P672305WB/WW	1Sol Tech 1STH-350-WH	Solar panel Heliene 96 M 420
GCI-10 k-LV	10 subsystem	N_{s_sub}	18	13	12	10	**9**
		N_{p_sub}	3	3	3	3	**3**
		N_{PV_sub}	54	39	36	30	**27**
		V_{sub}(V)	444.6	455.0	446.16	430.0	**445.77**
		I_{sub}(A)	23.13	23.13	24.63	24.39	**25.44**
Sunny Tripower 20000TL	5 subsystem	N_{s_sub}	27	19	17	15	17
		N_{p_sub}	4	4	4	4	3
		N_{PV_sub}	108	76	68	60	51
		V_{sub} (V)	666.9	665.0	632.06	645.0	842.01
		I_{sub}(A)	30.84	30.84	32.84	32.52	25.44
HS50K3	2 subsystem	N_{s_sub}	29	17	13	16	11
		N_{p_sub}	10	12	14	10	12
		N_{PV_sub}	290	204	182	160	132
		V_{sub}(V)	716.3	595.0	483.34	688.0	544.83
		I_{sub}(A)	77.1	92.52	114.94	81.30	101.76
HS100K3	1 subsystem	N_{s_sub}	20	17	19	15	11
		N_{p_sub}	29	24	19	21	24
		N_{PV_sub}	580	408	361	315	264
		V_{sub}(V)	494.0	595.0	706.42	645.0	544.83
		I_{sub}(A)	223.59	185.04	155.99	170.73	203.52

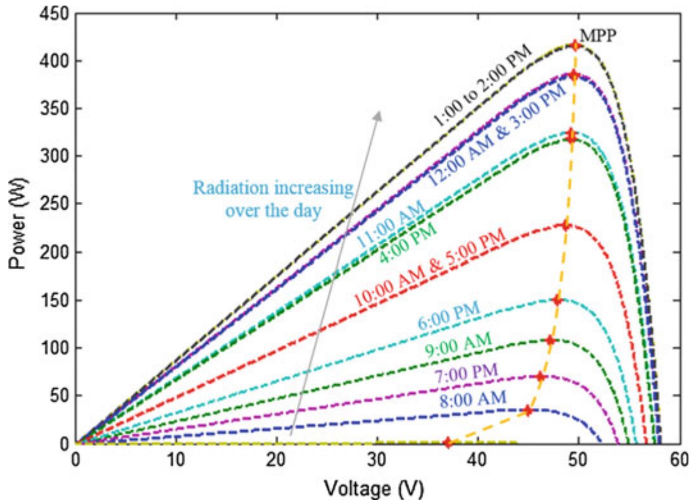

Fig. 3.10 P-V Characteristics of solar panel Heliene 96M 420 over day times in July

$$N_{\text{sub}} = \text{ceil}\left(\frac{P_{\text{system}}}{P_{\text{inverter}}}\right) = \text{ceil}\left(\frac{100,000}{10,200}\right) = \text{ceil}(9.8039) = 10 \text{ subsystems}$$

$$N_{PV\_sub\_i} = \text{ceil}\left(\frac{P_{inverter}}{P_{\max}}\right) = \text{ceil}\left(\frac{10,200}{420}\right) = \text{ceil}(24.2857) \cong 25 \text{ modules}$$

$$N_{\text{s\_min}} = \text{ceil}\left(\frac{V_{\text{mpp\_min}}}{V_{\text{mpp}}}\right) = \text{ceil}\left(\frac{150}{49.53}\right) = \text{ceil}(3.0284) \cong 4 \text{ modules}$$

$$N_{\text{s\_max}} = \text{ceil}\left(\frac{V_{\text{mpp\_max}}}{V_{\text{mpp}}}\right) = \text{ceil}\left(\frac{500}{49.53}\right) = \text{ceil}(10.0948) \cong 11 \text{ modules}$$

So, in order to stay within the voltage range at which the inverter will track the MPP of each subsystem, the number of modules in each string, $N_{\text{s\_sub}}$ must not be fewer than 4 and not be more than 11 as shown in column 2 from Table 3.15.

$$4 < N_{\text{s\_sub}} < 11$$

$$N_{\text{p\_min}} = \text{ceil}\left(\frac{N_{\text{PV\_sub\_i}}}{N_{\text{s\_max}}}\right) = \text{ceil}\left(\frac{25}{11}\right) = \text{ceil}(2.2727) = 3 \text{ modules}$$
$$N_{\text{p\_max}} = \text{ceil}\left(\frac{N_{\text{PV\_sub\_i}}}{N_{\text{s\_min}}}\right) = \text{ceil}\left(\frac{25}{4}\right) = \text{ceil}(6.25) = 7 \text{ modules}$$

Optimal number of parallel modules $N_{\text{p\_sub}}$ is located in the following range as shown in column 3 from Table 3.15:

Table 3.14 Generated output power for one module of solar panel Heliene 96 M 420

Hour	Month											
	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	**Dec.**
01:00 AM	0	0	0	0	0	0	0	0	0	0	0	0
02:00 AM	0	0	0	0	0	0	0	0	0	0	0	0
03:00 AM	0	0	0	0	0	0	0	0	0	0	0	0
04:00 AM	0	0	0	0	0	0	0	0	0	0	0	0
05:00 AM	0	0	0	0	0	0	0	0	0	0	0	0
06:00 AM	0	0	0	0	0	0	0	0	0	0	0	0
07:00 AM	0.3869	19.3269	7.5326	12.1424	13.5776	0	3.4555	3.4596	0.7194	21.8332	5.463	0
08:00 AM	40.2037	102.1675	98.6208	42.036	86.7179	18.378	34.7779	59.3259	40.7083	82.1584	82.0466	37.2135
09:00 AM	137.6023	157.1019	215.2645	71.2331	166.3914	91.0967	107.7298	145.465	140.4422	143.3796	190.8788	173.1567
10:00 AM	250.1059	218.7582	294.6442	117.9044	185.7772	186.0997	227.3243	236.1198	240.0051	207.6215	312.6241	260.8263
11:00 AM	308.7587	334.4683	382.4907	242.6693	231.0913	281.7559	324.2758	294.3231	303.322	344.1976	392.1934	276.6345
12:00 AM	362.3424	**416.8962**	**409.0517**	291.6883	317.8104	343.7468	385.5264	367.1668	377.7117	287.899	**416.9499**	263.648
01:00 PM	**380.964**	405.6504	405.0471	340.8543	**385.0717**	374.2697	**416.2453**	**394.1888**	**419.7569**	**302.2836**	396.319	**304.145**
02:00 PM	362.3424	411.8436	395.837	**357.2656**	369.8541	383.3138	415.3035	**394.1888**	409.0194	287.899	345.5775	186.0261
03:00 PM	319.9144	406.9542	251.8427	294.4165	346.4533	**385.0758**	382.8202	355.4236	368.898	217.4805	248.1239	61.7924
04:00 PM	206.0947	297.0598	183.835	214.7024	272.1748	362.6444	317.1134	314.9453	297.4624	109.8888	117.984	40.0349
05:00 PM	65.2221	185.3697	72.0128	101.0626	239.1108	312.2011	227.3243	240.5515	205.0627	52.6133	17.5918	8.3949
06:00 PM	0.5256	60.0357	12.6774	11.6208	153.9625	244.1347	149.9307	144.5447	101.4119	1.6095	0	0
07:00 PM	0	0.9498	0	0	56.7396	160.4276	69.6143	52.4465	12.6659	0	0	0
08:00 PM	0	0	0	0	5.0357	71.272	0.9678	2.7869	0	0	0	0
09:00 PM	0	0	0	0	0	10.3647	0	0	0	0	0	0

(continued)

Table 3.14 (continued)

Hour	Month											
	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	**Dec.**
10:00 PM	0	0	0	0	0	0	0	0	0	0	0	0
11:00 PM	0	0	0	0	0	0	0	0	0	0	0	0
12:00 PM	0	0	0	0	0	0	0	0	0	0	0	0

$$3 < N_{p\_sub} < 7$$

$$N_{p\_sub} = \text{ceil}\left(\frac{N_{PV\_sub\_i}}{N_{s\_sub}}\right) = \text{ceil}\left(\frac{25}{9}\right) = \text{ceil}(2.7777) = 3 \text{ modules}$$

$$N_{PV\_sub} = N_{s\_sub} \cdot N_{p\_sub} = 9 * 3 = 27 \text{ modules}$$

Assuming that the inverter is operating in the MPP voltage range, the operating input voltage and current of the inverter can be calculated as follows as shown in columns 5 and 7 in Table 3.15, respectively:

$$V_{mpp\_sub} = N_{s\_sub} \cdot V_{mpp} = 9 * 49.53 = 445.77 \text{ V}$$

$$I_{mpp\_sub} = N_{p_{sub}} \cdot I_{mpp} = 3 * 8.48 = 25.44 \text{ A}$$

Each nine modules will be connected in series to build three parallel strings. Considering open-circuit voltage $(V_{oc} = 60.55 \text{ V})$ and short-circuit current $(I_{sc} = 9.0 \text{ A})$ of Heliene 96 M 420 solar module at standard conditions, the open-circuit voltage and short-circuit current for resultant PV array.

$$V_{oc\_a} = 60.55 * 9 = 544.95 \text{ V}$$

$$I_{sc\_a} = 9 * 3 = 27 \text{ A}$$

Which also satisfy the voltage and current limits of selected inverter. MPP voltage range of the (GCI-10 k-LV) inverter is 150−500 V, as can be seen from Table 3.15, all configurations can be implemented according to operating voltage except the last one (case 8) because the voltage exceeds the maximum value of MPP voltage range. On the other hand, maximum DC input current of selected inverter is 30 A, so cases 1−5 from Table 3.15 cannot be implemented where resultant current is higher than maximum DC input current of selected inverter. Although the minimum number of PV modules for a subsystem is 25 as revealed in column 4 in Table 3.15, this number is not the optimal number of PV modules for a

Table 3.15 Optimal configuration of PV module and inverter in scenario no. 2

Case	N_{s_sub}	N_{p_sub}	N_{sub}	V_{sub}(V)	Voltage condition	I_{sub}(A)	Current condition	Optimal
1	4	7	28	198.12	Satisfied	59.36	Not Satisfied	
2	5	5	25	247.65	Satisfied	42.40	Not Satisfied	
3	6	5	30	297.18	Satisfied	42.40	Not Satisfied	
4	7	4	28	346.71	Satisfied	33.92	Not Satisfied	
5	8	4	32	396.24	Satisfied	33.92	Not Satisfied	
6	**9**	**3**	**27**	**445.77**	**Satisfied**	**25.44**	**Satisfied**	**Selected**
7	10	3	30	495.30	Satisfied	25.44	Satisfied	
8	11	3	33	544.83	Not Satisfied	25.44	Satisfied	

subsystem because the resultant current is 42.4 A, which is higher than the maximum DC input current of the inverter (30 A). Optimal total number of PV modules for each subsystem is selected according to minimum number of PV modules which satisfies not only MPP voltage range but also maximum DC input current of the inverter. So the optimal number of PV modules from the remaining cases 6 and 7 is 27 modules. The total number of PV modules can be calculated from the following equation as shown in Table 3.16:

$$N_{\mathrm{PV}} = N_{\mathrm{sub}} \cdot N_{\mathrm{PV\_sub}} = 10 * 27 = 270 \text{ modules}$$

Finally, layout of the PV system is illustrated in Fig. 3.11. The PV system is mainly composed of 270 Heliene 96 M 420 monocrystalline silicon PV modules. The PV modules are arranged in three parallel strings, with nine series modules in each. A power diode, called bypass diode, is connected in parallel with each individual module or a number of modules. The function of this diode is to conduct the current when one or more of these modules are damaged or shaded. Another diode, called blocking diode, is usually connected in series with each string to prevent reverse current flow and protect the modules. The diodes are physically mounted into a junction box on the rear side of the panel and are normally inactive. Each subsystem is connected to GCI-10 k-LV inverter which has the feature of controlling the MPP of PV array through a built-in DC–DC converter. Failure of one distributed inverter does not stop the operation of the entire PV system, because they operate separately. The generated AC power from the inverter is injected into the grid through a distribution transformer and/or utilized by the local loads.

From the proposed computer program shown in Fig. 3.9, the daily generated power for each module and the total number of PV modules for each subsystem can be calculated. To determine the total generated power for each month multiply the generated power for each module/month by the total number of modules for each type of PV modules. The generated power for each type of PV modules under GCI-10 k-LV inverter is shown in Table 3.17 and the reaming results of other inverters are given in Appendix A. Figure 3.12 shows the monthly generated PV power for the GCI-10 k-LV inverter under different PV modules.

3.4.2.3 Maximum Clearance Distance Between PV Rows

From Table 3.11 the width of selected PV module is about 1.31 m, where there are three parallel strings so the width of each PV array is

$$d = 3\ (\text{modules}) * 1.31\ (\text{m}) = 3.93 \text{ m}$$

Table 3.16 Optimal total number of PV modules for each system

Inverter	Module				
	Mitsubishi PV-UD190MF5	Suntech STP270S-24/Vb	ET-P672305WB/WW	1Sol Tech 1STH-350-WH	Solar panel Heliene 96 M 420
GCI-10 k-LV	540	390	360	300	270
Sunny Tripower 20000TL	540	380	340	300	255
HS50K3	580	408	364	320	264
HS100K3	580	408	361	315	264

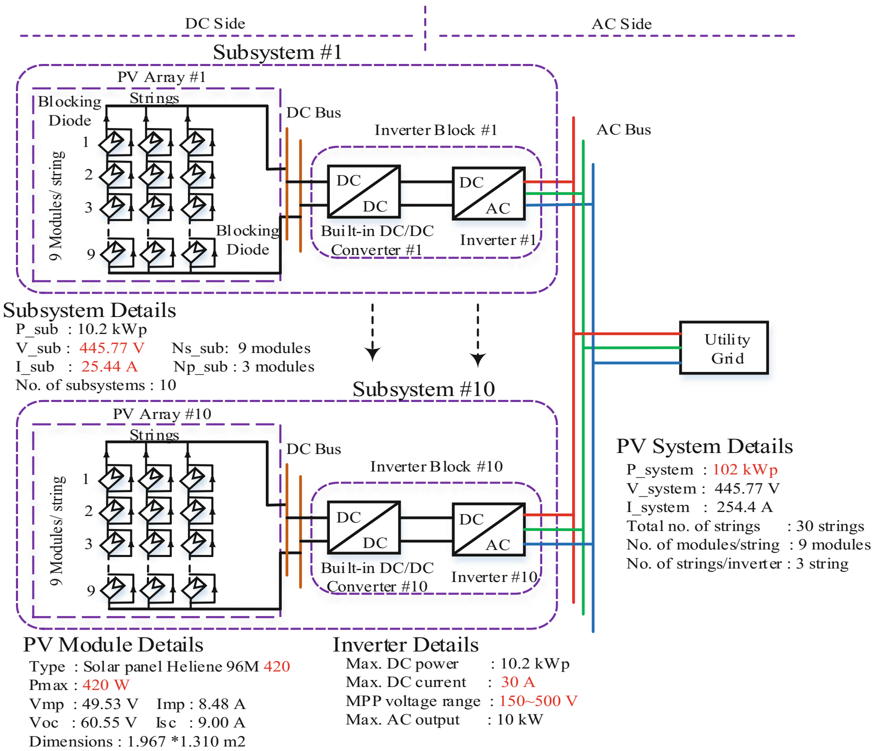

Fig. 3.11 Rooftop grid-connected PV system layout proposed in scenario no. 2

The horizon elevation angle can be calculated as follows:

$$\alpha_1 = 66.5^\circ - \emptyset = 66.5^\circ - 28.1^\circ = 38.4^\circ$$

From proposed computer program, the monthly best tilt angles are shown in Table 3.18. From Table 3.18 it can be concluded that the maximum clearance distance between PV rows is 6.326 m (Fig. 3.13).

3.4.2.4 Detailed Calculations for ST25000TL Inverter

ST25000TL inverter is not selected where the output DC current of subsystems exceed the maximum DC input current of the inverter according to the following calculations:

Table 3.17 Monthly generated PV power for the GCI-10 k-LV inverter at different modules

Power (MWh)	Module				
	Mitsubishi PV-UD190MF5	Suntech STP270S-24/Vb	ET-P672305WB/WW	1Sol Tech 1STH-350-WH	Solar panel Heliene 96 M 420
January	18.3541	18.8494	16.1013	18.5173	19.9930
February	22.5449	23.1328	19.9040	22.9430	24.7736
March	20.3224	20.8509	17.9910	20.7359	22.4107
April	14.7427	15.0863	13.6484	15.7505	17.2265
May	20.6593	21.1859	18.5745	21.3905	23.2394
June	23.0249	23.5827	21.0444	24.3313	26.4835
July	21.6247	22.1305	19.9295	23.0833	25.15
August	21.4202	21.9373	19.6029	22.6637	24.678
September	20.7607	21.2569	19.0201	22.0116	23.9573
October	14.8668	15.2379	13.4853	15.5108	16.9084
November	18.5825	19.0549	16.6013	19.1593	20.7427
December	11.9861	12.3031	10.6358	12.1903	13.2375
Total generated power	228.8893	234.6086	206.5385	238.2875	258.8006

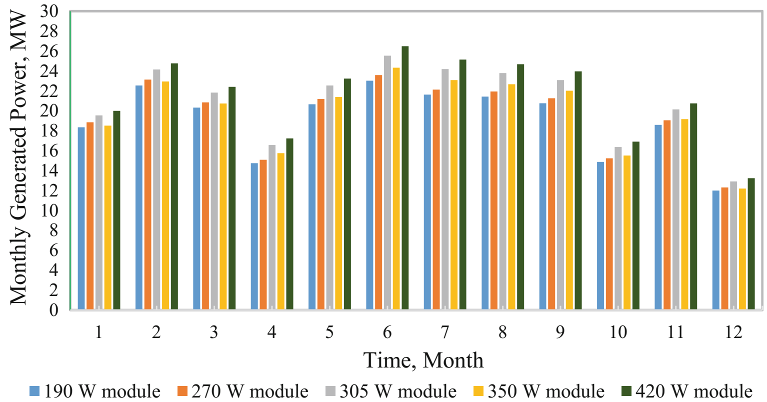

Fig. 3.12 Monthly generated PV power for the GCI-10 k-LV inverter at different modules

$$N_{\mathrm{PV\_sub\_i}} = \mathrm{ceil}\left(\frac{P_{\mathrm{inverter}}}{P_{\max}}\right) = \mathrm{ceil}\left(\frac{26,500}{420}\right) = \mathrm{ceil}(63.0952) \cong 64 \text{ modules}$$

$$N_{\mathrm{s\_min}} = \mathrm{ceil}\left(\frac{V_{\mathrm{mpp\_min}}}{V_{\mathrm{mpp}}}\right) = \mathrm{ceil}\left(\frac{450}{49.53}\right) = \mathrm{ceil}\ (9.0854) \cong 10 \text{ modules}$$

$$N_{\mathrm{s\_min}} = \mathrm{ceil}\left(\frac{V_{\mathrm{mpp\_min}}}{V_{\mathrm{mpp}}}\right) = \mathrm{ceil}\left(\frac{800}{49.53}\right) = \mathrm{ceil}(16.1518) \cong 17 \text{ modules}$$

Optimal number of series modules $N_{\mathrm{s\_sub}}$ is located in the following range as shown in column 2 from Table 3.19:

$$10 < N_{\mathrm{s\_sub}} < 17$$

$$N_{\mathrm{p\_min}} = \mathrm{ceil}\left(\frac{N_{\mathrm{PV\_sub\_i}}}{N_{\mathrm{s\_max}}}\right) = \mathrm{ceil}\left(\frac{64}{10}\right) = \mathrm{ceil}(6.4000) \cong 7 \text{ modules}$$

$$N_{\mathrm{p\_max}} = \mathrm{ceil}\left(\frac{N_{\mathrm{PV\_sub\_i}}}{N_{\mathrm{s\_min}}}\right) = \mathrm{ceil}\left(\frac{64}{17}\right) = \mathrm{ceil}(3.7647) \cong 4 \text{ modules}$$

Optimal number of parallel modules $N_{\mathrm{p\_sub}}$ is located in the following range as shown in column 3 from Table 3.19:

$$4 < N_{\mathrm{p\_sub}} < 7$$

$$N_{\mathrm{p\_sub}} = \mathrm{ceil}\left(\frac{N_{\mathrm{PV\_sub\_i}}}{N_{\mathrm{s\_sub}}}\right) = \mathrm{ceil}\left(\frac{64}{10}\right) = \mathrm{ceil}\ (6.4) \cong 7 \text{ modules}$$

Table 3.18 Clearance distance between rows

Month	Jan.	Feb.	March	April	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Best tilt angle (degree)	49.48	42.02	31.48	19.65	10.27	5.98	7.88	15.61	26.85	38.66	47.98	52.12
Distance, a (m)	6.322	6.238	5.940	5.368	4.751	4.425	4.572	5.119	5.745	6.166	6.314	**6.326**

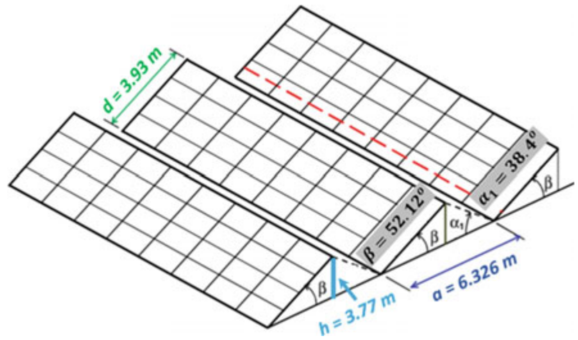

Fig. 3.13 PV modules with several stacked arrays

Assuming that the inverter is operating in the MPP voltage range, the operating input voltage and current of the inverter can be calculated as follows as shown in columns 4 and 6 in Table 3.19, respectively:

$$V_{mpp\_sub} = N_{s\_sub} \cdot V_{mpp} = 10 * 49.53 = 495.3\text{ V}$$
$$I_{mpp\_sub} = N_{p\_sub} \cdot I_{mpp} = 7 * 8.48 = 59.36\text{ A}$$

It is noticed that the DC output current of subsystem (59.36 A) is higher than the maximum DC input of the inverter (32 A) which makes ST25000TL inverter not suitable for this application as revealed in Tables 3.19 and 3.20.

Detailed calculations of subsystems with ST25000TL inverter which is not suitable for the proposed rooftop grid-connected PV systems are shown in

Table 3.19 Subsystems with ST25000TL inverter and Heliene 96 M 420 PV module

Case	N_{s_sub}	N_{p_sub}	N_{sub}	V_{sub}(V)	Voltage condition	I_{sub} (A)	Current Condition	Optimal
1	10	7	70	495.30	Satisfied	59.36	Not Satisfied	There is no optimal configuration
2	11	6	66	544.83	Satisfied	50.88	Not Satisfied	
3	12	6	72	594.36	Satisfied	50.88	Not Satisfied	
4	13	5	65	643.89	Satisfied	42.40	Not Satisfied	
5	14	5	70	693.42	Satisfied	42.40	Not Satisfied	
6	15	5	75	742.95	Satisfied	42.40	Not Satisfied	
7	16	4	64	792.48	Satisfied	33.92	Not Satisfied	
8	17	4	68	842.01	Not Satisfied	33.92	Not Satisfied	

Table 3.20, where the case in column 2 from Table 3.20 refers to the number of probable system configurations with each module type.

3.4.3 Economic Study Calculations

Using data from Tables 3.5, 3.11, and 3.12 and results from Tables 3.13 and 3.16, economic calculation of PV system can be done. Solar PV array is the most expensive component in the proposed system where system cost is determined primarily by the cost of PV modules as shown in Fig. 3.14. Thus, most of the research activities performed in this area are concerned with manufacturing low-cost solar cells with acceptable efficiencies. In the proposed approach, batteries are not considered, so the capital cost is reasonable. Detailed calculations for each system are given in Table 3.21.

According to methodology for COE shown in item 3.3.5.1., the COE can be calculated as follows:

1. Total cost of PV modules can be calculated as follows:

$$C_{\mathrm{PV}} = PV \text{ module cost}\left(\frac{\$}{\text{module}}\right) * N_{\mathrm{PV}}(\text{modules}) = 420 * 270 = \$113,400$$

Table 3.20 ST25000TL inverter under different PV modules

Module type	Case	N_{s_sub}	N_{p_sub}	N_{sub}	V_{sub} (V)	I_{sub} (A)	Condition
Mitsubishi PV-UD190MF5	Start (1)	19	8	152	469.30	61.68	Not Satisfied
	End (15)	33	5	165	815.10	38.55	Not Satisfied
Suntech STP270S-24/Vb	Start (1)	13	8	104	455.00	61.68	Not Satisfied
	End (11)	23	5	115	805.00	38.55	Not Satisfied
ET-P672305WB/WW	Start (1)	13	7	91	483.34	57.47	Not Satisfied
	End (10)	22	4	88	817.96	32.84	Not Satisfied
1Sol Tech 1STH-350-WH	Start (1)	11	7	77	473.00	56.91	Not Satisfied
	End (9)	19	4	76	817.00	32.52	Not Satisfied
Heliene 96M 420	Start (1)	10	7	70	495.30	59.36	Not Satisfied
	End (8)	17	4	68	842.01	33.92	Not Satisfied

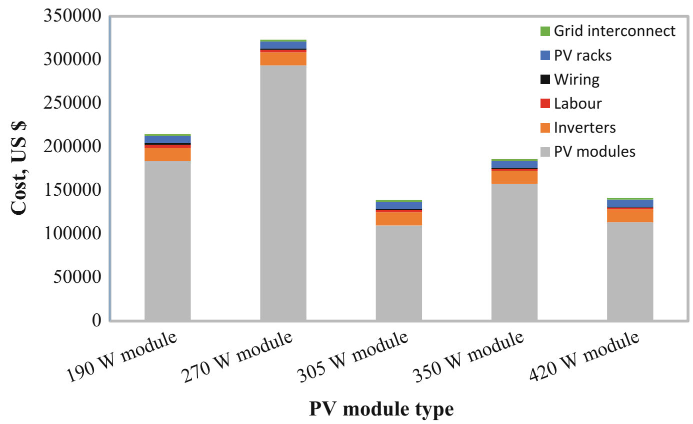

Fig. 3.14 Cost analysis for GCI-10 k-LV inverter under different types of PV modules

2. Total cost of inverters can be calculated as follows which depends on the number of subsystems:

$$C_{\text{inverter}} = \text{inverter cost}\left(\frac{\$}{\text{unit}}\right) * \text{No. of subsystems} = 1500 * 10 = \$15000$$

3. The miscellaneous cost which include labor cost, installation materials cost, mounting hardware cost, and grid interconnection cost:
   3-a Labor cost can be estimated as

$$C_{\text{labor}} = \text{installation labor cost}\left(\frac{\$}{\text{hr}}\right) * \left(\frac{\text{hr}}{\text{module}}\right) * N_{\text{PV}}(\text{modules})$$
$$= 16.66 * 0.43 * 270 = \$1934.226$$

   3-b Wiring cost can be estimated as

$$C_{\text{w}} = \text{installation materials}\left(\frac{\$}{\text{module}}\right) * N_{\text{PV}}(\text{modules}) = 3.6 * 270 = \$972$$

   3-c PV racks cost can be estimated as

$$C_{\text{racks}} = \text{mounting structure}\left(\frac{\$}{W_{\text{p}}}\right) * P_{\text{inverter}} * \text{No.of subsystems}$$
$$= 0.08 * 10200 * 10 = \$8160$$

   3-d grid interconnection cost which assumed to be $2000 as in Ref. [87].

Table 3.21 Detailed economic calculations for each system

Inverter	Cost ($)		Module				
			Mitsubishi PV-UD190MF5	Suntech STP270S-24/Vb	ET-P672305WB/WW	1Sol Tech 1STH-350-WH	Solar panel Heliene 96 M 420
GCI-10 k-LV	PV cost	Assume Grid interconnection cost = 2000 $ [87]	183,600	293,670	109,800	157,500	**113400**
	Inverters cost		15,000	15,000	15,000	15,000	**15000**
	Labor cost		3868.452	2793.882	2578.968	2149.14	**1934.226**
	Wiring cost		1944	1404	1296	1080	**972**
	PV rack cost		8160	8160	8160	8160	**8160**
	Capital cost		214572.452	323027.882	138834.968	185889.14	**141466.226**
Sunny Tripower 20000TL	PV cost		183,600	286,140	103,700	157,500	107,100
	Inverters cost		19,350	19,350	19,350	19,350	19,350
	Labor cost		3868.452	2722.244	2435.692	2149.14	1826.769
	Wiring cost		1944	1368	1224	1080	918
	PV rack cost		8180	8180	8180	8180	8180
	Capital cost		218942.452	319760.244	136889.692	190259.14	139374.769
HS50K3	PV cost		197,200	307,224	111,020	168,000	110,880

(continued)

Table 3.21 (continued)

Inverter	Cost ($)	Module				
		Mitsubishi PV-UD190MF5	Suntech STP270S-24/Vb	ET-P672305WB/WW	1Sol Tech 1STH-350-WH	Solar panel Heliene 96 M 420
	Inverters cost	16,120	16,120	16,120	16,120	16,120
	Labor cost	4155.004	2922.8304	2607.6232	2292.416	1891.2432
	Wiring cost	2088	1468.8	1310.4	1152	950.4
	PV rack cost	8800	8800	8800	8800	8800
	Capital cost	230363.004	338535.6304	141858.0232	198364.416	140641.6432
HS100K3	PV cost	197,200	307,224	110,105	165,375	110,880
	Inverters cost	14,500	14,500	14,500	14,500	14,500
	Labor cost	4155.004	2922.8304	2586.1318	2256.597	1891.2432
	Wiring cost	2088	1468.8	1299.6	1134	950.4
	PV rack cost	8800	8800	8800	8800	8800
	Capital cost	228743.004	336915.6304	139290.7318	194065.597	139021.6432

According to Eq. (3.28), the miscellaneous cost can be estimated as follows:

$$\begin{aligned} C_{\mathrm{m}} &= C_{\mathrm{labor}} + C_{\mathrm{wiring}} + C_{\mathrm{racks}} + C_{\mathrm{grid}} \\ &= \$1934.226 + \$972 + \$8160 + \$2000 = \$13066.226 \end{aligned}$$

According to Eq. (3.27), the capital investment cost can be determined as follows:

$$C_{\mathrm{cap}} = C_{\mathrm{PV}} + C_{\mathrm{inverter}} + C_{\mathrm{m}} = \$113400 + \$15000 + \$13066.226 = \$141466.226$$

3.4.3.1 Estimating AEP, Cash Flows, and COE

For each combination of input system device types, the yearly PV system energy production and the corresponding cash inflows resulting from the generated electric energy purchased to the UG are calculated by simulating the system operation for the lifetime period. According to the Egyptian legalization, the selling price of energy produced by the PV system has been set to P = 84.0 piaster/kWh (12.53 cent/kWh) for systems with installed peak power up to 100 kW. Figure 3.15 shows generated power for each PV module. From this figure, the monthly generated power can be calculated. AEP and corresponding cash inflows resulting from electric energy purchased to the UG for each configuration of PV system are shown in Table 3.22. It can be concluded that the optimal system configuration consists of PV module (Heliene 96 M 420) and inverter (GCI-10 k-LV) based on minimum cost of kWh generated which is equal to 0.5466 $/kWh. The monthly generated power for selected system is shown in Fig. 3.16. The COE can be determined from Eq. (3.30) as follows:

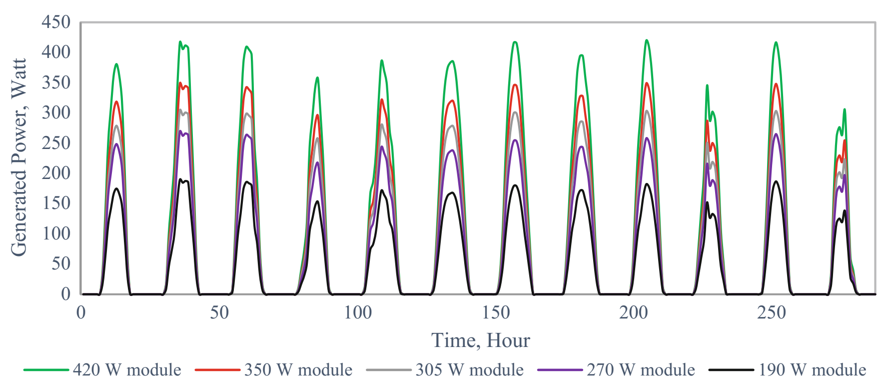

Fig. 3.15 Generated power for each PV module over the year

Table 3.22 AEP, selling price, and COE

Parameter	Inverter	Module				
		Mitsubishi PV-UD190MF5	Suntech STP270S-24/Vb	ET-P672305WB/WW	1Sol Tech 1STH-350-WH	Solar panel Heliene 96 M 420
AEP (MWh/year.)	GCI-10 k-LV	228.8893	234.6086	206.5385	238.2875	**258.8006**
	Sunny Tripower 20000TL	228.8893	228.5928	195.0641	238.2875	244.4227
	HS50K3	245.8443	245.4365	208.8333	254.1732	253.0494
	HS100K3	245.8443	245.4365	207.1121	250.2018	253.0494
Selling price ($/year)	GCI-10 k-LV	27466.71	28153.03	24784.62	28594.50	**31056.07**
	Sunny Tripower 20000TL	27466.71	27431.13	23407.69	28594.50	29330.72
	HS50K3	29501.31	29452.38	25059.99	30500.78	30365.92
	HS100K3	29501.31	29452.38	24853.45	30024.12	30365.92
COE ($/kWh)	GCI-10 k-LV	0.9374	1.3768	0.6721	0.7801	**0.5466**
	Sunny Tripower 20000TL	0.9565	1.3988	0.7017	0.7984	0.5702
	HS50K3	0.9370	1.3793	0.6792	0.7804	0.5557
	HS100K3	0.9304	1.3727	0.6725	0.7756	0.5493

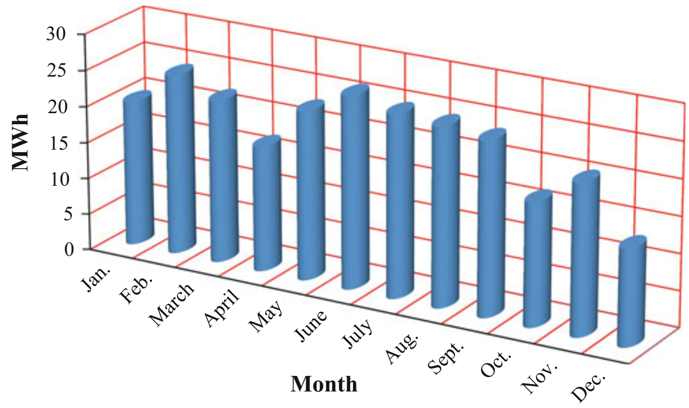

Fig. 3.16 Monthly generated PV power for the proposed system

$$\mathrm{COE} = \frac{C_{\mathrm{cap}} + C_{\mathrm{main}}}{\mathrm{AEP}\left(\frac{\mathrm{kWh}}{\mathrm{year}}\right)} = \frac{\$141466.226 + \$425.6}{258800.6} = 0.5466\ \$/\mathrm{kWh}$$

3.4.3.2 SPBT Estimation

SPBT for the rooftop grid-connected PV system can be calculated according to Eq. (3.30):

$$\begin{aligned}\mathrm{SPBT} &= \frac{C_{\mathrm{cap}}}{\mathrm{AEP} * -C_{\mathrm{cap}} * i - C_{\mathrm{main}}} \\ &= \frac{141466.226}{258.8006 * 10^3 * 0.1253 - 141466.226 * 0.0825 - 425.6} = 6.958\ \text{years}\end{aligned}$$

The cost of proposed rooftop grid-connected PV system can be recouped in 6.958 years, where systems with larger PV output always achieve a shorter payback period due to the lower cost.

3.4.4 GHG Emissions Reduction

The emission factor, F_E is set to be 0.699 kg $CO_{2\text{-eq}}$/kWh [91]. Annual GHG reduction income for a rooftop PV system is calculated using prices for tCO_2 reduction credits. Prices for CO_2 reduction credits differ based on many factors such as how the credit is generated and how it will be delivered. The model estimates that the PV system will reduce GHG emissions by 180.9016 tons of $CO_{2\text{-eq}}$

annually. Approximately 4522.54 tons of CO_2 emissions will be avoided as the rooftop grid-connected PV system replaces the need of some electricity from the existing power grid. At an assumed emission cost factor of about US$30/ton CO_2 as in Ref. [91], the emissions of 0.699 kg CO_2/kWh give a CO_2-revenue of 2.097 cent/kWh (14.68 piaster/kWh). Annual CO_2 emission reduction can be estimated as follows:

$$
\begin{aligned}
\mathrm{CO}_{2(\mathrm{emission})} &= F_E * \mathrm{AEP} \\
&= 0.699\left(\frac{\mathrm{kg}CO_{2-\mathrm{eq}}}{\mathrm{kWh}}\right) * 258.8006 * 10^3(\mathrm{kWh}) = 180.9016\, t\, CO_{2-\mathrm{eq}}/\mathrm{year}
\end{aligned}
$$

CO_2 emission reduction during the lifetime of the project

$$
\begin{aligned}
\mathrm{CO}_{2(\mathrm{emission})} &= F_E * \mathrm{AEP} * N \\
&= 0.699\left(\frac{\mathrm{kg}CO_{2-\mathrm{eq}}}{\mathrm{kWh}}\right) * 258.8006 * 10^3(\mathrm{kWh}) * 25(\mathrm{years}) \\
&= 4522.54 tCO_{2-\mathrm{eq}}
\end{aligned}
$$

*E*stimating PV System Size and Cost

RENEWABLE ENERGY
THE INFINITE POWER
OF TEXAS

SECO FACT SHEET **NO. 24**

HIGHLIGHTS

- **Off-grid photovoltaic (PV) systems can be affordable.**
- **Estimating the size and cost of a PV system to meet your needs is easy.**

INTRODUCTION

Photovoltaic (PV) energy generating systems (or PV systems) convert the sun's energy directly into electricity using state-of-the-art semiconductor materials. PV systems vary in complexity. Some are called "stand-alone" or "off-grid" systems, which means they are the sole source of power to a home, water pump or other load. Stand-alone systems can be designed to run with or without battery backup. Remote water pumps are often designed to run without battery backup, since water pumped out of the ground during daylight hours can be stored in a holding tank for use any time. In contrast, stand-alone home power systems often store energy generated during the day in a battery bank for use at night. Stand-alone systems are often cost-effective when compared to alternatives such as utility line extensions.

Other PV systems are called "grid-connected" systems. These work to supplement existing electric service from a utility company. When the amount of energy generated by a grid-connected PV system exceeds the customer's loads, excess energy is exported to the utility, turning the customer's electric meter backward. Conversely, the customer can draw needed power from the utility when energy from the PV system is insufficient to power the building's loads. Under this arrangement, the customer's monthly electric utility bill reflects only the net amount of energy received from the electric utility.

Each type of system requires specific components besides the PV modules. Generating AC power requires a device called an inverter. Battery storage requires special batteries and a battery charge controller. The final cost of any PV system ultimately depends on the PV array size, the battery bank size, and on the other components required for the specific application.

This fact sheet is designed to generate an estimate for the PV array size, battery bank size, and total cost of a stand-alone PV system. (It can be used for grid-connected systems, too, but with several caveats that are identified in the step-by-step instructions.) This will help you converse knowledgably with a professional PV designer or installer should you decide to purchase a system. To obtain a more complete system design that takes into consideration your particular power needs, site loca-

Appliance	AC or DC Watts		Hours Used/ Day		Watt Hours/ Day
Ceiling Fan	100	x	8.0	=	800
Coffee Maker	600	x	0.3	=	180
Clothes Dryer	4,856	x	0.8	=	3,885
Computer	75	x	2.0	=	150
Computer Monitor	150	x	2.0	=	300
Dishwasher	1,200	x	0.5	=	600
Lights, 4 Compact Fluorescents	4x15	x	5.0	=	300
Microwave Oven	1,300	x	0.5	=	650
Radio	80	x	4.0	=	320
Refrigerator	600	x	9.0	=	5,400
Television	300	x	8.0	=	2,400
Vacuum Cleaner	600	x	0.2	=	120
VCR	25	x	8.0	=	200
Washing Machine	375	x	0.5	=	188
Total					15,493

Table 1 *Typical household electrical appliances and run times*

tion, local weather conditions, and specific equipment used, it is suggested that you work with a qualified PV designer or installer.

ESTIMATING PV SYSTEM SIZE AND COST

The worksheet presented here will help you estimate the size and cost of a PV system. The worksheet is adapted from a method developed by Sandia National Laboratories, and the analysis is conducted in two sections. In the first section, we derive the system specifications by determining the load, available sunlight, and the size of the PV array and battery bank needed. In the second section, we convert the system specification into a cost for the PV system. Let's walk through the analysis, step by step.

STEP 1. DETERMINE LOAD, AVAILABLE SUNLIGHT, PV ARRAY SIZE, AND BATTERY BANK SIZE

1.a. Determine Load. The preferred method for determining PV system loads is a "bottom-up" approach in which every daily load is anticipated and summed to yield an average daily total. For PV systems designed to power simple loads, such as a single water pump, electric light or other appliance, this method is easy. Simply look at the nameplate power rating on the appliance to calculate its power consumption in watts (some labels show amperage and voltage only; to obtain watts, just multiply amps by the voltage). Then multiply by the number of hours it is expected to operate on an average day to obtain watt-hours (Wh).

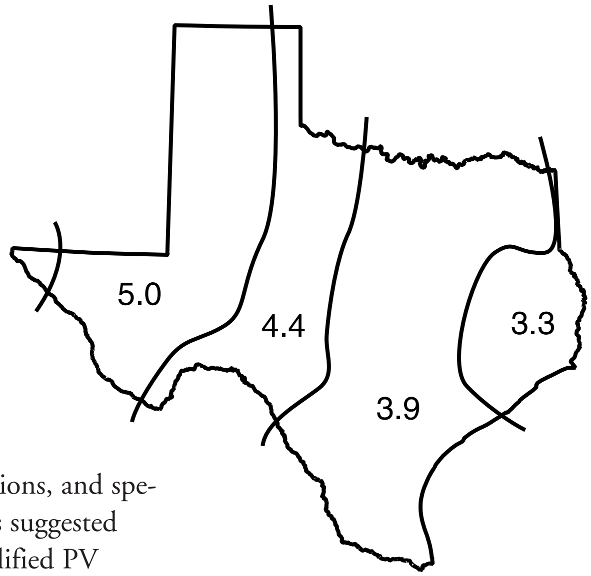

Figure 1 Solar Insolation Map for Texas *This shows the average number of hours of useful sunlight available in December for a PV module at latitude tilt.*

For more complex loads, such as powering a whole house, you will need to estimate all the different loads in the house on a typical day and sum them. Table 1 provides an example calculation for a household using this method.

For complex loads like households, it is sometimes difficult to anticipate every electric load. Electric clocks, TVs, stereos and other appliances sometimes draw small amounts of power even when they are turned off. For this reason, we recommend multiplying your estimated daily load by a "fudge factor" of 1.5. Some other elements accounted for by this factor are all the system efficiencies, including wiring and interconnection losses, as well as the efficiency of the battery charging and discharging cycles.

Of course, for grid-connected systems, you can simply review your monthly utility bills to get an accurate idea of monthly energy consumption.

1.b. Determine Available Sunlight. The amount of useful sunshine available for the panels on an average day during the worst month of the year is called the "insolation value." (We use the worst month for analysis to ensure the system will operate year-round.) In most of Texas, average solar insolation values range from about 3.3 to 5.0 hours per day in December, with the lowest values in east Texas and the highest values in the Panhandle and far west Texas (see Figure 1). The insolation value also can be interpreted as the kilowatt-hours per day of sunlight energy that fall on each square meter of solar panels at latitude tilt.

1.c. Determine PV Array Size. For a PV system powering loads that will be used every day, the size of the array is determined by the daily energy requirement (1.a.) divided by the sun-hours per day (1.b.). For systems designed for non-continuous use (such as weekend cabins), multiply the result by the days per week the loads will be active divided by the total number of days in the week. For example, for a weekend cabin, multiply by 2/7. Generally, grid-connected systems are designed to provide from 10 to 60% of the energy needs with the difference being supplied by utility power.

1.d. Determine Battery Bank Size. Most batteries will last longer if they are shallow cycled–discharged only by about 20% of their capacity–rather than being deep-cycled daily. A conservative design will save the deep cycling for occasional duty, and the daily dis-

The average Texas household uses approx. 1,100 kilowatt-hours (kWh) of electricity per month, or about 36,000 Wh of electricity per day. In contrast, a home designed to be energy efficient can use as little as 6,000-10,000 Wh per day. As you might guess, a PV system designed to power an energy efficient home will cost much less.

charge should be about 20% of capacity. This implies that the capacity of the battery bank should be about five times the daily load. It also suggests that your system will be able to provide power continuously for five days without recharging (such as during a winter storm). Multiply the daily load (1.a.) by 5, and then divide the result by the voltage of the battery bank you will use (typically 12 volts). The result is the recommended amp-hour rating of the battery bank. If you wish to be more secure and design for more days of cloudy weather multiply by a number greater than 5. However, it is generally not recommended to design for more than 12 days of cloudy weather unless it is a highly critical load. Of course, you can skip this step entirely if your system does not incorporate a battery bank, such as a water pump, or is grid-connected since the availability of grid power obviates the need for storage.

STEP 2. CALCULATE PV SYSTEM COSTS

2.a. Estimate PV Array Cost. Many PV modules can be purchased at retail for about $5 per watt for most small systems in the 150 – 8,000 watt range. Of course, there are opportunities to purchase modules for a lower price, especially when your system is larger and you can buy in bulk. When purchasing modules, look for a UL listing (which certifies that the modules meet electrical safety standards) and long-term warranties. Some manufacturers offer modules with 10-20 year warranties.

2.b. Estimate Battery Bank Cost (if needed). Many flooded lead acid batteries designed for use with PV systems can be purchased at retail for under $1 per amp-hour.

2.c. Estimate Inverter Cost (if needed). An inverter will be needed for systems that output AC power. For stand-alone systems the inverter should be sized to provide 125% of the maximum loads you wish to run simultaneously at any one moment. For example, if the total loads you wish to run will be 1,600 watts (a dishwasher, television and ceiling fan from Table 1) choose an inverter with a rated continuous power output of 2,000 watts. For grid-connected systems the maximum continuous input rating of the inverter should be about 10% higher than the PV array size to allow for safe and efficient operation. The input rating of the inverter should never be lower than the PV array rating. For more information contact an

WORKSHEET – ESTIMATING THE COST OF PHOTOVOLTAIC SYSTEMS

Step 1. Determine the load, available sunlight, array size, battery bank size:

a. Determine the energy load required in watt-hours (Wh) per day. Multiply the number of watts the load will consume by the hours per day the load will operate (see Table 1). Multiply your result by 1.5.

Total Wh per day required: ________Wh

b. Determine the hours per day of available sunlight at the site (see Figure 1).

Total available sunlight: _______ hrs/day

c. Determine the PV array size needed. Divide the energy needed (1.a.) by the number of available sun hours per day (1.b.).

Total array size required: _______ Watts

d. Determine the size of the battery bank (if one is desired). Multiply the load (1.a.) by 5 (result is watt-hours, Wh). Then divide by the battery voltage (for example, 12 volts) to get the amp-hour (Ah) rating of the battery bank.

Total Battery Bank Required: _______ Ah

Step 2. Calculate the cost of the PV system needed for this application:

a. Multiply the size of the array (1.c.) by $5 per watt.

Cost estimate for PV array: $ __________

b. If a battery bank is used, multiply the size of the battery bank (1.d.) by $1 per amp hour.

Cost estimate for battery bank: $ __________

c. If an inverter is used, multiply the size of the array (1.c.) by $1 per rated watt.

Cost estimate for Inverter: $ __________

Subtotal: $ __________

d. Multiply the subtotal above by 0.2 (20%) to cover balance of system costs (wire, fuses, switches, etc.).

Cost Estimate for Balance of System: $ __________

Total Estimated PV System Cost: $ __________

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inverter supplier. Inverters designed for residences and other small systems can be purchased at retail for about $1 per rated watt.

2.d. Estimate Balance of System Cost. Besides PV modules and batteries, complete PV systems also use wire, switches, fuses, connectors and other miscellaneous parts. We use a factor of 20% to cover balance of system costs.

COMPARE TO ALTERNATIVES

A final step in an economic feasibility study is to compare estimated costs of the PV system to other alternatives. The most common alternative to off-grid PV is a line extension from an electric utility company. Utilities in Texas typically charge anywhere from $5,000 to $30,000 per mile for line extensions, so for many small- or medium-sized loads in remote locations PV systems are the economically feasible choice. For this reason, several rural electric cooperatives in the state now offer their customers PV systems in lieu of more costly line extensions. Line extensions also may be prohibitively expensive even when the distance traveled is short, such as in urban areas where pavement cuts are required.

Other alternatives include on-site diesel generators, hybrid wind-solar systems, or simply making energy improvements such as installing energy-efficient appliances, improving insulation and sealing ducts. Each alternative comes with its own benefits and drawbacks, many of which are difficult to quantify. For example, the cost of purchasing and delivering diesel fuel to a remote generator should be considered in an economic analysis of alternatives, as well as the noise and exhaust generated as byproducts of the energy production.

STICKER SHOCK? THE IMPORTANCE OF EFFICIENCY

If you've just completed the worksheet to estimate the cost of a PV system for your home, chances are the price may seem a bit high. This is why most people who use PV to power their homes design them to be energy efficient. This means they build their homes with excellent insulation, take advantage of energy efficient designs, and pay attention to important factors such as site selection, shading, and orientation. With some careful planning, it is possible to reduce a home's electrical loads by 50 to 80 percent without sacrificing comfort and convenience.

RESOURCES

FREE TEXAS RENEWABLE ENERGY INFORMATION

For more information on how you can put Texas' abundant renewable energy resources to use in your home or business, visit our website at **www.InifinitePower.org** or call us at 1-800-531-5441 ext 31796. Ask about our free lesson plans and videos available to teachers and home schoolers.

ON THE WORLD WIDE WEB:

Center for Renewable Energy and Sustainable Technology (CREST)
www.solstice.crest.org

NREL'S National Center for Photovoltaics
www.nrel.gov/ncpv

Florida Solar Energy Center
www.fsec.ucf.edu

Department of Energy Solar Site
www.eren.doe.gov/RE/solar.html

Sandia Laboratory photovoltaics with load calculation worksheets
www.sandia.gov/pv

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