Chapter 2
Solar Photovoltaic Power Plants: Necessity and Techno-Economical Development

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2.1 Introduction

The demand of energy is increasing remarkably with the fast growth of population and economy in the world [1, 2]. Figure 2.1 shows the total population between 1950 and 2013 [3]. It is observed from the Fig. 2.1 that the number of population increases with a constant growth rate. It is predicted that this rate will continue in future. At the same time, the economical growth creates large number of industries, higher electricity demand and larger transportation requirement. These factors affect the environment by increasing carbon dioxide (CO_2) known as greenhouse gas due to consuming huge amount of fossil fuel. In 2012, power generation sector was significantly emitting CO_2 which is about 44% of total emission due to fossil fuel burning [3]. Transportation and industrial sectors represent the second and third contributors of CO_2 emission. In 2012, their shares were about 20.6 and 17.8% respectively [3].

In 2014, 10,000 million tons of CO_2 was emitted from 12,928.4 million ton of oil equivalent fossil fuel [2]. The amount of CO_2 increases significantly every year which increases global temperature. Figure 2.1 shows the global CO_2 emission from fossil fuels. Figure 2.2 shows the average global temperature and atmospheric CO_2 concentration between 1950 and 2013 [3]. It is observed that up to 1970, the

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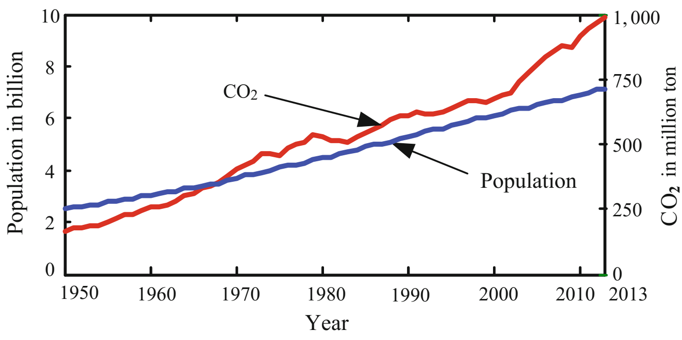

Fig. 2.1 Population and CO_2 emission from fossil fuel burning [3]

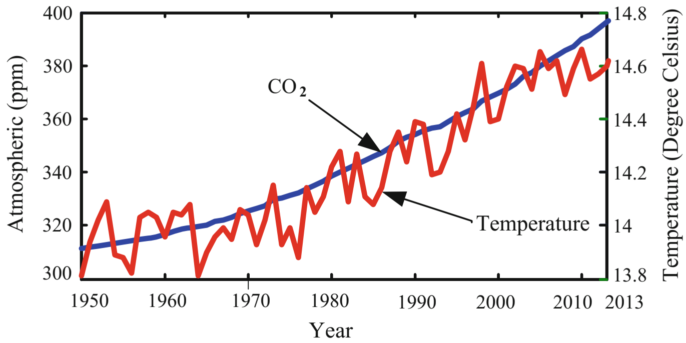

Fig. 2.2 Global temperature and atmospheric CO_2 concentration [3]

average temperature was about 14 °C but next four decades, it rose to 14.6 °C. At the same time, the concentration of CO_2 increased at constant rate. The concentration was about 325 ppm in 1970 whereas by 2013, it was increased to 398.55 ppm [3]. In addition, fossil fuel power plants generate some other greenhouse gases, e.g., carbon monoxide (CO), particulate matter (PM_x), nitrogen oxide (NO_2) and sulphur oxide (SO_x) which also affect the environment. Solid and liquid disposals of power plants affect surrounding water and soil. Nuclear power plant does not emit any green house gases but its radioactive operation, fuel and disposal make the environment radioactive near to the plant and mines.

On the other hand, the increasing energy demand is diminishing the reserve of fossil fuel. To solve these two major challenges, i.e., energy and environment, scientists all over the world are looking for alternative energy sources [4, 5]. Renewable energy may become one of the main alternative source which is richly available almost everywhere. Many countries have set targets for electricity generation from renewable sources, e.g., solar PV, concentrating solar power (CSP), wind power, biofuel and geothermal so that a significant amount of total electricity demand is fulfilled by nonconventional resources. Figure 2.3 shows the renewable electricity generation targets taken by various countries. Costa Rica and Iceland have set their electricity generation targets in such a value that they will not require any fossil fuel or other fuel based power generation system, i.e., 100% electricity demand will be obtained from renewable energy by 2021 [6]. Similarly, Brazil and Fiji also have taken initiatives so that they can generate 80 and 75% of their total electricity from renewable sources by 2021 and 2025, respectively [6]. Germany, UK, India, China, Italy, Japan, Philippines have also set their own targets for different periods as shown in Fig. 2.3.

Due to substantial decline in PV module cost, the annual growth rate of solar PV plant becoming higher than other electric power generation systems. Now, it is becoming feasible to install a solar PV power plant with a capacity of more than 500 MWp. Gujarat solar park shown in Fig. 2.4 is one of the biggest solar PV power plants in the world which is generating more than 856 MWp. In near future, 1000 MWp in capacity solar PV power plant will have thereby become a reality. Up to 2014, about 1600 PV power plants were already installed all over the world [2]. It is reported that 4.9–9.1% and 17–21% of global electricity demand will be met with solar PV power by 2030 and 2050, respectively [2].

This chapter reviews development, construction, and operation of large scale solar PV power plant technologies which give a brief understanding of its necessity and techno-economical development. The module cost, tilt angle, inverter, module arrangement, mounting and tracking system are also discussed which are essential elements of a solar PV power plant. Atmospheric conditions highly affect the performance of a solar PV power plant. Therefore, proper monitoring and appropriate site selection are really critical issues for a solar PV power plant. This chapter also covers latest monitoring systems and site selection techniques which help to design a modern solar PV power plant.

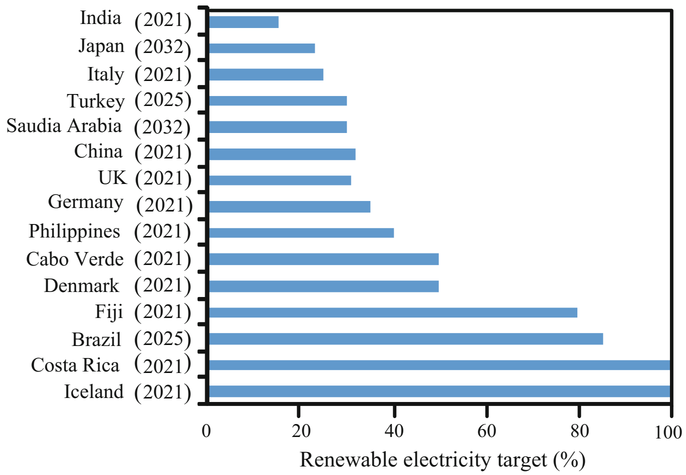

Fig. 2.3 Renewable energy targets by different countries [6]

Fig. 2.4 A photograph of Gujrat solar park [7]

2.2 The Use of Conventional Fuel

The present world still mainly depends on fossil fuel (coal, natural gas and oil) as most of the power plants are now using fossil fuel as source of energy. Moreover, many countries, e.g., France, Slovakia, Ukraine, Belgium and Hungary depend on nuclear energy as main energy source. Still coal, natural gas, oil and nuclear are the dominating conventional sources in the world.

2.2.1 Coal

Coal plays a very important role for the generation of electricity all over the world. Coal fired power is considered as a cheapest source of energy compared to other conventional energy sources, e.g., oil and natural gas [8]. Due to the lower generation cost, coal fired power plants generate 41% of the global electricity [9, 10]. Figure 2.5 expresses the consumption of coal for the generation of electricity from 1965 to 2013.

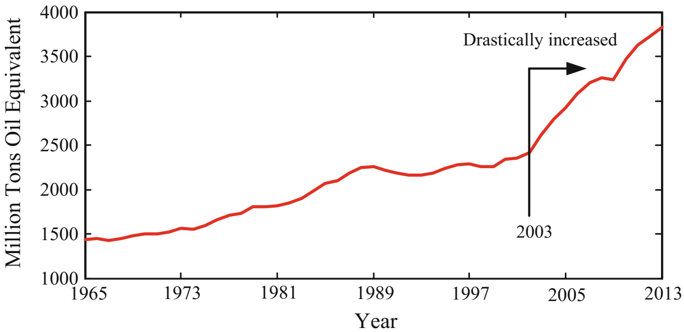

Fig. 2.5 Consumption of coal in the World [3]

Figure 2.5 also depicts that during 1965–1989, the consumption of coal was increased with almost a linear rate. After 1989, the coal consumption remained almost constant until 2003. Since 2003, the coal consumption has been drastically increasing to meet the rapid demand of electricity. In 2013, the amount of coal consumption for electricity generation was almost 4000 Million Tons Oil Equivalent.

2.2.2 Natural Gas

Due to the clean burning nature of natural gas compared to coal, it has become a very popular fuel for the generation of electricity. Figure 2.6 shows the worldwide natural gas consumption from 1965 to 2013. Figure 2.6 also depicts that the consumption of natural gas for electricity generation is increasing with a constant rate.

In 2012, about 22% of the global electricity was generated from natural gas. Literature shows that more than 28% of the global electricity will be generated from natural gas in 2040, i.e., about 2.7% annual growth rate until 2040 [11]. Natural gas is the least carbon-intensive fossil fuel which generates almost 50% less CO_2 than that of coal. In addition, natural gas based power generation technologies are more efficient than coal power generation.

2.2.3 Oil

To meet the growing demand of electricity, oil is the alternative option for producing electricity. In 2014, global oil consumption grew by 1.9 million barrels per day [12]. In 2012, about 5% of the global electricity generation was produced from liquid fuel. It is predicted that the share of the world electricity generation from

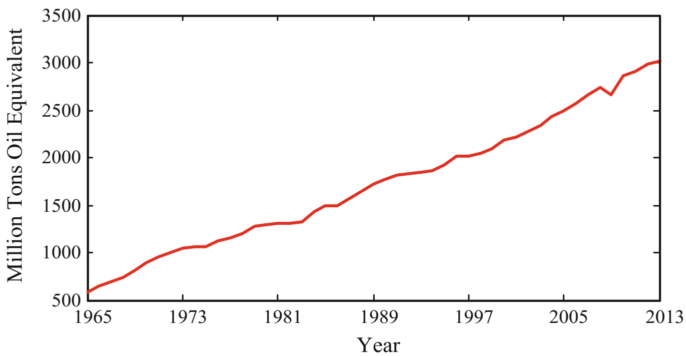

Fig. 2.6 Consumption of natural gas in the World [3]

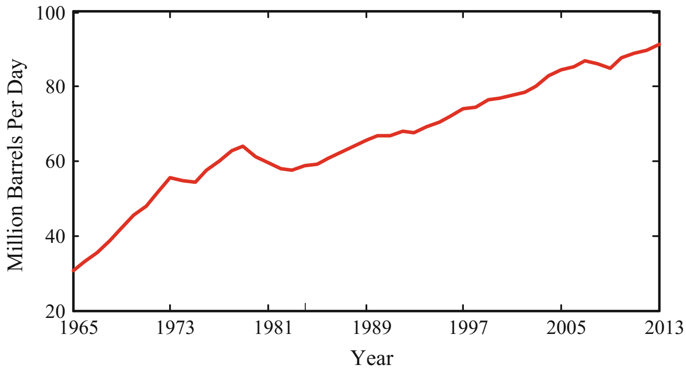

Fig. 2.7 Consumption of oil in the World [3]

liquid fuels will fall to 2% by 2040 as the prices of oil is getting higher [11]. Figure 2.7 demonstrates the oil consumption all over the world from 1965 to 2013.

2.2.4 Nuclear Power

In 2014, about 11% of the global electricity generation throughout the world was generated from nuclear power plants [13]. In France, 72.3% of the total electricity was produced by using nuclear energy in 2016. In 2016, about half of the total electricity demand in Slovakia, Ukraine, Belgium and Hungary was met using nuclear energy [13]. Figure 2.8 demonstrates the global electricity generation by nuclear power plants from 1970 to 2013.

Figure 2.8 also depicts that electricity generation from nuclear power grew until 2005 with almost a constant rate. In recent years, several nuclear power plants have

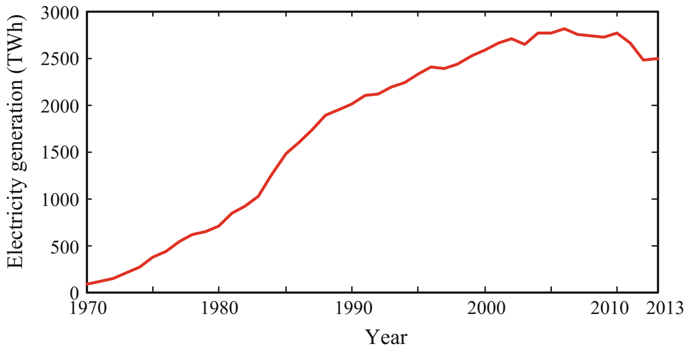

Fig. 2.8 Electricity generation using nuclear energy in the World [3]

been shut down permanently due to some natural disasters, e.g., earthquake and tsunami. In 2011, Fukushima Daiichi nuclear power plant was disabled due to earthquake and tsunami.

2.3 The Environmental Effects of Conventional Fuel Based Power Plants

The conventional power plants affect the environment by the various ways. The conventional fossil fuel based power plants emit greenhouse gases during fossil fuel burning. Moreover, during mining and transportation of fossil fuel, the environment is also affected. Nuclear power plant does not emit greenhouse gases as like fossil fuel based power plants. But, radioactive fuel and wastages of nuclear plants are dangerous for the environment. However, the toxic emission emitted from fossil fuel based power plants and nuclear power plants can deteriorate the ecosystem of the area near to the plants.

2.3.1 The Detrimental Effects of Fossil Fuel Based Power Plants

2.3.1.1 Air Pollution

During the operation of coal based plants, a huge amount of nitrogen oxide (NO_X), sulphur dioxides (SO_2), carbon monoxide (CO), carbon dioxide (CO_2) are produced which pollute air and are responsible for acid rain [8, 14–17]. Coal power plants also produce mercury and some unburned carbon which affects the environment [8, 14–17]. The natural gas based power plants also affect the environment by emitting carbon monoxide (CO), particulate matter (PM_x), nitrogen oxide (NO_2) and sulphur oxide (SO_x). Although, the amount of these pollutants is less compared to the coal based plants, the higher methane leakage during transportation and extraction of natural gas from mines jeopardize the climate benefits. Similarly, fossil oil, e.g., diesel, heavy fuel oil (HFO) and light fuel oil (LFO) based power plants emit CO, CO_2, NO_X, SO_X which pollute the environment.

2.3.1.2 Health Hazards

Due to the toxic emissions or pollutants from fossil fuel based power plants, people are suffering from many difficult diseases like as respiratory, cardiovascular, and cerebrovascular and so on [8, 16]. Mercury is also very toxic element emitted from the coal fired power plants available in both organic and inorganic forms.

The mixture of methyl-mercury (MeHg) with water is harmful for fish and rice as well. When people are having of that fish and rice, they are at health risk due to its bio-magnification property of toxic element [18].

2.3.1.3 Global Warming

The greenhouse gases (CO, CO_2, NO_X, SO_X, methane) emission from fossil fuel increases the global temperature. Scientists and researchers believe that continuous increase of greenhouse gases create rising sea level, altered ocean current, melting of glaciers and polar ice caps, climate alternation and severe storms, which significantly change the ecosystem [19].

2.3.1.4 Water Pollution

From coal fired power plants, a lot of wastage like as arsenic, selenium, boron, cadmium and mercury is disposed to waterways. As a result, water is being polluted. These pollutants lead to the negative impacts on nature and environment. Due to spills and leaks of chemical additives, diesel or other liquids from equipment and different storages appear as a risk of surface water. Moreover, huge amount water is used in condenser of a thermal power plant and is finally returned to the river at warmer temperature. This water affects the water plants, fish, and microbial activities. Moreover, ground water becomes contaminated with fracking fluid and gas near the oil and gas wells.

2.3.2 The Detrimental Effects of Nuclear Power Plants

Though nuclear power plants do not produce fly ash or a toxic or harmful gas, the radioactivity [20] that is released from the nuclear fission seriously affects the public health and environment [21]. The input of nuclear power plant is uranium oxide fuel prepared in few steps such as mining and milling of uranium, transport and reprocessing of irradiated fuel called nuclear fuel cycle. Huge amount of wastage is produced in each step. The serious impact on land, water and occupational health hazards during uranium mining and likely to increase cancer incidence on miners due to radon produced from radioactivity [21].

Moreover, health hazards are occurred due to use of toxic hydrogen fluoride and fluorine in fuel fabrication process. In addition, the gamma ray is emitted from fuel fabrication and nuclear fission process. Again, during serious accident, the cask walls are being ruptured while transporting radioactive materials leads to serious impact on health and environment [21, 22]. Radioactivity has its long term reaction on public health. Due to the thermal discharges from nuclear plant, normal life of biota is affected by hampering reproduction, growth, survival of larval forms, juveniles and adults. Similarly, all fisheries are obstructed to lead normal life due to increase temperature of water by thermal discharge [20, 22].

2.4 Prospect of Renewable Energy

Solar energy is the one of the largest source of renewable energy. In the last decade, a remarkably change has been observed in solar PV market. In 2007, the total global installed capacity of solar PV was only 7.6 GW and it exceeded 100 GW in 2012 [23]. In 2013, the growth rate of solar PV was 28%. Up to 2013, roughly 58% of total capacity of solar PV plants has been installed in Europe. Now China's market is growing rapidly. By 2013, the installed capacity in China increased to 13 GW, whereas it was only 0.3 GW in 2009. In Italy, more than 7.8% of total electricity is generated from solar PV [23]. CSP is a solar thermal power generation technology that uses solar energy to generate electricity. Up to 2013, the global cumulative installed capacity of CSP was 3.4 GW [23]. About two-third of this capacity was installed in Spain. In total 5 MW projects of CSP are currently under construction in Australia, India, China, Chile, South Africa, Middle East and North African region. Wind energy is also dominating renewable source. Up to 2013, total cumulative installed capacity of wind power was 318 GW, whereas it was only 94 GW in 2007. Significant amount of wind power comes from Demark, Germany and US. At present, more than 240,000 wind turbines are operating in all over the world [23]. China, India, Brazil, Mexico and South Africa are becoming big markets for wind power development. Other renewable sources, e.g., biomass and geothermal are attracted less attention and getting smaller growth rate. In 2013, geothermal resources contributed only 76 TWh electricity with an installed capacity of 12 GW [23]. In recent years, the growth rate of geothermal power utilization remains almost constant at about 3%. The use of biomass in power sector is increasing every year. The total installed capacity of biomass power increased from 45 GW in 2007 to 88 GW in 2013 [23]. In 2013, the growth rate of biomass power was 12%. Total installed capacity of different renewable energy is shown in Table 2.1.

Table 2.1 Total installed capacity in GW [22]

Year	2007	2008	2009	2010	2011	2012	2013
Solar photovoltaic	7.6	13.5	21	40	71	100	139
Concentrating solar power	0.4	0.5	0.7	1.1	1.6	2.5	3.4
Wind power	94	121	159	198	238	283	318
Biomass	45	46	51	70	74	78	88
Geothermal power	10.4	10.7	11	11.2	11.4	11.7	12
Hydro power	920	950	380	935	960	990	1000

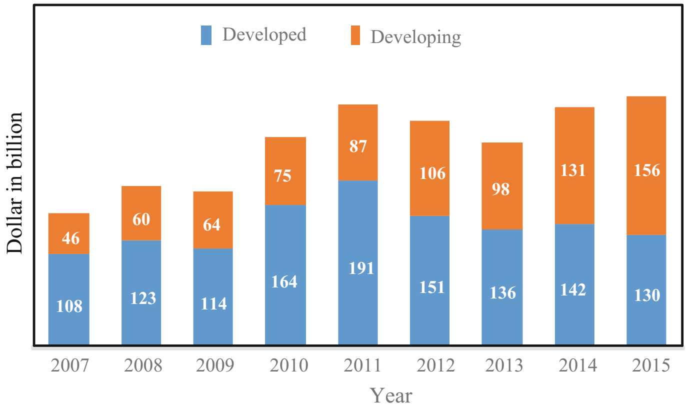

Fig. 2.9 Global new investment in renewable energy (billion dollar) [24]

Total investment in renewable sector increases continuously with some variation. The investment in developing countries also increases every year. In 2015, the investment in developing countries was USD 156 billion, whereas in 2007, it was only USD 46 billion [24]. On the other hand, up to 2011, the investment in developed countries had an increase trend and reached at USD 191 billion. After that, the investment is decreasing continuously. In 2015, the investment was decreased to USD 130 billion. Figure 2.9 shows the global new investment in renewable energy sector. However, solar and wind dominate in the total investment.

2.5 Historical Development of Solar PV Power Plants

A significant growth in solar PV power occurs all over the world in recent decades. Due to its versatility and advances in solar cell technologies, a substantial decline in the installation cost of solar PV power plants has been observed. About 80% of solar cell cost has been reduced in recent decades [25]. Because of huge cost reduction, it reduces the need for subsidies and helps to compete with other power generation systems. As a result, the number of PV power plants is continuously increasing every year in the world.

In recent years, the solar photovoltaic power plants have been gaining significant attention and show a dramatic growth in its cumulative installations. Figure 2.10 shows the cumulative installed capacity of solar PV power [23]. Till now, developed countries generate significant amount of total solar power generation. Day by day, solar PV power is getting popular in developing countries.

Figure 2.11 shows solar-generated electricity in leading countries from 2000 to 2013. Germany is the leading country for the generation of electricity from solar PV. Every year, in total, 30,000 GWh electricity has been generated from solar PV

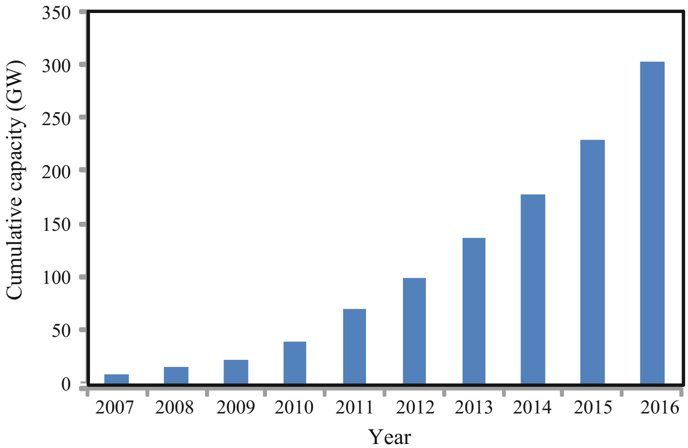

Fig. 2.10 Installed PV capacity worldwide [23]

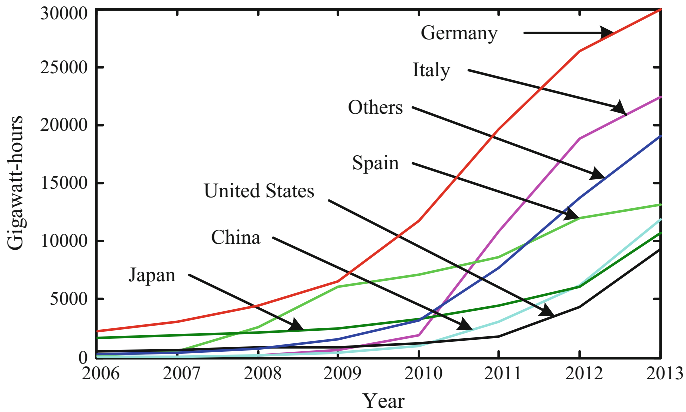

Fig. 2.11 Solar-generated electricity in leading countries [3]

systems, which accounts almost 24% of total global generation [3]. In 2013, Italy also generated significant amount of electricity from solar PV, which was the second largest contributor of global solar PV power and accounts for 18%. At the same time, Spain, China, Japan, US and France generated 10.5, 9.5, 8.6, 7.5 and 3.7% of the global generation, respectively.

Hi-Ren Scenario roadmap reported that future solar PV capacity will see a dramatic change. By 2030, the total cumulative installed capacity will be 1722 GW [26]. The report also shows that by 2050, solar PV sector will share about 16% of the world total power generation. It is expected that by 2050, the total installed capacity of solar PV system will reach at 4674 GW [26]. At present, Europe is the largest market of solar PV system. But, by 2030, China will be the leading country

Table 2.2 Solar PV power in different regions by 2030 and 2050 (GW) [26]

Year	US	EU	China	India	Africa	Middle east	Others	World
2030	246	192	634	142	85	94	329	1722
2050	599	229	1738	575	169	268	1096	4674

Table 2.3 Successful large scale PV plants by ABB [27]

Country	Location	Capacity (MW_p)	Structure	Year of installation
Italy	La Sugarella	24.2	Tracker	2010
Spain	Leon	13.3	Tracker	2010
Italy	Sicilia	6	Fixed	2011
India	Rajasthan	5	Fixed	2011
Italy	Puglia	5	Tracker	2011
Bulgaria	Poveda	50	Fixed	2012
USA	Nevada	24.8	Tracker	2012
Thailand	Lopburi	55	Fixed	2013
USA	Arizona	146	Fixed	2013

for generation of electricity from solar PV power plants and will share 36.84% of total global solar PV power. At the same time, US will be the second leading country for solar PV power plant installation, which will account for 14.3%, followed by EU (11.2%). The prediction shows that China and US will hold their position in future. The total installed capacity will be reached at 4674 GW in 2050. A significant change will be observed in India in solar PV power generation. By 2050, India will share about 12.3% of total global solar PV power which will be the third largest in the solar PV market. Similarly, Africa, Middle East and other developing countries will generate large amount of power from solar PV power plants. The future solar PV capacities are tabulated in Table 2.2 [26].

There are many companies that develop the components of large scale solar PV plants. ASEA Brown Boveri (ABB), Fuji Electric and Siemens are the main leading companies in the world. Currently, a large number of solar PV plants are in operation. Some successful projects installed by ABB are listed in Table 2.3.

2.6 Solar PV Modules in Solar PV Power Plant

The solar photovoltaic means producing electricity from sunlight. A PV cell consists of a positive semiconductor layer and a negative semiconductor layer [6]. When photon of sunlight is absorbed by semiconductor layer, electrons form negative layer are released. If an external circuit is used to interconnect these two layers, a current is established in it. PV cell technology can be categorized into three groups: (i) first generation, (ii) second generation and (iii) third generation.

Crystalline silicon (c-Si) cells are the first generation cells and thin film cells are the second generation cells. Concentrated PV, dye-sensitized cells (DSC) and organic cells are third generation solar cells. Third generation solar cells are not commercially available. First and second generation solar cells mainly dominate in solar cell market. Currently, c-Si cell technology dominates about 85% of the total PV market share [28–30]. It has two types, e.g., mono crystalline (Mono-c-Si) and multi crystalline (Multi-c-Si) cells. Both types are based on silicon wafer. A large silicon crystal ingot is sliced in a process to make mono-c-Si wafer. Multi-c-Si is fabricated over a large area and plasma processing is used to absorb larger light. Multi-c-Si is not as efficient as mono-c-Si.

On the other hand, thin film cells are made of a thin film deposition of a semiconductor on low cost substrate. One of the advantages of thin film technology is that it is cheaper than the crystalline silicon. But, the commercial efficiency is still lower which varies from 7.1 to 11.2%, hence it requires larger area than that of crystalline silicon [2]. There are mainly four types of thin film cell technologies, e.g., amorphous silicon (a-Si) cell, amorphous and micromorph silicon multi-junction (a-Si/μc-Si), copper-indium-[gallium]-[di]-sulfide (CI[G]S), and cadmium telluride (CdTe) [2]. Because of lower efficiency, solar PV plants based on thin film modules require larger space compared to plants based on c-Si modules. It is predicted that the commercial efficiency will achieve to 16% by 2020. It is surveyed that the life time of all types of solar cell is about 25 years. Performance of different types solar PV technologies are shown in Table 2.4.

The production of solar PV modules is increasing day by day. It was about 4028 MW in 2007 and increased to 39,987 MW in 2013. China dominates the production of PV modules. In 2010, China shared 53% of total market. The production capacity of PV modules is continuously increased. In 2013, Chinese PV module shared 64% of the global generation. Annual solar photovoltaic's module production by different countries is shown in Figs. 2.12 and 2.13.

The market price of PV modules is decreasing day by day due to the technical advancement of solar PV technologies. In 2009, the price of high efficiency c-Si was USD 2.45 per watt whereas in 2012, it was only USD 1.94 [31]. The price of Japanese c-Si decreased from USD 1.98 in 2010 to USD 1.22 per watt in 2012. Market price of PV module in Europe is tabulated in Table 2.5.

Table 2.4 Performance of commercial solar PV technologies [2]

PV technology		Efficiency (%)			Area/kW (m^2/kW)
		Module	Lab	Commercial	
c-Si	Mono-c-Si	13–19	24.7	22	7
	Multi-c-Si	11–15	–	20.3	8
TF	a-Si	4–8	10.4	7.1	15
	a-Si/μc-Si	7–9	13.2	10	12
	CI[G]S	7–12	20.3	12.1	10
	CdTe	10–11	16.5	11.2	10

Fig. 2.12 Annual solar photovoltaics' module production in 2010 by different countries [3]

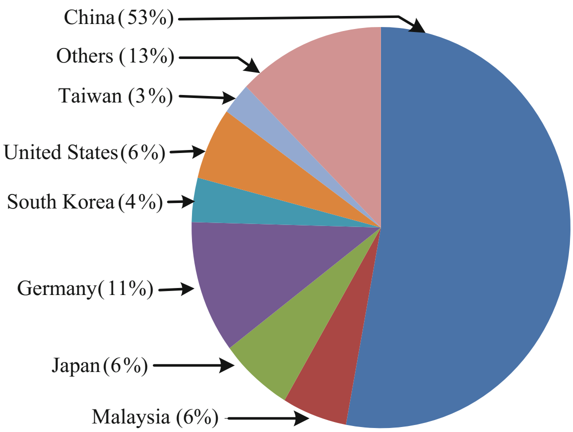

Fig. 2.13 Annual solar photovoltaics' module production in 2013 by different countries [3]

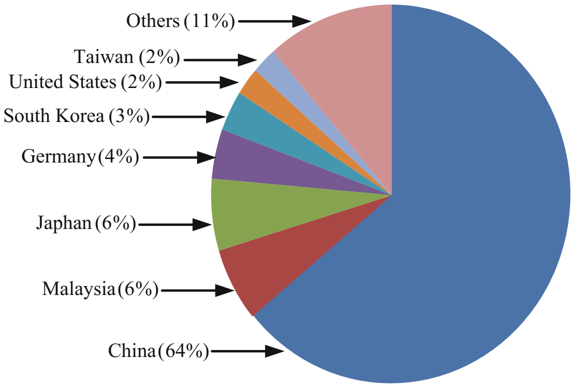

Table 2.5 Market price of PV module in Europe (USD/Watt) [31]

Year	2009	2010	2011	2012
High efficiency c-Si	2.45	2.21	2.00	1.94
Japanese/western c-Si	1.98	1.66	1.22	1.22
Chinese major c-Si	1.51	1.45	1.39	1.24
Emerging economies c-Si	1.45	1.43	1.02	1.02
High efficiency thin-film	1.26	1.27	0.93	0.93

2.7 Inverters in Solar PV Power Plant

Solar PV cell actually generate DC voltage which is variable in magnitude. This variable magnitude DC voltage requires converting into fixed magnitude AC voltage before supplying to the grid. That's why; a power electronic circuit called inverter is commonly used. In addition, to extract maximum power from PV array, maximum power point tracker (MPPT) is also necessary [32–36]. Inverter can be classified based on the number of power stages such as single stage inverter, dual stage inverter and multi stage inverter [37–39]. In single stage inverter system, the inverter performs both inversion and MPPT operation. In dual stage inverter system, the DC-DC converter section performs the MPPT operation and DC-AC converter section performs the inversion. In large scale PV plant, a high value of stray capacitance exists which creates dangerous leakage current. This leakage current may affect system efficiency and output power quality. To overcome these problems, high frequency isolation transformer based multi-stage inverter is commonly used. In multistage inverter, DC power from PV array is first converted to high frequency AC and then passed through a high frequency transformer. After high frequency transformer, the high frequency power is converted to DC and line frequency AC through rectifier and inverter, respectively. Central and string inverters are two most commonly used inverter topologies especially for large scale solar applications [5]. In centralized PV inverter technology, a large number of solar PV modules are connected in series known as string to meet the voltage requirements. To obtain larger AC power, multiple numbers of strings are connected in parallel to an inverter (DC-AC) circuit. Both single stage and double stage topologies can be implemented in this inverter system. For large scale solar PV plant, central inverter topology is normally used. A centralized inverter system is shown in Fig. 2.14.

In DC-DC converter based inverter, many stings of PV modules are used and each string is connected with an individual DC-DC converter as shown in Fig. 2.15. The output of all DC-DC converters delivers power into a DC link. The common DC link voltage performs the input of the inverter circuit (DC-AC) and then the output of inverter is fed into the utility grid. The efficiency of these technologies is lower due to much more losses in DC-DC converter which also increases the component cost that makes system costlier. Only multistage topology is used in this converter.

There are many vendors who supply a sort of inverters for various power rating. ABB offers PVS 800 version inverter for power range 100–1000 kW. Central inverter is used in these types of inverter. Some specifications for a few PVS 800 inverters are tabulated in Table 2.6.

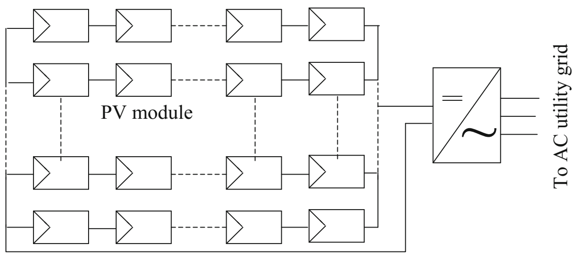

Fig. 2.14 A centralized inverter topology [39]

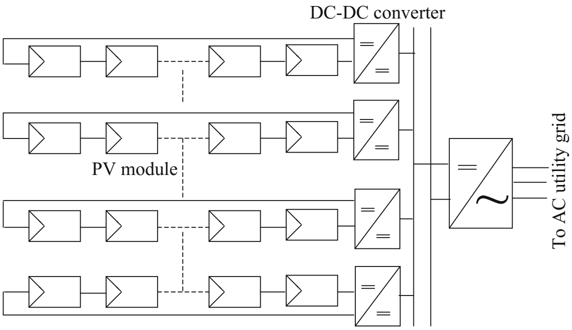

Fig. 2.15 A string inverter topology with DC-DC converter [39]

ABB also provides the ultra utility scale central inverter range from 700 to 1400 kW. It can operate under wide range of operating conditions. High speed MPPT leads it to obtain maximum efficiency. Ultra-1400-TL is the largest power inverter among ABB's inverter product with efficiency up to 98.7%. Some technical data are listed in Table 2.7.

Siemens is another leading inverter supplier in the PV market. Siemens offers central inverters SIVERT PVS 600 series with the power capacity range 500–2520 kW for medium and large scale solar PV plants. The maximum efficiency of these types of inverter is 98.7%. They provide five years' warranty as standard. These types of inverters are operated according to the master slave principle. In this concept, PVS inverters are integrated in an inverter station having a rotating master. It connects or disconnects the inverter subunit depending on the solar irradiance. Some technical data of SIVERT PVS 600 series central inverter is depicted in Table 2.8.

Fuji Electric offers a sort of inverters known as power conditioning systems (PCSs). Some are outdoor self-standing type PCS (PVI1000-3/1000 and PVI750-3/750) and some are indoor self standing type PCS (PVI500-3/500). Some specifications of Fuji PCSs are depicted in Table 2.9.

2.7.1 Substations in Solar PV Power Plant

Substation includes all the electrical components connected in between inverter output and medium voltage utility grid. Step-up power transformer, switchgear, monitoring system, and metering are basic elements of solar PV substations. Both power and distribution transformers are used in substation. Power transformer steps up the inverter output voltage to medium voltage level whereas distribution transformer is required to meet internal power demand. Transformer for solar PV

Table 2.6 Specifications of ABB's PVS 800 central inverters [40]

Type Code	Features	PVS 800-57-0500 kW-A	PVS 800-57-0630 kW-B	PVS 800-57-0875 kW-B	PVS 800-57-1000 kW-C
Input DC	Maximum input power	600 kWp	756 kWp	1050 kWp	1200 kWp
	DC voltage range	450–825 V	525–825 V	525–825 V	600–850 V
	Maximum DC voltage	1000 V	1000 V	1100 V	1100 V
	Maximum DC current	1145 A	1230 A	1710 V	1710 V
Output AC	Nominal AC output power	500 kW	630 kW	875 kW	1000 kW
	Maximum AC output power	500 kW	700 kW	1050 kW	1200 V
	Nominal AC current	965 A	1040 A	1445 A	1445 A
	Nominal output voltage	300 V	350 V	350 V	400 V
	Output frequency	50/60 Hz	50/60 Hz	50/60 Hz	50/60 Hz
	Harmonic distortion (Current)	<3%	<3%	<3%	<3%
	Maximum Efficiency	98.6%	98.6%	98.7%	98.8%

Table 2.7 Specification of Ultra utility scale central inverters [40]

Type code	Features	Ultra-700-TL	Ultra-1050.0-TL	Ultra-1400-TL
Input DC	MPPT DC voltage range at P_{acr} and V_{acr}	585–850 V, 750 kW 645–850 V, 780 kW	585–850 V, 1050 kW 645–850 V, 1170 kW	585–850 V, 1400 kW 645–850 V, 1560 kW
	Maximum DC voltage	1000 V	1000 V	1000 V
	Maximum DC current	1388 A	2082 A	2776 V
	Number of MPPT multi-master	2	3	4
Output AC	Nominal AC output power	780 kW	1170 kW	1560 kW
	Maximum AC output power	780 kVA	1170 kVA	1560 kVA
	Nominal AC current	650 A	975 A	1300 A
	Nominal output voltage	690 V	690 V	690 V
	Output frequency	50/60 Hz	50/60 Hz	50/60 Hz
	Harmonic distortion (Current)	<3%	<3%	<3%
	Maximum Efficiency	98.7%	98.6%	98.7%

Table 2.8 Specification of inverters SINVERT PVS 600 [41]

Type code	Features	PVS 600	PVS 1200	PVS 1800	PVS 2400
Input DC	Rated input power	613 kWp	1226 kWp	1839 kWp	12,452 kWp
	DC voltage range	570–820 V	570–820 V	570–820 V	570–820 V
	Number of DC inputs	3	6	9	12
	Maximum DC current	1104 A	2208 A	3212 V	4416 V
Output AC	Rated output power	600 kW	1200 kW	1800 kW	2400 kW
	Nominal AC current	936 A	1872 A	2808 A	3744 A
	Nominal output voltage	370 V	370 V	370 V	370 V
	Output frequency	50/60 Hz	50/60 Hz	50/60 Hz	50/60 Hz
	Maximum Efficiency	98.7%	98.7%	98.7%	98.7%

plant is specially designed to reduce size, weight and losses. There are many vendors, e.g., ABB, Fuji Electric and Siemens manufactures various transformers for solar PV plants. ABB supplies both liquid-filled and dry type transformers. They are designed so that transformers become compact, reliable and high efficient. Siemens also offers a special transformer, e.g., GEAFOL cast-resin for solar PV applications. However, there are varieties types of switchgear and protection system

Table 2.9 Specification of some PCSs supplied by Fuji Electric [42]

Type code	Features	PVI1000-3/1000	PVI750-3/750	PVI500-3/500
Input DC	DC voltage MPPT range	460–950 V	320–750 V	320–700 V
	DC voltage range	1000 V	750 V	750 V
Output AC	Rated output power	1000 kW	750 kW	500 kW
	Rated AC current	2138 A	2165 A	1444 A
	Rated output voltage	270 V	200 V	200 V
	Output frequency	50/60 Hz	50/60 Hz	50/60 Hz
	Maximum Efficiency	98.5%	97.8%	97.7%
	Output current distortion factor	<5%	<5%	<5%
Step-up transformer	Capacity	1000 kVA	750 kVA	500 kVA
	Number of phase	Three-phase	Three-phase	Three-phase
	Cooling system	Oil immersed self cooling	Oil immersed self cooling	Oil immersed self cooling

used to provide disconnection, isolation, earthing and protection during maintenance and in case of fault conditions. Up to 33 kV, SF_6 and vacuum circuit breakers are normally used. For over-current protection, string fuse or miniature circuit breakers are normally used. Different types of transformer protection systems are used such as Buchholz relay, pressure relieve device, over temperature protection, and oil level monitoring. All switchgear should be recognized by relevant international electro technical commission standards and national codes. ABB provides different range of medium voltage switchgear including air insulated and gas insulated switchgear [40]. A high level of reliability and personnel safety are ensured by a sealed string with constant atmospheric conditions.

ABB offers megawatt station PVS 800 which includes two inverters, transformer, switchgear, monitoring system and DC connection from solar array. Its capacity varies from 1 to 1.25 MW. Some technical specifications of megawatt stations PVS 800 are tabulated in Table 2.10. In addition, ABB provides inverter station PVS 800 with capability of 1.25–2 MW. For both PVS 800 MWS and PVS 800-IS, central inverter topology is commonly used to convert DC to AC voltage for medium voltage station. The schematic diagram of an inverter station PVS 800-IS is given in Fig. 2.16.

Auxiliary transformer can be used in case of unavailability of external energy supply. Some technical data of inverter stations PVS 800-IS are tabulated in Table 2.11.

Table 2.10 Specification of ABB's megawatt stations PVS 800-MWS [40]

Type code	Features	PVS 800-MWS-1000 kW-20 1 MW	PVS 800-MWS-1250 kW-20 1.25 MW
Input DC	Maximum input power	2 × 600 kW	2 × 760 kW
	Dc voltage range	450–825 V	525–825 V
	Maximum DC voltage	1000 V	1000 V
	Maximum DC current	2 × 1145 A	2 × 1145 A
	Number of MPP trackers	2	2
Output AC	Nominal AC output power	1000 kW	1250 kW
	Nominal AC current	28.9 A	36.1 A
	Nominal output voltage	20 kV	20 kV
	Output frequency	50/60 Hz	50/60 Hz
	Harmonic distortion (Current)	<3%	<3%
	Maximum Efficiency	98.7%	98.6%
	Inverter type (2 × ABB central inverter)	PVS 800-57-0500 kW-A	PVS 800-57-0630 kW-B
	Transformer type	ABB Vacuum cast coil dry type	

Due to the demand of the society, ABB and other vendors are trying to develop high power devices for large scale solar PV power plants. Recently ABB has developed multi-megawatt system PVS 980 MWS whose capacity varies from 3.6 to 4.6 MW. The electrical connection diagram of PVS 980 MWS is shown in Fig. 2.17.

2.7.2 *Monitoring Systems in Solar PV Power Plant*

A monitoring system offers the details information on systems performance, measurement of voltage, current and power. It also provides information for identifying the different types of faults and control mechanism depending on the weather condition and plant performance. In addition, monitoring system offers clear instruction on how to conduct and analyze the measurement and how to determine

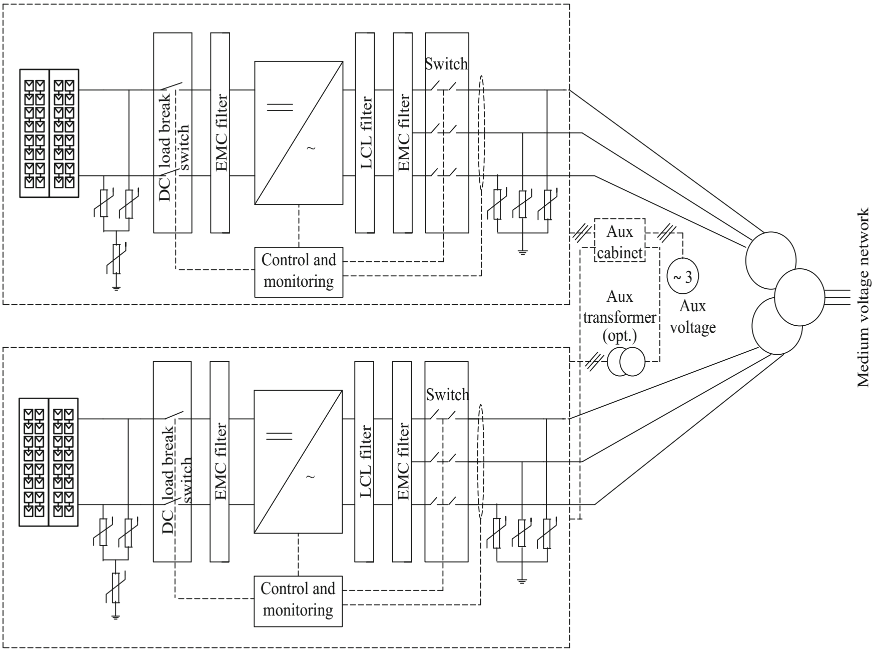

Fig. 2.16 ABB Inverter station design and power network connection [40]

Table 2.11 Specification of ABB's inverter stations PVS 800-IS [40]

Type code	Features	PVS 800-IS-1750 kW-B 1.75 MW	PVS 800-IS-2000 kW-C 2 MW
Input DC	Maximum input power	2 × 1050 kW	2 × 1200 kW
	Dc voltage range	525–825 V	600–850 V
	Maximum DC voltage	1100 V	1100 V
	Maximum DC current	2 × 1710 A	2 × 1710 A
	Number of MPP trackers	2	2
Output AC	Nominal AC output power	2 × 875 kW	2 × 1000 kW
	Maximum AC output power	2 × 1050 kW	2 × 1200 kW
	Nominal AC current	2 × 1445 A	2 × 1445 A
	Nominal output voltage	350	350
	Output frequency	50/60 Hz	50/60 Hz
	Harmonic distortion (Current)	<3%	<3%
	Maximum Efficiency	98.7%	98.6%

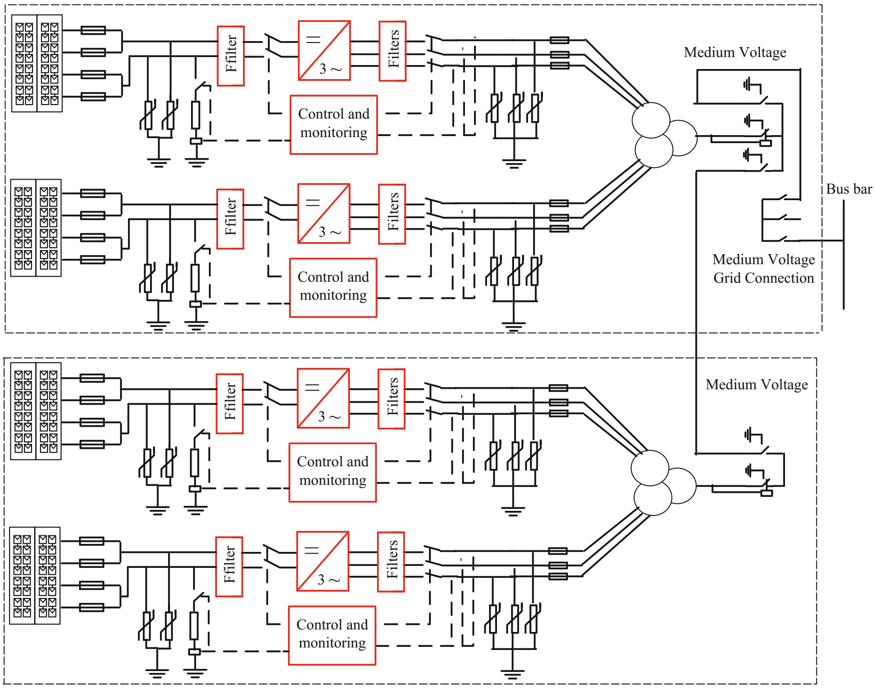

Fig. 2.17 ABB megawatt station design and grid connection [40]

whether the system is performing as expected. A schematic diagram of a monitoring system is shown in Fig. 2.18.

The measurement of DC and AC voltage, current and power in a PV power plant are done by different types of sensors and transducers, e.g., the Hall Effect transducer LEM LV25-P is used to sense the DC and AC voltages [43]. The transducers LA 305-S and LF305-S are used to measure DC and AC current, respectively. Different types of conditioning circuits are used to regulate the points of the data acquisition condition. Sometimes, wire sensor network is also used in PV power plant such as; a wireless sensor network (WSN) is used to record the atmospheric conditions and power generation related to inverters. A weather station is also installed for recording rain index, wind speed and direction, pressure and temperature of plant environment. The weather station also includes the wireless remote sensor incorporated into a computer. To visualize the plant information especially weather condition, Cumulus software is commonly used. The synchronization system synchronizes all subsystems and maintains a universal time reference with high precision for all wireless measurement. A robust communication network is required for real time monitoring system to ensure the reliability and continuity of the plant. A supervisory control and data acquisition (SCADA) system is used for real-time monitoring of the status of the data acquisition equipment and the collected measurements which is called PV–on time system.

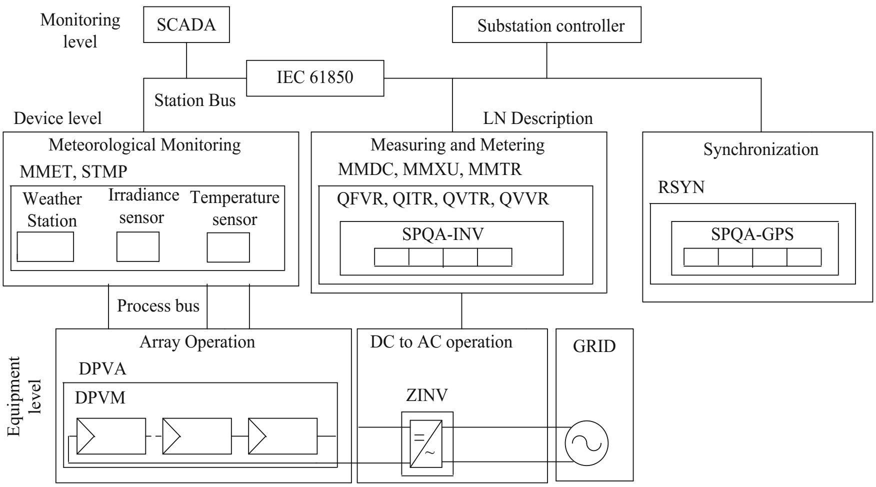

Fig. 2.18 A schematic diagram of a monitoring system [43]

ABB offers different types monitoring and communication devices, e.g., data logger VSN 700, Wi-Fi logger cards VSN 300 and the remote monitor PVI-AEC-EVO [40]. Data logger VSN 700 records data and events from inverters, energy meters, weather stations, and from other devices. It provides an internet gateway to transmit data securely and reliably for monitoring and recording data. There are three types of data loggers VSN 700, e.g., VSN 700-01, VSN 700-03, and VSN 700-05 data loggers. Among them, only VSN 700-05 is used for utility PV operation and SCADA integration. On the other hand, logger card VSN 300 is an advance monitoring and controlling system. Both remote and local monitoring system is achieved by the Wi-Fi logger card VSN 300. In addition, it offers the ability to use a standard web browser to access inverter data. The remote monitor PVI-AEC-EVO is also used for remote monitoring for PV plant with all ABB devices. The modular and expendable architecture is combined with din rail mountain system that makes PVI-AEC-EVO suitable for any kind of installation in PV plant. A proprietary Aurora Protocol is used for communication between remote monitor PVI-AEC-EVO and ABB devices. To store data for back up, 2 gigabyte secure digital card flush memory is used. In case of absent of local area network Ethernet, global system for mobile communication (GSM) can be used in remote monitoring PVI-AEC-EVO system. A block diagram of remote monitor PVI-AEC-EVO is shown Fig. 2.19.

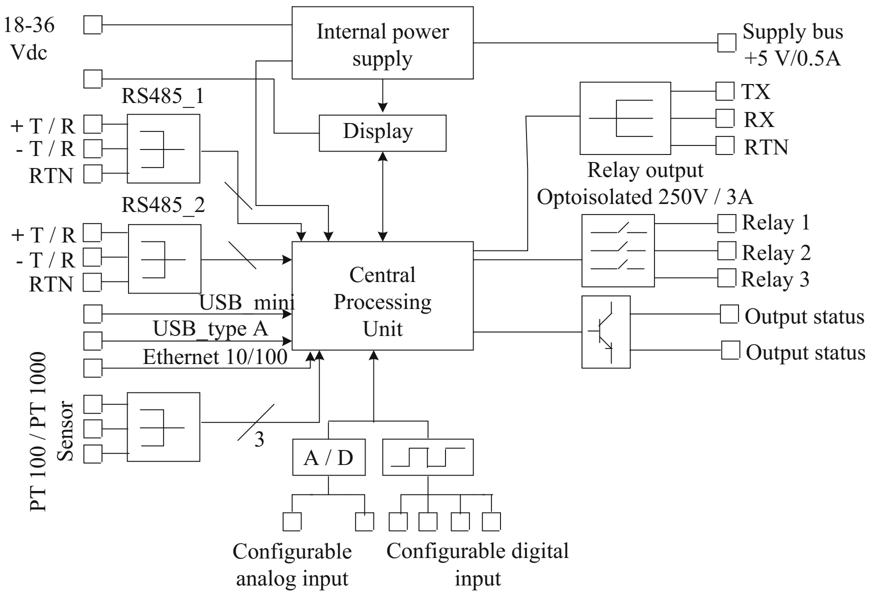

Fig. 2.19 Block diagram of the remote monitor PVI-AEC-EVO [40]

2.8 Mounting and Tracking Systems in Solar PV Power Plant

PV modules are usually set on a structure with supports and tracking systems. The tracking system helps to keep their orientation in the right direction. In fixed position system, PV modules are tilted away from horizontal plane with an optimum angle to get maximum annual irradiance. The fixed system requires less installation and maintenance cost than that of tracking based system. Tracking system can extract 30–50% additional energy depending on geographical location and day time [44]. Tracking system consumes a small amount of power to derive their motors. There are two types of tracking systems, e.g., single axis and double axis [45]. Double axis tracking system is more efficient than single axis tracking system as double axis tracking system can control both orientation and tilt angle [46, 47]. On the other hand, single axis tracking system can control either orientation or tilt angle. Single axis tracking system is cheaper and higher reliability than double axis tracker [46, 47]. However, tracking system is normally used for c-Si modules because of its higher efficiency. A number of vendors have been manufacturing controllers especially for tracking systems. Siemens provides tracking system based on controller SIMATIC S7-1200. Both single axis and double axis tracker systems can be controlled by this controller. KIPP & ZONEN offers two types of tracking systems or sun trackers, e.g., sun tracker SOLYS 2 and sun tracker 2AP [48]. Global positioning system is integrated in SOLYS 2 that locates the position of the sun. The sun tracker SOLYS 2 does not need any additional

Table 2.12 Specifications of trackers SOLYS 2 and 2AP [48]

Specifications	SOLYS 2	2AP
Pointing accuracy	<0.10° passive tracker <0.02° active tracking	<0.10° passive tracker <0.02° active tracking
Torque	>23 Nm (when sun tracking)	>40 Nm (when sun tracking)
Angular velocity	Up to 5°/s	Up to 1.8°/s
Payload (balance)	20 kg	65 kg
Supply voltage	18–30 VDC 90–264 VAC, 50/60 Hz	24 VDC 115–230 VAC, 50/60 Hz
Power sun tracker	21 W	50 W
Operating temperature	−20–+50 °C (DC power) −40–+50 °C (AC power)	0–+50 °C −20–+50 °C (DC power) (cold cover) −50–+50 °C (AC power) (Cold and heater cover)
Dimension (W × D × H)	50 × 34 × 38 cm	42 × 26 × 38 cm

computer or software. The sun tracker 2AP is normally used in the worst environment, e.g., high speed wind and snow fall. Pre- programmed movement of tracker can be achieved by software Win2AP. Some specifications of sun trackers SOLYS 2 and 2AP are given in Table 2.12.

2.9 Site Selection Criteria for Solar PV Power Plant

Site selection is one of the vital works for installing a solar PV plant which is a multi objectives problem. Many factors have to be considered during the selection of a site. These factors are classified into two classes, e.g., analysis criteria and exclusion criteria [49]. The selection criteria include solar radiation, availability of land, accessibility, and distance from the utility grid. Since the output of PV cells mostly depends on solar radiation, the availability of proper solar irradiance is an important factor to select a site. Land should be low price to reduce investment. There should be kept a possibility for further extension. Similarly, the exclusive criteria include local climate, module soling and topography of site, geotechnical issue. Climate affects the construction of plant. Flood, high speed wind and snow may affect the support of PV plant [25]. In addition, the efficiency of PV cell declines with increase of temperature. Efficient output is obtained from solar cells if they operate in between 25 and 45 °C [49]. In case of topography of site, south facing slope is preferable for projects in the northern hemisphere. Geotechnical factors, e.g., resistivity of soil, ground water level, soil pH and load bearing properties also affects during selection of site [46]. Software geographic information system (GIS) is mostly used to select a site for solar PV plant [50, 51]. This software helps to manage, analyse and to visualize the geographical data. There are many vendors, e.g., MapInfo, Autodesk, Bentley systems, Eredas Imagine, ESRI, IGIS, who dominates in supplying software GIS [49].

Table 2.13 Capital expenditure for installing a 100 MW solar PV plant [52]

Category	Description	USD/ W_{DC}	Total cost (USD)
Hard cost	Module	0.75	75,000,000
	Inverter	0.218	21,800,000
	BOS	0.1	10,000,000
Soft cost	Mounting Racks	0.083	8,300,000
	Civil works	0.06	6,000,000
	EC contract	0.0336	3,363,889
	Contingency	0.0673	6,727,778
	Pre-operative cost	0.0202	2,018,333
	Financial cost	0.0135	1,345,556
Total		1.3456	134,555,556

2.9.1 Capital Expenditure

Capital expenditure is an important issue for the installation of solar PV power plants. Although, the cost of PV module decreases substantially, still per unit cost is higher than the average cost of generation of electricity. The capital cost varies region to region because of many reasons, e.g., labor cost, the subsidy, taxes and incentives. The capital cost can be classified into two major categories, e.g., hard cost and soft cost. Hard cost is the main cost of a PV plant accounting for about 79.3% [52]. It includes the cost of solar module, inverter and balancing of system (BOS). The cost of BOS covers the cost of transformer, monitoring system, switchgear, cabling. The PV module cost is the main cost that covers about 55.7% which is much larger than cost of inverter and BOS accounting for 16.2 and 7.4%, respectively. On the other hand, soft cost includes the cost of civil cost, engineering and commissioning (EC), mounting rocks and project management. The share of soft cost is about 20.7%. In [52], the capital cost of a 100 MW solar PV plant in Ghana was analyzed. The costs of PV module, inverter and BOS have been assumed as USD 0.75 per W_{DC}, USD 0.75 per W_{DC} and USD 0.75 per W_{DC}, respectively. Table 2.13 shows the capital expenditure of a typical 100 MW solar PV plant. However, different software, e.g., RET Screen modeling software is used to analyze cost of PV power plant [53].

2.10 Conclusion

This chapter demonstrates the prospect and technical advancement of large scale solar PV power plants. Solar PV power plant is dramatically getting a platform of generating electricity all over the world. Till now, it is facing problems due to its higher installed cost. But, due to technical advancement, cost reduction and renewable energy policy, solar PV power will be the one of the leading source of electricity in near future. International collaboration on research and development can enhance the success of large scale solar PV plant by reducing module cost, sharing planning, financing and grid integration. Governments can make policy to ensure a stable, predictable financial environment as well as to cut the soft cost. This system not only mitigates the carbon emission or improves the energy security but also plays an important factor in economy of a country by reducing dependence on imported fuel. In addition, solar PV plant becomes a field of investment and job sector. This analysis can play a part of research in the field of large scale solar PV plant as a de-carbonized energy system.

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