Chapter 7
Solar Photovoltaics (PV): A Sustainable Solution to Solve Energy Crisis

A.K. Pandey, N.A. Rahim, Md. Hasanuzzaman, P.C. Pant, and V.V. Tyagi

Abstract Although sun is the source of all forms of energy including the energy contained in fossil fuels, the term "solar energy" is meant the energy obtained directly from sun's radiation. Solar photovoltaic (PV) is the most promising of all the active solar energy technologies. This technology is affordable and the source of this energy is inexhaustible. Moreover, it is the cleanest source of energy developed so far, thereby establishing it as a sustainable solution to solve energy crisis. This chapter presents a succinct picture of the solar PV technology along with classification and application areas. The status of the technology maturity and energy–exergy and economic aspects of PV technology has also been addressed.

1 Introduction

Solar power is regarded as one of the most momentous breakthroughs of the last century. This source of energy is the most susceptible alternative to the dependence on fossil fuels, which are not only pernicious to the environmental but also been consumed over the time. It has been estimated that sunlight falling on the Earth in 1 h, if it could be harvested, is enough to fulfill the world's energy need for 1 year (Green 2012). Solar photovoltaic (PV) is now established as a proven technology. Solar PV devices directly transmute sunlight into electricity without any interposing

A.K. Pandey (✉) • M. Hasanuzzaman
UM Power Energy Dedicated Advanced Centre (UMPEDAC), University of Malaya, Kuala Lumpur 59990, Malaysia
e-mail: adarsh.889@gmail.com; adarsh@um.edu.my

N.A. Rahim
Renewable Energy Research Group, King Abdulaziz University, Jeddah 21589, Saudi Arabia

UM Power Energy Dedicated Advanced Centre (UMPEDAC), University of Malaya, Kuala Lumpur 59990, Malaysia

P.C. Pant
Ministry of New and Renewable Energy, Govt. of India, New Delhi 110003, India

V.V. Tyagi
Department of Energy Management, Shri Mata Vaishno Devi University, Katra, Jammu and Kashmir 182320, India

© Springer International Publishing AG 2017

R. Singh, S. Kumar (eds.), *Green Technologies and Environmental Sustainability*, DOI 10.1007/978-3-319-50654-8_7

device; it needs neither combustion nor any moving parts for power generation (Roger et al. 2009). Solar PV devices can be employed for power generation anywhere the sun shines.

Photovoltaic cells, also called solar cells, are the basic units of a solar PV system. Solar cells are essentially a type of electric device that can convert light into electrical energy through the photovoltaic effect. The photovoltaic effect was discovered in 1839 by Edmond Becquerel, then in 1954 the scientists of Bell Laboratories discovered that silicon can create an electric charge when exposed to sunlight (Philibert 2011). Photovoltaic energy conversion takes place in two steps: first, generation of electron–hole pair through the absorption of light in semiconductor material; secondly, severance of electron to the negative terminal and hole to the positive terminal by the structure of the device, thereby producing electricity (Markvart and Castafier 2003).

Solar cells should be capable of absorbing light and create electron–hole pairs, separating the charge carrier from opposite types and conducting the extraction of charge carriers through an external circuit connected to it. In order to meet the above requirements, semiconductor materials like silicon (Si) are used to manufacture PV cells. PV cells are basically wafers of semiconductor materials treated with such chemicals as allow formation of electric field. An isolated silicon solar cell has a voltage near about 0.6 V under 25 °C and AM1.5 illumination. Solar cells are arranged mostly in series to increase power and voltage and embedded on a frame to provide a voltage of 12 V (or 24 V and 48 V for greater sizes) forms a solar PV module. Multiple modules may be connected together to build an array in order to produce greater amount of electrical energy. Although the majority of the solar PV systems are made from traditional Si-based solar cells, the use of new thin films is growing day by day. The simplest layout of a solar PV system is shown in Fig. 7.1.

Solar energy is renewable and derived from the inexhaustible source of the sun. One of the most expedient features of solar system is that these systems can be constructed as stand-alone plants providing electricity to practically any extent, from low to high. That is why PV devices are in usage as the power supply for small-scale appliances like calculators to even megawatt-scale power plants.

Another key advantage of solar PV systems is that they do not produce any further pollution while generating power. Solar PV systems are simple in design, have

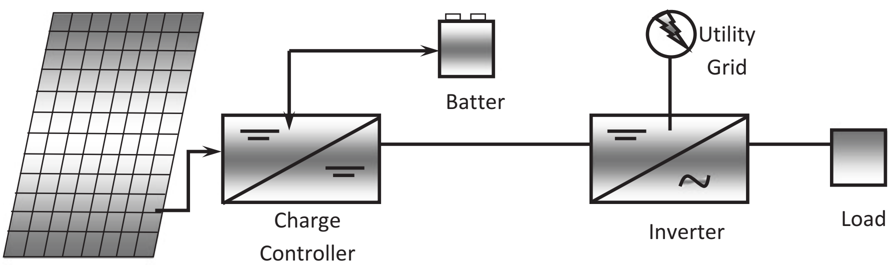

Fig. 7.1 Layout of a solar PV system

long operating life, require very little maintenance and run with high reliability even under harsh weather conditions. However, there are also some short comings of these systems. Solar energy is intermittent in nature and solar electricity needs to be stored in some storage device like batteries. The batteries will require maintenance and replacement which may intervene the smooth operation of the system and will also involve extra cost. Moreover, solar PV systems so far are cost-effective only in the small scale.

2 Classification of PV Systems and Their Applications

The PV systems can be classified based on the operation, components, and their end use. This section presents the classification of PV systems and their applications.

2.1 Classification

The classification of solar PV systems is mainly based on the factors like the functional and operational constraints of the system, configuration of the components involved, and how the system is attached to other power fonts and electrical loads. However, solar PV systems are broadly classified as utility-interactive or grid-tied systems and stand-alone systems. A detailed classification is given in Table 7.1.

2.1.1 Stand-Alone Solar PV Systems

Stand-alone PV systems are designed to operate as autonomous system and supply certain DC and/or AC electrical loads. These systems are basically suitable to provide electricity to isolated users, distant from the electricity grid and that are hard to feed. Energy storage is an important issue at these plants to guarantee energy supply at night or when there is no sun. The small plants only for illumination purpose needs only 12 V DC, however for greater scale 24 V or 48 V stand-alone systems may be designed. In order to have AC power, an inverter may be used that transforms energy from the batteries in DC to AC with 220 V. The key component of a stand-alone solar PV system is a charge controller which regulate charging rates according to the battery's charge level to allow charging near to the battery limit as well as control battery temperature to prevent overheating. There are two types of charge controllers commonly used, viz., *pulse width modulation* (PWM) and *maximum power point tracking* (MPPT), the later one being more expensive but efficient (Esram and Chapman 2007).

The DC output from a stand-alone PV system may directly be fed to the DC load, as shown in Fig. 7.2, without any provision for energy storage. These are called direct-coupled PV system and operate during day time only.

Table 7.1 Classification of solar PV systems

Classification norms	PV class
Materials of PV cell	1. Silicon PV
	I. Crystalline silicon PV
	a. Monosilicon (m-Si) PV b. Polysilicon (p-Si)
	II. Amorphous silicon (a-Si) PV
	a. Single junction
	b. Double junction
	c. Triple junction
	2. Group III–V material-based PV
	3. Thin film solar cell (TFSC)-based PV
	a. a-Si-based PV
	b. CdS/CdTe-based PV
	c. CIS/CIGS-based PV
	4. Dye sensitized solar cell (DSSC)-based PV
	5. Organic/polymer-based PV
Interfacing with load	1. Utility-interactive or grid-connected PV
	2. Off-grid or stand-alone PV
Installation mode	1. Building integrated PV (BIPV)
	2. Rack-mounted PV (RPV)
	a. Roof-top RPV
	b. Ground-mounted RPV
Tracking facility	1. Tracking system PV
	2. Fixed tilt PV
Module geometry	1. Flat plate PV (FPPV)
	2. Concentrator PV (CPV)
System complexity	1. Simple photovoltaic system (PV-only)
	2. Hybrid photovoltaic thermal system (PVT)

Fig. 7.2 Direct-coupled PV system

In some stand-alone PV systems, batteries are used for energy storage. Figure 7.3 shows such a typical stand-alone PV system connected to both DC and AC loads. One of the favorable features of stand-alone PV systems is that no network association is required for these systems. In order to acquire the complete benefit from the stand-alone PV system, low energy and energy-efficient appliances should be used.

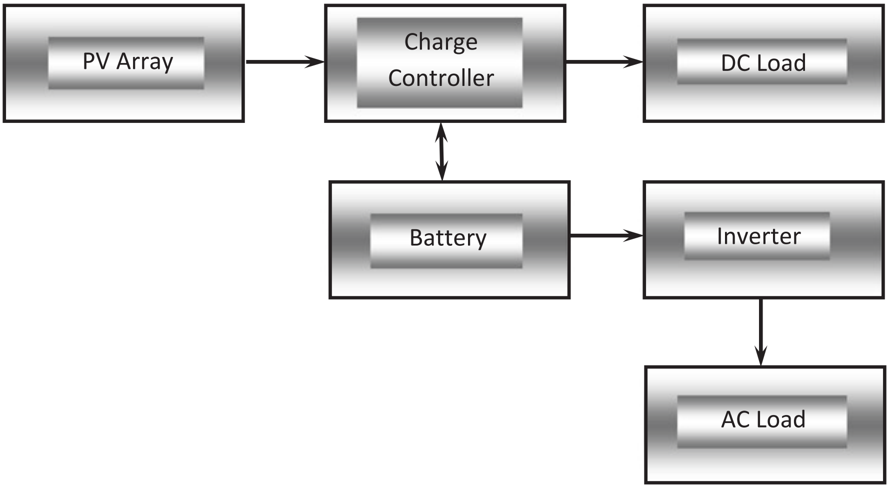

Fig. 7.3 Stand-alone PV system with battery storage powering DC and AC loads

2.1.2 Utility-Interactive Solar PV Systems

Solar PV systems depend on the availability of daylight for power generation. To ensure a connection between the continuing demand and supply of energy, backup is necessary for these systems. Backup for a PV system may be ensured by connecting the system to the utility grid through power conditioning unit (PCU) which may be a high-quality inverter. Utility-interactive PV systems are meant to function in parallel with and interconnected with the electric utility grid (Fig. 7.4). An inverter converts DC output from PV into AC power compatible with the voltage and power quality requirements of the utility grid and automatically stops supplying power to the grid when the utility grid is not energized. A bi-directional interface permits the AC power generated by the PV system to either supply on-site electrical loads or to back-feed the grid when the PV system output is greater than the on-site load demand. On the other hand, when electrical loads are greater than the PV output, the balance of power required by the loads is received from the electric utility. This safety feature ensures the PV system not to operate and feed back into the utility grid when the grid is disconnected for repair and maintenance.

A hybrid scheme of the stand-alone and grid-connected PV system is shown in Fig. 7.5.

2.2 Applications

2.2.1 Stand-Alone Solar PV Systems

As stand-alone PV systems can produce and supply electricity anywhere, the potential applications are increasing day by day. Out of numerous applications of the stand-alone system, the most recurrent ones are discussed below (NCSC 2002).

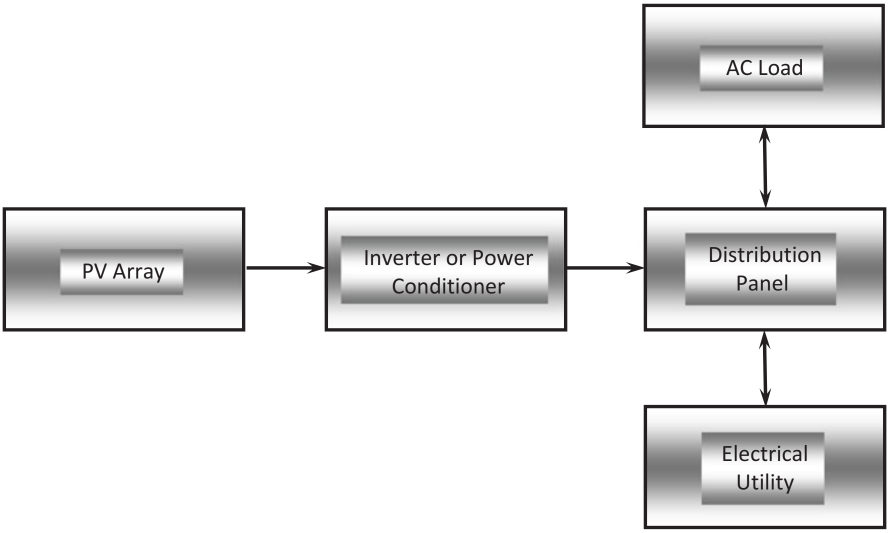

Fig. 7.4 Diagram of grid-connected photovoltaic system

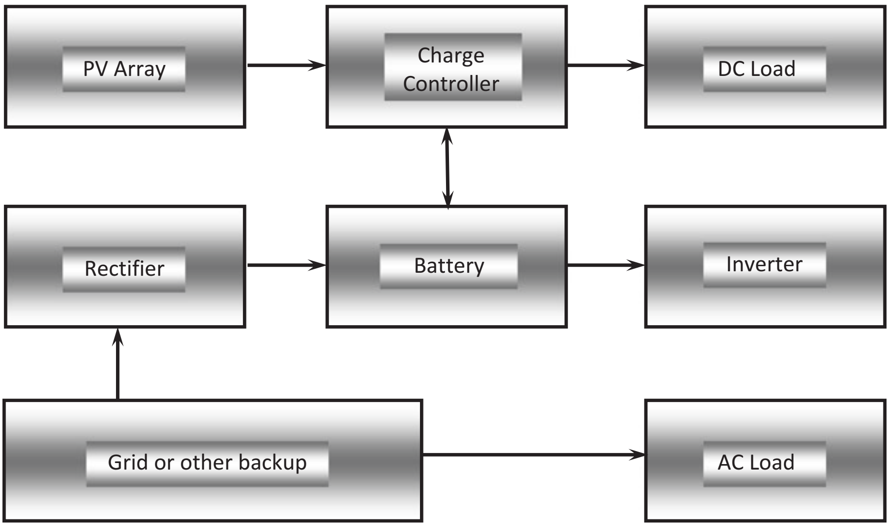

Fig. 7.5 Diagram of photovoltaic hybrid system

1. *Lighting*: Stand-alone solar PV with adequate battery support is ideal source for illuminating the low power DC lighting, such as sodium and fluorescent lights. Also these PV systems may be used to illuminate billboards, highway signs, etc.
2. *Communications*: Stand-alone solar PV system may provide the best possible solution to power the relay towers, installed on the highest possible elevation of remote sites for amplifying the signal of radio, television, and telephone. Small

PV modules may also be used to power portable computers, mobile radio system, and public telephone booths.

3. *Rural electrification*: The electrification of the remote areas that are not yet at the reach of the main electricity grid may be achieved through installation of small-scale diesel generators. Stand-alone PV systems may be the best possible way to provide electricity in remote areas far from utility grid. This may be achieved through installing separate PV systems for individual users or through hybrid generation system wherein diesel generator or wind turbine or micro-hydro generator may be coupled with solar PV system including a storage unit for uninterrupted power supply (Akikur et al. 2013).
4. *Remote monitoring*: Temporary scientific research facilities that are far from utility grid may be run by stand-alone PV systems. Likewise, PV systems can be an effective power source for meteorological information collection, seismic recording, highway traffic situation, structural condition, and irrigation control.
5. *Signs and signals*: Stand-alone PV systems are particularly reliable power source for signal devices as most of these are used at locations that are out of the range of the utility grid. These applications include navigation beacons, sirens, highway warning signs, railway signals, aircraft warning beacons, buoys, and lighthouses.
6. *Irrigation*: Stand-alone solar PV systems are often used for running water pumps for irrigation purpose especially in remote areas. These systems can consistently produce adequate electricity to power livestock and irrigation watering systems. A distinctive advantage solar energy to run agricultural water pumping systems is that increased water requirements for livestock and irrigation tend to match with the seasonal increase of solar insolation. These systems are economic in terms of long-term cost savings with negligible environmental affect compared to conventional power systems (Teresa and Busch 2010).
7. *Vehicle charging*: Stand-alone solar PV system-based charging stations are now providing electric vehicles (EV) with sufficient energy on the way. Electric vehicle needs to be charged at regular interval, but all owners cannot afford to install the charging infrastructure at home. So, installation of solar power EV charging stations at different point of a city may inspire EV ownership. Moreover, these facilities are environmental friendly and low cost. Solar PV-based charging stations will increase the utility of EVs and may contribute to increased adoption of this environmental friendly vehicle (Denholm et al. 2013; NREL 2014).
8. *Natural calamity relief applications*: Natural calamities like hurricanes, floods, tornadoes, and earthquakes often obliterate electricity generation and distribution systems. In such critical state where the power may be cut-off for a long time, portable PV systems are very useful for providing power needs of the affected people including water purification, refrigeration foods and drugs and pumping water as well as operating the communication devices. PV electricity is often a better choice than conventional fuel generators for makeshift shelters or medical clinics, because they are almost noiseless, needs no fuel transport and provide a nonpolluting reliable operation.

9. *Cathodic protection*: Metal structures like pipes, tanks, bridges, and buildings exposed to soil and water undergo corrosion that may reduce their lifetime and reliability. Cathodic protection is an effective technique to prevent corrosion in these cases which is done by applying a small DC voltage to those structures. Utility power in this application suffers from two limitations: first thing is the need for the conversion of AC power to DC and secondly, it will cost extra expense. PV systems can produce low voltage DC power directly, resulting in a much more efficient and cost-effective method to achieve cathodic protection of the metal structures.
10. *Refrigeration*: Mobile storage of medicines and vaccines and medicine storage in remote places can be ensured by supplying DC current from stand-alone PV systems.
11. *Consumer products*: Small-scale PV systems are used to power small DC appliances like watches, radio, television, lanterns, flashlights, calculators, security systems, fans, etc.

2.2.2 Utility-Interactive Solar PV Systems

Not all PV systems may be large enough to meet all the energy needs. Utility-interactive or grid-connected PV systems have got wide and extensive applications in residential or commercial buildings to compensate electricity costs. These systems are particularly good in reducing power bought from the utility during peak hours, which usually coincide with peak sunlight hours. Hence, use of PV systems can significantly reduce electrical bills by curtailing peak demand surcharge charged by power supply companies. Accurately sized PV system with adequate battery backup can be used to supply power during peak hours that may help better savings.

2.3 *Other Emerging Applications of PV*

The emerging applications of PV such as building integrated solar PV systems (BIPV), concentrated solar PV systems (CPV), photovoltaic thermal (PVT), solar PV desalination systems, and in space was discussed by Pandey et al. in detail (Pandey et al. 2016).

2.3.1 Building Integrated Solar PV Systems

The PV systems can be utilized by integrating them into buildings which is known as building integrated photovoltaic (BIPV) systems. These can be applied to rooftops of the buildings or some other parts viz. window glasses, balcony, or walls. The BIPV systems have several advantages such as utilization of unused space in building, electricity generation, and regulation of indoor environment.

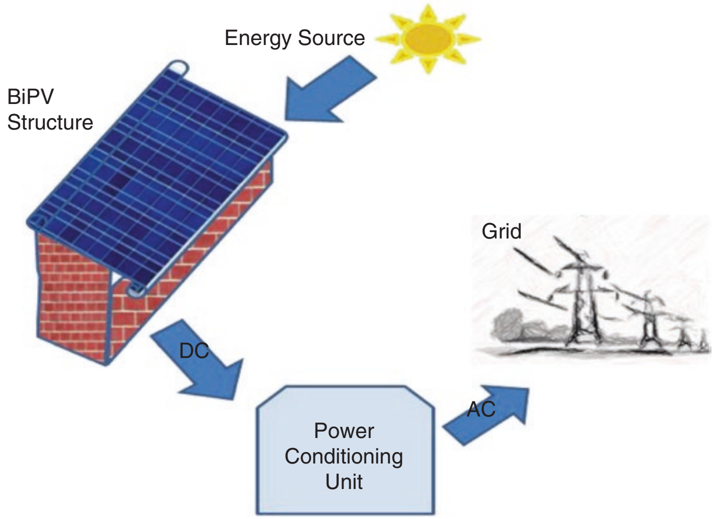

Fig. 7.6 Schematic diagram of the BIPV system (Aaditya et al. 2013)

The application of PV in building has been classified in two ways viz. building applied photovoltaic (BAPV) and building integrated photovoltaic (BIPV) by Peng et al. When the PV is installed on the top of the existing building it is known as BAPV system, while if the PV is part of building material then it is known as BIPV system (Peng et al. 2011).

The performance evaluation of BIPV system in the typical climatic condition of Bangalore, India having capacity of 5.25 kWp was studied by Aaditya et al., the schematic view of the studied system is given in Fig. 7.6. The system was found to be having overall efficiency of 6% (Aaditya et al. 2013).

2.3.2 Photovoltaic Thermal Systems

The solar energy falling on the surface of the PV module is not completely utilized, some part reflected and some transmitted and this increase the temperature of the PV module which ultimately reduces the efficiency of the PV module. Therefore, to reduce the temperature and to utilize the waste thermal energy hybrid photovoltaic thermal (PVT) collector has been developed which can serve both purposes, i.e. electricity and thermal energy at the same time. The temperature rise in silicon PV modules above 25 °C exhibits a power loss with a temperature coefficient of – 0.65%/C (Du et al. 2013).

The PVT collectors are also being encapsulated with phase change materials to enhance the efficiency as well as to store the energy which can be used for later use; these systems are known as photovoltaic-thermal phase change material (PVT-PCM) systems. Browne et al. carried out the indoor performance evaluation of the hybrid PVT-PCM system. As can be seen from Fig. 7.7, PVT-PCM has good potential and performs better than PV alone encapsulated PCM (PV-PCM) systems (Browne et al. 2015).

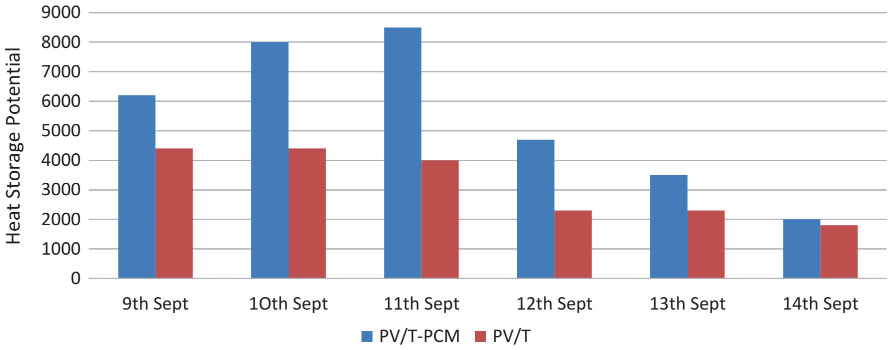

Fig. 7.7 Daily heat storage potential of PVT-PCM and PVT-water systems (Browne et al. 2015)

2.3.3 Space Applications

The PV application in solar is very old; initially, only silicon-based solar cells were employed to harness the energy in space via satellites. But, currently the high-efficiency multi-junction solar cells have come as a solution which has advantage of high power conversion efficiency in compact size. Different aspects of the space solar power have been studied by different authors (Mankins 1997; Jaffe et al. 2012; Jaffe and McSpadden 2013).

2.3.4 Concentrated Solar PV

When the incident solar radiation is concentrated on solar cells, using the mirrors which increases the amount of incident solar radiation many folds is known as concentrated photovoltaic (CPV). This increase in the solar radiation increases the efficiency of the solar cell. However, increasing the amount of solar radiation on the solar cell can cause many problems such as deformation and can damage the solar cell. As the efficiency can be improved drastically by concentrating the solar radiation, therefore the work on CPV is going on Worldwide to overcome the related issues (Looser et al. 2014).

2.3.5 Photovoltaic Desalination Systems

Clean water for drinking is one of the biggest problems in many of the developing and underdeveloped countries. Contaminated water causes lot of health issues especially in rural areas. There are many water cleaning methods available, solar desalination is one of them. There are basically two ways of solar desalination: one is thermal process where phase change occurs and another is using PV modules for producing electricity to support the membrane process in the desalination. The

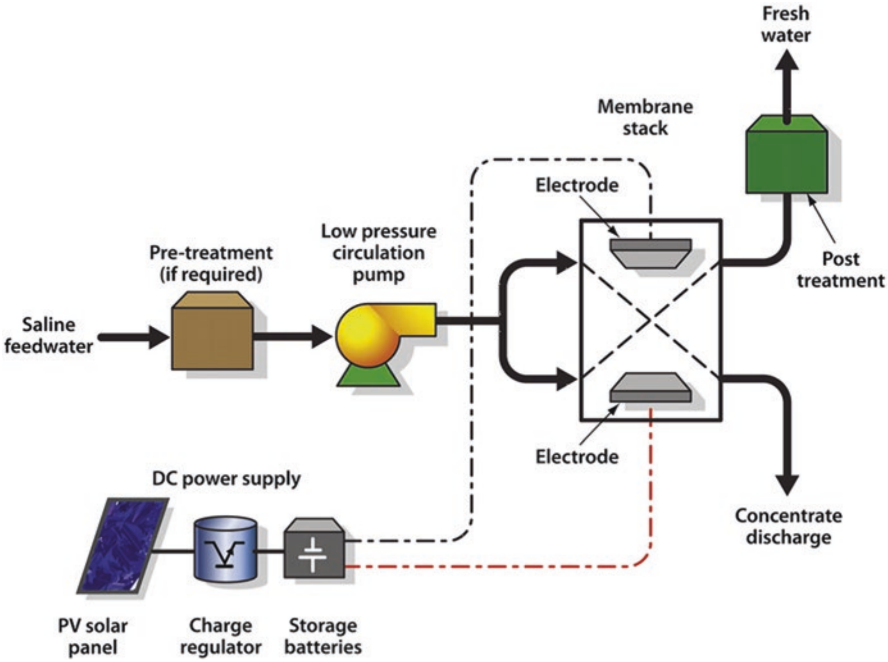

Fig. 7.8 A schematic diagram of a PV-ED system (Al-Karaghouli et al. 2010)

involvement of PV modules and batteries make PV desalination cost-ineffective. However, there are positive changes being made around the World and in future PV desalination will be one of the cost-effective solution (Avlonitis et al. 2003; Susanto 2011).

Al-Karaghouli et al. discussed the technical and economical aspect of PV desalination system which can be seen in Fig. 7.8. They found that small-scale PV desalination systems are technologically as well as economically viable and can be used in the rural areas where there is need of clean water. But, large-scale implementation of such systems is still economically not viable and needs more R&D to overcome technological barriers (Al-Karaghouli et al. 2010).

3 Status of Technology Maturity

Green et al. (2016) continuously publish the latest confirmed highest efficiencies for solar cells and modules. The results from the latest solar efficiency table (version 48) for one cell is shown in Table 7.2 and for module it is shown in Table 7.3 (Green et al. 2016).

Table 7.2 Confirmed terrestrial cell and sub-module efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at 25 °C (IEC 60904–3:2008, ASTM G. 173.03 global) (Green et al. 2016)

Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	I_{sc} (mA/cm^2)	Fill factor (%)	Test centre (date)	Description
Silicon							
Si (crystalline cell)	25.6 ± 0.5	143.7(da)	0.740	41.8[a]	82.7	AIST (2/14)	Panasonic HIT, rear junction
Si (multicrystalline cell)	21.3 ± 0.4	242.74(t)	0.6678	39.80[b]	80.0	FhG-ISE (11/15)	Trina Solar
Si (thin transfer submodule)	21.2 ± 0.4	239.7(ap)	0.687[c]	38.50[c]	80.3	NREL (4/14)	Solexel (35 μm thick)
Si (thin film submodule)	10.5 ± 0.3	94.0(ap)	0.492[c]	29.7[c]	72.1	FhG-ISE[e] (8/07)	CGS Solar (<2 μm on glass)
III–V cells							
GaAs (thin film cell)	28.8 ± 0.9	0.9927(ap)	1.122	29.68[f]	86.5	NREL (5/12)	Alta Devices
GaAs (multicrystalline)	18.4 ± 0.5	4.011(t)	0.994	23.2	79.7	NREL (11/95)[d]	RTI, Ge substrate
InP (crystalline cell)	22.1 ± 0.7	4.02(t)	0.878	29.5	85.4	NREL (4/90)[d]	Spire, epitaxial
Thin film chalcogenide							
CIGS (cell)	21.0 ± 0.6	0.9927(ap)	0.757	35.70[g]	77.6	FhG-ISE (4/14)	Solibro, on glass
CIGS (minimodule)	18.7 ± 0.6	15.892(da)	0.701[c]	35.29[c]	75.6	FhG-ISE (9/13)	Solibro, 4 serial cells

CdTe (cell)	21.0 ± 0.4	1.0623(ap)	0.8759	30.25[d]	79.4	Newport (8/14)	First Solar, on glass
CZTSSe (cell)	9.8 ± 0.2	1.115(da)	0.5073	31.95[i]	60.2	Newport (4/16)	IMRA Europe
CZTS (cell)	7.6 ± 0.1	1.067(da)	0.6585	20.43[i]	56.7	NREL (4/16)	UNSW
Amorphous/microcrystalline							
Si (amorphous cell)	10.2 ± 0.3[j]	1.001(da)	0.896	16.36[d]	69.8	AIST (7/14)	AIST
Si (microcrystalline cell)	11.8 ± 0.3[k]	1.044(da)	0.584	29.39[g]	73.1	AIST (10/14)	AIST
Perovskite							
Perovskite cell	19.7 ± 0.6[l]	0.9917(da)	1.104	24.67[i]	72.3	Newport (3/16)	KRICT/UNIST
Dye sensitized							
Dye (cell)	11.9 ± 0.4[m]	1.005(da)	0.744	22.47[n]	71.2	AIST (9/12)	Sharp
Dye (minimodule)	10.7 ± 0.4[m]	26.55(da)	0.754[c]	20.19[c]	69.9	AIST (2/15)	Sharp, 7 serial cells
Dye (submodule)	8.8 ± 0.3[m]	398.8(da)	0.697[c]	18.42[c]	68.7	AIST (9/12)	Sharp, 26 serial cells
Organic							
Organic (cell)	11.2 ± 0.3[o]	0.992(da)	0.780	19.30[i]	74.2	AIST (10/15)	Toshiba
Organic (minimodule)	9.7 ± 0.3[o]	26.14(da)	0.806	16.47[c,g]	73.2	AIST(2/15)	Toshiba (8 series cells)
Multijunction							
Five junction cell (bonded) (2.17/1.68/1.40/1.06/0.73 eV)	38.8 ± 1.2	1.021(ap)	4.767	9.564	85.2	NREL (7/13)	Spectrolab

(continued)

Table 7.2 (continued)

Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	I_{sc} (mA/cm^2)	Fill factor (%)	Test centre (date)	Description
InGaP/GaAs/InGaAs	37.9 ± 1.2	1.074(ap)	3.065	14.27[p]	86.7	AIST (2/13)	Sharp
GaInP/GaAs/Ge; Si (minimodule)	34.5 ± 2.0	27.83(ap)	2.66/0.65	13.1/9.3	85.6/79.0	NREL (4/16)	UNSW/Azur/Trina
GaInP/GaAs (monolithic)	31.6 ± 1.5	0.999(ap)	2.538	14.18[i]	87.7	NREL (1/16)	Alta Devices
GaInP/Si (mech.stack)	29.8 ± 1.5[k]	1.006(da)	1.46/0.68	14.1/22.7[b]	87.9/76.2	NREL (10/15)	NREL/CSEM, 4-terminal
a-Si/nc-Si/nc-Si (thin film)	13.6 ± 0.4[j,k]	1.043(da)	1.901	9.92[g]	72.1	AIST (1/15)	AIST
a-Si/nc-Si (thin film cell)	12.7 ± 0.4[j,k]	1.000(da)	1.342	13.45[d]	70.2	AIST (10/14)	AIST

CIGS CuIn1-yGaySe2, *a-Si* amorphous silicon/hydrogen alloy, *nc-Si* nanocrystalline or microcrystalline silicon, *CSTSS* Cu2ZnSnS4-ySey, *CZTS* Cu2ZnSnS4; *(ap)* aperture area, *(t)* total area, *(da)* designated illumination area, *FhG-ISE* Fraunhofer Institutfür Solare Energie systeme, *AIST* Japanese National Institute of Advanced Industrial Science and Technology

[a]Spectral response and current–voltage curve reported in Version 44 of these tables
[b]Spectral response and current–voltage curve reported in Version 47 of these tables
[c]Reported on a 'per cell' basis
[d]Spectral responses and current–voltage curve reported in Version 45 of these tables
[e]Recalibrated from original measurement
[f]Spectral response and current–voltage curve reported in Version 40 of these tables
[g]Spectral response and current–voltage curve reported in Version 46 of these tables
[h]Spectral response and current–voltage curve reported in Version 43 of these tables
[i]Spectral response and current–voltage curve reported in the present version of these tables
[j]Stabilised by 1000 h exposure to 1 sunlight at 50 C
[k]Not measured at an external laboratory
[l]Notstabilized, initial efficiency. Reference 19 reviews the stability of similar devices
[m]Initial performance (not stabilized). Reference 62 reviews the stability of similar devices
[n]Spectral response and current–voltage curve reported in Version 41 of these tables
[o]Initial performance (not stabilized). References 63 and 64 review the stability of similar devices
[p]Spectral response and/or current–voltage curve reported in Version 42 of these tables

Table 7.3 Confirmed terrestrial module efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at a cell temperature of 25 °C (IEC 60904–3: 2008, ASTM G-173-03 global) (Green et al. 2016)

Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	I_{sc} (mA/cm^2)	Fill factor (%)	Test centre (date)	Description
Si (crystalline)	23.8 ± 0.5	11,562 (ap)	53.4	6.32[a]	81.6	AIST (1/16)	Panasonic (72 cells)
Si (multicrystalline)	19.5 ± 0.4	15,349 (ap)	41.53	9.299[a]	77.4	FhG-ISE (12/15)	Hanwha Q Cells (120 cells)
GaAs (thin film)	24.1 ± 1.0	858.5 (ap)	10.89	2.255[b]	84.2	NREL (11/12)	Alta Devices
CdTe (thin film)	18.6 ± 0.6	7038.8 (ap)	110.6	1.533[a]	74.2	NREL (4/15)	First Solar, monolithic
CIGS (Cd free)	17.5 ± 0.5	808 (da)	47.6	0.408[c]	72.8	AIST (6/14)	Solar Frontier (70 cells)
CIGS (large)	15.7 ± 0.5	9703 (ap)	28.24	7.254[d]	72.5	NREL (11/10)	Miasole
a-Si/nc-Si (tandem)	12.3 ± 0.3[e]	14,322 (t)	280.1	0.902[f]	69.9	ESTI (9/14)	TEL Solar, Trubbach Labs
Organic	8.7 ± 0.3[g]	802 (da)	17.47	0.569[c]	70.4	AIST (5/14)	Toshiba
Multijunction							
InGaP/GaAs/InGas	31.2 ± 1.2	968 (da)	23.95	1.506	93.6	AIST (2/16)	Sharp (32 cells)

CIGSS CuInGaSSe, *a-Si* amorphous silicon/hydrogen alloy, *a-SiGe* amorphous silicon/germanium/hydrogen alloy, *nc-Si* nanocrystalline or microcrystalline silicon, *(t)* total area, *(ap)* aperture area, *(da)* designated illumination area, *FF* fill factor

[a]Spectral response and/or current–voltage curve reported in the present version of these tables

[b]Spectral response and current–voltage curve reported in Version 41 of these tables

[c]Spectral response and/or current–voltage curve reported in Version 45 of these tables

[d]Spectral response reported in Version 37 of these tables

[e]Stabilized at the manufacturer to the 2% level following IEC procedure of repeated measurements

[f]Spectral response and/or current–voltage curve reported in Version 46 of these tables

[g]Initial performance (not stabilized)

4 Energy and Exergy Analysis

The energy and exergy aspects of solar PV systems are of great importance to clearly define their performance. The energy and exergy analyses of a solar PV as presented by several researchers have been presented in this section (Pandey et al. 2015; Joshi et al. 2009).

4.1 Energy Analysis

The incident solar energy is given by

$$Q_{in} = I_s A \tag{7.1}$$

where I_s is the incident solar radiation in W/m2 and A is the area of the PV module surface in m2.

Actual output of the PV module is given by

$$Q_o = V_{oc} I_{sc} FF \tag{7.2}$$

where V_{oc} is the open circuit voltage, I_{sc} is the short circuit current, and FF is the fill factor which is the ratio of the product of voltage corresponding to maximum power (V_m) and the current corresponding to maximum power (I_m) to the product of open circuit voltage (V_{oc}) and short circuit current (I_{sc}) and is given by

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}} \tag{7.3}$$

So, combining Eqs. (7.2) and (7.3), the output may be written as

$$Q_o = V_m I_m \tag{7.4}$$

Therefore, the energy efficiency can be found from the following expression as

$$\eta = \frac{Q_o}{Q_{in}} = \frac{V_m I_m}{I_s A} \tag{7.5}$$

4.2 Exergy Analysis

The input exergy, i.e., exergy of solar radiation is given by

$$Ex_{\mathrm{solar}} = Ex_{\mathrm{in}} = \left(1 - \frac{T_{\mathrm{a}}}{T_{\mathrm{s}}}\right) I_{\mathrm{s}} A \tag{7.6}$$

where T_s is the temperature of the sun which is generally taken as 5777 K.

The exergy output of the solar PV systems can be given by

$$Ex_{\mathrm{out}} = Ex_{\mathrm{elec}} + Ex_{\mathrm{therm}} + Ex_{\mathrm{d}} = Ex_{\mathrm{elec}} + I' \tag{7.7}$$

where I' includes internal as well as external losses. Internal losses are electrical exergy destruction and external losses are heat loss which is equal to the thermal exergy of the PV system.

Electrical exergy of the PV system is expressed as follows on basis of the assumption that exergy content received by the PV surface is fully utilized to generate maximum electrical energy,

$$Ex_{\mathrm{elec}} = E_{\mathrm{elec}} - I' = V_{oc} I_{sc} - \left(V_{oc} I_{sc} - V_{\mathrm{m}} I_{\mathrm{m}}\right) \tag{7.8}$$

where $V_{oc}I_{sc}$ represents the electrical energy and $(V_{oc}I_{sc} - V_m I_m)$ represents the electrical exergy destruction. Therefore,

$$Ex_{\mathrm{elec}} = V_{\mathrm{m}} I_{\mathrm{m}} \tag{7.9}$$

The thermal exergy of the system is the heat loss from the PV surface to the ambient and can be given by

$$Ex_{\mathrm{therm}} = \left(1 - \frac{T_{\mathrm{a}}}{T_{\mathrm{cell}}}\right) Q \tag{7.10}$$

where $Q = h_{ca}A(T_{cell} - T_a)$ and $h_{ca} = 5.7 + 3.8v$ in which h_{ca} is the convective heat transfer coefficient and v is the wind speed.

Combining the above equations, exergy of the solar PV system can be written as

$$Ex_{pv} = V_{\mathrm{m}} I_{\mathrm{m}} - \left(1 - \frac{T_{\mathrm{a}}}{T_{\mathrm{cell}}}\right) h_{ca} A \left(T_{\mathrm{cell}} - T_{\mathrm{a}}\right) \tag{7.11}$$

The solar cell power conversion efficiency is the ratio of actual electrical output to the incident solar radiation energy on the PV surface and can be given by

$$\eta_{pcc} = \frac{V_{\mathrm{m}} I_{\mathrm{m}}}{I_{\mathrm{s}} A} = \frac{FF V_{oc} I_{sc}}{I_{\mathrm{s}} A} \tag{7.12}$$

Therefore, exergy efficiency which is the ratio of output exergy to the input exergy can be expressed as

$$\eta_{ex} = \frac{V_m I_m - \left(1 - \frac{T_a}{T_{cell}}\right) h_{ca} A \left(T_{cell} - T_a\right)}{\left(1 - \frac{T_a}{T_s}\right) I_s A} \tag{7.13}$$

5 Economic Discretion of Technology

Photovoltaics cost is one of the most motivation components that influence the share of solar energy in the total power generation in the global. Decreasing cost of photovoltaic systems is very helpful for commercially as well as individually established solar systems and technologies. The global photovoltaic systems installed capacity has been increased very rapidly in last few years due to decreasing PV price, government subsidies and incentives. The U.S. Department of Energy's (DOE) Sun Shot has estimated that the PV systems cost can be decreased up to 75% within 2012–2020 (Feldman et al. 2012). Australian solar pioneer Stuart Wenham forecasted that the solar module price can be fallen 50% within 2020 (CT 2013).

The cost of PV system consists of mainly two components:

1. PV module cost
2. Balance of System (BOS) cost.

Normally, the module costs are in the range of 40–60% of the total PV system costs. The total system installation costs include the cost of site preparation, systems design, and installation labor cost (Dahlan et al. 2014). A commercial PV systems cost about 50–60% of PV modules, 10% of Inverter, 23–32% of BoS, and 7% of procurement (EPIA 2011). According to the global average PV module prices, the PV module cost also depend on the costs of raw materials, silicon prices, silicon processing, cell manufacturing cost, and module organization costs. Generally PV module cost is 40–60% of total PV systems. The cost depends on the project size and PV module types. Table 7.4 shows the module prices from different suppliers for year 2014. Munsell (2016a) mentioned that according to Green Technology Media (GTM) Research's latest edition of the PV Pulse, the tier-1 Chinese produces multicrystalline PV modules fell 10% annually and reached USD0.57/W in Q4, 2015 that is shown in Fig. 7.9. Gallagher (2016) also mentioned that according to

Table 7.4 PV module prices from different suppliers of China for year of 2014 (SHLSC 2014; SP 2014a, b, c)

Type of cell (model number)	Efficiency (%)	Price (USD/W)
Polycrystalline (RS6S-300P)	16	0.50–0.75
Polycrystalline (BCT300–24)	17	0.55–0.70
Monocrystalline (HPSM-300 W)	15	0.73–0.85

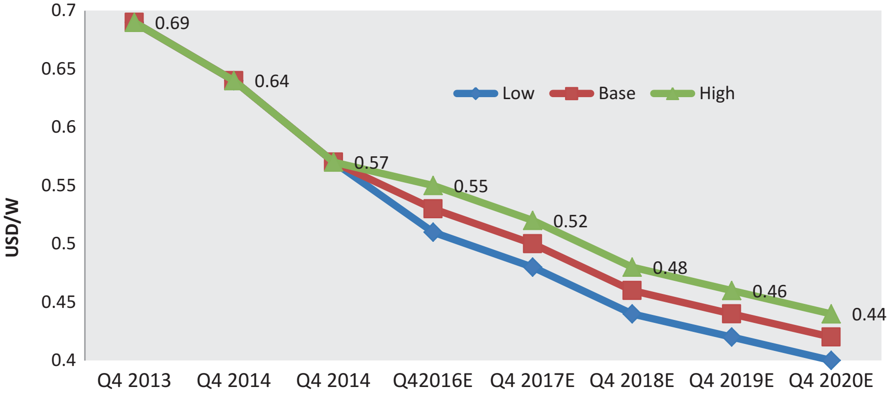

Fig. 7.9 Industry average multi-module Price, Chinese product (Munsell 2016a)

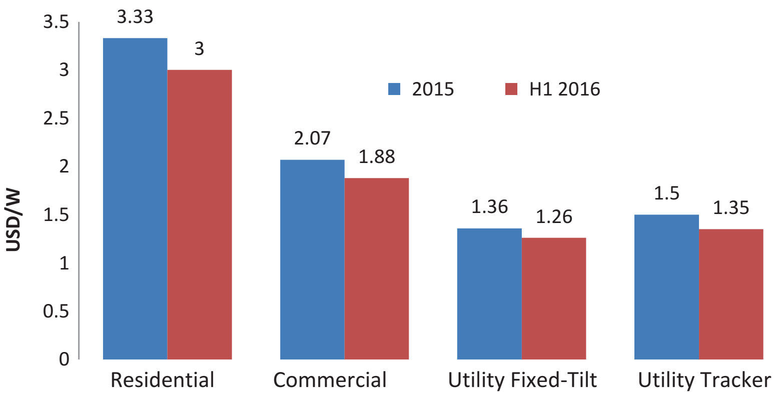

Fig. 7.10 U.S. PV System Pricing $/W(2015 & H1 2016) (Gallagher 2016)

GTM Research's latest report, *"U.S. Solar PV Price Brief H1 2016: Pricing, Breakdowns and Forecasts"*, prices of the fixed-tilt ground-mount PV systems will hit USD 0.99/W by 2020. GTM Research also estimated that modules prices for a utility-scale fixed-tilt ground-mount PV systems about USD1.26/W that is shown in Fig. 7.10 (Gallagher 2016; Munsell 2016b).

6 Contribution of Technology Towards Sustainable Development

Energy generation and use in the current era is dominated by the fossil fuels which is polluting the environment which causes serious health issues in the society. The population is growing at the fast rate on the average of 2%, in the coming time more

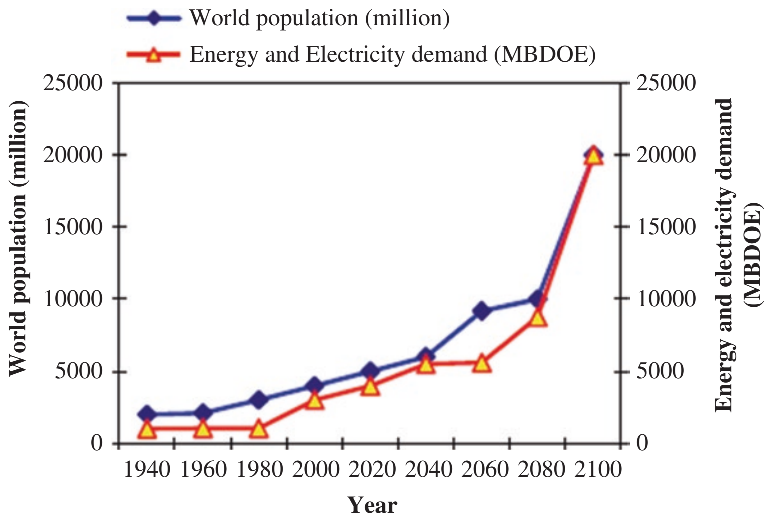

Fig. 7.11 Annual and estimated world population and energy demand. Millions of barrels per day of oil equivalent (MBDOE) (Omer 2008)

energy will be needed for human survival. The lifestyle is increasing and industrialization is growing at fast rate. Increase in population, lifestyle, and growing industrialization increases the use of energy which is currently mostly from fossil fuels. It is estimated that 80% of carbon emission is from the energy fuels and the rate at which fossil fuels are being used may be depleted within few decades such as oil and gas however, coal may be depleted in two centuries. The figure shows prediction of world population and energy and electricity demand by the time. It can be seen from Fig. 7.11 that population and energy and electricity demand is directly proportional to each other. The population and energy demand is continuously increasing and estimated to increase in the coming time, too (Omer 2008).

Therefore, in future, the huge amount of energy will be required and all cannot be fulfilled by fossil fuels. The uses of renewable energies are mandatory for the sustainable development of any country. The sustainable development of any country needs the use of technology which is socially fit, economically viable, pollution free, and technologically sound. The renewable energies such as solar, wind, biomass, and geothermal are clean and green and can fulfill the need of energy in sustainable way (Dincer 2000; Lund 2007). Solar energy being available abundantly in almost all over the world can be harnessed using photovoltaics (PV) or solar thermal. The PV technology is growing and has the potential to fulfill the demand of energy however, the low efficiency is still a cause of concern and the research for enhancing the efficiency and lowering the price is going on worldwide to accommodate the technology for contribution of sustainable development of any country.

7 Conclusions

In this chapter, a layout of the PV technology has been presented for the sustainable development of any country. The types of PV systems, their applications, efficiency status, energy and exergy analysis, economic view, and the contribution of PV technology have also been presented. The scientists around the world are making their effort to enhance the efficiency by discovering new materials or by other method such as concentrating the lights and the introduction of new materials. Solar PV technology has good potential to fulfill all the energy needs by a sustainable way.

Acknowledgement The authors (A. K. Pandey, N.A. Rahim and M. Hasanuzzaman) would like to acknowledge the financial support from the University Malaya Research Grant (UMRG) scheme (Project No: RP016B-15SUS) to carry out this research.

References

Aaditya G, Pillai R, Mani M (2013) An insight into real-time performance assessment of a building integrated photovoltaic (BIPV) installation in Bangalore (India). Energy Sustain Dev 17(5):431–437

Akikur RK, Saidur R, Ping HW et al (2013) Comparative study of stand-alone and hybrid solar energy systems suitable for off-grid rural electrification: a review. Renew Sust Energ Rev 27:738–752

Al-Karaghouli A, Renne D, Kazmerski LL (2010) Technical and economic assessment of photovoltaic-driven desalination systems. Renew Energy 35(2):323–328

Avlonitis S, Kouroumbas K, Vlachakis N (2003) Energy consumption and membrane replacement cost for seawater RO desalination plants. Desalination 157(1):151–158

Browne MC, Lawlor K, Kelly A et al (2015) Indoor characterisation of a photovoltaic/thermal phase change material system. Energy Procedia 70:163–171

CT (2013) Solar PV costs will fall by half By 2020, But Prices Won't. CleanTechnica. http://cleantechnica.com/2013/

Dahlan NY, Jusoh MA, Abdullah WNAW (2014) Solar grid parity for Malaysia: analysis using experience curves. In: IEEE 8th International Power Engineering and Optimization Conference (PEOCO2014), Langkawi, The Jewel of Kedah, Malaysia, 24–25 March 2014, pp 461–466

Denholm P, Kuss M, Margolis RM (2013) Co-benefits of large scale plug-in hybrid electric vehicle and solar PV deployment. J Power Sources 236:350–356

Dincer I (2000) Renewable energy and sustainable development: a crucial review. Renew Sust Energ Rev 4(2):157–175

Du D, Darkwa J, Kokogiannakis G (2013) Thermal management systems for Photovoltaics (PV) installations: a critical review. Sol Energy 97:238–254

EPIA (2011) Solar generation. European Photovoltaic Industry Association and Greenpeace. www.epia.org, p 6

Esram T, Chapman PL (2007) Comparison of photovoltaic array maximum power point tracking techniques. IEEE Trans Energy Convers 22(2):439

Feldman D, Barbose G, Margolis R, et al. (2012) Photovoltaic (PV) pricing trends: historical, recent, and near-term projections. SunShot, U.S. Department of Energy. http://www.osti.gov/bridge.

Gallagher B (2016) U.S. Solar PV Price Brief H1 2016: system pricing, breakdowns and forecasts. http://www.greentechmedia.com/research/report/us-solar-pv-price-brief-h1-2016

Green D (2012) Advantages and disadvantages of solar photovoltaic—quick pros and cons of solar PV. http://www.renewableenergyworld.com/. Accessed 22 July 2016

Green MA, Hishikawa Y, Warta W et al (2016) Solar cell efficiency tables (version 48). Prog Photovolt Res Appl 24:905–913. doi:10.1002/pip.2788

Jaffe P, McSpadden J (2013) Energy conversion and transmission modules for space solar power. Proc IEEE 101(6):1424–1437

Jaffe P, Hodkin J, Harrington F (2012) Development of a sandwich module prototype for space solar power. Paper presented at the Aerospace Conference, 2012 IEEE

Joshi AS, Dincer I, Reddy BV (2009) Thermodynamic assessment of photovoltaic systems. Sol Energy 83(8):1139–1149

Looser R, Vivar M, Everett V (2014) Spectral characterisation and long-term performance analysis of various commercial Heat Transfer Fluids (HTF) as Direct-Absorption Filters for CPV-T beam-splitting applications. Appl Energy 113:1496–1511

Lund H (2007) Renewable energy strategies for sustainable development. Energy 32(6):912–919

Mankins JC (1997) A fresh look at space solar power: New architectures, concepts and technologies. Acta Astronaut 41(4):347–359

Markvart T, Castafier L (2003) A Practical Handbook of Photovoltaics: Fundamentals and Applications. Elsevier, London, UK

Munsell M (2016a) Solar module prices reached 57 cents per watt in 2015, will continue to fall through 2020. http://www.greentechmedia.com/articles/read/solar-pv-module-price-reach-57-cents-per-watt-in-2015-continue-to-fall-thro. Accessed 10 Mar 2016

Munsell M (2016b) Solar PV prices will fall below $1.00 per watt by 2020. http://www.greentechmedia.com/articles/read/solar-pv-prices-to-fall-below-1.00-per-watt-by-2020. Accessed 1 June 2016

NCSC (2002) Photovoltaic applications. In: N. C. S. Center (ed). State Energy Office, NC Department of Administration, Raleigh, NC

NREL (2014) Distrubuted solar photovolatics for electrical vehicle charging. In: N. R. E. Laboratory (ed). Office of Energy Efficiency and Renewable Energy, Denver

Omer AM (2008) Energy, environment and sustainable development. Renew Sust Energ Rev 12(9):2265–2300

Pandey AK, Pant PC, Sastry OS et al (2015) Energy and exergy performance evaluation of a typical solar photovoltaic module. Therm Sci 19(2):S625–S636

Pandey A, Tyagi V, Jeyraj AS et al (2016) Recent advances in solar photovoltaic systems for emerging trends and advanced applications. Renew Sust Energ Rev 53:859–884

Peng C, Huang Y, Wu Z (2011) Building-integrated photovoltaics (BIPV) in architectural design in China. Energ Buildings 43(12):3592–3598

Philibert C (2011) Solar energy perspective. International Energy Agency(IEA), France

Roger M, Yogi G, Hari MU (2009) Photovoltaics Fundamentals, Technology and Application Handbook of Energy Efficiency and Renewable Energy, 2nd edn. Taylor & Francis, Philadelphia, PA

SHLSC (2014) Solar panel prices, solar panel Malaysia, Singapore, Thailand, Chile, Colombia, Mexico, South Africa, Canada. Shandong Hilight-Solar. ALIbaba.com

SP (2014a) Blue carbon poly pv sunpower solar panel 300 W. Alibaba.com

SP (2014b) Hot sale sunpower 300 W poly pv flexible solar panel manufacturer with TUV CE IEC certificate from China in low price. Alibaba.com

SP (2014c) Import sunpower mono solar panel 200w 250w 300w. Alibaba.com

Susanto H (2011) Towards practical implementations of membrane distillation. Chem Eng Process Process Intensif 50(2):139–150

Teresa DM, Busch J (2010) Design of small photovoltaic (PV) solar-powered water pump systems. In: McDuff E (ed). United Sates Department of Agriculture (USDA), Portland, OR