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Recent advances in solar photovoltaic systems for emerging trends and advanced applications

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ABSTRACT

This communication presents a comprehensive review on the solar photovoltaic (SPV) systems for recent advances and their emerging applications in the present and future scenario. Besides, the performance study of off grid and grid connected SPV power plant has been discussed and presented in detail. From the literature, it is found that the efficiency of photovoltaic (PV) systems varies from 10% to 23%. Thus, the efficiency is the important factor which needs to be explored further for the best implementation and utilization of this emerging and useful technology around the globe. However, among all the applications discussed here, Building integrated photovoltaics (BIPV), Concentrated photovoltaics (CPV) and photovoltaic thermal (PV/T) are found to be the most technically sound and exhibit that SPV may be a feasible solution for the future energy challenges. Again, the building integrated PV system not only reduces the area requirement, but also cuts the material and infrastructure costs of the building and hence, fulfills the technical thrust for smart building requirements. Recently developed CPV cells are found to be feasible, most promising and cost effective technology having higher efficiency and lesser material requirements than those of the other solar cells. On the other hand, as the PV/T systems produce not only the electricity but also the heat energy are found to be more useful, suitable, and promising for most of the real life applications especially, where both forms of energy are required simultaneously.

Contents

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1. Introduction

The demand for energy has been increasing for the last several decades, due to the enhanced industrialization, growing population and improvement in the living standard of the people, globally. The International Energy Agency (IEA) estimated that the developing countries are increasing their energy consumption at the faster pace than that of developed ones and will require to almost the double of their present installed generation capacity by the year 2020 for meeting their demand of energy [1]. It is also projected that the total energy consumption of the world to increase by 44% from 2006 to 2030 [1–3] which is very likely as can be seen from Fig. 1. The IEA has also reported that more than 1.3 billion people in the developing countries are living in the scarce or without any access to electricity due to unavailability of grid in these areas and other constraints [3,4].

In the developing countries, more than 80% population lives in the rural areas and continuously harnessing the traditional source of energy to meet their day to day requirements of energy. For example, wood for cooking and home heating, kerosene for home lighting, animals for agricultural activities, solar and wind energy for crop drying, harvesting and separation purposes, while diesel engine, canal, ponds, rivers, etc. for irrigation purposes when and where a respective resource is available to meet their energy needs. However, the use of wood for cooking, home heating, food processing, etc. consumes a huge amount of energy and creates the deforestation and pollution in the environment. In the current scenario, the reserved energy sources or fossil fuels such as coal, oil and gas are the major driver of economy for the whole world and also the main contributor of environmental pollution [5]. Thus, for the growing industrialization with the increasing population, there is an urgent need of more and more energy for healthy and competitive economic growth, while keeping the environmental fact in the mind. It means the time has come when there is an urgent need to explore the renewable energy resources which not only meet the increasing energy requirements of the world but are also environmental friendly. Therefore, the time has come when the world community requires the energy sources which are technologically, economically, environmentally, and socially compatible is the need of time, for the sustainable development [6,7].

Also the renewable energy sources such as, solar, Bioenergy, wind, small hydro, geothermal and tidal, etc. are the promising sources of energy with all the qualities required to meet the present and future energy need. The renewable energy sources are free and abundantly available in the environment, however, facing some serious challenges regarding the low efficiency, higher capital cost and unequal availability over the time and location around the globe. The capital cost of these systems is much higher than that of the fossil fuel based systems while, the efficiency is quite low and hence, are not much economical at this point of time. The scientists and engineers around the globe are continuously making numerous efforts to overcome these issues and make this world a livable place for the common population [8].

1.1. Background of solar PV

There has been a continuous growth in the utilization of renewable energy in general and solar energy in particular for useful applications, especially, after the oil crisis during the late 1970s. This has compelled the scientists and policy makers around the globe to emphasize on different ways to harness solar energy more effectively and efficiently, especially, in the area of thrust. In the terrestrial regions, solar energy can be utilized in two different ways; one through solar thermal route using solar collectors, heaters, dryers, etc. and the other is solar electricity using solar photovoltaic (SPV) as can be seen in Fig. 2 [9]. The photovoltaic is the direct conversion of sunlight into electricity without using any interface. Solar PV systems are rugged and simple in design, modular in the nature, requires a little maintenance and stand alone can generate the power from microwatts to megawatts. The standalone PV system has played a very important and critical role in the electrification of the rural areas, especially, in the developing world [10–13]. A solar PV module along with the charge controller and battery as per the requirement is sufficient for electrifying the rural home and known as the solar home lighting system. This increases

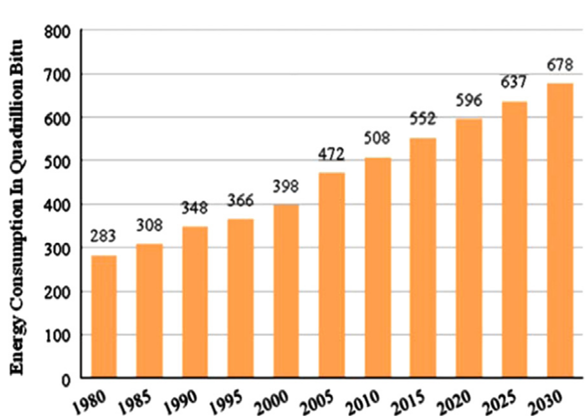

Fig. 1. World marketed energy[1].

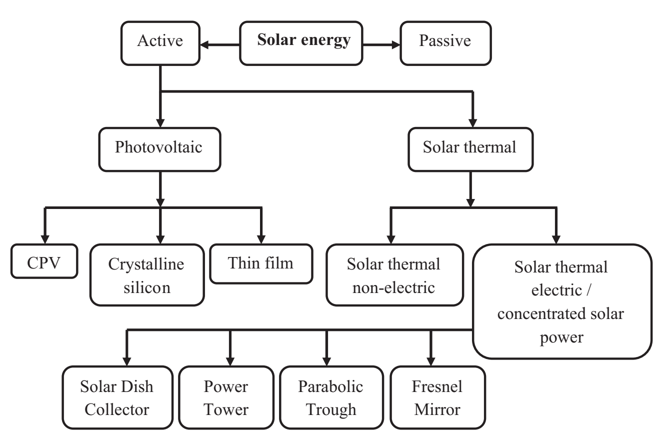

Fig. 2. Assorted types of solar energy based on global market availability [9].

the demand for solar PV for a variety of applications. The cost per watt of the solar PV has been declined 3.50 $/Wp for first generation solar cells to 1.0 $/Wp for second generation solar cells and expected to decrease further up to 0.50 $/Wp in the near future [14,15]. The Government policies for providing the feed in tariff in many developing countries have helped in the popularization and installation of PV systems. For the countries participating in the IEA-PVPS program, the total installation capacity has been found to be increased from 103 MW in 1992 to 63,611 MW in the year 2011 [16].

1.2. Recent advances in solar PV systems

Many solar energy systems, including but not limited to solar water heaters, solar air heater/dryer, solar desalination, solar home lighting, concentrated PV, Building integrated PV (BIPV) has been implemented and studied using energetic and exergetic approaches for different purposes [10–12]. The different types of PV materials for solar cells are available in the market nowadays, but due to high efficiency and matured technology, Silicon based solar cells are leading the market from the beginning. However, researchers around the world are exploring the other options to produce electricity more efficiently by means of solar cells and hence, R&D for developing new material is going on. Many authors have reviewed the recent studies and developments on solar PV systems and their possible applications in different areas [17–24]. However, low cost and flexibility in nature makes the thin film technology to be the potential technology for the solar cells [25]. First Solar reduced its price down to $0.75 per watt, 50% less than crystalline solar cells. But its conversion efficiency is still a cause of concern among the scientific community. Therefore, the experimental work on different materials such as, amorphous silicon, CdS/CdTe and CIS is going on for efficiency enhancement of the thin film solar PV technology [26]. Also options in selection of materials such as, material polymer or organic material as a solar cell are the other competent options in the thin film technology which not only enhanced the conversion efficiency but also suitable to meet the concern over the environmental problems [27]. Advancement in the research and development related to different types of solar cell materials is going on. The latest developments in the solar cell efficiency is given in the Fig. 3 [28] while, the detailed developments is given in the next section of this article.

The objective of the present paper is to reflect the recent advances in the solar PV systems and its emerging applications and to find out the thrust area of the research in PV technology in the current scenario. Section 1 of the paper presents the introduction part, which includes current energy scenarios in general and for solar PV in particular. Section 2 presents the classification of solar PV and deals with the different types of solar PV cells available for the use. Section 3 describes the advances in the solar PV based systems and their emerging applications. Section 4 covers the recent advances in the performance evaluation of solar PV systems, both the grid connected and the stand alone systems. Finally, the results from the study have been concluded in the last section along with recommendations for future scope of the work and the utilization of this fast growing technology for a wide range of applications globally.

2. Classification of solar photovoltaic

The types of PV materials on which solar cells are available in the market is given in Fig. 4 [29]. However, due to high efficiency and matured technology, the Silicon based solar cells are leading the market till now as can be seen in the Fig. 5 [30]. World's overall PV cell/module production is increasing day by day. Fig. 6 shows the world wide PV cell/module production for the years 2005 to 2013. As can be seen from the figure, China is the leader as far as PV production is concerned followed by Taiwan and Japan in the year 2013 [31]. Crystalline semiconductors viz. Si and GaAs have the highest performance as compared the other options available in the market. While, the solar cells based on the less pure materials viz. polycrystalline or amorphous inorganic or organic materials, or combination of these having less performance but cost is low [32]. Therefore, researchers all over the world are exploring other options with higher performance to produce electricity by the means of solar cells. Also due to low cost and light weight as compared to the mono and poly crystalline solar cells, the thin film technology has been seen as a potential technology but its low efficiency is still a cause of concern among the scientific community [25]. For efficiency enhancement of

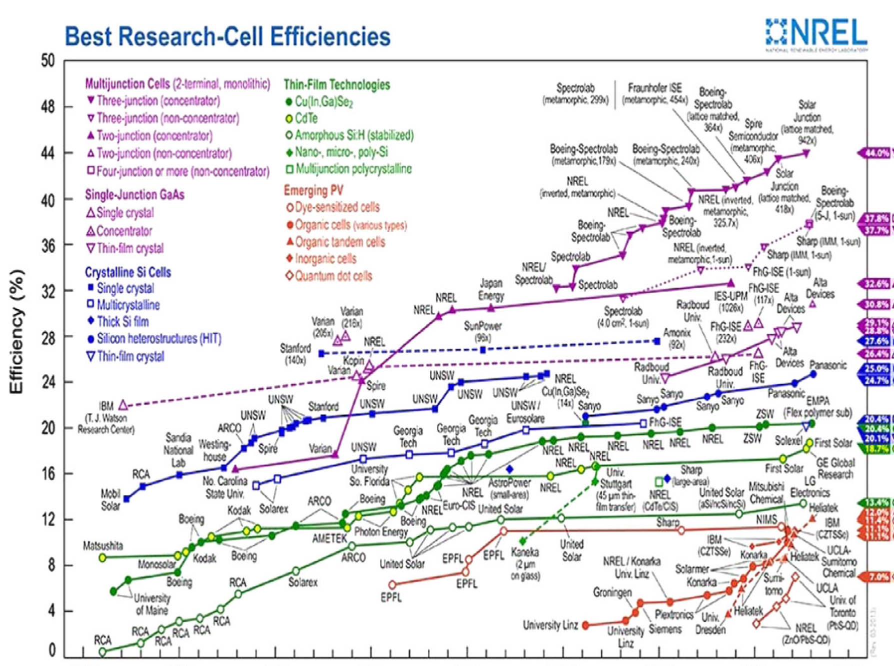

Fig. 3. Best research cell efficiencies [28].

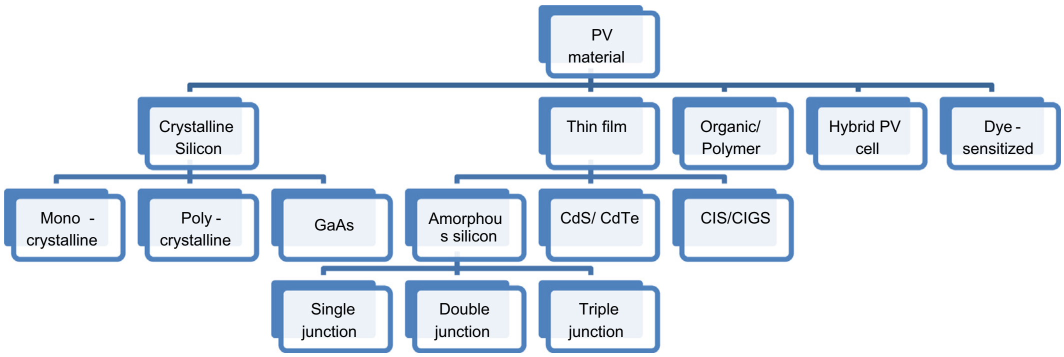

Fig. 4. PV material chart [29].

Fig. 5. Annual PV production capacities of thin-film and crystalline silicon based solar modules [30].

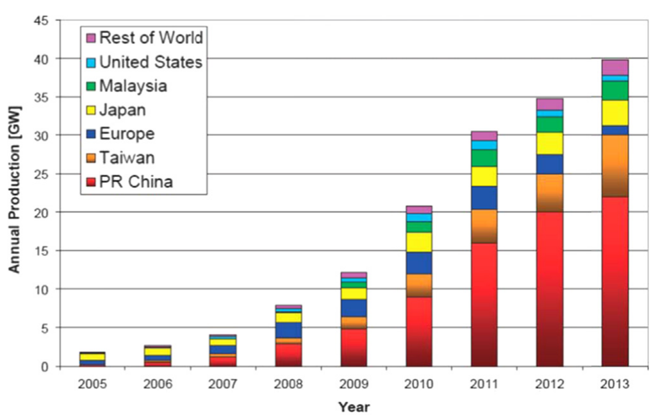

Fig. 6. World PV cell/module production from 2005 to 2013 [31].

the thin film technology, the experimental work on three different materials such as, the amorphous silicon, CdS/CdTe and CIS is going on worldwide [26]. However, due to the environmental related problems associated to these materials, the polymer and organic materials based thin film technology are the other competent options [27]. The advancement in the research related to different types of solar cell materials are given as below:

2.1. Crystalline materials

The crystalline silicon solar cells have many advantages such as, high efficiency than that of other solar cells and easy availability which forced the manufacturers to use them as a potential material for solar cells [33]. In most of the cases, the monocrystalline type solar cells are used as they have high efficiency but due to higher cost of the material, it is still a cause of concern for both the manufacturers and the end users. Therefore, the industries are looking for alternatives and polycrystalline type of solar cell may be another option which has lower cost as compared to the mono crystalline cell [34]. The scientific community also looking for GaAs based solar cell as an alternative, which is a compound semiconductor, form by gallium (Ga) and arsenic (As) having the similar structure as silicon. The GaAs material is having high efficiency and low weight, but higher cost as compared to the mono- and polycrystalline silicon solar cells. However, the GaAs based solar cell exhibits to have high heat resistance and found to be suitable for concentrated PV module for power generation, hybrid use and space applications [35].

2.2. Thin film solar cells

The thin film technology based solar cells are cheaper as compared to silicon based solar cells due to the fact that the requirement of material is lesser in the manufacturing process of the former [26]. The amorphous silicon being non-crystalline and disordered structure form of silicon is having 40 times higher absorptivity rate of light as compared to the monocrystalline silicon. Thus the amorphous silicon based solar cells are very famous as compared to other materials such as, CIS/CIGS and CdS/cdTe due to the higher efficiency of the former. Williams et al. [36] presented the challenges and prospects in developing the CdS/CdTe substrate solar cells on Mo foil. By combining the close-space sublimation and RF sputtering, ITO/ZnO/CdS/CdTe/Mo solar cells have been grown in the substrate configuration. $CdCl_2$ annealing process was developed using the two stage process, CdTe doping was done in the first stage while second stage contributes to the CdTe/CdS interdiffusion by secondary ion mass spectrometry analysis. The efficiency had been found to be increased from 6% to 8% by the inclusion of a ZnO layer between CdS and ITO layers and increasing the shunt resistance from 563 $\Omega\,cm^2$ to 881 $\Omega\,cm^2$. However, for improving the CdTe solar cell characteristics, an experiment study has been conducted by Soliman et al. [37] which revealed that the chemical heat treatment is needed to produce better cells. On the other hand, the copper indium gallium selenide (CIGS) based polycrystalline semiconductor is found to be one of the most popular choice for materials in the recent years due to its higher laboratory scale efficiency of about 20.3% [38,39]. Jun-feng et al. [40] investigated the selenization and annealing in CIGS films and found that after selenization at 450 °C, two separated phases as CIS and CGS at the top and bottom of the film as were formed. Kumar and Rao [41] presented the review on fundamentals and critical aspect of CdTe/CdS thin film heterojunction photovoltaic devices from the both physics and chemistry point of view. Efficiency enhancement, reliability and life time of this device were the prime target among the researchers around the globe, but the target achieved till date is far from the theoretical limits. They found that lack of understanding of some points such as junction activation treatment, the formation of stable back contacts, interfacial and grain boundary properties and impurities diffusion within the device are responsible for the slow progress towards the achievement. The champion

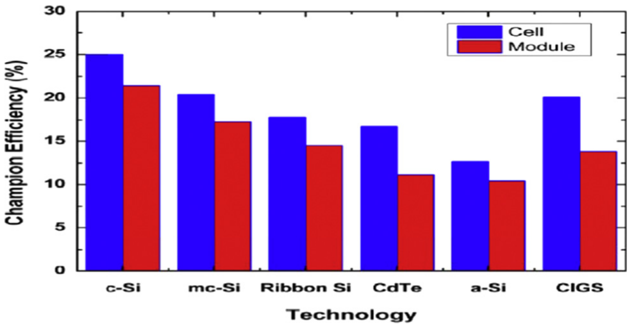

Fig. 7. Champion efficiencies reported for cells and commercial modules for the established PV manufacturing technologies. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

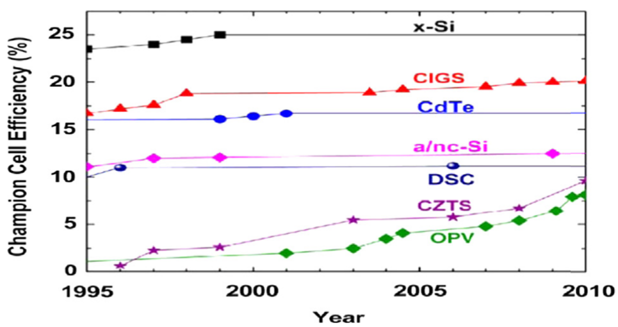

Fig. 8. The evolution of champion cell efficiencies since 1995 for various PV technologies. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

cell and module efficiency by 2010 as published by Wolden et al. [42] is given in Figs. 7 and 8.

However, recently published external quantum efficiency (EQE) of the different types of solar cells are given in Fig. 9(a) and (b) while, the terrestrial cell and submodule efficiencies and the terrestrial module efficiencies at STC is given in Tables 1 and 2 respectively as confirmed by Green et al. [43].

2.3. Concentrated solar PV

When the solar energy concentrated and made fall onto the photovoltaic cells thereby, enhancing the irradiance for improving the conversion efficiency by replacing the highly expensive solar cell material by less expensive concentrating mirrors or lenses is termed as the concentrated solar photovoltaic (CPV) system. The concentrated solar irradiance has been classified by Looser et al. [44] in different forms as shown in the schematic diagram of Fig. 10. In this arrangement, the low cost solar concentrating collector with a concentration ratio of 3–5 along with a laboratory scale PV cell which is quite expensive may be used. Therefore, the cost of using higher number of low efficiency PV cells may be compensated by using smaller size and lesser number of PV modules with the availability of higher intensity radiation and hence, can make the system more efficient, economical and reliable. High efficiency is one of the key factor which is necessary to make CPV a cost effective technology. Therefore, most of the research is going on enhancing the efficiency at cell or module level. The developments in the efficiency improvements of CPV from the year 2000 onwards and future prediction for the improvements is shown in Fig. 11 [45]. However, the durability and life cycle of such systems needs further R&D in this direction because high intensity radiation may cause deformation and damage to some parts of the PV panel. As a fact, only a fraction of the incident solar radiation striking the cell is being converted into electrical energy. While, the remaining gets absorbed and converted

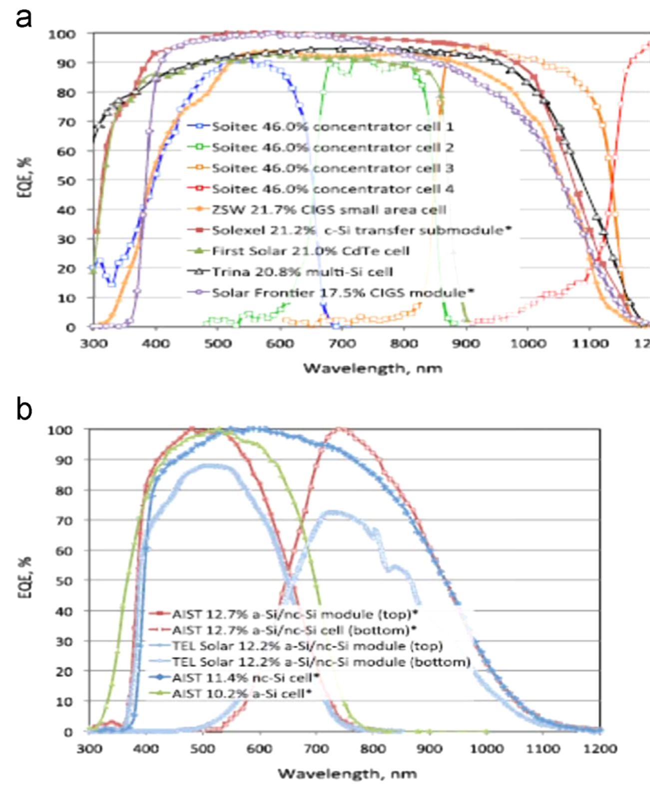

Fig. 9. (a) External quantum efficiency (EQE) for the new silicon, CdTe, CIGS and concentrator cell results in this issue; (b) external quantum efficiency (EQE) for the new amorphous (a-Si) and nanocrystalline (nc-Si) silicon results in this issue (* asterisk denotes normalized values; others are absolute values) [43].

into thermal energy in the cell and may cause the junction temperature to rise unless the heat is efficiently dissipated to the environment. As the temperature of the solar cell increases, the photovoltaic cell efficiency decreases and also the cells exhibit long-term degradation with increment in the temperature. Thus the use of the extracted thermal energy from the CPV system through a suitable cooling medium can also lead to a significant increase in the overall conversion efficiency of the combined system [46]. The major challenges and promise of concentrators is presented by Swanson [47].

Several researchers around the globe have made attempts to analyze the performance of the CPV systems for long term applications in different sectors leading to the sustainable development, globally. The performance of various concentrated (1x to 950x) solar cells was investigated by Cotal and Sherif [48] between the temperature of 25 °C to 85 °C. The experimental results show that dV_{oc}/dT decreases less and reaches a constant value by increasing concentration level. The finite element (FEM) or finite difference (FDM) based software was used to efficiently predict the thermal characteristics of the electronic packaging of the high concentration photovoltaic system (HCPV). Kuo et al. [49] worked on the design and development of the 100 kW high concentration photovoltaic (HCPV) with passive cooling system at Institute of Nuclear Research in Taiwan. The system module efficiency with a concentration ratio of 476x was found to be 26.1% at solar radiation of 850 W/m^2. Min et al. [49] also designed a thermal model for concentrator solar cells using energy conservation principles. They studied the temperature dependence of the cell on the area of the heat sink for different concentration ratios. Zahedi [50] presented the review of modeling details for low concentrating photovoltaic (LCPV) system and analyzed the effect of increased irradiance and temperature on solar photovoltaic.

A procedure for the assessment of the reliability functions of concentrated solar photovoltaic (CPV) systems subject to real working conditions i.e. outdoor degradation has been described by

Table 1
Confirmed terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at 25 °C (IEC 60904-3: 2008, ASTM G-173-03 global) [43].

Classification[a]	Efficiency	Area[b]		V_{oc}	J_{sc}	Fill factor	Test center[c]
	(%)	(cm^2)	(V)	(mA/cm^2)	(%)	(date)	Description
Silicon							
Si (crystalline)	25.6 ± 0.5	143.7 (da)	0.740	41.8[d]	82.7	AIST (2/14)	Panasonic HIT, rear junction
Si (multicrystalline)	20.8 ± 0.6	243.9 (ap)	0.6626	39.03	80.3	FhG-ISE (11/14)[e]	Trina Solar
Si (thin transfer submodule)	21.2 ± 0.4	239.7 (ap)	0.687[f]	38.50[e,f]	80.3	NREL (4/14)	Solexel (35 μm thick)
Si (thin film minimodule)	10.5 ± 0.3	94.0 (ap)	0.492[f]	29.7[f]	72.1	FhG-ISE (8/07)[g]	CSG Solar (< 2 μm on glass; 20 cells)
III–V cells							
GaAs (thin film)	28.8 ± 0.9	0.9927 (ap)	1.122	29.68[h]	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)[g]	RTI, Ge substrate
InP (crystalline)	22.1 ± 0.7	4.02 (t)	0.878	29.5	85.4	NREL (4/90)[g]	Spire, epitaxial
Thin film chalcogenide							
CIGS (cell)	20.5 ± 0.6	0.9882 (ap)	0.752	35.3[d]	77.2	NREL (3/14)	Solibro, on glass
CIGS (minimodule)	18.7 ± 0.6	15.892 (da)	0.701[f]	35.29[f,i]	75.6	FhG-ISE (9/13)	Solibro, 4 serial cells
CdTe (cell)	21.0 ± 0.4	1.0623 (ap)	0.8759	30.25[e]	79.4	Newport (8/14)	First Solar, on glass
Amorphous/microcrystalline Si							
Si (amorphous)	10.2 ± 0.3[k]	1.001 (da)	0.896	16.36[e]	69.8	AIST (7/14)	AIST
Si (microcrystalline)	11.4 ± 0.3[l]	1.046 (da)	0.535	29.07[e]	73.1	AIST (7/14)	AIST
Dye sensitized							
Dye	11.9 ± 0.4[m]	1.005 (da)	0.744	22.47[n]	71.2	AIST (9/12)	Sharp
Dye (minimodule)	10.0 ± 0.4[m]	24.19 (da)	0.718	20.46[e]	67.7	AIST (6/14)	Fujikura/Tokyo U.Science
Dye (submodule)	8.8 ± 0.3[m]	398.8 (da)	0.697[f]	18.42[f]	68.7	AIST (9/12)	Sharp, 26 serial cells
Organic							
Organic thin-film	11.0 ± 0.3[o]	0.993 (da)	0.793	19.40[e]	71.4	AIST (9/14)	Toshiba
Organic (minimodule) Multijunction devices	9.5 ± 0.3[o]	25.05 (da)	0.789[f]	17.01[e,f]	70.9	AIST (8/14)	Toshiba (4 series cells)
InGaP/GaAs/InGaAs	37.9 ± 1.2	1.047 (ap)	3.065	14.27[j]	86.7	AIST (2/13)	Sharp
a-Si/nc-Si/nc-Si (thin-film)	13.4 ± 0.4[p]	1.006 (ap)	1.963	9.52[n]	71.9	NREL (7/12)	LG Electronics
a-Si/nc-Si (thin-film cell)	12.7 ± .4%[k]	1.000 (da)	1.342	13.45[e]	70.2	AIST (10/14)	AIST

[a] CIGS = $CuInGaSe_2$; a-Si = amorphous silicon/hydrogen alloy; nc-Si = nanocrystalline or microcrystalline silicon.
[b] (ap) = aperture area; (t) = total area; (da) = designated illumination area.
[c] FhG-ISE = Fraunhofer Institut für Solare Energiesysteme; AIST = Japanese National Institute of Advanced Industrial Science and Technology.
[d] Spectral response and current–voltage curve reported in Version 44 of these tables.
[e] Spectral response and current voltage curve reported in the present version of these tables.
[f] Reported on a "per cell" basis.
[g] Recalibrated from original measurement.
[h] Spectral response and current–voltage curve reported in Version 40 of these tables.
[i] Spectral response and current–voltage curve reported in Version 43 of these tables.
[j] Spectral response and/or current–voltage curve reported in Version 42 of these tables.
[k] Stabilised by 1000-h exposure to 1 sun light at 50 C.
[l] Not measured at an external laboratory.
[m] Initial performance (not stabilised). References [12] and [13] review the stability of similar devices.
[n] Spectral response and current–voltage curve reported in Version 41 of these tables.
[o] Initial performance (not stabilised). References [14] and [15] review the stability of similar devices.
[p] Light soaked under 100 mW/cm^2 white light at 50 °C for over 1000 h.

Fucci et al. [51]. An experimental set-up of two-axis sun tracker CPV system in the outdoor conditions installed at ENEA labs in Portici (Italy), is shown in Fig. 12.

The experimental set-up of CPV has been modified by inserting the by-pass diodes and connecting the solar cells in series configuration. Different parameters such as open circuit voltage (V_{oc}), short circuit current (I_{sc}), shunt resistance (R_s) and Fill factor (FF) was evaluated to get the real performance of the system in outdoor conditions.

2.4. Organic and polymer cells

In recent years, the organic solar cells are becoming favorable choice as the alternative material for solar cells because of their suitable prosperities such as, mechanical flexibility, low fabrication cost, semi transparency and light weight. However, the efficiency of these types of solar cells is still very low as compared other types of solar cells and has been reported around 8% in the literature [52]. The high performance solar cells using poly (3-hexylthiophene) (P3HT) as the donor, and [6, 6]-phenyl C60 butyric acid methyl ester (PCBM) as the acceptor and/or bulk heterojunction (BHJ) structures has been developed by many laboratories around the world [53,54]. Gilot et al. [55] found that under the applied optical and electrical bias, the external quantum efficiency of two terminal tandem solar cell changed by 16%. Lizin et al. [56] presented the review on life cycle analyses (LCA) of organic solar photovoltaics (OPV) and found that OPVs are the one of the best performing cells as far as environmental point of view is concerned. Pei et al. [57] investigated the metal–organic interfaces of a P3HT:PCBM bulk-heterojunction (BHJ) organic solar cell using X-ray photoelectron spectroscopy (XPS) under high electrical field. They reported that power conversion efficiency of a polymer solar cell enhanced by more than 8% using the above arrangement in solar cells. For improving the performance of polymer solar cell a controlled layer of multi-wall carbon nanotubes (MWCNT) was grown directly on top of fluorine-doped tin oxide (FTO) glass electrodes as a surface modifier by Capasso et al. [58]. The power conversion efficiency of polymer solar cells with FTO/CNT electrode was found to be higher than 2%, which may further improve the overall performance of polymer based solar cells.

2.5. Hybrid solar cells

Conventional solar cells are being made by using the inorganic materials such as Silicon. The efficiency of these solar cells is comparatively high but, the materials and processing techniques are costly. On the other and, organic materials and their processing

Table 2
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) [43].

Classification[a]	Effic.[b] (%)	Area[c] (cm^2)	V_{oc} (V)	I_{sc} (A)	FF[d] (%)	Test center (date)	Description
Si (crystalline)	22.9 ± 0.6	778 (da)	5.60	3.97	80.3	Sandia (9/96)[e]	UNSW/Gochermann
Si (large crystalline)	22.4 ± 0.6	15,775 (ap)	69.57	6.341[f]	80.1	NREL (8/12)	SunPower
Si (multicrystalline)	18.5 ± 0.4	14,661 (ap)	38.97	9.149[g]	76.2	FhG-ISE (1/12)	Q-Cells (60 serial cells)
GaAs (thin film)	24.1 ± 1.0	858.5 (ap)	10.89	2.255[h]	84.2	NREL (11/12)	Alta Devices
CdTe (thin-film)	17.5 ± 0.7	7021 (ap)	103.1	1.553[i]	76.6	NREL (2/14)	First Solar, monolithic
CIGS (Cd free)	17.5 ± 0.5	808 (da)	47.6	0.408[j]	72.8	AIST (6/14)	Solar Frontier (70 cells)
CIGS (thin-film)	15.7 ± 0.5	9703 (ap)	28.24	7.254[k]	72.5	NREL (11/10)	Miasole
a-Si/nc-Si (tandem)	12.2 ± 0.3[l]	14,322 (t)	202.1	1.261[j]	68.8	ESTI (6/14)	TEL Solar, Trubbach Labs
Organic	8.7 ± 0.3[m]	802 (da)	17.47	0.569[j]	70.4	AIST (5/14)	Toshiba

[a] CIGSS = CuInGaSSe; a-Si = amorphous silicon/hydrogen alloy; a-SiGe = amorphous silicon/germanium/hydrogen alloy; nc-Si = nanocrystalline or microcrystalline silicon.
[b] Effic. = efficiency.
[c] (t) = total area; (ap) = aperture area; (da) = designated illumination area.
[d] FF = fill factor.
[e] Recalibrated from original measurement.
[f] Spectral response and current–voltage curve reported in Version 42 of these tables.
[g] Spectral response and/or current–voltage curve reported in Version 40 of these tables.
[h] Spectral response and current–voltage curve reported in Version 41 of these tables.
[i] Current–voltage curve reported in the Version 44 of these tables.
[j] Spectral response and/or current–voltage curve reported in the present version of these tables.
[k] Spectral response reported in Version 37 of these tables.
[l] Stabilised at the manufacturer for 149 h to the 2% IEC criteria.
[m] Initial performance (not stabilised).

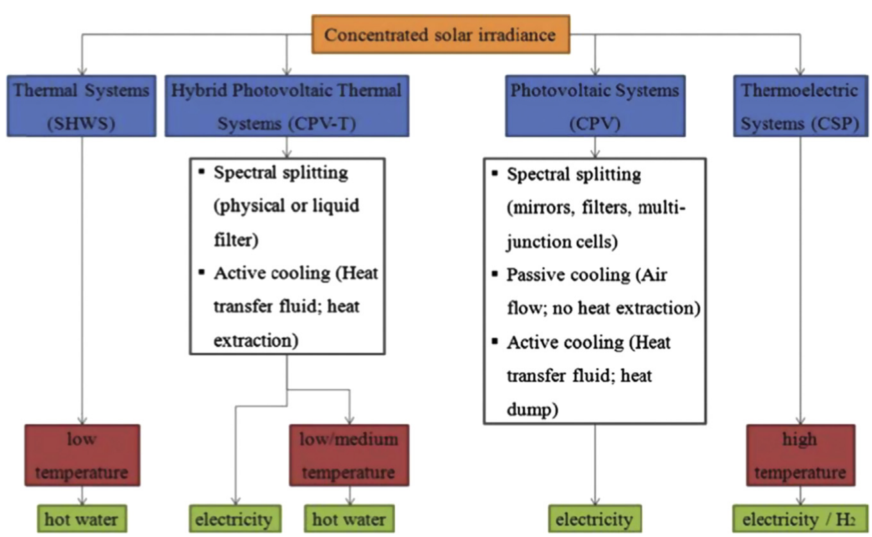

Fig. 10. Classification of common technologies and system set-up for concentrated solar irradiance conversion [44].

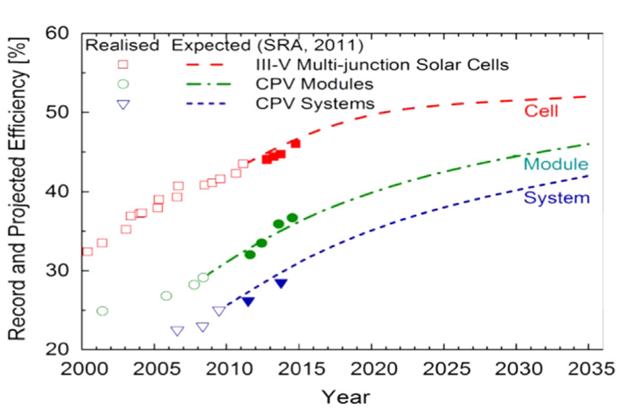

Fig. 11. Development of record efficiencies of III–V multi-junction solar cells and CPV modules (cells: x*AM1.5d; modules: outdoor measurements) [45].

techniques are cheap and their functionality can be tailored by molecular design and chemical synthesis. Therefore, the combination of both the inorganic and organic materils leads to the best and cheap alternative for the solar cells and combination of these two is known a the hybrid solar cells [59] and a schematic diagram of hybrid structure is shown in Fig. 13 [60]. Due to combination of high charge-carrier mobility of inorganic semiconductors along with the strong optical absorption of the organic semiconductors, the hybrid organic-inorganic solar cells got much attention in the recent era. Zhang et al. [61] fabricated and investigated the amorphous undoped intrinsic silicon, B-doped silicon and P-doped silicon hybrid bilayer structures with poly (3-hexylthiophene). The open-circuit voltages (V_{oc}) and fill factors (FF) of the devices are found to be moderate while these are found to be strongly dependent on the doping type of a-Si:H films.

Fig. 12. ENEA's outdoor facility [51].

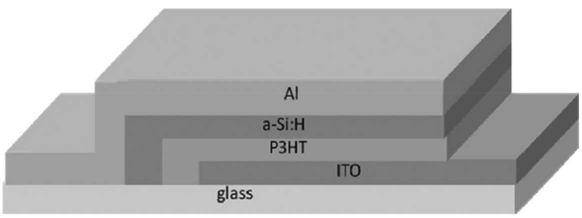

Fig. 13. Schematic diagram of the hybrid structure [61].

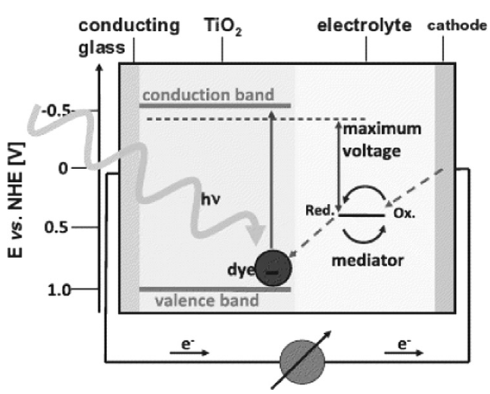

Fig. 14. Operating principle of dye-sensitized solar cell [62].

2.6. Dye-sensitized solar cell

The dye-sensitized (DS) solar cells exhibit certain qualities including lower cost and simple manufacturing process as compared to silicon based which make them suitable and potential alternative for the future application as solar cells. O'Regan and Gratzel [62] developed the dye-sensitized solar cells (DSSCs) in the early 1991, the operating principal of dye-sensitized solar cell is shown in Fig.14. Generally, this type of material comprises of five working principles such as, a mechanical support coated with Transparent Conductive Oxides; the semiconductor film, usually TiO_2; a sensitizer adsorbed onto the surface of the semiconductor; an electrolyte containing a redox mediator; a counter electrode capable of regenerating the redox mediator like platine [63]. Ahmad et al. [64] reported a new cost effective platinum-free counter electrodes (CEs) for dye sensitized solar cells (DSSCs). The power conversion efficiency of these electrodes was found to be around 4%, which is slightly higher than that of the DS solar cells with a standard Pt based CE.

2.7. Other technologies

As discussed above, many new materials have been invented so far, however, more invention is underway for solar cells, with the objectives to improve the performance of solar cells, while a few advanced technology has been ascertained in the processing of PV solar cells. The band gap can be controlled by nanoscale components to increase the power conversion efficiency of solar cell using nanotechnology or sometimes referred as "third-generation PV". Three different devices are used in nanotechnology for the production of PV cell such as, carbon nanotubes (CNT), quantum dots (QDs) and "hot carrier" (HC) based solar cell, respectively [65].

3. Emerging applications of solar PV technology

There has been an enormous effort from the scientific community to look for alternative and clean energy resources to fulfill the present and future needs. Also, due to limitation of conventional energy resources, there is an urgent need to explore renewable energy resources for healthy, competitive and sustainable economic growth worldwide, while keeping the environment neat and clean for the coming generation. The recent advances of PV technologies have filled up certain gaps between demand and supply of energy in a wide range of new and emerging applications in general and in some areas of technical thrust in particular, globally. Nowadays, there are different technologies available in PV sector to meet the increasing demand of energy with certain limitations. Among the available PV technologies, there is certain advancement in some specific areas, such as, solar PV based water pumping, solar PV home lighting systems, solar PV powered desalination plant, solar PV thermal, space technology, building integrated solar PV systems and concentrated solar PV systems and few of which are performing well in the field of real life applications. Thus, some of the recent advances in the solar PV systems and their emerging applications in the area of thrust within the current and future scenario are given as below:

3.1. Solar water pumping

One of the most important applications of solar photovoltaic technology is the is pumping of water for both irrigation and drinking purposes, especially in remote and rural areas [66–69]. From the last few decades, PV water pumping system has become a very popular technology and shows the good potential for providing good quality water at the desired site [70]. As per the World Bank report, more than ten thousand solar PV water pumping systems were installed by the year 1993, which has increased to over sixty thousand by the year 1998 worldwide [71,72]. Usefulness of solar PV water pumping systems becomes more visible when it comes to the rural and remote areas, especially, where the connectivity through the grid is not a feasible option. A solar photovoltaic water pumping system is the combination of a PV array, a DC/AC surface mounted/ submersible/floating motor pump set, some electronics parts "On–Off" switch and interconnecting cables. The solar PV panels are mounted on a suitable structure and the electronics parts could also include Inverter for DC to AC conversion of current and the maximum power point tracker (MPPT). In general, the batteries are not the part of the solar PV water pumping system as water pumping for irrigation purposes can be done during the daytime while for drinking purpose a suitable storage facility may be installed at the nearby suitable place[73].

Kaldellis et al. [74] carried out the detailed study on solar PV water pumping system (SPVPS) to calculate the overall efficiency and the total quantity of water that such a system can deliver on daily basis. A total of 12 PV panels (50 Wp, 6 series and 2 parallel) were used in the study as can be seen in the schematic diagram of Fig. 15. The electrical losses in the systems were found to be very low because the energy efficiency was mainly concerned about the two factors, one is the PV generator and the other is the efficiency of the pumping set. The overall energy efficiency of the proposed

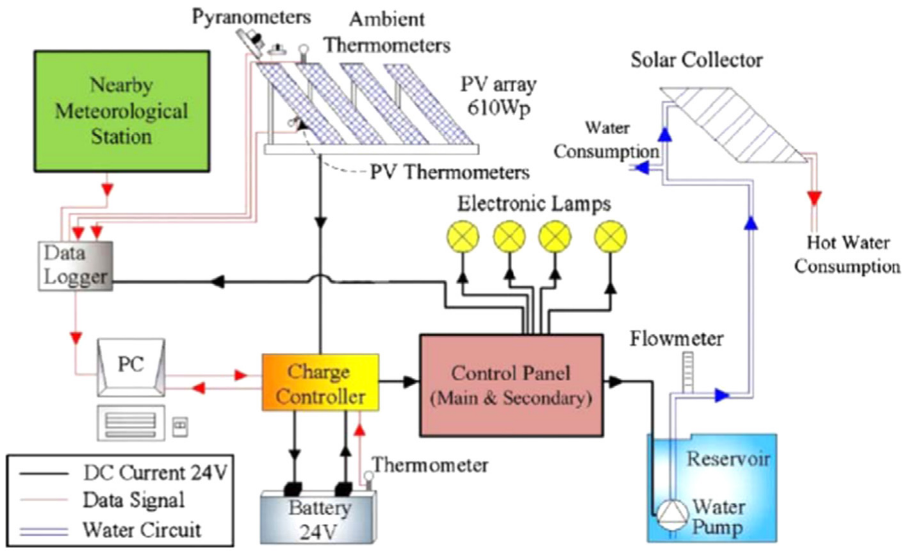

Fig. 15. Experimental PV-pumping unit [74].

system was found to be around 5%, which is relatively good enough, because the efficiency of PV panel used in this study was merely 8%. Therefore, by using the proposed solar PV water pumping system (610 Wp PV), more than 200 remote consumers can be benefitted by meeting their daily water need. The hybrid water pumping system which is a combination of wind turbine and solar PV array and an individual water pumping system using wind turbine and solar PV array was also studied by Vick and Neal [75]. For performance analysis, three different PV arrays (320, 480, and 640 W) and a 900 W wind turbine was selected and the hybrid water pumping system was also analyzed using the three different configurations. Based on the experimental observations, they [75] found that the hybrid system has pumped around 28% more water than those of the WT and PV systems individually in the month of greatest water demand (August). The performance of the hybrid water pumping system with the configuration of 900 W WT/320 W PV array was found to be the best among the other two configurations, mentioned above, due to the lowest voltage mismatch.

Al-Smairan [76] presented the case study of a solar PV water pumping system as an alternative to the diesel engine based pumping systems at Tall Hassan station, Badia in Jordan. The comparison is made for a various variable values such as, the tank capacity, total head, pumping requirements and PV array peak power between the two different energy sources viz. the DG set and the solar PV array for the same supply of water as per the details given Table 3. The PV water pumping system was found to be more cost effective than that of the diesel engine based water pumping system for the typical climatic condition of Jordan. Benghanem et al. [77] carried out the performance analysis of a solar photovoltaic water pumping system under composite climate of Madinah in Saudi Arabia for a typical specification having the head of 80 m. In this study, they configured the four different designs to get the optimum power from the PV water pumping system to get the best possible performance such as, 6SX3P, 8SX3P, 12SX2P and 6SX4P where S stands for series rows and P stands for parallel rows as can be seen in experimental set-up shown in Fig. 16. A helical type of water pump was connected to the PV panel for the fixed head of 80 m for carrying out the outdoor tests during the months of May to July and all the four configurations were tested ten times during the sunny days. All the important parameters for the performance analysis such as, instantaneous output power, current, voltage, hourly flow rate and the solar radiation were recorded with the help of a data logger Agilent 34970A. Finally, based on the

Table 3
Comparison among photovoltaic and diesel engine pumping systems [76].

US	Photovoltaic	Diesel engine
Initial investment	20,790	4500
Operational cost	416	7342.5
Present value cost (PVC)	24,566	71,148
Annual equivalent cost (AEC)	2706.4	7826.3
US$/m^3.	0.200	58

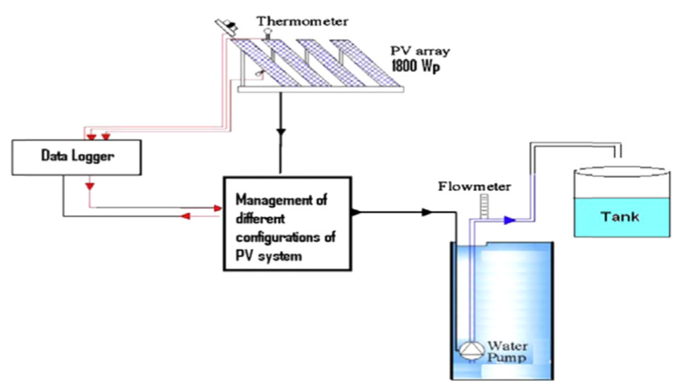

Fig. 16. Control and data acquisition for PV water pumping system [77].

performance evaluation and observations, they concluded that the 8SX3P configuration is the most suitable for the supply of 22 cubic meters of water requirements per day.

Gao et al. [78] presented the feasibility study and performance evaluation of a field scale solar photovoltaic pumping system for irrigation purposes at a typical climatic condition of the southern part of Qinghai province in Tibet. To find out the feasibility and performance of solar PV system for irrigation purposes, first of all they analyzed the water demand of pasture for different hydrological level years i.e. normal year, wet year and dry year, then based on the artificial neutral network modeling, the change of groundwater table of the pumping well was analyzed. Finally, based on the end cost benefit analysis, a set of optimized parameters were proposed for the designing of SPV based water pumping system. Based on their study, they concluded that solar PV based water pumping for irrigation has better an ecological and economic performance as compared to the diesel engine based water pumping system for

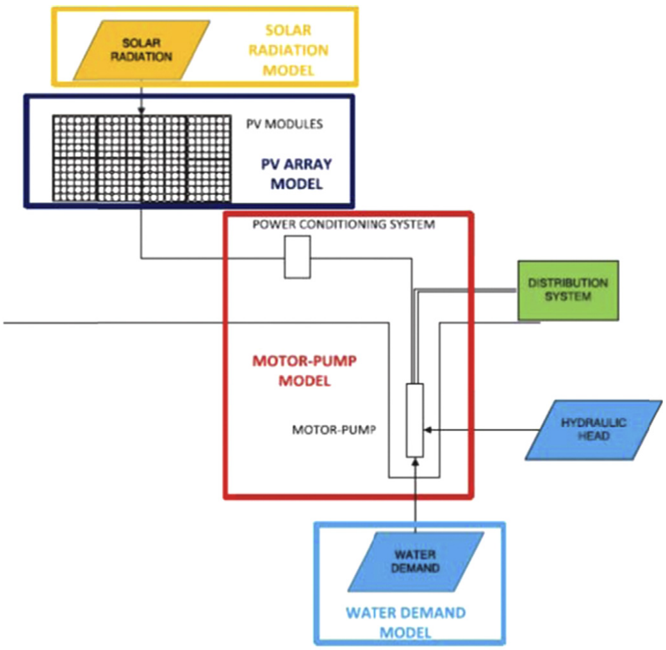

Fig. 17. Schematic diagram of a photovoltaic water pumping system [79].

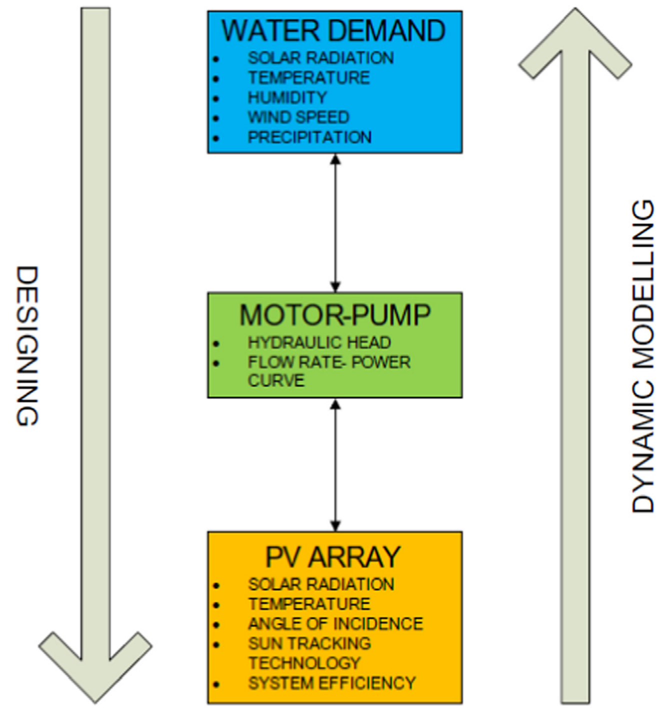

Fig. 18. Designing and dynamic modeling procedure [79].

irrigation and other necessary related purposes. Campana et al. [79] developed a dynamic simulation tools for the designing and validation of solar PV based water pumping system by combining the demand of water and requirement of power from solar PV for different pumping systems.

In the study the technical and economic analysis were presented for AC and DC pumps having both fixed type and two-axis type sun tracking systems. The schematic diagram of the solar PV based water pumping system and the flow chart of the designing process along with the dynamic simulation tools used in the study are shown in Figs. 17 and 18, respectively. From the study, it was found that the AC pumping set having fixed type sun tracking system is the best and cost effective solution among all the other solutions presented in the study.

Mekhilef et al. [80] presented the studies on application of solar energy in agriculture sector including solar water pumping systems, solar crop dryer, solar green houses and solar refrigeration. They found that solar energy systems are the most suitable options for agricultural and other domestic applications, as they have no impact on environment and require a very less maintenance as compared to the conventional energy systems. However, the investment cost of these systems is still a cause of concern because both the initial investment and per unit generation cost is higher in the case of solar energy systems as compared to those of the conventional energy systems. Benghanem et al. [81] carried out the effect of pumping head for selecting four different pumping heads such as 50 m, 60 m, 70 m and 80 m on photovoltaic water pumping system in outdoor conditions of Madinah, Saudi Arabia and selected and tested for the optimum design. The system efficiency was found to be strongly dependent on the solar radiation and pumping head. The efficiency was found to be increasing in nature with increase in solar radiation and decrease in pumping head. The system efficiency was found to be increasing with decreasing pumping head for low solar radiation. However, the efficiency of the system was found to be best at 80 m head at high solar radiation conditions. For the particular case, this pumping head should be considered as the optimum pumping head profile however, this may vary for different PV array size as flow rate and system efficiency varies with the PV array size. Dursun and Özden [82] presented the case study of PV powered irrigation system with modeling of soil moisture distribution for a typical climate in Turkey. Authors used soil moisture distribution map obtained via the artificial neural networks method for determining the area needed for the irrigation in an orchard. By using the system and software the soil moisture distribution was determined by them. They claimed that using the model developed by them may reduce the daily water and energy consumption by 38% of the given orchard and hence, it is also possible to manage the power of pump as per the water requirement for the irrigation thereby, reducing the overall cost of the system.

3.2. Solar home lighting systems

The home lighting is one the key factors for the development process and in most of the developing especially in the rural and remote areas, people still use traditional and conventional sources such as, kerosene for home lighting. The kerosene based home lighting is not only inefficient source of lighting but also having lack of visibility and causing health related problems among the users. According to the world energy outlook report [83] for the 2013, it was revealed that approximately 1.3 billion people are in the scarce of electricity around the globe and kerosene is the only source being used for home lighting especially, in Asia and Africa. It is found that the lamp powered by conventional sources like kerosene not only produces very poor quality of light but also emits toxic gases and the children using kerosene based lighting cannot read properly and also inhale toxic gases. Also use of kerosene for home lighting provides only 0.03 lumens/Watt in comparison of the compact fluorescent with 30–70 lumens/Watt and white light emitting diode with 50–100 lumens/Watt of light. According to the World Bank estimation, more than 780 million women and children are breathing harmful particulate matter due to the use of kerosene lamps from home lighting only. The kerosene based lighting is dangerous, unhealthy and insufficient and causes serious health hazards such as, respiratory and eye problems, especially, in the developing countries. This affects overall development in the country as the children using the kerosene lamps are exposed to the toxic gases and hence, are living in unhealthy environment which ultimately creates barrier in the education [84].

Therefore, the clean energy sources like solar PV are desperately needed for the lighting purposes which can not only

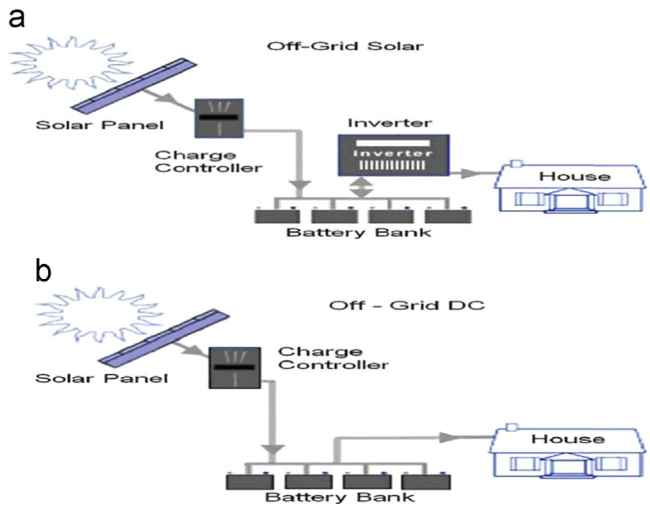

Fig. 19. (a) Off-grid AC solar power systems to provide power for normal AC appliances. (b) Off-grid DC solar power systems to provide power for only DC appliances [89].

produce the sufficient and good quality light but also environmental friendly energy source. In this context, solar photovoltaic based CFLs and WLEDs provide an option for clean, safe and good quality home lighting systems. The home lighting systems based on SPV for individual households is hard to reach in areas where there grid connectivity is more popular and easy to reach. The use of SPV systems for lighting purposes by replacing the kerosene and paraffin can reduce not only the running costs on a daily basis, but also the reduces the health risks among the end users, besides, it may contribute in terms of utility as the children will get the more time to study [85–88].

The detailed study on the home lighting pattern in the rural areas of mostly Asia and Africa was carried out by Pode [89] where he suggested the use of LED based solar home lighting systems to enhance the popularity and utility of these systems with better visibility (lumens/Watt) for home lighting solutions. He also discussed different aspects and case studies of conventional home lighting systems being used by the poor people around the globe including health issues, fire danger and green house gas emissions by using kerosene oil besides, the economics of solar powered CFL and LED in detail. The schematic view of off grid AC and DC powered solar home lighting system and photographic view of LED bulbs are shown in Figs. 19 and 20, respectively. The quality of light was found to be improved by replacing the kerosene with the LED lights with number of co-benefits such as, the increased in study time with lower air pollution, while reducing the monthly electricity bill significantly, i.e. almost 70% by the use of later lighting systems. Sastry et al. [90] developed high performance white light emitting diode (WLED) based solar home lighting systems under the joint project between Solar Energy Centre (Gurgaon) and Agency for Non-Conventional Energy and Rural Technology (ANERT), India. In this project, a 100 lm/W WLED, 6W at 16.4V PV module with 20 V of open circuit voltage and 0.4A current and 12 V and 7AH capacity of sealed maintenance free (SMF) valve regulated lead acid (VRLA) battery was selected for the performance analysis. The schematic of the experimental set-up for the electronic measurement is shown in Fig. 21. From this study, they concluded that the said home lighting system is better choice than that of CFL based system in terms of output and cost for solar PV applications.

Komatsu et al. [91] determined the characteristics of households installing solar home systems (SHS) in Bangladesh and the factors affecting SHS user satisfaction were determined for making this technology popular in rural areas. It was found that the users who found the SHS system as a replacement of kerosene were more satisfied and the users whose children got the extra time for study were highly satisfied. While from the econometrics analysis, it was found that SHS battery replacement has the negative impact on user satisfaction. Therefore, the reduction in frequency of battery replacement can improve the user satisfaction. Hong and Abe [92] presented the detailed mathematical modeling and optimizing technique for a sub-centralize LED lanterns for actual rural island case (Pangan-an Island, Philippines), the sub-centralized rental system is shown in the Fig. 22. The study throws a light into many key aspects including, planning, policy selection, operations and management for LED lamps rental systems. However, the dynamically optimized lamp (s) purchase policy was found to be better than that of statically optimized policy in terms of financial returns. They also proposed that sub-centralized lantern rental approach can serve as an option for providing clean energy especially, for the hard to reach areas in the country. The outcome of the study was found to be very useful with new opportunities for the stakeholders including investors, manufacturers and project developers who are working in the area of solar photovoltaic based home lighting systems.

Raman et al. [93] presented the opportunities and challenges regarding the use of solar PV based systems such as solar home systems, mini grids, etc. in the rural areas of India having the economic feasibility of various components of micro grid PV systems viz. battery, inverter etc. has been explained in detail. They [93] found that main reason behind the discouraged use of SPV systems is low efficiency and high investment cost and suggested for more R&D efforts should be made by the scientific community to come out with a higher efficiency and improved technology to make these products useful and cost effective for the end users. They also suggested that law must be made for the different organizations such as, industries, shopping malls, schools and colleges to meet at least there 30% of their energy demand by the means of solar PV system. Bond et al. [94] discussed the development impact of three different sizes of solar home lighting systems such as, 10, 40 and 80 Wp for rural East Timor by combining the participatory and quantitative tools for studying the solar home system for 77 small groups. In total, 24 rural communities and supplemented with a household survey of 195 solar home lighting systems users. They found that increase in the size of solar home lighting systems not provided the proportionate increases in development impact or we can say that small SHS has much development impact than that of larger one. They suggested three fold significant implications of solar home lighting systems for the East Timor viz. prefer small systems rather than larger ones, PV lighting in the kitchen in every possible ways and matching of solar home lighting systems operating cost with the user's income.

Komatsu et al. [95] again discussed the factors affecting the users satisfaction using the solar home lighting systems in the rural areas of Bangladesh. The study revealed very important facts which may be useful for the satisfactory installations of solar home lighting systems in the rural areas in the long run. He emphasized that frequent battery repair, maintenance and replacement play a negative role on the satisfaction of the end user and suggested that there is a need for more research about the life cycle analysis of batteries used in the SHS as confirmed by econometric analysis. However, the higher level of satisfaction was found to be for among those users who get benefitted due to increase in the study time of the children. The impact of switching from CFL to LED lights for solar home lighting systems in India on government policy, reduction in price and other factors has been presented by Harish et al. [96]. Around seven different companies working in the area of developing solar products has been chosen for the study of operations, distribution network and current products out of which four companies are exclusively making the LED based solar lanterns and SHSs, while, rest three are in the process to switch from CFL based product to LED based. Many factor such as, luminosity, price, service and maintenance and product configuration were found

Fig. 20. LED lamp sources for lighting [89].

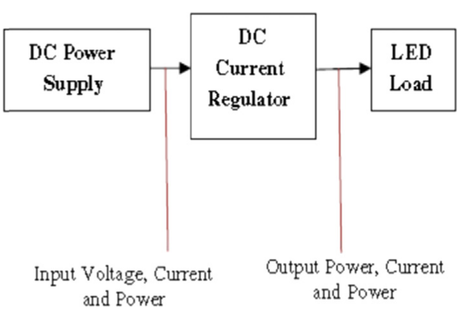

Fig. 21. Schematic of the experimental set-up for electronics measurement [90].

Fig. 22. Lamp rental system and cycle [92].

which can be considered before the transition from CFL to LED based products. However, the price reduction which is about 20% was found to be the significant driving factor in the adopting of the LED based products than that of the CFL based products. McHenry et al. [97] designed the 1000 lumens (lm) of light based on solar PV LED system with battery for the use of artisanal light fishers for 8 h per night on Lake Victoria and other lakes in the region. They also developed the simulation and economic model for the performance analysis of the designed system and suggested that the designed system is sufficient for providing additional lighting for fishers for the day and night use.

3.3. Solar PV desalination

Many countries especially, the developing, less developing, under developing and poor are facing scarcity of fresh drinking water which is one of the basic needs after air, as contaminated water causes many diseases. According to the World Health Organization (WHO) estimation, more than 20% of the world population has scarcity of potable drinking water and the majority of people are from the developing world. There are many traditional and modern techniques to purify the contaminated water from canal, river, pond, lake, sea, etc. and to make it suitable for drinking and related purposes. The desalination of sea/brackish water is a technique by which water can be purified for drinking and other related purposes. The desalination of water can be accomplished basically by using three common processes, thermal processes, membrane processes and hybrid process. In thermal process, the phase change occurs such as Multi Stage Flash (MSF) and Multi-Effect Distillation (MED) however, in Membrane processes, phase change don't occurs such as Electro dialysis (ED), Reverse Osmosis (RO) and hybrid process is the combination of both i.e. thermal and membrane such a membrane distillation (MD). Some work has been reported in the literature [98,99] to use solar energy for desalination which can be done in two ways; firstly, the thermal process in which the phase change of water occurs and secondly, by producing the electricity to support the membrane process using solar PV modules. However, depending on the requirement of electrical energy for the process, the size of the PV array along with other sub systems such as, battery for storage of power, charge controller and Inverter for DC to AC conversion of current can be modeled. But due to the due to involvement of batteries and other components, the economics of the entire system is not yet popular however, these technologies (PV-RO and PV-ED) are growing rapidly globally. Therefore, it is the need of the time to develop suitable and applicable technology

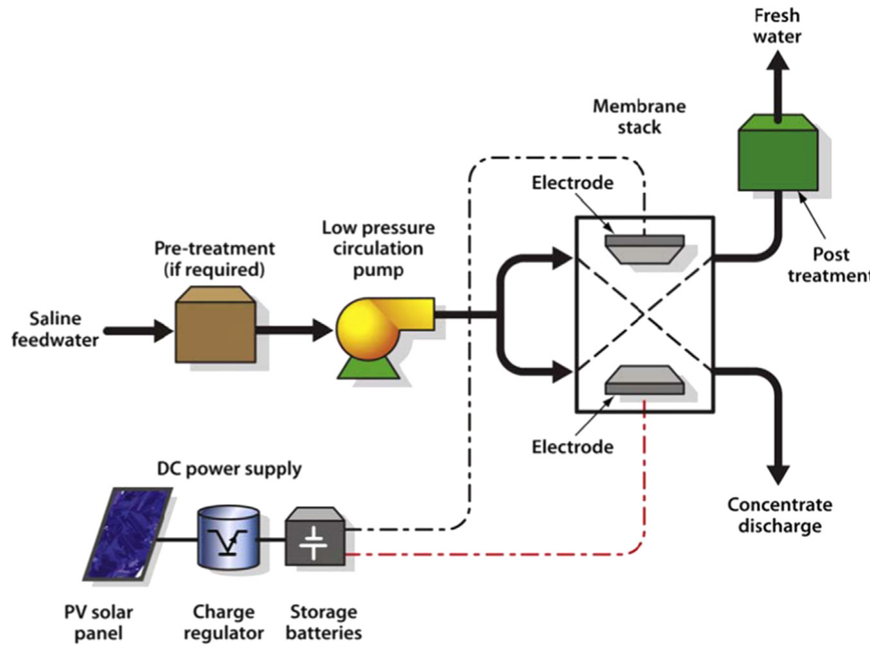

Fig. 23. A schematic diagram of a PV-ED system [106].

which can provide economical and acceptable solution for water purification to reduce the scarcity of fresh water to the people around the globe especially, in the rural and remote areas. However, it is evident from the literature that the scientific community is making continuous effort to get the economical solution for water purification and to meet the needs of the people globally [100–105] and the work in this direction has been summarized here.

The technical and economical aspects of PV based solar desalination system were discussed by Al-Karaghouli et al. [106] and suggested that for small scale PV powered distillation systems are successful and even economically viable for rural and remote areas, especially, where both grid electricity and fresh water availability is a problem, a schematic diagram of typical PV-ED system is also shown in Fig. 23. However, the large scale implementation of such systems is still a cause of concern due to many technological barriers including large initial investment. Also for the rapid development and deployment of this technology at the ground root level, the collaborations between industry and R&D institutions were suggested through on-site experiments with more installations. Koutroulis and Kolokotsa [107] proposed a methodology for optimal sizing of photovoltaic system and wind powered desalination systems. The developed methodology for the designing of desalination system tested for the design of two different types of desalination systems, covering the potable water demands of a small community and of a residential household in order to prove its on-site effectiveness. It was found that the capital cost of these systems play the major role and affect the overall configuration cost which reaches to 72% and 84% of the total cost for the household and the community, respectively. However, the operational cost which is affected by solar radiation availability and wind energy potential being intermittent in nature are found to be cost effective. Finally it was concluded that using the PV-WG hybrid system is more cost effective than that of using PV and wind alone systems, separately and individually.

Qiblawey et al. [108] worked on the design and performance evaluation of the PV powered water desalination RO pilot plant under the climatic condition of Jordan. The system is composed of a softener, PV modules of 433 Wp and RO unit with 500 L capacity of pure water production per day. The effect of different performance parameters such as, the ambient temperature, solar radiation, operating pressure, etc. on the RO-PV system was also studied in detail and it was found to be better when softener was used and produced water at 13.82 kWh/m^3 and 1.9 kWh/m^3 without using the softener [what does these results exhibit]. Karellas et al. [109] investigated the case study of an autonomous hybrid solar thermal ORC-PV RO desalination system in Chalki Island. They found that the designed system delivers potable water in the anhydrous areas at a cost of 10.17 V/m^3 which can be reduced to 9.33 V/m^3. According to them, the selected case study can be described as a mid capital project and can deliver about 83,000 m^3 capacity of water annually but ultimately depends on the meteorological conditions and other parameters of the specified area. However, they also suggested that the project is cost effective, if a subsidy of 40% for the capital cost is given, which may ensure the production of potable water at a cost of 6.52 V/m^3.

Ghaffour et al. [110] presented the technological development of solar desalination system and the contribution of the Middle East Desalination Research Center (MEDRC), Oman. They also reported that for the promotion of solar desalination systems, MEDRC has sponsored 17 different R&D projects on solar desalination and other renewable energy technologies for remote areas. As it is evident that it is beneficial technologically by coupling the conventional desalination processes like Electrodialysis (ED), Multi Effect Distillation (MED), Reverse Osmosis (RO) and Multi Stage Flash (MSF) with solar photovoltaic. However, from economic point of view the coupling of conventional desalination processes with solar photovoltaic is still a cause of concern. Keeping this in mind the fact that the coupling of the conventional desalination processes with the solar PV systems are not economical and unviable for rural areas hence, MERD has sponsored a project on "small solar multi effect desalination plant" for rural applications and is shown in Fig. 24. After analyzing the different sponsored R&D projects, they found that solar desalination technology is beneficial at small/medium scale applications in remote areas where there is unavailability of grid. However, more R&D efforts on the coupling of solar desalination with other renewable energy technologies has been suggested for enhancing the performance and reducing the cost of the fresh water obtained. The state of the art solar PV based membrane distillation processes was given by Abraham and Luthra [111] for social-economic development in India. The comparative study of reverse osmosis and electrodialysis membrane desalination processes powered by solar PV was presented. Also the economic analysis of pure water obtained through PV-RO and PV-ED processes was carried out and compared with that of the diesel powered RO and ED processes, respectively for a capacity of 50 m^3 of water per day for a life span of 20 years. As per the study, the desalination capacity is expected to increase to 1,449,942 m^3/day by 2015 and 291,820 m^3/day in 2008 due to growing demand and more focus on desalination by the states specially Gujarat, Tamil Nadu and Andhra Pradesh. For sea water and brackish ground water, the membrane desalination processes of PV-RO and PV-ED were found to be the most suitable processes due to less energy intensive than that of the thermal processes.

The environmental impact assessment of three different types of desalination systems including the passive solar still, solar PV powered RO module and truck delivery from a conventional RO plant using life cycle analysis (LCA) approach has been studied by Jijakli et al. [112]. The schematic of the PV powered solar desalination system is given in Fig. 25. In order to get the deeper insight into the model, the basic system components and processes were modeled and varied. The PV powered RO system was found to be having the least environmental impact among the three cases studied. Qtaishat and Banat [113] reviewed the literature on solar energy based membrane distillation (MD) unit, while discussing the principle, types, advantages and disadvantaged, economic feasibility and mathematical model of the solar energy based MD systems. The MD system is a hybrid technology of both the thermal energy and distillation and membrane processes and relatively a new process for distillation of water. The principle of MD is shown in Fig. 26, while Fig. 17 shows the vacuum membrane

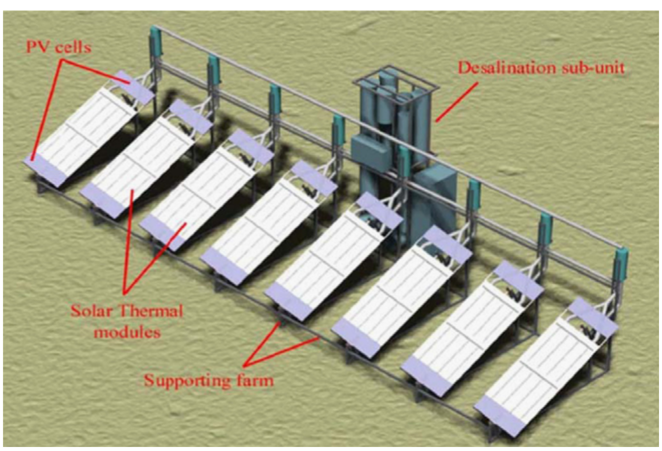

Fig. 24. Small solar MED desalination unit [110].

distillation (VMD) system for the production of potable distilled water. Based on the results from these systems, they concluded that the system is still costly and has not been commercialized so far however, exhibits the potential for future use not only for remote areas but also for urban areas, if the cost of the MD systems can be lowered further by means technological advancement through more R&D activities in this direction. (Fig. 27).

3.4. Solar photovoltaic thermal (PV/T)

The solar radiation incident on the surface of the PV panel not only being converted into electricity, but is also being converted into heat, partly and ultimately increases the temperature of the PV cells thereby, reducing the overall electrical efficiency of the solar cell [114–116]. Therefore, integrating both the concepts of PV for electricity generation and the produced heat energy for other thermal application can be more efficient and economical leading to a new technical term as the photovoltaic-thermal (PV/T) system. The PV/T collector system is a concept in which a solar PV panel is utilized for electricity generation by using electromagnetic radiations from the Sun, while the part of radiation absorbed by the panel raises the temperature and may be used as the thermal energy for other useful purposes and hence, both power and heat can be produced by the single systems simultaneously. The PV material plays a very important role in the PVT technology, as the temperature of the PV material increases, the electrical conversion efficiency decreases due to drop in the open circuit voltage [116]. Therefore, the choice of PV material to be used for the PV/T collector is a key factor in the design of the PV/T system which ultimately depends on the type of application. The PV material is selected based on the operating temperature, in general, the crystalline Silicon cells (c-Si) having temperature coefficient is 0.45%/K are used for low temperature, while, the triple-junction PV materials are typically used for higher operating temperatures [117]. On the other hand, the amorphous Silicon cells (a-Si) with temperature coefficient of about 0.2%/K may be an option as these are more economical than that of c-Si and triple-junction PV materials.

The heat and electricity are often supplementary to each other on most of the cases; therefore, it is a good idea to develop a device that can fulfill both the needs at the same time thereby, reducing the overall cost of the system [117]. Although the basic concept of combining the two technologies came into existence about 40 years ago, but still it is not a matured commercialized technology due to various constraints. However, due to the usefulness of the PV/T technology, the research on decreasing the temperature of PV panel and hence, to increase the cell efficiency

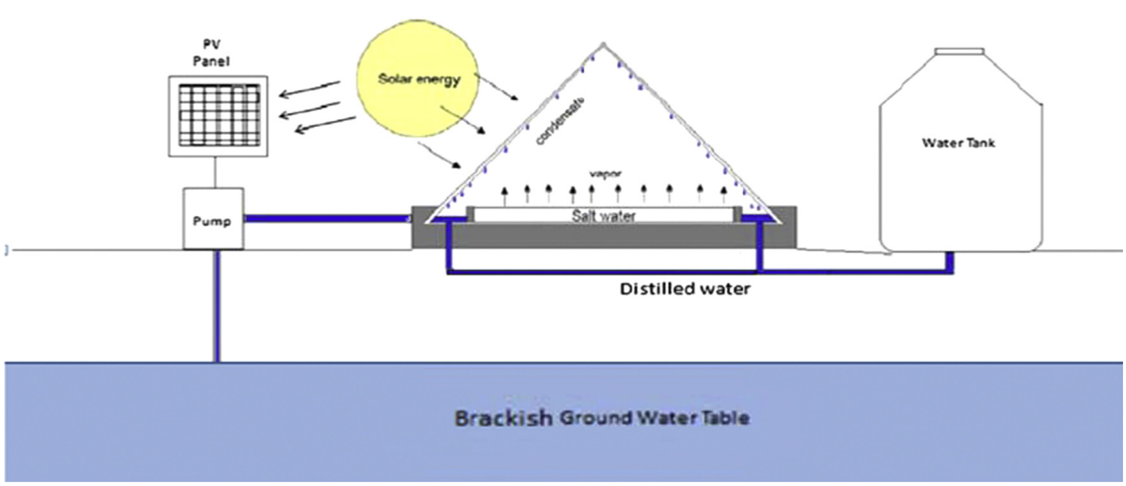

Fig. 25. Schematic of a solar still desalination system used in the study [112].

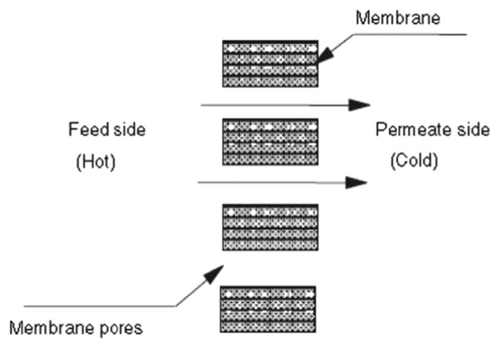

Fig. 26. Principle of membrane distillation [113].

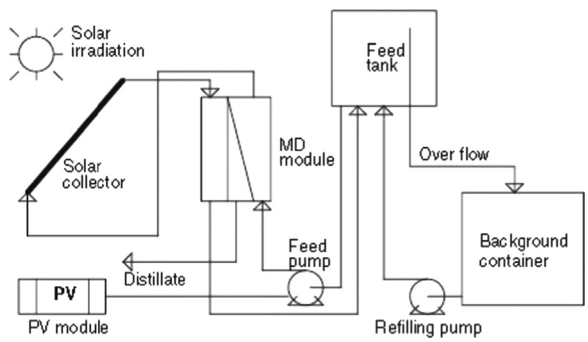

Fig. 27. Schematic drawing of the compact system (one loop desalination system [113].

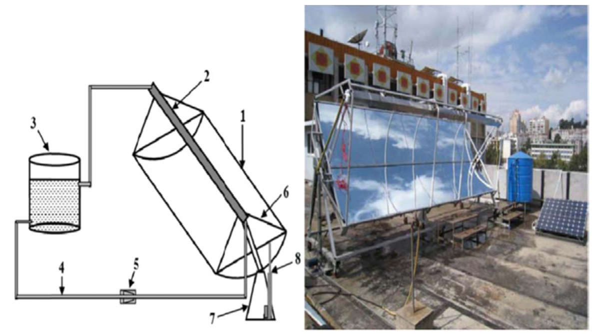

Fig. 28. The sketch and photograph of Trough Concentrating PV/T system [128], 1. Trough Concentrator, 2. Receiver, 3. Storage tank, 4. Pipe, 5. Pump, 6. Connecting rod, 7. Supporter, 8. Push rod.

and finally to maximize the use of incident solar energy on the PV panel is going on worldwide [118]. Work on methods to evaluate and optimize the efficiency and performance of PV/T systems have been carried out [119,120], also a few studies were investigating for possible commercial applications [121,122]. During the last few decades, several authors have developed and designed different types of innovative PV/T collectors such as, PVT/air, PVT/water and concentrated PV/T (CPVT) collector [123–125].

The performance evaluation of PV/T double passes facade system for space heating applications were presented by Kamthania et al. [126] including the detailed thermal modeling, energy analysis of the proposed system. From the above study, the electrical efficiency of the semi transparent PV module was higher than that of the opaque PV module due to the retention of heat in the later type, while, the annual electrical and thermal energy was found to be 469.87 kWh and 480.81 kWh, respectively. The system was found to be fit for space heating application as the temperature inside the room was 5–6 °C higher than that of ambient temperature during the winter season, which exhibits a significance rise of room temperature and a good indication for the real life applications. Kumar and Rosen [127] presented the advancement in the different types of PV/T air collector, research and development and commercial development of the systems through a critical review on hybrid PV/T collector especially, for solar air heating applications. They also point out that till now most of the research concentrates on simulation work rather than the development and commercialization of technology for long term benefits and the enhancement techniques for the performance of these systems is also missing. However, they projected that the PV/T technology to be a future technology for fulfilling the thermal and electrical energy needs simultaneously for all the sectors in the coming time.

Li et al. [128] carried out the theoretical and experimental study to analyze the performance of the parabolic trough type concentrating PV/T system using four different types of solar cells such as, single and poly crystalline silicon cell, the super cells and triple junction GaAs cells as shown in the schematic and photographic view of Fig. 28.

For the super cell array and single crystalline silicon solar cell array, the optimum concentration ratio was found to be 8.46 and 4.23, respectively. However, for the polycrystalline solar cell array, the performance was found to be poor at higher concentration ratio, while, the performance of the GaAs cells was found to be better at higher concentration ratios. The short circuit current of the single and polycrystalline, super cell and GaAs was found to be decreased by 0.11818A, 0.05364A, 0.0138 A and 0.00215A respectively, by each degree increment in the temperature of the solar cell.

Calise et al. [129] worked on the energetic and exergetic analyses of a finite-volume model of concentrating PV/T (CPV/T) system consisting of parabolic trough concentrator and a linear triangular receiver (Fig. 29) and found that the performance of the CPV/T system is strongly dependent on the operating flow rate and the intensity of the solar radiation. The exergy efficiency was found to be increasing function of the mass flow rate of water increased from .03 kg/s to 0.30 kg/s and the highest efficiency was recorded at 0.300.30 kg/s of water. However, they pointed out that such a system is very expensive due to the fact that it consists of a triple-junction PV cell, which is economically unfit in the present time more R&D is required to further study it to explore the new area for such applications.

Amori and Al-Najjar [130] presented the electrical and thermal performance evaluation of a hybrid PV/T system under the climatic condition of Iraq taking into consideration the five different performance parameters including maximum power point of PV, cell and ambient temperatures, thermal gain and fill factor using Matlab computer simulation program. The model was applied for summer and winter days for two different cities i.e. Fallujah and Baghdad of Iraq, respectively. The electrical, thermal and overall collector efficiencies respectively, were found to be about 9%, 22.8% and 47.8% for the summer days while, they were found to be about 12.3%, 19.4% and 53.6% of winter days. Tyagi et al. [131] gave an overview of the advancement in the hybrid PV/T systems, while summarizing and emphasizing the work done on different types of PV/T collectors, including PV/T liquid collector, PV/T air collector and PV/T concentrator, respectively. So far, the PV/T systems had been evaluated for many real life applications such as, water desalination, solar still, building integrated photovoltaic/thermal (BIPVT) solar collector, solar cooling, etc. Although the system was found to be very useful for both electricity and thermal energy production, but it was found that no major steps have been taken so far for the commercialization of this important and futuristic technology in real life applications.

Al-Alili et al. [132] had carried out the performance analysis of high efficiency solar air conditioner driven by concentrating PV/T system using the TRNSYS simulation program as shown in Fig. 30. The CPV/T system is composed of a conventional vapor compression cycle (VCC) driven by electric energy and solid desiccant wheel

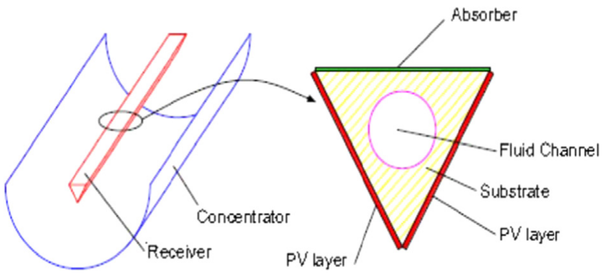

Fig. 29. CPV/T layout [129].

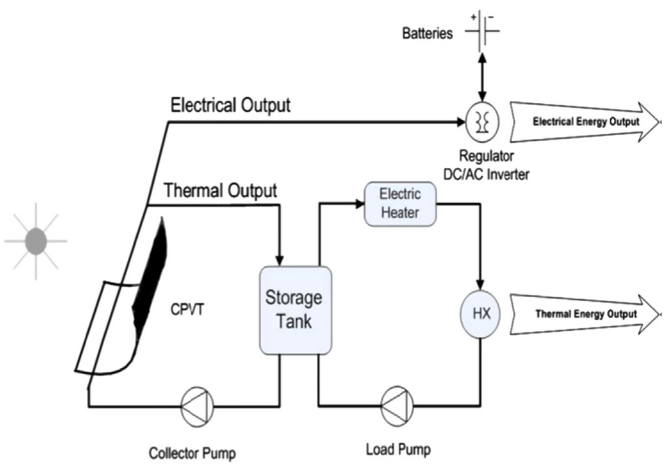

Fig. 30. The solar sub-system [132].

cycle (DWC) driven by thermal energy. The better results were found by combining the conventional VCC with DWC, although the COP of the CPV/T powered solar air conditioner (COP=0.68) had been found to be better than that of the solar absorption cycle (COP=0.29) and VCC powered by PV panels alone (COP=0.34).

The design and simulation model of a high temperature concentrating photovoltaic thermal (CPV/T) collector up to 180 °C was presented by Buonomano et al. [133]. The designed system was a combination of high efficiency triple junction solar photovoltaic cell and a parabolic dish type solar thermal collector with dual axis tracking arrangement which obviously can produce electrical and thermal energy at a time. The thermal and electrical efficiencies were found to be higher as compared to other systems, the electrical efficiency was found to be in the range of 19–25% while, the thermal efficiency was found to be around 60% and are applicable for the wide range of real life applications. Yin et al. [134] designed and evaluated the performance of a building integrated solar photovoltaic thermal (BIPV/T) system for efficient applications in the buildings. They presented a novel design and holistic approach to PV/T system integrated with, a building which also have phase change material (PCM) for energy storage (Fig. 31) and can be used when the irradiance is not available or in the night time. The efficiency of the system was found to be increased due to reduction in the temperature of PV module. Hence, the energy demand was found to be less due to building envelops and finally the total cost and material for the construction of the building was found to be less.

The enviroeconomic analysis and energy matrices such as, electricity production factor (EPF), energy payback time (EPBT), inflation and life cycle conversion efficiency (LCCE) for hybrid PV/T air collector was studied by Agrawal and Tiwari [135] using the overall yearly thermal energy and exergy gain. The energy payback time had been found to be 7.8 and 1.8 years, respectively, while the annualized cost/kWh was found to be 15.7 Rs./kWh and 3.6 Rs./kWh respectively for exergy and thermal energy. However, the efficiency/payback

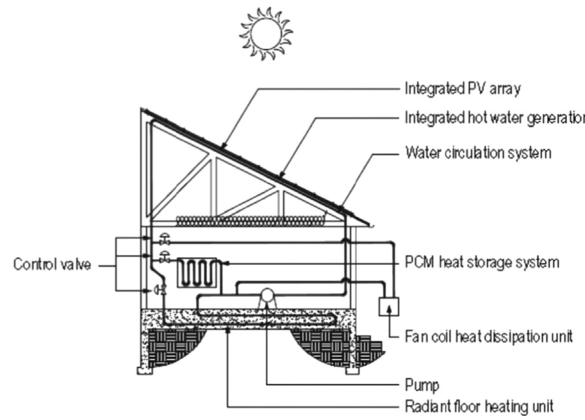

Fig. 31. Cross section of residential system [134].

period was found to be varying after including the cost of manufacturing of the components of the proposed PV/T system. Two different types of hybrid PVT system under four different climatic conditions of India have been studied by Rajoria et al. [136] using exergy and enviroeconomic approach. Out of the two designs, in the first case, two columns each with 18 PVT modules in series are connected in parallel while, in the second case, two columns of 18 modules each with 36 PVT tiles in the module is connected in series. Second case had been found to be better than that of first case in all the aspects i.e. having higher electrical efficiency (6.5%), higher average outlet air temperature (18.1%) and lower cell temperature (19.0%) than that of first case. The annual overall thermal energy and exergy gain for the city Banglore was found to be higher than that of other cities viz. Delhi, Jodhpur and Srinagar as presented in the study. Also, the overall thermal energy and exergy gain for the month of May was found to be better than that of other months for both the cases. Helmers and Kramer [136] presented the linear performance model for both concentrating and non-concentrating hybrid PV/T system. The linear parameterizations of electrical and thermal power outputs were derived similar to quasi dynamic model for thermal collectors and for validating the model, the real measured data of a CPV/T collector was used in the analysis.

Othman et al. [137] carried out the work based on air and water as a heat carrier at Solar Energy Research Institute (SERI), Universiti Kebangsaan Malaysia on hybrid PV/T system. They carried out the work on different types of PV/T collectors such as, double pass PV/T collector with fins, double pass PV/T collector with fin and CPC (Fig. 32), single pass PV/T collector with V-groove absorber as shown in Fig. 33. The results showed that PV/T collector with CPC and fins are better than that of without fins.

Recently the theoretical and experimental study on the different configurations such as, tube and sheet based hybrid PV/T collector has been studied by Touafek et al. [138] and showed better heat absorption and lower cost production. Theoretical thermal and electrical efficiency and overall effectiveness of the PVT system had been calculated and the same was found to be better as compared to PV alone system.

3.5. Space technologies

The Sun has unlimited power supply but the terrestrial collection of solar energy has many constraints including the atmospheric attenuation and weather conditions, which act as hindrance in the collection. However, the collection of solar energy in space via satellite coupled with its wireless transmission to the ground overcomes these problems but it has some serious issues regarding technical and economical aspects. Initially the power in space was only provided by Si based solar cells but recently the

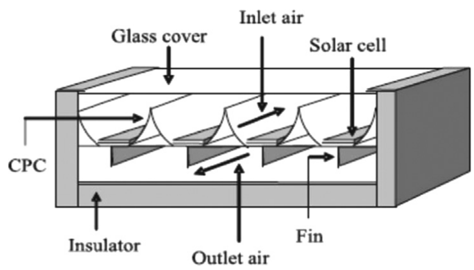

Fig. 32. Schematic diagram of double pass PV/T [137].

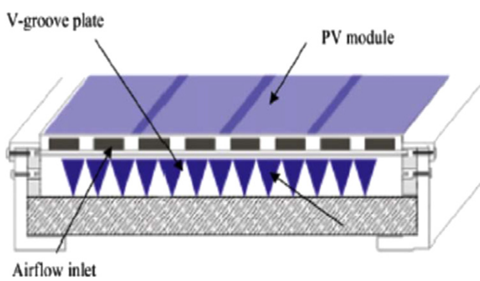

Fig. 33. Schematic diagram of the PV/T collector with V groove absorber collector [137].

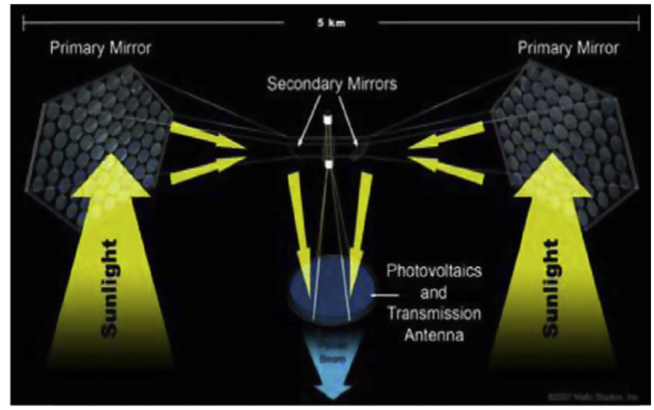

Fig. 34. Modular Symmetrical Concentrator architecture [148].

high-efficiency multi-junction solar cells have been emerged as an alternative for the space solar power [139,140]. The multi-junction solar cells have an advantage of high energy conversion efficiency while these are having more density and thickness and relatively costly as compared to Si-solar cells. Therefore, the multi-junction solar cells or the hybrid of Si-solar cells and are used when a high amount of power with compact size solar array are needed in the spacecraft because the larger size creates few problems for the attitude control systems onboard a satellite.

The performance analysis, weight, area and economics of different solar cell technologies have been studied by several authors [141–143]. Solar powered space satellite concepts have been reported in many studies [144] including the number of recent developments in the recent years [145,146]. Three different parameters viz. radiation resistance, cost and energy conversion efficiency have been optimized for the development of both types of solar cells for space applications. The efficiency of rad-hard Si-solar cells have been found to be 17% under the single Sun and zero air mass however, the efficiency of dual- and triple-junction InGaP/GaAs/Ge solar cells have been reported to be as high as 23% and 26%, respectively under the same test conditions i.e. zero air mass and one Sun [147]. The implementation status and testing results in developing photovoltaic arrays, microwave conversion electronics, power electronics and antennas for microwave-based “sandwich” module prototypes was presented by Jaffe et al. [148]. The modular symmetrical concentrator (MSC) architecture, solar power satellite via arbitrarily large phased array (SPS–ALPHA) offers the variety of advantages such as increased efficiency, low cost besides, some disadvantages like thermal challenges. The schematic view of the proposed MSC Space solar power (SSP) satellite is shown in Fig. 34. Sandwich module as originally investigated in collaboration with NASA/DOE in the late 1970s is the key element in the modular SSP, a sandwich type module is shown in Fig. 35. Upper and lower radiator surfaces are added to provide additional heat rejection in the step module design. The benefit of additional radiator surface is strongly dependent on the distance from the heat source, as distance increases the benefit decreases. Fig. 36 represents the schematic view of the photovoltaics and transmit antenna comprised of step modules.

3.6. Building integrated photovoltaic system (BIPV)

The solar PV system which is integrated as an on-site building envelope, typically a roof and/or a facade, are known as the building integrated photovoltaic (BIPV) system. In other words, the photovoltaic cells installed either on rooftops or other parts of buildings such as, walls, balcony or window glasses are known as the building integrated photovoltaic [149]. The building applied photovoltaic (BAPV) is another term used for solar PV systems which are integrated into buildings for useful application after finishing the construction works. Since, more than 40% of energy and 24% of green gases emission is contributed by buildings only [150], therefore, the R&D on BIPV systems are going on around the world due to its dual advantages such as, regulating the indoor environment and generation of electricity. Also, due to the ability of space in buildings, the BIPV systems are gaining huge popularity for energy production because these systems reduce the requirement of land for off-site solar PV installations, besides, the transmission and distribution losses [151]. So far, the most research has been focused on the building attached/applied photovoltaic (BAPV) and the true BIPV systems are yet to be investigated thoroughly.

The clear concept of two types of solar photovoltaic systems in buildings such as, BAPV and BIPV was given by Peng et al. [152]. According to them, if the integration is made by installing the solar PV modules on top of the existing structures (retrofitting) then the system is known as building applied photovoltaic (BAPV) while, it is BIPV if the solar PV panel is part of the building material/ element. As of now, a few researchers have investigated the BIPV systems based on their performance while, in most of the cases only the simulation studies were performed. However, the existing simulation models are still in the developing mode and further validation is required for their applicability. Santos and Rüther [153] quantified the potential of BIPV and BAPV generators on detached residential buildings in Florianopolis (Brazil). They compared the performance of thin-film amorphous silicon, and the traditional crystalline silicon solar PV technologies annually. The typical single-family, detached home roof covers can easily accommodate the proposed PV kits, with 87% of these generators yielding at least 95% of the maximum theoretical generation output of an ideally oriented and tilted PV system.

Aaditya et al. [154] carried out the real time performance assessment of 5.25 kWp building integrated photovoltaic (BIPV) system installed at Center for Sustainable Technologies, Indian Institute of Science, Bangalore (India). The data on different parameters such as, solar radiation, ambient temperature etc. were collected to find out the efficiency and performance ratio of the BIPV system as shown in photographic and schematic views in Figs. 37 and 38, respectively. The overall average efficiency of the system, performance ratio and average inverter efficiency was found to be, respectively, found to be 6%, ~0.5 and 91% for the period May 2011 to April 2012. However, the performance of the BIPV system does not find coinciding with the output and efficiency of the system because for lower output and the higher average efficiency and vice-versa. The comparative studies on long term surface temperature characteristics of amorphous silicon based

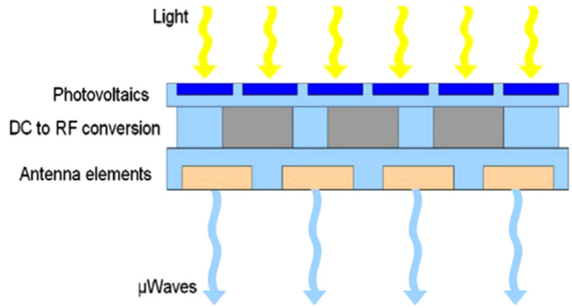

Fig. 35. Depiction of the functional layers of the sandwich module [148].

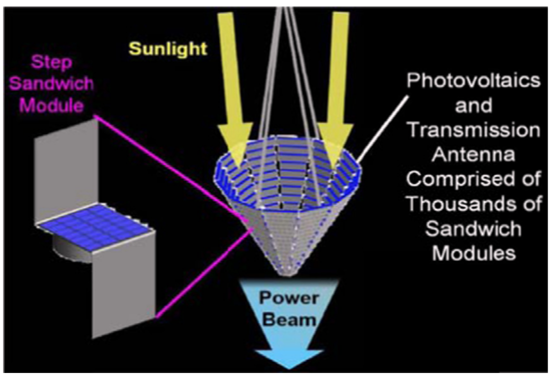

Fig. 36. Photovoltaic and transmission antenna comprised of step modules [148].

Fig. 37. BIPV system under study [154].

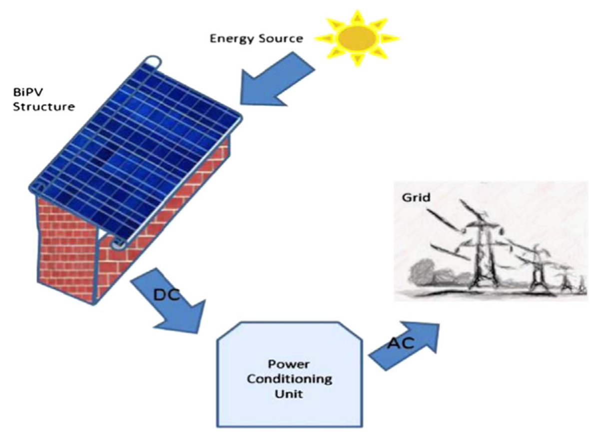

Fig. 38. Schematic diagram of the BIPV system [154].

BIPV windows and normal clear windows using mock-up test facility were studied by Yoon et al. [155]. The year round data were collected for clear double windows and BIPV double windows at an inclination angle of 0°, 30°, and 90° sky day and was analyzed using various statistical tools. The temperature of the window was found to be increased for vertical plane in winter season while, for summer season it was found to be enhanced for horizontal and inclined plane. The surface temperature of BIPV window was found to be lower by 1.0 °C in the summer season while, it was found to be higher by 2.0 °C in the winter season as compared to that of the normal window, respectively and hence, reveals a very important result about the advantage of PV systems being used in the buildings and its role in maintaining the thermal comfort.

Koyunbaba et al. [156] presented the comparative study on simulation and experimental results of energy modeling of BIPV trombe wall system in Izmir (Turkey). In this case they applied computational fluid dynamics (CFD) to study the temperature and velocity distribution in the test room model. The results between the simulation and experimental values for surface temperatures of PV module, thermal wall; indoor, inter-space, inlet and outlet air were found to be in a good agreement which exhibits the authentication of the results. The daily average electrical and thermal efficiency of this experimental system was found to be 4.52% and 27.2%, respectively. Ng and Mithraratne [157] examined the six commercially available semi-transparent BIPV modules for window application under the climatic conditions of Singapore on the basis of life cycle environmental and economic performance. They suggested that for urban areas where buildings have very less area but large façade, semi-transparent BIPV windows are good option for BIPV applications.

4. Advances in performance study of solar PV systems

The growth rate of the photovoltaic industry has been increasing annually due to the government support, installation of the grid connected plants and residential rooftop program globally. The public, private and government sectors around the world are promoting the solar energy based power plants to increase the share of renewable energy based electricity production for real life applications leading to the sustainable development, while keeping the environmental aspects as a priority. Most of the countries are providing incentive for solar in particular and renewable energy based energy production in general to reduce the burden on the environment. During the recent past, the installations of several major projects related to the grid connected PV plants have been completed and some more are in the pipeline and also increasing continuously. This section of the paper provides the performance study of the PV cells and installed PV system performance study in different countries including the energy and exergy analysis [158].

The performance study of a grid connected photovoltaic system of 200 kW at Jaen University was done by Drif et al. [159]. The major objective of the said project was to integrate a medium scale PV plant into the University campus for R&D activities and its performance evaluation. The total capacity of the PV system was around 8% of the total electricity demand of the University. They studied the performance of the system during 2000–2003 and found that system 1 (70 kW) and system 3 (20 kW) showed good behavior in comparison of system 2 (70 kW) and system 4 (40 kW). After the evaluation of the data, they found that the average annual energy production registered was around 168 MWh per year, which is around 6.4% of the total power consumption of the University. Congedo et al. [160] studied the performance measurements of mono crystalline silicon PV modules installed in South-eastern Italy with a total capacity of 960 kWp in the two lots (353.3 kWp and 606.6 kWp). They analyzed the energy and power generated, final yield, photovoltaic system efficiency, performance ratio and cell temperature losses in two different angles. The result of this study showed that the PV system efficiency vary between the highest value of about 17% in spring to the lowest value of about 15% in summer, and the performance ratio reaches the maximum level of 86.5% in March to the minimum level of 79% in June. On the other hand, the cell temperature losses were recorded to an absolute minimum of −3.5% in October to an absolute maximum of 8% in June. From the investigated result, they found that the system has good levels of performance, typically of 80%, and sometimes higher, also the values of final yield and reference yield were found to be above the average measured values in other PV systems.

Pietruszko and Gradzki [161] have monitored a small grid connected PV system consists of 20 double-junction thin-film amorphous silicon PV modules of 1.0 kW each manufactured by BP Solar, which was kept on the rooftop of the building at Warsaw in Poland for a period of one year. They monitored different parameters, i.e. DC and AC voltages, DC and AC currents, AC power, cumulated AC energy supplied to grid, daily AC energy production, utility grid impedance, solar irradiance on a horizontal plane, irradiance on the PV array, ambient temperature, PV module temperature and wind velocity. They plotted the graph for output power versus solar irradiance and found that the power output increases linearly with the irradiance as shown in Fig. 39. Also the efficiency of the PV modules was found to be in the range of 4–5%, while it was observed to be slightly higher, i.e. around 6% under the standard test condition (STC), which is an obvious case in most of the application of the experimental devices. As a result, the production of energy was found to be around 830kWh during the period of first year operation which is also found to be higher than that of the simulated result of the above mentioned installed PV system. Also the efficiency drop of the system may be due to some common reasons such as, high temperature of the module, low irradiation level and deposition of dust particles on the PV module.

Leloux et al. [162] presented a detailed review and analysis based on the operational data of 993 PV plants installed on the residential buildings in Belgium following three key approaches i.e. the level of energy production, the level of performance and the key parameters which influence the quality of such plants. After the analysis, they found that the optimally oriented PV system produces a mean annual energy of around 892 kWh/kWp for the middling commercial plant, as can be seen from Fig. 40. It is also found that the optimally oriented PV systems can produce around 6% more energy as compared to that of the generally orientated PV generators as a whole. The mean performance ratio was found to be of 78%, while the mean performance index was found to be of 85%. It is also found that on an average, the real power of the PV modules falls around 5% below the corresponding nominal power mentioned by the manufacturers on their datasheet. In some of the cases, the difference between the real and nominal power was observed up to 16%. Finally, it was concluded from this study that the energy produced by a typical PV system in Belgium is around 15% inferior to the energy produced by a very high quality PV system.

Another study was performed on the energy production in France [163] during the year 2010 by the same group exhibits that 78% of the installed PV systems are made from classic crystalline silicon, 17% are from of HIT, 2% are from amorphous silicon, 2% are from made of CIS and another 2% are made from CdTe, while the total annual energy production was found to be around 1163 kWh/kWp. They concluded that in general, the energy produced by a typical PV system in France is around 15% inferior to the energy produced by a very high quality PV system at the same location, which is also found to be similar to that of the Belgium case, mentioned above. Again, the real power of the PV modules was found to be around 4.9% below than that of the corresponding nominal power mentioned on the manufacturer's datasheet on an average. Also the PV systems equipped with heterojunction with intrinsic thin layer (HIT) modules exhibit the higher performance than the average vale, while on the other hand, the systems equipped with the copper indium (di)

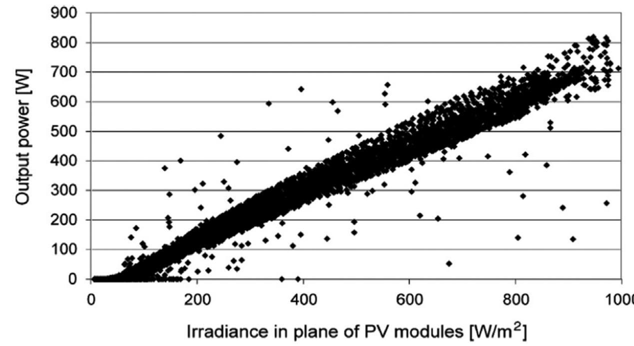

Fig. 39. Output power vs. irradiance for August 2001 [161].

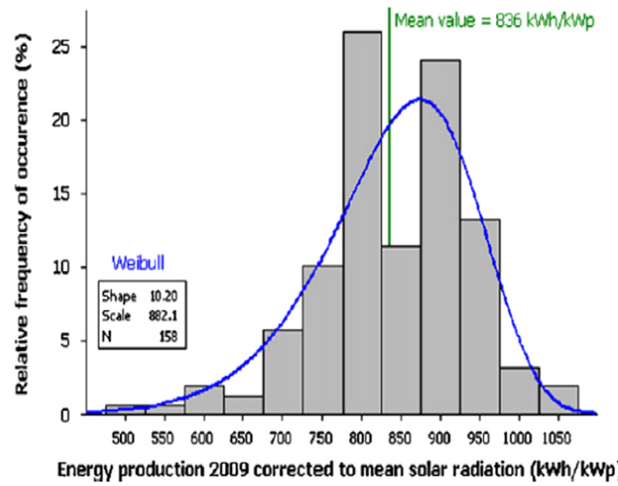

Fig. 40. PV systems production in 2009 [162].

selenide (CIS) modules exhibit around 16% lower real power than that of their nominal values.

Sastry et al. [164] conducted a performance study and quality of on mono crystalline PV module after being exposed to the outdoor environment for around ten years continuously at a typical location in northern part of India. They tested more than thirty five different types of PV modules supplied by more than different eleven manufacturers and the photographic view of the outdoor test bed at Solar Energy Centre (Gurgaon) India is shown in Fig. 41.

Out of total thirty five modules, thirty modules were installed outdoor, while another four modules were kept a spare and one model was used as a reference module. As usual, the voltages, current and power output from PV are the parameters that have been taken into account here just like other project and all the PV modules were grouped under certain category. Based on their analysis, it was observed that after ten years in continuous use, the power output from group 1 and 2 degraded by 10%, while for group 3 and 4 it was found to be lower by 28% on an average, as can be seen in Fig. 42.

Sasitharanuwat et al. [165] evaluated the performance of a 10 kWp PV system for an isolated building in Thailand for a period of 6 months. The system was comprised of an array having three different types of PV modules consisting of amorphous thin film of 3672 W, polycrystalline solar cell of 3600 W and the hybrid solar cell of 2880 W, respectively and making up a total peak power of 10.152 kW. After studying the system for six month continuously, they found that all the components and the system performed effectively and generated about 7852 kWh of energy with an average daily production of 43.6 kWh. The average efficiency of the amorphous thin film panel, polycrystalline panel, hybrid solar cell panel and entire PV panel system was found to be 6.26%, 10.48%, 13.78% and 8.82%, respectively. A performance study for 120 kWp PV system

Fig. 41. PV system setup [164].

using poly crystalline type PV module installed at SRET, Naresuan University, Thailand was also done by Chimtavee et al. [166]. In this study, the data on irradiation, module temperature, voltage, current and power has been monitored from November 2008 to October 2009 and results for energy output and efficiency are given in Fig. 43. The result exhibits that the high solar radiation on an average of 5.50 kWh/m² was received during the winter and summer seasons, while during rainy season it was around 4.81 kWh/m² on an average per day. On the other hand, the efficiency of the module was found to be 11.66% and 11.81% during the winter and summer season, respectively.

Rustu and Huseyin [167] analyzed the performance of a multi crystalline Si PV module on monthly, seasonal and annual basis under the climatic conditions of Mugla in Turkey. The data during the monitored period from the site showed that the annual total PV module plane of array or in-plane (POA) irradiance, electricity generation and the average efficiency of the module were found to be 1963.90 kWh/m^2, 182.83 kWh and 9.54%, respectively. The monthly total generated electricity of the PV system was found to be varying between 78.47 kWh/kWp during the month of December to 206.19 kWh/kWp during the month of August, while the total annual generated electricity was found to be 1741.24 kWh/kWp.

Ying Ye et al. [168] studied the outdoor performance of PV module for tropical climatic condition like Singapore where more than half of the irradiance is classified as the fluctuating irradiance. The data was collected with the fluctuating irradiance between high and low irradiance using typical meteorological day (TMD) irradiance data as the base. The monitored data of five different PV module technologies over a period of one year starting from January to December in 2011 was used to study the performance of different PV module technologies including the short-circuit current, module temperature and average efficiency under the fluctuating irradiance. In this study, the average efficiency of mono c-Si modules was found to be affected mainly by the module temperature, while the efficiency for a-Si thin-film modules showed a much stronger dependency on the irradiance level than that of the fluctuations in the radiation and/or the module temperature. Also the micromorph Si module showed similar characteristics as mono c-Si for high irradiances including temperature dependency having a lower efficiency for low irradiances, which has possibly caused by the internal current mismatch between the bottom and top cells. The method proposed in the study allows a deeper insight into the dependence of module performance on the fluctuating irradiance conditions, which is very important, especially for the tropical regions where the radiance exhibits the high level of variability.

So et al. [169] conducted performance analysis of 3 kW PV modules for one year in which 2 modules are made from the mono crystalline silicon cell and another 2 modules are made from the poly crystalline silicon cell. All the PV modules were installed at Field Demonstration Test Center in Korea during November 2002 until October 2003. They monitored different parameters including the voltage and current for AC and DC, irradiation and the temperatures for ambient and PV panels, while the monthly power output for every PV system is shown in Fig. 44. From Fig. 44, it is seen that all the PV modules exhibit a drop in energy output during January due to snow fall and during July due to cloudy weather and the conversion efficiency for all the systems was found between 9.2% and 10.1%. This study also indicated that the power output from the PV module strongly depends on the ambient temperature, irradiation level, dust level of environment and shading of PV module, the overall, PR for every PV system in this study was found to be between 63.3% and 75.1%.

The performance evaluation of a 5.28 kW off-grid photovoltaic system in Saudi Arabia was carried out by Rehman and El-Amin [170] by collecting the experimental data for PV panel surface temperature, solar radiation and power output with the help of sensors and data loggers. They studied impact of the effect of PV surface temperature and dust collected on the panels for the power output of individual arrays and total power from complete plant. The result showed that the hourly mean energy yield was found to be decreasing with increasing the surface temperature of the PV panel during the months of July and August. The daily energy yield also showed a decreasing trend with days of the month which could be accounted for dust accumulation on the PV panel surface.

The study of a grid connected PV system was carried out by Li et al. [171] in Hong Kong by systematically recording and analyzing the technical data including the available solar radiation and the output energy. In this study the PV modules covering the total area of 6.75 m^2 were tilted by 23° and the performance was elaborated in terms of energy, environmental and financial aspects. After the evaluation of experimental data, it was found that the monetary payback period (MPBP) for the PV system is of 72.4 years, if the electricity buying price is equal to the electricity selling price. If carbon trading was considered, the payback period was shortened to be of 61.4 years. The embodied energy payback period (EEPBP) was estimated to be 8.9 years, while the average conversion efficiency of the system for 2 years was found to be 11.9%, whereas the graph of energy output for twelve months is shown in Fig. 45. They concluded that these findings would be very useful for planning the grid connected PV installations and are applicable for other places having similar architectural layouts.

Elhodeiby et al. [172] conducted a performance analysis of a 3.6 kW grid connected thin film PV system in Cairo, Egypt by monitoring the system for a complete year starting from Jan 2010 until Dec 2010. Total 90 PV numbers of modules were installed on the roof of renewable energy shop in Cairo covering the total area of 70 m^2. The average energy generated from PV module is given in Fig. 46, while the PV system was installed at angle 35° facing south. It was found that the maximum irradiation of 7.1 kWh/m^2/day was received in the month of June, while the minimum irradiation received was of 4 kWh/m^2/day in the month of December. The highest system efficiency was observed to be of 4.8% in the month of January and the average efficiency for the whole year was found to be of 4.02%, while the average efficiency for PV only was found to be of 4.22%. They concluded that the cumulative energy produced is higher than that of the simulation based energy production with a total of 5712.25 kWh which is due to the fact that the availability of higher solar irradiation has helped in optimizing the power output from PV even with the higher ambient temperature and lower wind velocity.

Ayompe et al. [173] performed a study on 1.72 kW PV system in at a typical location of Dublin in Ireland with latitude and longitude of 53.4°N and 6.3°E, respectively, by monitoring the system for a

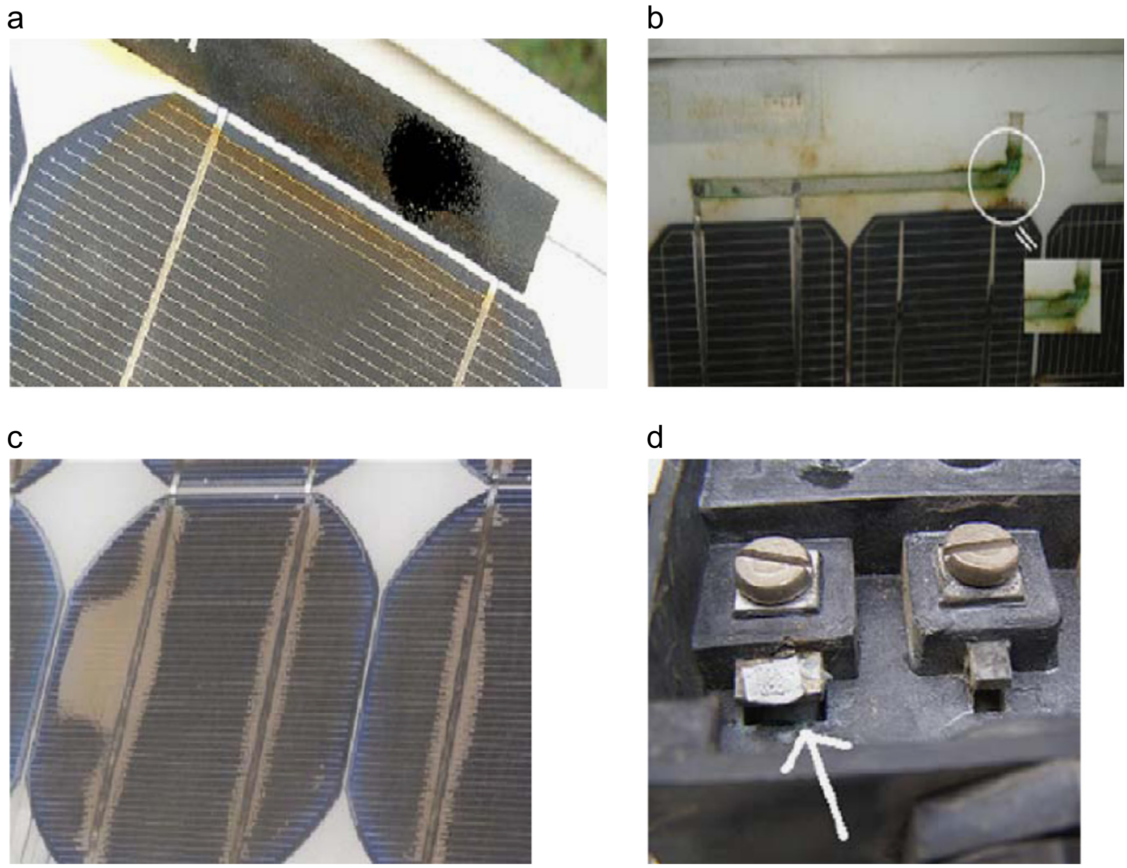

Fig. 42. Defects in PV module after long term outdoor performance [164].

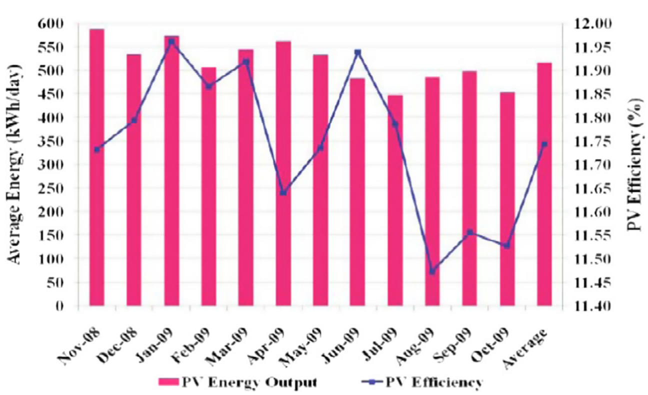

Fig. 43. Energy output and efficiency result [166].

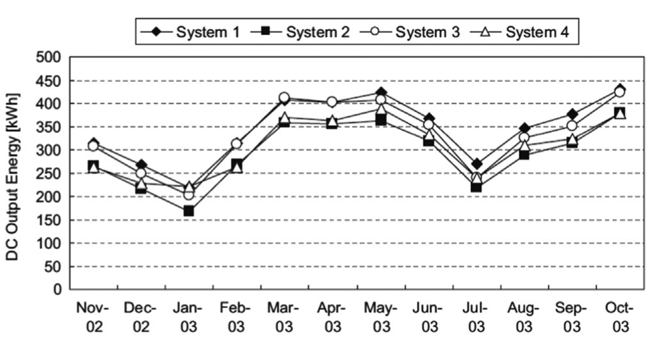

Fig. 44. Monthly output energy from PV system [169].

year during November, 2008 to October, 2009. Total eight PV modules made from mono crystalline silicon and manufactured by Sanyo [country] were used in this project were installed on 12m high building tilted at 53°, while the efficiency of the modules was found to be 17.2% under standard test condition (STC). The PV is. From the results, the maximum energy generated was found to be in the month of May and June due to the availability of the higher irradiation during these months, while the lowest energy generated was found to be in the month of December due to higher wind speed and lower irradiation, whereas the performance study is shown in Fig. 47. The annual total energy generated was found to be of 885.1 kWh/kWp, while the annual average daily final yield, reference yield and array yield were found to be 2.41 kWh/kWp/day, 2.85 kWh/kWp/day and 2.62 kWh/kWp/day, respectively. The annual average daily PV module efficiency, system efficiency and inverter efficiency were found to be 14.9%, 12.6% and 89.2% respectively, while the annual average daily performance ratio and capacity factor were found to be 81.5% and 10.1%, respectively.

Jo et al. [174] studied the utility-scale grid connected solar photovoltaic systems and the optimum amount of solar PV energy generation for the state of Illinois in USA. They found that the overall electrical generation from the installed PV systems at the level of the current solar carve out of 6% of the state's RPS would be fully utilized and none would be wasted. By dividing the state into two different regions based on the existing power utilities in the state, PJM and MISO, and taking into account the data on their respective weather patterns, they estimated the regional potential more accurately. The solar carve-out of 6% for the PJM region was found to be close to the level at which the generated electricity can be fully utilized. For the MISO region, it was found to be of 7.2% to reflect a 100% utilization potential of the solar PV systems.

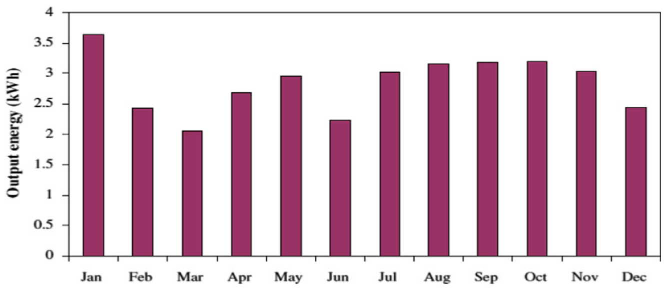

Fig. 45. Output energy for 12 months [171].

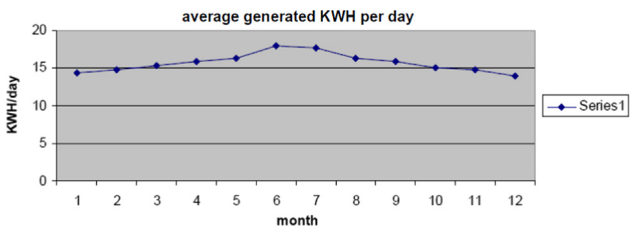

Fig. 46. Averaged energy generated from PV module [172].

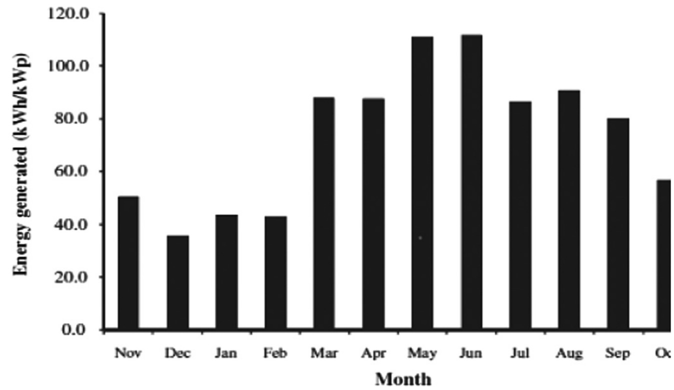

Fig. 47. PV performance in Dublin [173].

Fig. 48. PV module configuration [176].

Similar performance and economical analysis of grid-connected photovoltaic systems in Daegu, South Korea was carried out by Kim et al. [175]. They performed for two plants one system at Dongho elementary school was of 25,848 kWh and the other system at Osan building was of 40,094 kWh. The annual power generation efficiency of each photovoltaic system was found to be of 10.8% for Dongho elementary school, whereas for Osan building it was found to be of 13.8% higher than the former. The Osan building system showed a better economic efficiency as the unit power production cost of the photovoltaic system was $0.824/kW for Dongho Elementary School and $0.531/kW for the Osan Building. The different PV module performance was also presented by Ueda et al. [176] for a grid connected residential area in Japan for various configurations of the PV system including single-array-oriented south, multiple array-oriented south and/or east and/or west and arrays not oriented south. The objective of this project was to analyze the performance and loss for different configurations as shown in Fig. 48 and compare them with one another by collecting the data during July 2006 to June 2007. The parameters that have been looked into are the temperature, power output, current, voltage and irradiation. From the study, they concluded that the south oriented configuration produced around 11–22% more power as compared to the other configurations, mentioned above.

Hajiah et al. [177] carried out the performance study of grid-connected PV system for the two different sites namely, Al-Wafra and Mutla in Kuwait by collecting meteorological data for three years and analyzed the 100 kWp grid-connected PV system proposed for both sites. The proposed systems showed the higher energy productivity, whereas the annual capacity factors for Mutla and Al-Wafra were found to be of 22.25% and 21.6%, respectively. Also the annual yield factors for Mutla and Al-Wafra were found to be of 1861 kWh/kWp/year and 1922.7 kWh/kWp/year, respectively. On the other hand, the cost of the energy generated by both systems was found to be of about 0.1 USD/kWh which is very close to the price of the energy sold by the Ministry of Electricity and Water (MEW) in Kuwait. Furthermore, it was also found that the invested money could be recovered during the assumed life cycle time, whereas the payback period for both sites was found to be about 15 years. Mondol et al. [178] presented the long term comparative study for grid connected PV system using TRNSYS simulation tool. Over the simulation period, the average monthly errors between measured and predicted PV output before and after the modification of the TRNSYS model were found to be of 10.2% and 3.3%, for the isotropic sky model and 15.4% and 10.7% for the anisotropic sky model, respectively. The predicted PV performance parameters were found to be in good agreement with the measured parameters during the high insolation months, but for the low insolation months, the deviation was found to be larger. The predicted parameters differed by 1–2% for an isotropic and an anisotropic tilted surface radiation models. The results showed that the relationships developed using long term performance data improved the accuracy of the simulation model.

The performance of the 500 kW grid connected photovoltaic system in Son Province, of Thailand was carried out by Chokmaviroj [179]. The system consists of a photovoltaic array having 1680 modules (140 strings, 12 modules, 300 W/module) with power conditioning units and battery converter system. During the first eight months of the operation, the PV system generated about 383,274 kWh of energy with an average production of 1695.9 kWh ranging from 1452.3 to 2042.3 kWh per day. The efficiency of the PV array system was found ranging from 9% to 12%, while the efficiency of the power conditioning units (PCU) was found to be in the range of 92 to 98%. A pilot PV grid-connected system rated at 36 kWp has been designed and studied by Al-Sabounchi et al. [180] at the Abu Dhabi distribution network. The performance of the system was evaluated in terms of power and energy production, conversion efficiency, consistency of voltage and frequency, along with the impact of ambient temperature under the actual weather conditions. Additionally, the influence of accumulated dust deposition on the production of the PV array has been also evaluated. The evaluation showed consistent operation of the system with a moderate conversion efficiency even with the higher ambient temperatures at the site. However, the dust deposition on the glazing of PV modules was found to seriously degrading the performance of the PV system. They found that the highest reduction up to 27% in power production was recorded during the month of July due to the accumulated dust deposition. This may lead to a conclusion that, for a reasonable amount of PV power production in the climate of Abu Dhabi, it is appropriate to perform a monthly cleaning of the surface of the PV modules.

Mondal and Islaml [181] studied the potential and viability of grid-connected 1.0MW solar PV generation plant in Bangladesh. The estimation of the potential of power generation of gird-connected solar PV in Bangladesh was about 50174 MW. They found that the annual electricity generation of the proposed solar PV system varies between a minimum of 1653 MWh/year at Barisal with a maximum of 1844 MWh/year at Dinajpur. The per unit electricity production cost from the system was found to be varying from 13.25 to 17.78 BDT which is quite competitive with grid-connected fuel-oil based power generation of around 15 to 18 BDT per unit. If clean development mechanisms (CDM), carbon tax, and oil price fluctuation are taken into consideration, the unit cost would be lower than that of the grid connected fuel-oil based power generation. Also condition was found to be favorable based on all economic indicators for the development of the proposed 1.0 MW grid-connected solar PV system in Bangladesh.

Paudel and Sarper [182] presented the economic analysis of a 1.2 MW capacity grid-connected photovoltaic power plant installed at the Colorado State University, Pueblo in USA. The project was commissioned by a regional utility company as per the renewable energy portfolio standards guidelines of the state. The system was installed on the customer's property funded by a third party investor who will receive the tax credits and rebates in addition to the monthly revenue from the energy sales. After the performance of the PV system analysis, the amount of energy generation and project investment costs and revenues, suitability etc. shows the IRR of the project is around 10.7% for the given tax credits and rebates. For the favorable condition of PV project installation, at least 4% tax credit is required to have a breakeven of the project. The first zero-energy office building in Singapore uses photovoltaics to meet its energy target. Wittkopf et al. [183] studied the 142.5 kWp grid-connected rooftop PV system to meet the zero energy building system in Singapore. The analysis is based on the eighteen months of operation which is the guidelines of the IEC standard 61724 for measurement, data exchange and analysis. The performance analysis showed the good overall performance ratio of 0.81 and the overall inverter efficiency of 94.8%. The system and array efficiencies were found to be of 11.2% and 11.8%, respectively, as compared to the nameplate PV module efficiency of 13.7%. They also studied for impact of shading, orientation/tilt, and PV module temperature.

The economic performance and policies for grid-connected residential solar PV system in Brazil was studied by Mitscher [184]. The analysis was done for economic competitiveness of grid-connected, distributed solar photovoltaic generation through small-scale roof top installations in five Brazilian state-capitals. The locations represent a comprehensive set of the two essential parameters for the economic viability of solar PV, irradiation and local electricity tariffs. The analysis comprises three different interest rate scenarios reflecting different conditions for capital acquisition to finance the generators; subsidized, mature market and country-specific risk-adjusted interest. Using the subsidized interest rates, the analysis showed that solar PV electricity is already competitive in Brazil, while in the country-specific risk-adjusted rate, the declining, but still high capital costs of PV make it economically unfeasible. They also demonstrated the high potential of distributed generation with photovoltaic installations in Brazil, and found that under certain conditions, the grid-connected PV can be economically competitive in a developing country, like Brazil.

5. Conclusions and recommendations

Based on the study summarized in this article, the following conclusions are drawn, while some recommendations are also made for the future research based on the conclusions, as given below:

5.1. Conclusions

This article presents the recent advances in solar photovoltaic systems for emerging trends and advanced applications and performance analysis of the solar photovoltaic systems. The recent developments in the research on different applications such as, water pumping, home lighting, space technology, building integrated PV systems, concentrated PV, desalination and photovoltaic thermal have been reviewed and presented. The PV/T, BIPV, desalination and CPV applications of solar PV are found to be most emerging applications and needs further R&D to make them economically competitive at the user end. Temperature enhancement in concentrating the light in CPV system is found to be major challenge. This increase in the temperature reduces the efficiency of the PV and hence degrades the performance of the overall PV system. Therefore, it is necessary to investigate other options of reducing the temperature of the CPV than conventional one. It is found that most of the study is on air or water as a medium at the back of the PV panel is currently being used for the regulation of temperature. Concentrated PV/T (CPV/T) systems may be an efficient option for harnessing heat and electricity at the same time particularly in the low solar radiation areas. The BIPV systems will play crucial role in the energy solution due to its bi-advantages such as electricity production and reduction in the material cost of the building. Because of the modular nature of solar PV systems, it is very useful for water pumping and home lighting, especially in the rural areas where grid connectivity is the problem. Solar PV desalination systems are found to un-economical and not commercialized yet, but shows good potential for providing fresh water for rural as well as urban areas in the coming time. Application of solar PV systems in the space is very old, however, needs further R&D in discovering new solar cell materials for the efficiency enhancement and hence a reduction in the area of the module. This paper would not only be useful for the researchers, academicians, manufactures, but also for policy makers.

5.2. Recommendations

After the rigorous literature review on different aspects of applications of solar PV systems, few PV systems such as PV/T, BIPV, CPV and PV powered desalination systems are found to be potential applications of PV and are capable of fulfilling the future energy solutions. Also, it is recommended to put more efforts in developing the PV/T and CPV systems having thermal energy storage and which can be commercialized as these are not commercialized yet. The BIPV being used in the buildings and require no extra space for the installation, which is a critical issue for the PV systems, can be focused more. Therefore, it is recommended to put on more R&D efforts in the efficiency improvement on PV/T, BIPV, CPV and PV powered desalination systems to make them not only technically but also economically competitive for real life applications.

Acknowledgments

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