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High Efficiency Concentrated Photovoltaic Solar Energy —A Promising Alternative Energy for the Arabian Gulf Climate

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ABSTRACT*: This report represents the final summary of a joint research project conducted on the proposed use of high efficiency concentrated photovoltaic solar cells for possible applications in desert-type climates such as the Arabian Gulf region. The report covers the various aspects of photovoltaic solar energy and compares the efficiency of the different techniques currently in use or soon will be introduced.*

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I. RESEARCH AIM

The current research focuses on the feasibility of utility-scale concentrated solar photovoltaics energy as an alternative and renewable energy source for the Arabian Gulf region. Through this study, the advantages and disadvantages of traditional photovoltaic (PV), concentrated photovoltaic (CPV), and high concentration photovoltaic thermal (HCPVT) are evaluated for utility-scale applications in regions with abundance of solar radiation such as the State of Kuwait. The technical as well as the economics factors for using such a promising technology are evaluated and recommendations to the appropriate authorities are made.

II. INTRODUCTION

Renewable energy sources are promising and effective way to address global warming and the increase in greenhouse gases emissions. In particular, solar energy has attracted much attention especially in regions where there is abundance of solar radiation. Many studies have been conducted on various photovoltaic (PV) cells in order to increase their efficiencies, which typically range from 15% to 20% for single-junction PV cells. Most recently, however, multi-junction PV cells have shown an increase in conversion efficiency of up to 40% using concentrated solar energy. Concentrated Photovoltaic (CPV) energy is one of the most effective ways of converting solar energy into electricity at the utility scale level.

Solar energy holds the potential to become a cost-effective source of energy in the near future[1]. There are two main pathways for harvesting solar energy: Solar Thermal and Solar Photovoltaic. Solar thermal collectors transform the solar radiation into heat that can be either stored for later use or directly fed to further conversion stages, while photovoltaic receivers (PV cells) can produce electricity directly from sunlight. Differently from thermal absorbers, which are able to capture the entire solar spectrum, PV cells have a fixed spectral response that depends intrinsically on the nature of the material. Semiconducting materials absorb photons having energies greater than the band gap: the band gap energy is partially transferred to useful electrical charge

carriers, while the excess energy is quickly dissipated as heat after carriers' thermalization[2,3]. On the other hand, photons with energies lower than the material band gap do not generate carriers and are often weakly absorbed. Given the wide spectral content of the sunlight (most of the power lies between 350 and 2000 nm, corresponding to a range of energies from 3.55 to 0.62 eV), a single material cannot efficiently generate electricity. Shockley and Queisser studied the theoretical limit of the efficiency of a single junction solar cell and found that the limit for a silicon PV cell under 1 sun illumination is approximately 30%[4]. Polman and Atwater calculated the energy losses due to thermalization and lack of absorption in a single junction solar cell and concluded that these two mechanisms account for at least 40-45% of the total losses[5]. Reducing these losses, even partially, could allow the development of solar cells with efficiencies above 50%.

2.1 First Generation Solar Cells, 1G

The first conventional photovoltaic cells were produced in the late 1950s, and throughout the 1960s were principally used to provide electrical power for earth- orbiting satellites. In the 1970s, improvements in manufacturing, performance and quality of PV modules helped to reduce costs and opened up a number of opportunities for powering remote terrestrial applications, including battery charging for navigational aids, signals, telecommunications equipment and other critical, low-power needs.

In the 1980s, photovoltaics became a popular power source for consumer electronic devices, including calculators, watches, radios, lanterns and other small battery- charging applications. Following the energy crises of the 1970s, significant efforts alsobegan to develop PV power systems for residential and commercial uses, both for stand- alone, remote power as well as for utility-connected applications. During the same period, international applications for PV systems to power rural health clinics, refrigeration, water pumping, telecommunications, and off-grid households increased dramatically, and remain a major portion of the present world market for PV products. Today, the industry's production of PV modules is growing at approximately 25 percent annually, and major programs in the U.S., Japan and Europe are rapidly accelerating
the implementation of PV systems on buildings and interconnection to utility networks.

2.1.1 How a Photovoltaic Cell Works

A typical silicon PV cell is composed of a thin wafer consisting of an ultra-thin layer of phosphorus-doped (N-type) silicon on top of a thicker layer of boron-doped (P-type) silicon.

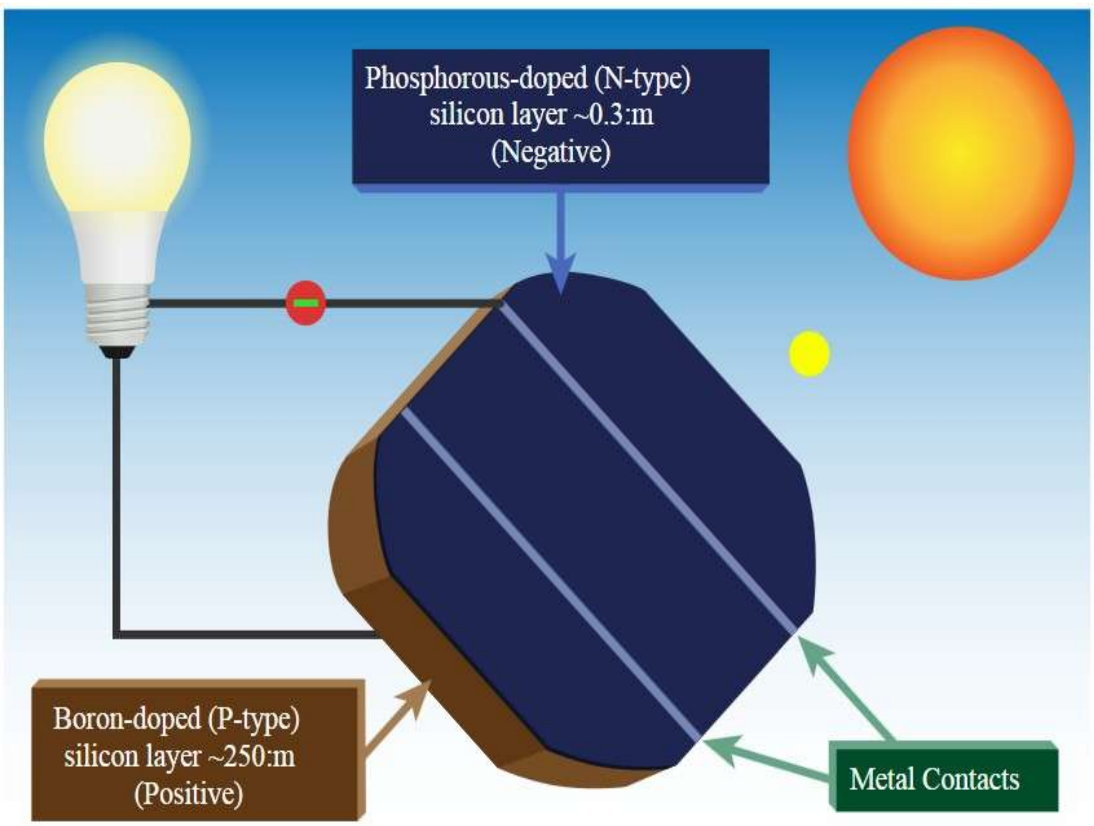

Figure 1. Diagram of a Photovoltaic Cell[6].

An electrical field is created near the top surface of the cell where these two materials are in contact, called the P-N junction. When sunlight strikes the surface of a PV cell, this electrical field provides momentum and direction to light-stimulated electrons, resulting in a flow of current when the solar cell is connected to an electrical load[6].

Regardless of size, a typical silicon PV cell produces about 0.5 – 0.6 volt DC under open- circuit, no-load conditions. The current (and power) output of a PV cell depends on its efficiency and size (surface area), and is proportional to the intensity of sunlight striking the surface of the cell. For example, under peak sunlight conditions, a typical commercial PV cell with a surface area of 160 cm^2 (~25 in^2) will produce about 2 watts peak power. If the sunlight intensity were 40 percent of peak, this cell would produce about 0.8 watts.

2.1.2 How Solar Cells are Connected

Photovoltaic cells are connected electrically in series and/or parallel circuits to produce higher voltages, currents and power levels. Photovoltaic modules consist of PV cell circuits sealed in an environmentally protective laminate, and are the fundamental building blocks of PV systems. Photovoltaic panels include one or more PV modules assembled as a pre-wired, field-installable unit. A photovoltaic array is the complete power-generating unit, consisting of any number of PV modules and panels.

The performance of PV modules and arrays are generally rated according to their maximum DC power output (watts) under Standard Test Conditions (STC). Standard Test Conditions are defined by a module (cell) operating temperature of 25o C (77o F), and incident solar irradiance level of 1000 W/m2 and under Air Mass 1.5 spectral distribution. Since these conditions are not always typical of how PV modules and arrays operate in the field, actual performance is usually 85 to 90 percent of the STC rating.

Today’s photovoltaic modules are extremely safe and reliable products, with minimal failure rates and projected service lifetimes of 20 to 30 years. Most major manufacturers offer warranties of 20 or more years for maintaining a high percentage of initial rated power output.

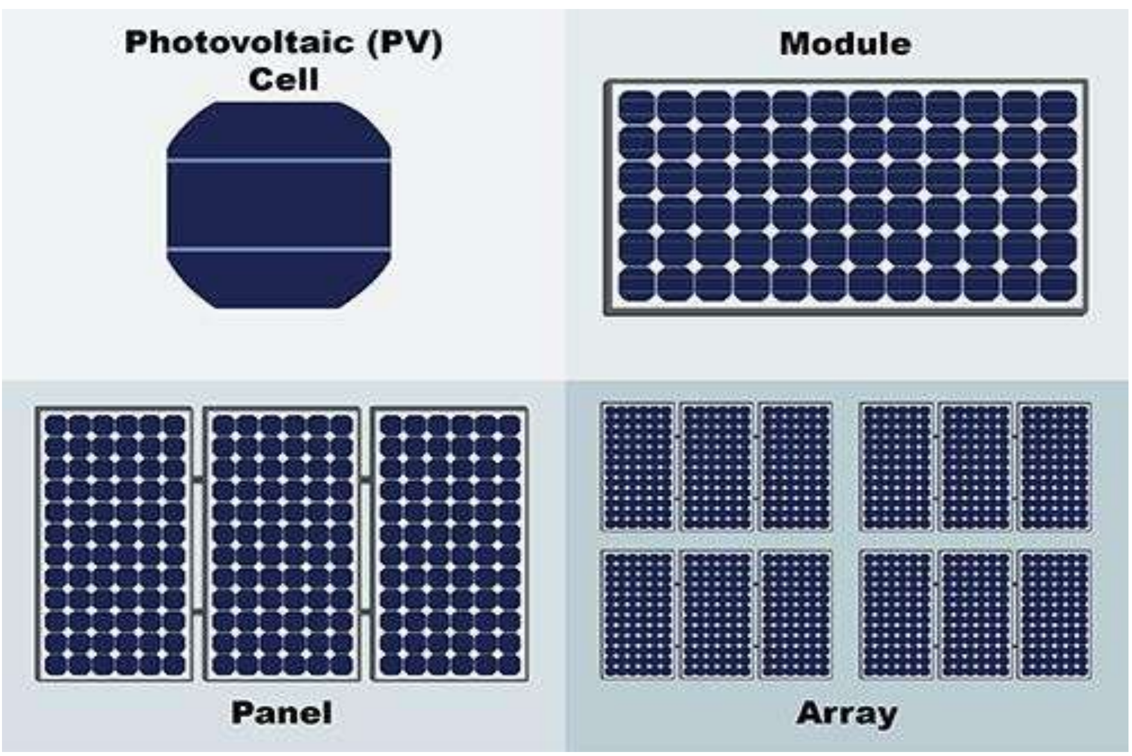

Figure 2. Photovoltaic cells, modules, panels and arrays[6].

2.1.3 Solar Photovoltaic Systems

PV systems are like any other electrical power generating systems, just the equipment used is different than that used for conventional electromechanical generating systems. However, the principles of operation and interfacing with other electrical systems remain the same, and are guided by a well-established body of electrical codes and standards.

Although a PV array produces power when exposed to sunlight, a number of other components are required to properly conduct, control, convert, distribute, and store the energy produced by the array. Depending on the functional and operational requirements of the system, the specific components required may include major components such as a DC-AC power inverter, battery bank, system and battery controller, auxiliary energy sources and sometimes the specified electrical load. Inaddition, an assortment of balance of system (BOS) hardware, including wiring, overcurrent, surge protection and disconnect devices, and other power processing equipment. Figure 3 show a basic diagram of a photovoltaic system and the relationship of individual components. Batteries are often used in PV systems for the purpose of storing energy produced by the PV array during the day, and to supply it to electrical loads as needed (during the night and periods of cloudy weather).

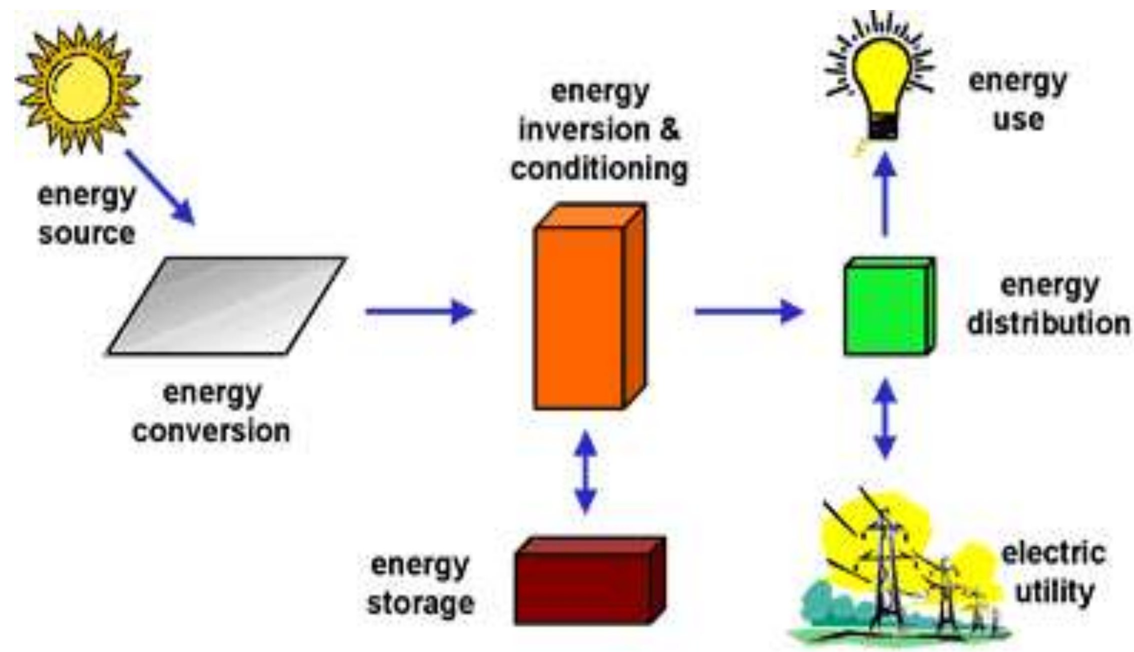

Figure 3. Major photovoltaic system components[6].

Other reasons batteries are used in PV systems are to operate the PV array near its maximum power point, to power electrical loads at stable voltages, and to supply surge currents to electrical loads and inverters. In most cases, a battery charge controller is used in these systems to protect the battery from overcharge and over-discharge.

Photovoltaic power systems are generally classified according to their functional and operational requirements, their component configurations, and how the equipment is connected to other power sources and electrical loads. The two principal classifications are grid-connected or utility-interactive systems and stand-alone systems. Photovoltaic systems can be designed to provide DC and/or AC power service, can operate interconnected with or independent of the utility grid, and can be connected with otherenergy sources and energy storage systems. Grid-connected or utility-interactive PV systems are designed to operate in parallel with and interconnected with the electric utility grid. The primary component in grid-connected PV systems is the inverter, or power conditioning unit (PCU). The PCU converts the DC power produced by the PV array into AC power consistent with the voltage and power quality requirements of the utility grid, and automatically stops supplying power to the grid when the utility grid is not energized. A bi-directional interface is made between the PV system AC output circuits and the electric utility network, typically at an on-site distribution panel or service entrance. This allows the AC power produced by the PV system to either supply on-site electrical loads, or to back-feed the grid when the PV system output is greater than the on-site load demand. At night and during other periods when the electrical loads are greater than the PV system output, the balance of power required by the loads is received from the electric utility This safety feature is required in all grid-connected PV systems, and ensures that the PV system will not continue to operate and feed back into the utility grid when the grid is down for service or repair.

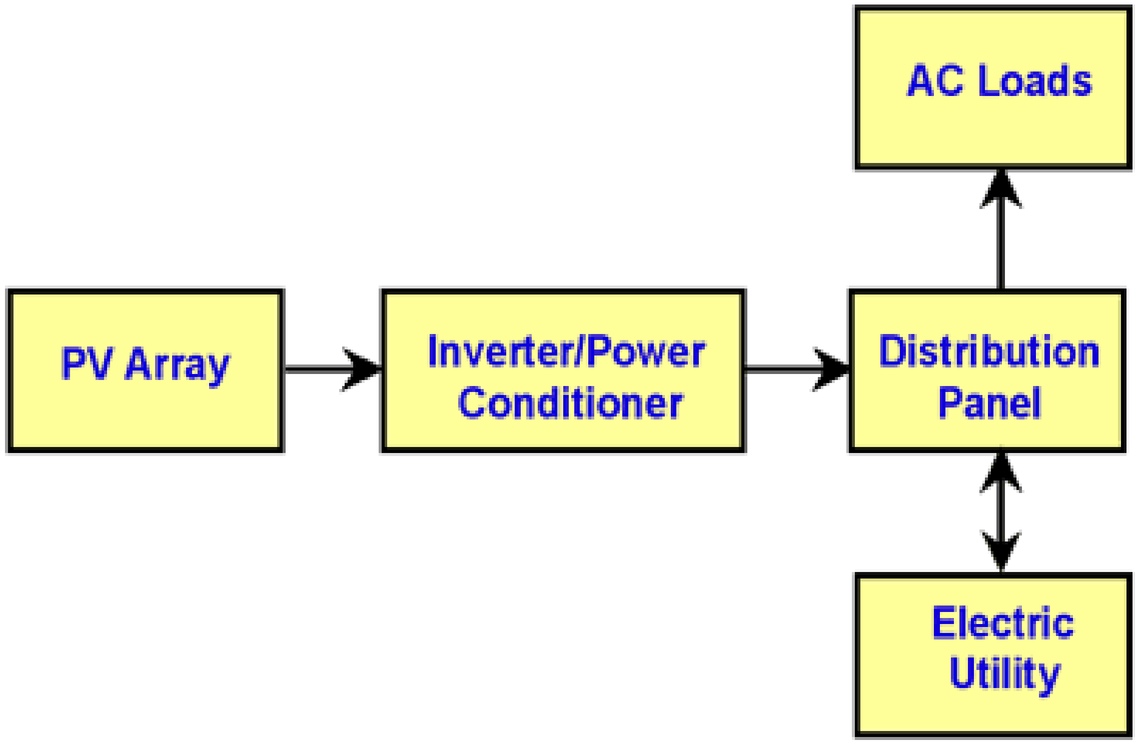

Figure 4. Diagram of Grid-Connected Photovoltaic System[6].

2.1.4 Stand-Alone Photovoltaic Systems

Stand-alone PV systems are designed to operate independent of the electric utility grid, and are generally designed and sized to supply certain DC and/or AC electrical loads. These types of systems may be powered by a PV array only, or may use wind, an engine- generator or utility power as an auxiliary power source in what is called a PV-hybrid system. The simplest type of stand-alone PV system is a direct-coupled system, where the DC output of a PV module or array is directly connected to a DC load (Figure 5). Since there is no electrical energy storage (batteries) in direct-coupled systems, the load only operates during sunlight hours, making these designs suitable for common applications such as ventilation fans, water pumps, and small circulation pumps for solar thermal water heating systems. Matching the impedance of the electrical load to the maximum power output of the PV array is a critical part of designing well- performing direct-coupled system. For certain loads such as positive-displacement water pumps, a type of electronic DC-DC converter, called a maximum power point tracker (MPPT), is used between the array and load to help better utilize the available array maximum power output.

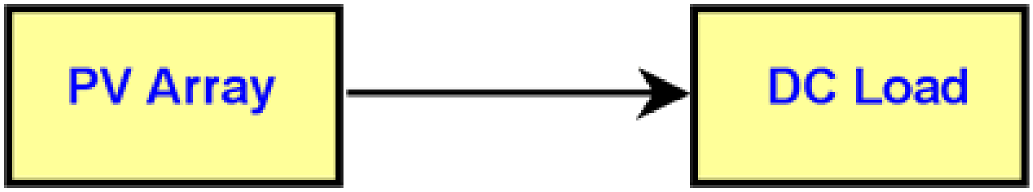

Figure 5. Directly-Coupled PV System[6].

In many stand-alone PV systems, batteries are used for energy storage. Figure 6 shows a diagram of a typical stand-alone PV system powering DC and AC loads.

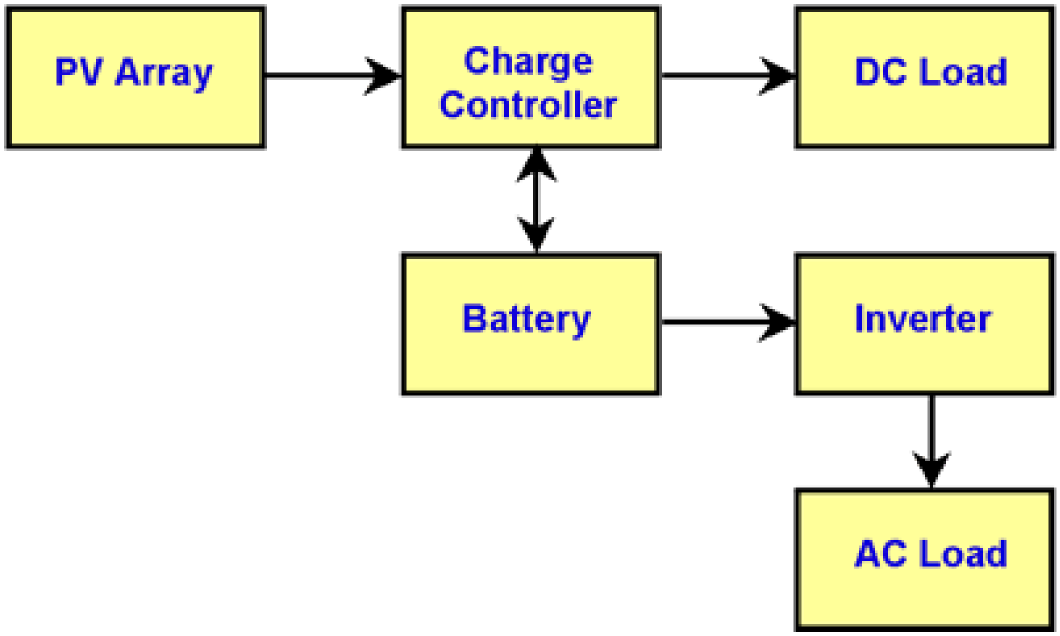

Figure 6. Diagram of a Stand-Alone PV System with Battery Storage Powering DC and AC loads[6].

Figure 7 shows how a typical PV hybrid system might be configured.

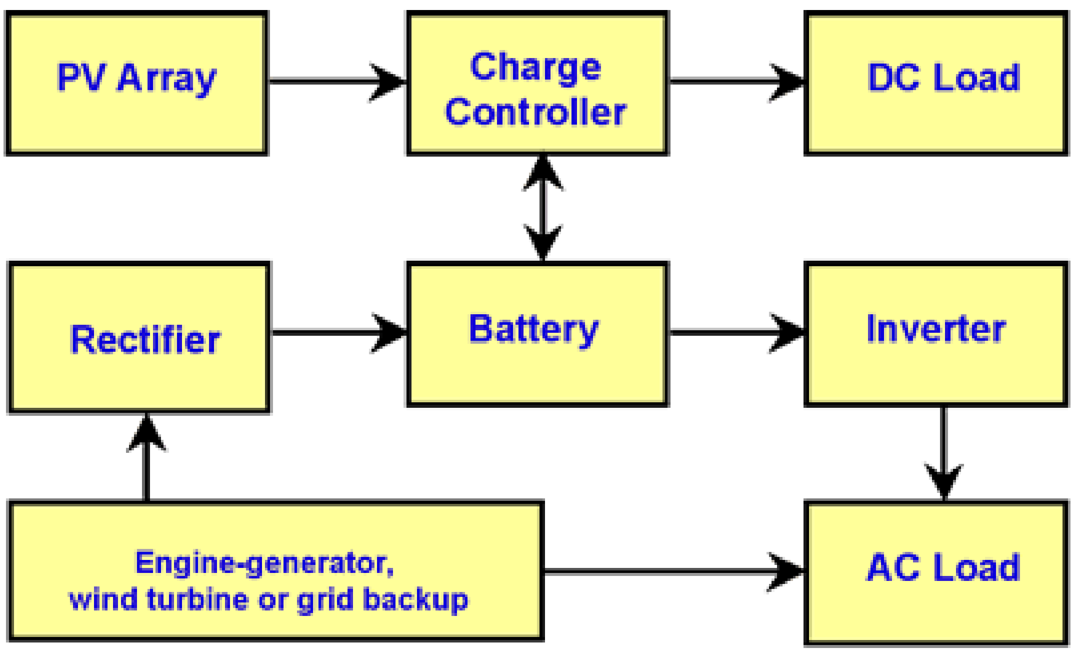

Figure 7. Diagram of a Typical Photovoltaic Hybrid System[6].

Photovoltaic systems operate normally in grid-connected mode but simple modifications can be made to operate critical loads when utility service is disrupted. Inthis case, battery storage must be used. This type of system is extremely popular for homeowners and small businesses where a critical backup power supply is required for critical loads such as refrigeration, water pumps, lighting and other necessities. Under normal circumstances, the system operates in grid-connected mode, serving the on-site loads or sending excess power back onto the grid while keeping the battery fully charged. In the event the grid becomes de-energized, control circuitry in the inverter opens the connection with the utility through a bus transfer mechanism, and operates the inverter from the battery to supply power to the dedicated loads only. In this configuration, the critical loads must be supplied from a dedicated sub panel. Figure 8 shows how a PV system might be configured to operate normally in grid-connected mode and also power critical loads from a battery bank when the grid is de-energized.

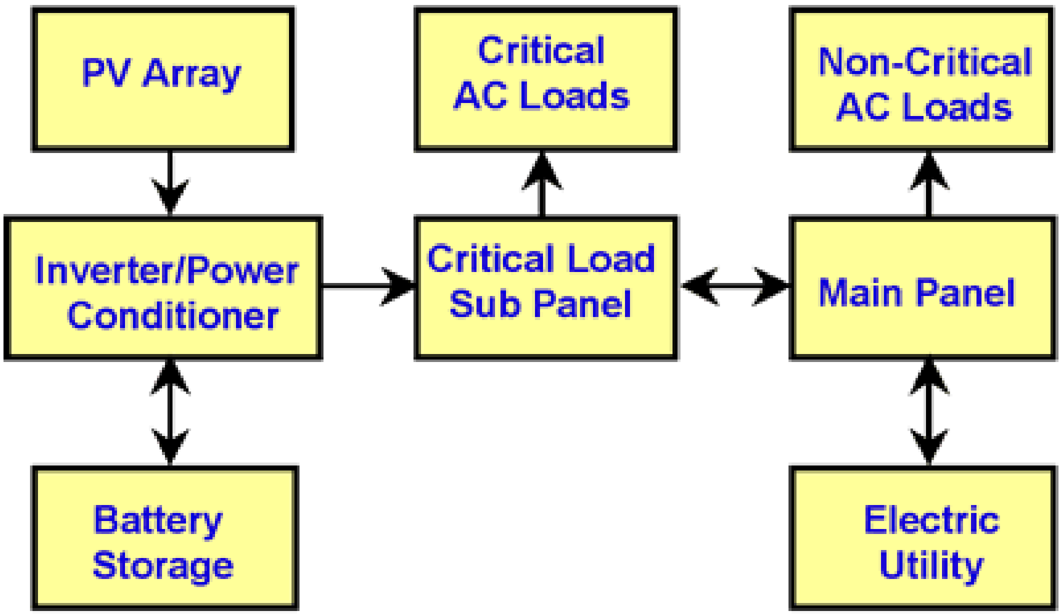

Figure 8. Diagram of a Grid-Connected Critical Power Supply System[6].

2.2 Second-Generation Solar Cells, 2G

The second-generation solar cells, 2G, were developed with the aim of reducing the high costs prevalent in the first generation through the utilization of thin film technology; the idea being to save on bulk material cost with a significant reduction in the quality and quantity of the material used and the challenge of increasing the thin film absorption to compensate for the reduced thickness in the photoactive layers. This second generationthin film technology was based on PV materials identified during the development of 1G PVs and was extended to include amorphous or polycrystalline Si, CIGS, and CdTe. While the 2G PV family addresses the cost issues associated with thick films, the performance of such 2G solar cells is known to be poor compared to their 1G counterpart. Therefore, the challenge was to improve the efficiency as much as possible within the inexpensive material envelope that encouraged the chemical vapor deposition of thin films and thermal crystallization, where appropriate.

In the case of amorphous materials, to compensate for the significantly reduced active volume, an intrinsic layer was grown to produce p–i–n devices where photo-generated carriers could be swept to the doped materials by the built-in field.

Figure 9. Second Generation Solar Cells, 2G[7].

The key factor that worked in favor for 2G PV cells was the cost per watt delivery but the need for extended surface areas to compensate for the lower efficiency was an issue.
This in turn pushed the development of the third-generation (3G) solar cells, including nanocrystalline films, PVs based on active quantum dots, tandem or stacked multilayers of inorganics based on III–V materials such as GaAs/Ge/GaInP2, or novel device concepts such as hot carrier cells where the aim was to obtain higher performance than their 2G counterparts, at a lower cost. These cells were known as Plasma EnhancedChemical Vapor Deposition (PECVD). In this generation, four types of solar cells were introduced, including the amorphous silicon cells which can be deposited over large areas with the help of PECVD. Their band gap was about 1.7 eV and function was similar to c-SI. Polycrystalline silicon, made of pure silicon grains, works better than the previous designs because of their mobility. These can be easily moved over a large magnitude. Cadmium telluride (CdTe) cells are formed with cadmium and tellurium mixed with zinc cubic crystal structure. This material is cheaper than silicon but not as efficient as silicon. Copper indium gallium diselenide (CIGS) alloy cells are deposited on glass or stainless steel and are a complex model. Their band gap is about 1.38 eV.

2.3 Third-Generation Solar Cells, 3G

Thereafter began a true race to design materials at the nanoscale and scale-up to the macroscopic areas. For the first time, significant attention was paid to the charge and energy transfer processes and the respective routes to optimize charge collection, thereby enhancing the energy capture within the solar spectrum. With the introduction of organic materials exhibiting photovoltaic properties, their potential for low cost and high optical absorption placed them as a 3G technology. In addition to organic (or polymer) solar cells, another candidate that grew to dominate 3G PV technologies is dye or semiconductor sensitized solar cells (DSSCs). Despite the reasonable success of 3G cells, significant improvements in device performances are required if this technology is to be competitive with the previous PV generations in terms of cost per watt. This generation was very different from the previous one due to the use of innovative semiconductors. The various types of solar cells introduced in this generation, include Nanocrystal solar cells, Photo-electrochemical (PEC) cells, Gräetzel Cell, Dye- sensitized hybrid solar cells, and Polymer solar cells.

Nanocrystal solar cells were based on silicon substrate with coating of nano-crystals. A thin film of nano-crystals is used along with it which was obtained by the process of spin coating. They create a higher potential for solar cells. PECs were second on the list and consisted of a semiconducting photo-anode. It works best with electrons and can also separate non-salacity of semi- conductors. Gräetzel cells were dye sensitized and usedphotoelectrons to increase power efficiently. Dyes were made of metal organic complex and its molecules are hit by increasing heat. The polymer solar cells were the last invention of this generation; they were lightweight, inexpensive, flexible, and disposable at any molecular level. They have little negative impact on the environment. In turn, these 3G cells offer significant cost improvements on first and second

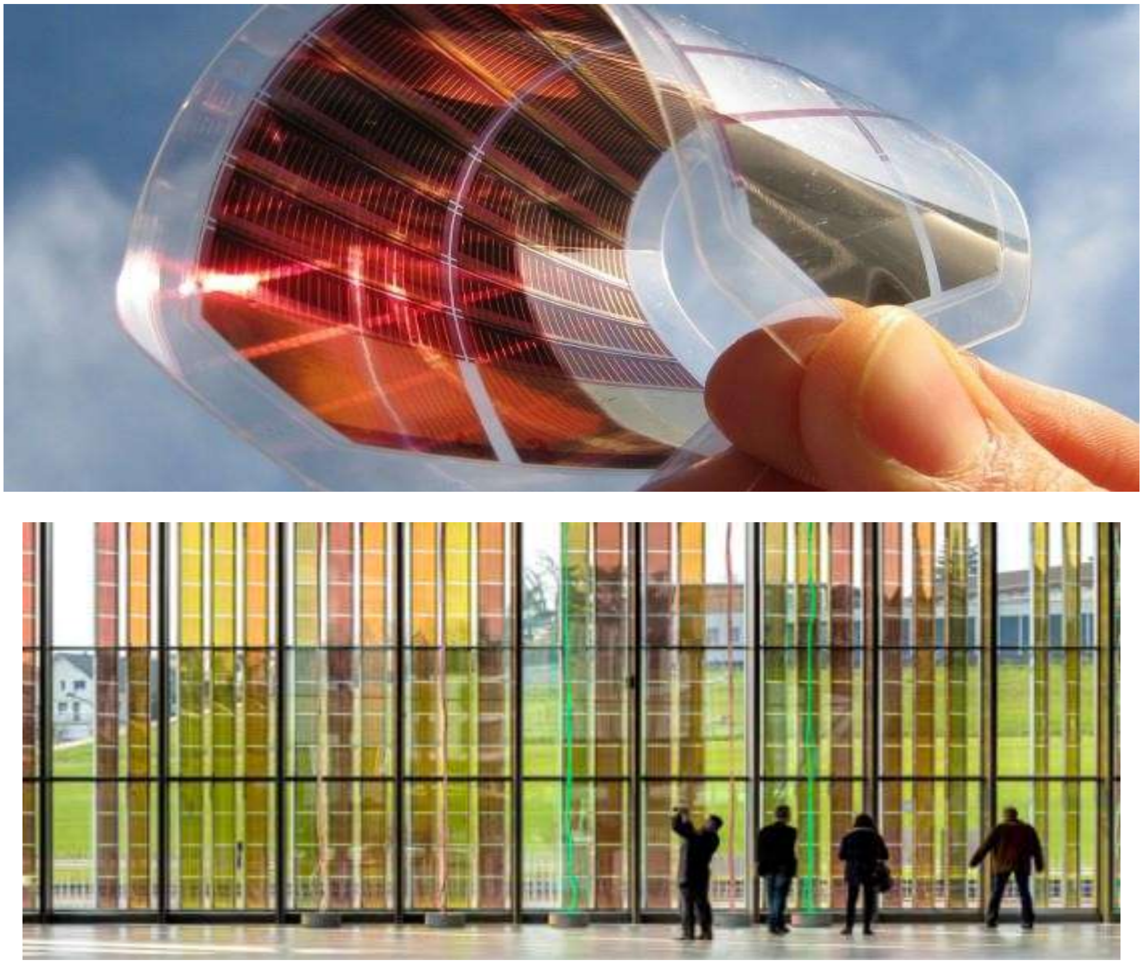

Figure 10. Third Generation Solar Cells, 3G[8].

generation solar cells—based on crystalline and polycrystalline silicon—which are still responsible for over 90 per cent of the solar power being generated today.

2.4 Fourth-generation Solar Cells, 4G

The fourth generation (4G) of PV technology, which combines the low cost/flexibility of polymer thin films with the stability of novel inorganic nanostructures was introduced with the aim of improving the optoelectronic properties of the low-cost thin film PVs. These device architectures are meant to maintain the inexpensive nature of a solution- processable PV device structure; but incorporate inorganic components to improve on energy harvesting cross-sections, the charge dissociation, and charge transport within the PV cells. While the previously introduced mesoscopic solar cells may be considered as a 4G technology due to the incorporation of an inorganic component (usually titania), especially when combined with a polymer or organic layer as a solid-state DSSC, this inorganic component is a requirement for the functionality of the cell and does not

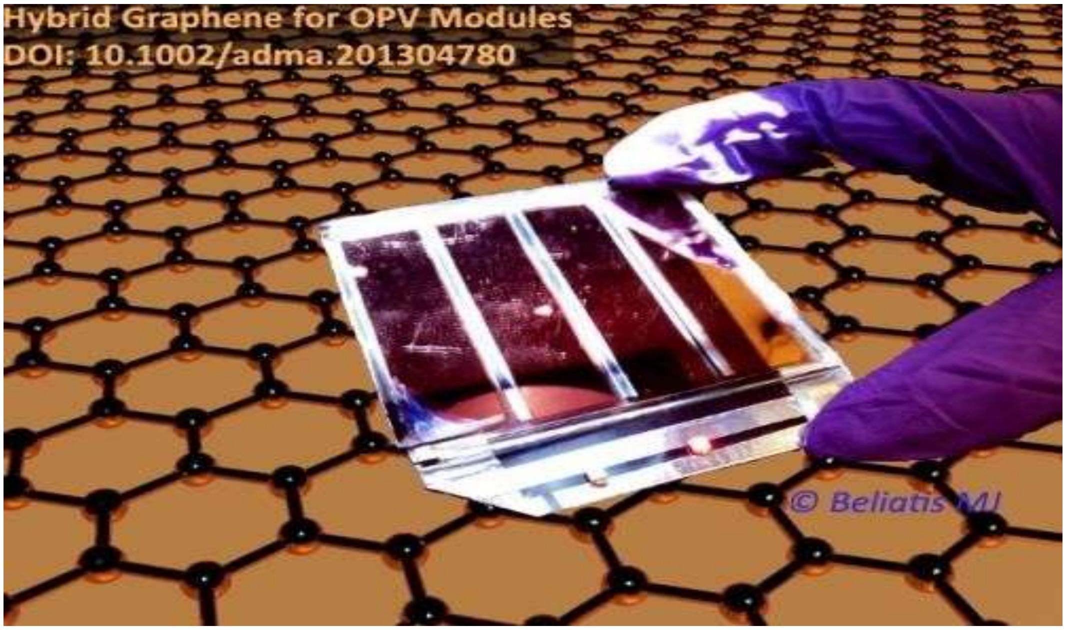

Figure 10. Fourth Generation Solar Cells, 4G[9].

introduce additional benefits as for the inorganics-in-organics architectures. To date,the most effective polymer solar cells (PSCs) have been based on the bulk heterojunction

(BHJ) concept. The 4G solar cells are a hybrid that combine the low cost and flexibility of conducting polymer films (organic materials) with the lifetime stability of novel nanostructures (inorganic materials). This inorganics- in-organics technology improves the harvesting of solar energy and its conversion into electricity, offering better efficiency than the current 3G solar cells while maintaining their low cost base.

These new generation materials for solar cells have been truly engineered at the nanoscale. They are designed to maximize the harvesting of solar radiation, and thereby efficiently generate electricity. It is believed that 4G solar cells will be the technology for future photovoltaic energy sources. This generation brings most successful types of solar cells for mankind and those were hybrid- nanocrystal cells. For generation of these cells polymers and nanoparticles were mixed to make on layer which can help electrons and protons to move for producing better voltage and good quality of direct current.

2.5 Next Generation Solar Cells

So far, most of the solar cells are entirely made of inorganic semiconductors, usually silicon, but these materials are not as energy efficient as organic semiconductors. The new method lies in the groundwork for building a new generation of solar cells made up of both organic and inorganic material. In silicon solar cells, every single particle of light (photon) can excite one electron only, but with a new material (naturally present in green leaves), the same quantity of light releases not one but two electrons, doubling the energy capacity of the semiconductor. This improves the energy efficiency ratio to up to

95 per cent, a figure impossible to reach with conventional, inorganic semiconductors. The process ‘clears the way for hybrid solar cells which could far surpass current efficiency limits’. The next- generation solar cells could be infinitely more useful, thanks to a newly discovered nanotube structure capable of transporting electrical charges 100 million times higher than previously measured.

Most solar cells currently use silicon to absorb light, however inefficiencies in the material have led scientists to develop carbon nanotubes that can be implemented toenhance the light absorption capabilities of current cells. However, until now the nanotubes have been randomly placed within the solar cells in suboptimal structures as they are difficult to arrange. Scientists are able to manipulate the carbon nanotubes using controlled, nano-scale dimensions inside a polymer matrix. This method allowed rearranging the nanotubes into complex networks that reduced the cost of nanotubes needed. Extremely small amounts of nanotubes can be used—less than 1 per cent—and still produce efficient devices leading to lower material cost. Solar cells made of these materials are solution processable, implying that do not require expensive equipment and yet increase the conductivity within the cell. The resulting nano networks possess exceptional ability to transport charges up to 100 million times higher than previously measured carbon nanotube random networks produced by conventional methods.

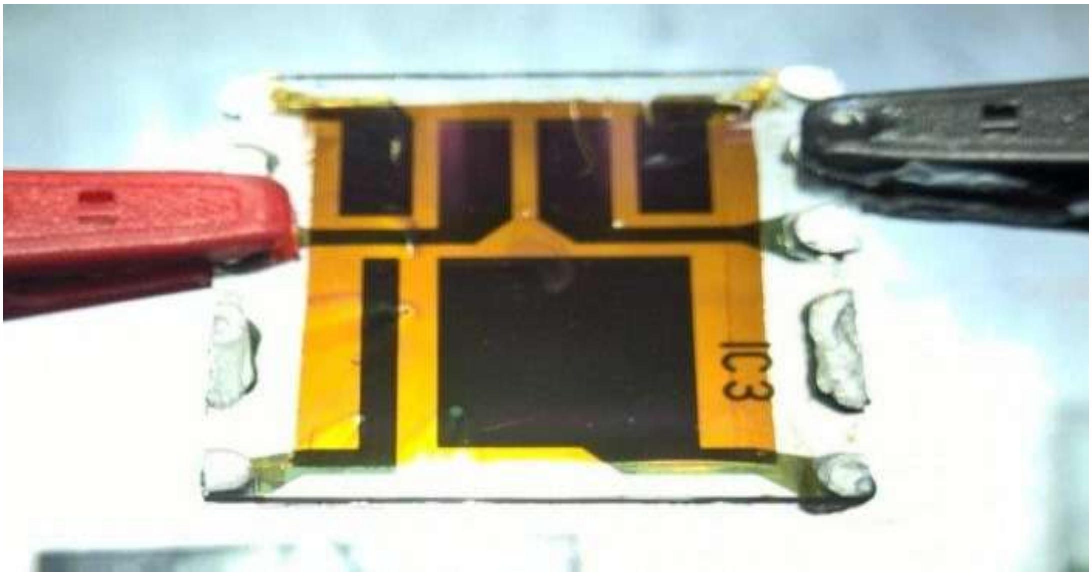

Figure 11. Next Generation Solar Cells[10].

However, photovoltaic cells continue to depend on light to produce electricity, and so, generate a negligible amount of power when there are clouds overhead. But, researchers wondered whether it would be possible to create all-weather solar cells. Rain helps solar cells operate efficiently by washing away dust and dirt that block the sun's rays. Solar cells could someday generate electricity even during rain showers with the help of graphene. Raindrops contain salts that split up into positive and negative ions. In order to manipulate that bit of chemistry, researchers turned to graphene, the one-atom-thick sheet of carbon. Graphene's electrons can attract the positively charged ions, such as sodium, calcium, and ammonium, resulting in separated layers of positive and negative ions that act much like a capacitor to store energy. With that in mind, scientists added graphene to a dye-sensitized solar cell, a kind of inexpensive thin-film solar cell, thereafter placed these on a flexible, transparent backing of indium tin oxide and plastic. The resulting flexible solar cell demonstrated a solar-to-electric conversion efficiency of up to 6.53 per cent, and generated hundreds of microvolts from slightly salty water that was used to simulate rainwater. Therefore, future solar cells may produce electricity in
all-weather conditions with high efficiency, desired geometry and long life span.

3. Concentrated Solar Photovoltaic

Concentrator Photovoltaic (CPV) technology has recently entered the market as a utility- scale option for the generation of solar electricity. This report explores the current status of the CPV market, industry, research, and technology. The CPV industry has struggled to compete with PV prices, with many companies exiting the market, leading to challenges in raising the capital required to scale. However, CPV modules continue to achieve efficiencies far beyond what is possible with traditional flat-plate technology and have room to push efficiencies even higher in the future, providing a potential pathway for significant reductions in systems costs.

The key principle of CPV is the use of cost-efficient concentrating optics that dramatically reduce the cell area, allowing for the use of more expensive, high-efficiency cells and potentially a levelized cost of electricity (LCOE) competitive with Concentrated Solar Power and standard flat-plate PV technology in certain sunny areas with high Direct Normal Irradiance (DNI). Figure 1 shows two exemplary concepts using Fresnel lenses and mirrors as concentrating optics.

Figure 12. Left and middle: CPV Using Fresnel lenses Right: Mirror-Based.

CPV is of most interest for power generation in sun-rich regions with Direct Normal Irradiance (DNI) values of more than 2000 kWh/(m²a). The systems are differentiated according to the concentration factor of the technology configuration (see Table 1). More than 90% of the capacity publicly documented to be installed through end July 2015 is in the form of high concentration PV (HCPV) with two-axis tracking. Concentrating the sunlight by a factor of between 300x to 1000x onto a small cell area enables the use of highly efficient but comparatively expensive multi-junction solar cells based on III-V semiconductors (e.g. triple- junction solar cells made of GaInP/GaInAs/Ge). Low concentration designs – those with concentration ratios below 100x – are also being deployed. These systems primarily use crystalline silicon (c-Si) solar cells and single- axis tracking, although dual axis tracking can also be used.

A key reason for the increasing number of large-scale power plants using HCPV is the significant increase in the efficiency of individual modules, which also leads to a reduction of area-related system costs. Soitec recently demonstrated a CPV module efficiency of 38.9% at Concentrator Standard Test Conditions (CSTC) and efficiencies of commercially available CPV modules exceed 30%.

In recent years, AC system efficiencies have also increased, reaching 25-29% and companies predict further increases in efficiency for CPV systems to over 30% in the next couple of years driven largely by improvements in cell efficiency but also in the optical efficiency. In addition to these higher efficiencies, tracking allows CPV systems to produce a larger amount of energy throughout the day in sunny regions, notably during late part of the day when electricity demand peaks. At the same time and in contrast to CSP, the size of the installations can be scaled over a wide range, i.e., from kW to multi-MW, and in this way adapted to the local demands. Some CPV systems also disturb a smaller land area, since the trackers, with relatively narrow pedestals, are not closely packed. This makes it possible to continue to use the land for agriculture. Finally, HCPV is advantageous in hot climates in particular, since the output of the solar cells used does not decline as severely at high temperatures as that of conventional c-Si solar modules.

Table 1: Description of CPV Classes.

Class of CPV	Typical Concentration Ratio	Tracking	Type of Converter
High Concentration PV (HCPV)	300-1000	Two-axis	III-V multi-junction solar cells
Low Concentration PV (LCPV)	< 100	One or two-axis	c-Si or other cells

Industry reports indicate that the total capital equipment (capex) requirement, while varying by design and manufacturing process, can be lower for CPV than for traditional flat- plate technologies, including c-Si. Additionally, a bottom-up analysis from NREL based on a specific HCPV system with a Fresnel lens primary optic and refractive secondary lens estimates the total capex for cells and modules in this design (assuming a vertically integrated company) to be around $0.55/Wp(DC), with a much lower capex for variations on the design. Most HCPV companies have their optics and cellsmanufactured by a third party, in which case the capital equipment requirements for the HCPV company itself can be quite low.

Reports indicate that the installed system prices for CPV systems have declined significantly since the technology was introduced on the market. In 2013, a Fraunhofer ISE report found that installed CPV power plant prices for 10 MW projects were between €1400/kW and €2200/kW. The wide range of prices results from the different technological concepts as well as the nascent and regionally variable markets. LCOEs based on these systems prices calculated by Fraunhofer ISE range from €0.10/kWh to
€0.15/kWh for a location with a DNI of 2000 kWh/(m²a) and €0.08/kWh to
€0.12/kWh for 2500 kWh/(m²a). These numbers provide a basis for comparison of current CPV projects with the analyzed values for utility-scale PV and concentrating solar power (CSP) power plants, as will be discussed in more detail in section 2.2.1. Table 2 summarizes the strengths and weaknesses of CPV.

Although research on cells, modules, and systems for CPV has been ongoing for decades, CPV only entered the market in the mid-2000s. While it has seen strong market growth in recent years, it is still a young and – compared to conventional flat-plate PV – small player in the market for solar electricity generation. This implies a lack of reliable data for market, prices, and status of industry.

Table 2: Analysis of the Strengths and Weaknesses of CPV.

CPV Strengths	CPV Weaknesses
High efficiencies for direct-normal irradiance	HCPV cannot utilize diffuse radiation LCPV can only utilize a fraction of diffuse radiation
Low temperature coefficients	Tracking with sufficient accuracy and reliability is required
No cooling water required for passively cooled systems (as is required for CSP)	May require frequent cleaning to mitigate soiling losses, depending on the site
Additional use of waste heat possible for systems with active cooling possible (e.g. large mirror systems)	Limited market – can only be used in regions with high DNI, cannot be easily installed on rooftops
Modular – kW to GW scale	Strong cost decrease of competing technologies for electricity production
Increased and stable energy production throughout the day due to tracking	Bankability and perception issues due to shorter track record compared to PV
Very low energy payback time	New generation technologies, without a history of production (thus increased risk)
Potential double use of land, e.g. for agriculture. Low environmental impact[1]	Additional optical losses
Opportunities for cost-effective local manufacturing of certain steps	Lack of technology standardization
Less sensitive to variations in semiconductor prices	
Greater potential for efficiency increase in the future compared to single-junction flat plate systems could lead to greater improvements in land area use, system, BOS and BOP costs	

4. Solar Cell Efficiency

The efficiency of III-V multi-junction solar cells is the key driver to lower the LCOE of energy produced by HCPV technology. In Figure 13, record efficiencies for these solar cells are displayed. Since 2002 the efficiency has increased by 0.9 % absolute per year.

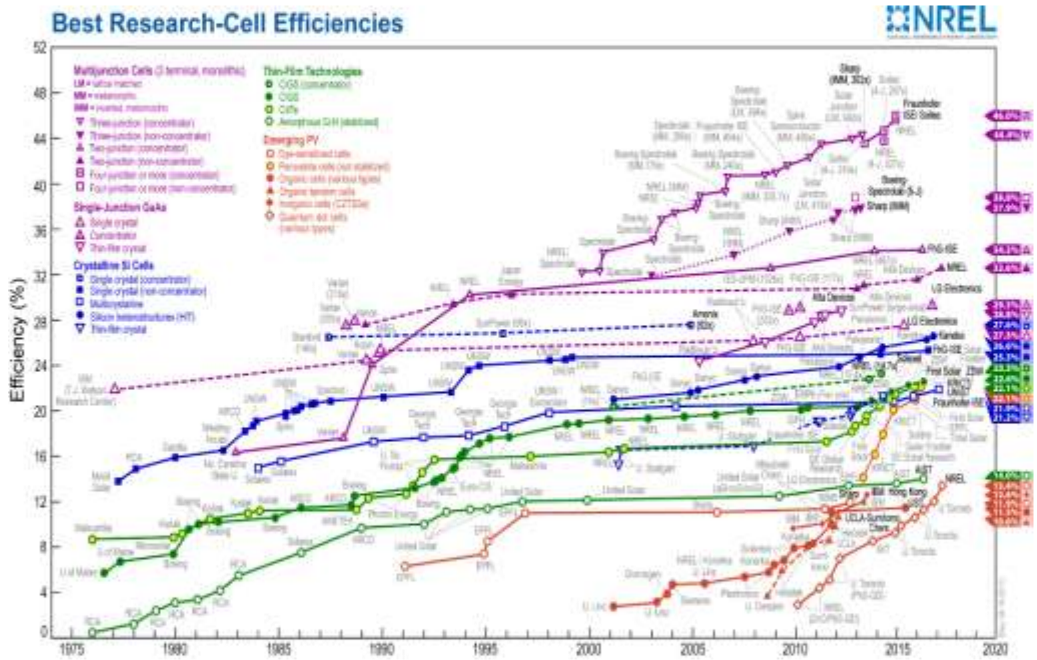

Figure 13. Solar Cell Efficiencies through the Years.

Solar cells made by Fraunhofer ISE and Soitec CEA achieved today´s champion efficiencies of 46 %.

There are several main reasons why III-V multi-junction solar cells reach the highest efficiencies of any photovoltaic technology. III-V solar cells are composed of compounds of elements from groups III and V of the periodic table. In the corresponding multi-junction devices, several solar cells made of different III-V semiconductors are stacked with decreasing bandgaps from top to bottom. This reduces thermalisation losses as phometric tons are mostly absorbed in layers with a bandgap close to the photon’s energy. Moreover, transmission losses are reduced as the absorption range of the multi-junction solar cell is usually wider than for single-junction devices. Finally the use of direct bandgap III-V semiconductors facilitates a high absorption of light even in comparably thin layers.

The most common III-V multi-junction solar cell in space and terrestrial concentrator systems is a lattice-matched Ga0.50 In0.50P/Ga0.99 In0.01 As/Ge triple-junction solar cell. The device is grown with high throughput in commercial metal-organic vapor phase epitaxy (MOVPE) reactors. All semiconductors in this structure have the same lattice constant as the Ge substrate, which facilitates crystal growth with high material quality. However, its bandgap combination is not optimal as the bottom cell receives

significantly more light than the upper two cells resulting in about twice the photocurrent of the upper two subcells. Nevertheless, as record efficiency for this triple- junction concentrator solar cell 41.6% (AM1.5d, 364 suns) has been achieved in 2009. Various approaches are under investigation to further increase in solar cell efficiencies. Table 3 presents cell architectures that have achieved record cell efficiencies above 41%. These use different elements from the wide range of technology building blocks
available for III-V multi-junction solar cells.

Table 3: Summary of Record Concentrator Cell Efficiencies Above 41% Based on III-V Multi-Junction Solar Cells.

Cell Architecture	Efficiency (Accredited Test Lab)	Institution	Comments
GaInP/GaAs//GaInAsP/GaInAs	46.0 @ 508 suns (AIST)	Fraunhofer ISE/ Soitec/ CEA	4J, wafer bonding, lattice matched grown on GaAs and InP
GaInP/GaAs/GaInAs/GaInAs	45.7% @ 234 suns (NREL)	REL	4J, inverted metamorphic
GaInP/GaAs/GaInAs	44.4 @ 302 suns (Fraunhofer ISE)	Sharp	3J, inverted metamorphic
GaInP/GaAs/GaInNAs	44.0% @ 942 suns (NREL	Solar Junction	3J, MBE, lattice matched, dilute nitrides, grown on GaAs
GaInP/Ga(In)As/GaInAs	42.6% @ 327 suns (NREL) (40.9% @ 1093 suns)	NREL	3J, inverted metamorphic
	42.4% @ 325 suns (NREL) (41% @ 1000 suns)	Emcore	
GaInP-GaAs-wafer-GaInAs	42.3% @ 406 suns (NREL	Spire	3J, epi growth lattice matched on front and inverted metamorphic on back of GaAs wafer
GaInP-Ga(In)As-Ge	41.6% @ 364 Suns (NREL)	Spectrolab	3J, lattice matched, commercially available;
GaInP-GaInAs-Ge	41.1% @ 454 Suns (Fraunhofer ISE)	Fraunhofer ISE	3J, upright metamorphic; commercially available from AZUR SPACE, Spectrolab

5. Solar Radiation

Some of the solar radiation entering the earth's atmosphere is absorbed and scattered. Direct beam radiation comes in a direct line from the sun. Diffuse radiation is scattered out of the direct beam by molecules, aerosols, and clouds. The sum of the direct beam, diffuse, and ground and surroundings reflected radiation arriving at the surface is called total or global solar radiation.

GHI is the total amount of solar energy incident on a horizontal surface. DNI is the amount of radiation incident on a surface that is always kept perpendicular (normal) to the direct solar beam. Part of the solar radiation that arrives on a horizontal surface, called diffuse horizontal irradiance (DHI), is due to scattering of sunlight in the atmosphere and reaches the horizontal surface from all directions of the sky. These three quantities are related via the expression $GHI = DNI \cos Z + DHI$, where Z is the sun zenith angle. GHI is the important parameter for photovoltaic applications (PV), while DNI is the most important parameter for CSP plants and Concentrating Photovoltaic (CPV) plants. The amount of GHI and DNI vary due to variation in geographical location and due to local climate effects. Table 4 provides ranges of the solar resource data for the WEC geographical regions. It is to be noted that all solar technologies can use trackers to increase the overall output. Trackers are mechanical parts that facilitate solar modules to track sun. Tracking could be for over a day only or can also include seasonal tracking.

Table 4: Annual Global Horizontal Irradiance (GHI) & Direct Normal Irradiance (DNI) for WEC Geo-Regions

WEC Geo region	GHI range (kWh/ m² per year)	DNI range (kWh/m² per year)
Africa	1600 – more than 2700; Lowest: Congo Basin Highest: Sahara & Namib Deserts	900 – 3200; Lowest: Congo Basin Highest: Southern Namibia & North-western South Africa
Middle East & North Africa	1700 – more than 2700; Lowest: Caspian region of Iran Highest: Saudi Arabia & Sahara region of North Africa	1100 – 2800; Lowest: Caspian region of Iran Highest: North-western Saudi Arabia & Sahara region of North Africa
Latin America & Caribbean	1000 – more than 2700; Lowest: Patagonia region of Argentina & Southern Chile Highest: Atacama region of Chile	800 – 3800; Lowest: Patagonia region of Southern Chile Highest: Atacama region of Chile
North America	Less than 700 – more than 2600; Lowest: Arctic region of Canada & United States Highest: Sierra Madre region of Mexico	700 – 3100; Lowest: Arctic region of Canada & United States Highest: Mojave & Sonoran Deserts of United States & Mexico
Europe	Less than 700 – 2100; Lowest: Arctic region of Russia & Scandinavia Highest: Southern Spain	500 – 2300; Lowest: Arctic region of Russia & Scandinavia Highest: Southern Spain
South & Central Asia	1400 – 2400; Lowest: Northern India & Pakistan Highest: Afghanistan & Southern Pakistan	1100 – 2500; Lowest: Northern India & Pakistan Highest: Afghanistan
East Asia	1000 – 2300; Lowest: Eastern foot of Tibetan Plateau Highest: Tibetan Plateau of South-western China	500 – 2600; Lowest: Eastern China Highest: Tibetan Plateau of South-western China & Mongolian steppes
South East Asia & Pacific	900 – 2600; Lowest: Southern New Zealand Highest: Great Sandi Desert of Australia	900 – 3200; Lowest: Indonesia Highest: Western Australia

6. New Applications

With advancements in solar technology, the range of potential applications of solar power widens further. The combination of perovskite and graphene to produce semi- transparent panels could lead to high-efficiency solar windows. Utility-scale solar is already providing water desalination services in the Middle East, and in Oman solar energy is utilized to recover oil from the country's reserves, as the case study below shows.

Solar panels are being built and deployed in ingenious manners, on freshwater dams and lakes, in order to save land and in some cases water. For example, the 13.7 MW Yamakura solar power station in Japan will employ 51,000 solar modules built on the freshwater dam, which will save agricultural land and reduce water evaporation. A similar concept is being developed in India at a much smaller scale. The project consists of covering a 750 meter stretch water canal (from the total 85,000 km) in the province of Gujarat with solar panels that will generate 1 MW of electricity. The project has great potential for expansion given the long size of the canal, so if only 10% would be covered with solar panels the generating capabilities would be around 2,200 MW. Using the canals to produce this much energy would save 11,000 acres of land and would eliminate the loss of millions of liters of water per year.

6.1 Solar-Powered Oil Production in Oman

Oil companies are increasingly producing heavy oil, which accounts for 70% of today's remaining reserves. Heavy oil is abundant, but difficult to extract. The leading method of producing heavy oil is steam injection, a type of thermal enhanced oil recovery (EOR) that injects steam into a reservoir to heat the oil making it easier to pump to the surface. Steam injection can boost well productivity by up to 300%, but is an energy intensive process.

To produce the steam for EOR, oil companies burn an enormous amount of gas—a valuable resource that is in short supply in many oil-producing regions. Solar-powered EOR replaces burning natural gas with concentrated solar power. Solar energy can provide a significant amount of an oilfield's steam needs, significantly reducing theamount of gas consumed. To maintain steam injection around the clock, solar steam is injected during the day, and steam produced by burning natural gas is injected at night. Enclosed trough technology is built to meet the unique needs of the oil industry. Curved mirrors inside a glasshouse ck the sun, focusing heat onto a pipe containing water. The concentrated sunlight boils the water to generate steam. The glasshouse protects the mirrors from wind, dust and sand. It has an automated washing machine to maintain performance in harsh desert environments.

Solar energy produces steam with zero emissions; the gas saved can be exported or redirected to higher value uses such as power generation or industrial development. As a result, solar-powered EOR can boost the local economy and help create jobs too.

Petroleum Development Oman (PDO), Oman's largest producer of oil and gas, partnered with solar steam generator company GlassPoint to develop the Middle East's first Solar-powered EOR system. The 7MWth pilot began producing steam in December 2012 and continues to operate successfully, producing an average of 50 tons of emissions-free steam per day. The solar steam is fed directly to PDO's existing steam distribution network. The pilot has achieved above 98% uptime, maintaining regular operations even during severe dust and sand storms.

Figure 14. Solar-Powered EOR Project in Oman.

The success of the pilot is now paving the way for larger solar EOR projects in Oman and the rest of the Gulf region. In July 2015, PDO and GlassPoint signed an agreementfor a 6000 t/d facility (equivalent to just over 1 GWth) in the south of Oman. The project named Miraah ("mirror" in Arabic) is expected to save 5.6 trillion Btu of gas and
300,000 tons of CO2 emissions per year. First steam is expected in 2017.

6.2 Compact Solar Powered Water Treatment Stations in India

In a rural village (of Andhra Pradesh state of India) with no access to clean water and irregular power supply, SunSource Energy Pvt Ltd. in association with an NGO named as SANA installed a solar system to purify waste water and make it potable. Local governance body of the village (Panchayat) with the co-operation was made a partner in the model, and representatives of the Panchayat were trained for the up keeping of the water station, the solar panels and water distribution. The water station converts 1.8 million litres of contaminated water into WHO standard potable drinking water for the local villagers. This project has won the Google Impact Award for 2013 and SunSource Energy Pvt. Ltd is looking for other such villages in rural parts of India and nearby countries where solar energy can bring change to lives of rural people.

7. State-of-the-Art Solar Concentrator

In 2014, IBM has developed an even more efficient way to convert solar energy into usable energy with up to 80% efficiency[11]. Using a 40 m^2 parabolic dish coated with 36 plastic foil elliptical mirrors just 0.2 mm thick, IBM was able to concentrate the sun's radiation over 2,000 times on a small area and then transforms 80 percent of that into usable energy (Fig. 15). This new system is called High Concentration PhotoVoltaic Thermal (HCPVT). Using several receivers, each equipped with an array of multi- junction photovoltaic chips, each HCPVT can produce enough power, water, and cooling to supply several homes with energy. The HCPVT prototype concentrates the sun's radiation onto liquid-cooled microchannel receivers (Fig. 16), each of which contains an array of 1-cm2 (0.39 in2) chips that generates up to 57 watts of electrical power when operating during a typical sunny day. The combed system produces 12 kW of electrical power and 20 kW of heat.

The new system uses micro-structured conduits that pumps treated water around the receivers to carry away excess heat at a rate that is 10 times more effective than passive

Figure 15. HCPVT Dish. **Figure 16. Liquid-Cooled**

Microchannel Receiver. air cooling. Although the water is still subsequently heated to around 85-90° C, the removal of heat from the chips keeps them at a relatively safe operating temperature of around 105° C. Without this cooling, the concentrated solar energy would increase the chips temperatures to over 1,500° C.

The HCPVT system can also be adapted to use the cooling system to provide drinkable water and air conditioning from the hot water output produced. Salt water is passed through the heating conduits before being run through a permeable membrane distillation system, where it is then evaporated and desalinated. To produce cool air for the home, the waste heat can be run through an adsorption chiller, which is an evaporator/condenser heat exchanger that uses water, rather than other chemicals, as the refrigerant medium (Fig. 17).

All of these factors, – waste energy used for distillation and air-conditioning combined with a 25 percent yield on solar power – along with the setup's sun tracking system that continuously positions the dish at the best angle throughout the day, combine to produce the claimed 80 percent energy efficiency.

The CPV, which looks like a 33-foot-high sunflower, can generate 12 kilowatts of electrical power and 20 kilowatts of heat on a sunny day — enough to power several average homes, according to Bruno Michel, the project's lead scientists at IBM Research in Switzerland.

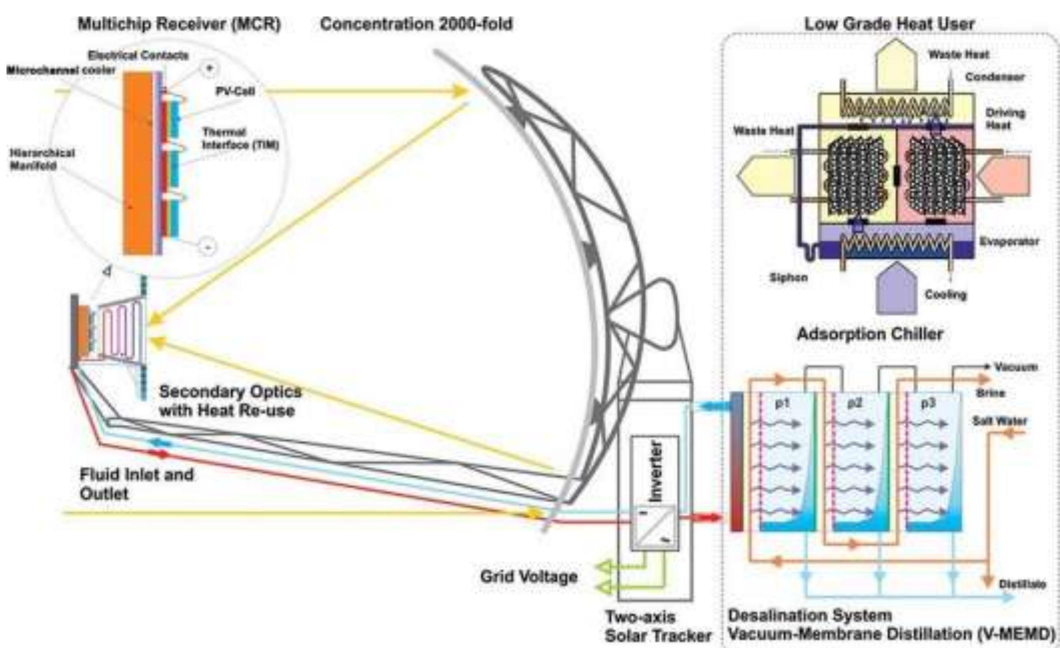

Fig. 17. HCPVT with Desalination System.

The mirrors concentrate the sun on the chips to produce electricity. Normally, the chips would ignite, since they reach temperatures of 1,500 degrees Celsius. But IBM scientists are taking a page from the supercomputer playbook to keep them at a relatively cool 105 degrees with a water radiator system. The dense array of multi-junction photovoltaic (PV) chips, mirrors and the electrical receiver are encased in a large inflated transparent plastic enclosure to protect the system from rain or hail.
IBM and Airlight Energy are currently piloting the technology and expect to begin selling it in 2017.

Figure 18. Multi-Junction Solar Array Enclosure.

Because the sun's rays are concentrated onto an array of PV chips, the array needs to be cooled to remain within operating temperatures. The water-filled radiator system that does that also creates hot water that can be used in other ways, such as space heating and air conditioning through an absorption chiller.

The hot water can then be used in an attached desalination system that creates drinkable water by passing itwater through a Gortex-like membrane. A 40-square meter CPV system could produce up to almost 350 gallons of water a day. In order to obtain these three separate functions [energy, potable water and a heating or cooling system] you would need three different products. This is where cost efficiency comes from.
IBM and Airlight claim the CPV system could provide eight to 10 gallons of drinkable water per square meter of receiver area per day, while still generating electricity with a more than 25% yield or two kilowatt hours per day — little less than half the amount of

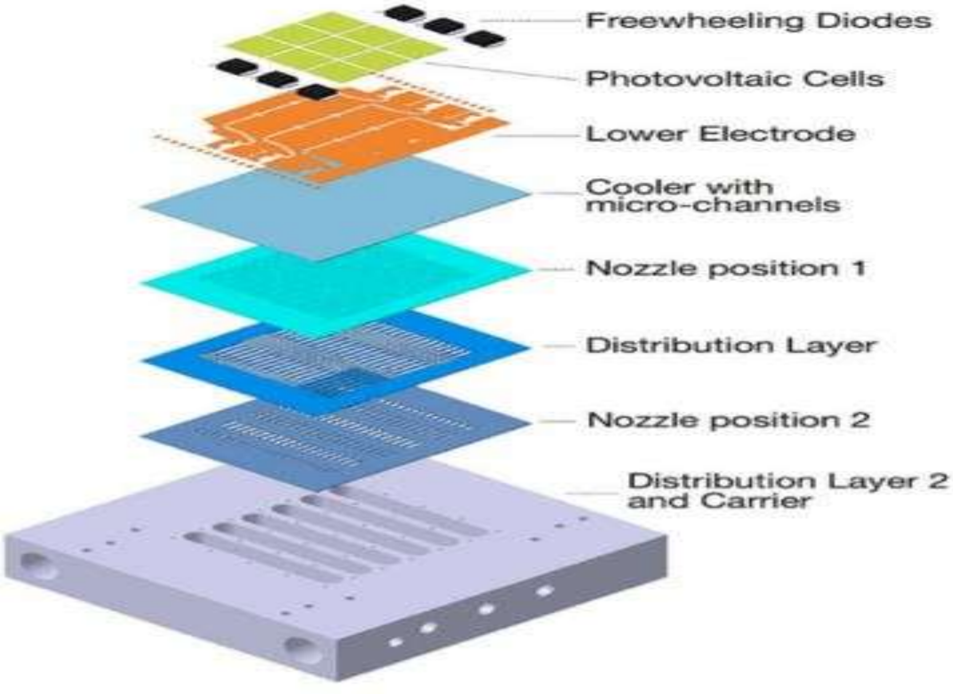

Figure 19. The System behind the Concentrator Photovoltaic System.

water the average person needs per day. A large multi-dish installation could provide enough water for a town," the companies said in their marketing material. Because it's still in the pilot phase, the companies are not disclosing prices. But because the parabolic dish is also constructed of less expensive concrete and aluminum, its cost is four to five times cheaper than comparable systems. Typically, CPV systems are made of glass and aluminum.

Figure 20. The Actual Size of a Single Solar Concentrator.

The parabolic dish has 36 elliptic mirrors made of 0.2 millimeter thick recyclable aluminum foil with a silver coating. The foil is slightly thicker than a chocolate bar wrapper.

8. Summary and Conclusions

This research report represents a summary of a thorough study of the various solar photovoltaic cells and their efficiencies. Four generations of solar PV cells were described and a future fifth generation was introduced. The study focuses on the intended use of concentrated solar photovoltaic cells in a desert-type climate such as the Gulf region. The latest state-of-the-art research shows that efficiencies in the excess of 80% are feasible when considering the usable energy versus the solar energy collected.

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