Sun power

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The rapidly growing solar and wind energy programmes in India have created a techno-economic opportunity in the energy market. Apart from the possibility of providing the much-needed energy solution to our citizens, the promise to young academicians and workforce is significant in the new clean energy sector. All these have happened in the last four to five years and, if the country were to take the National Solar Mission initiative forward, developments in solar photovoltaic power generation are likely to realize grid parity within the next few years and mitigate the energy deficiency to a great extent.

Keywords: Grid parity, National Solar Mission, Photovoltaic cell, solar PV power plant.

LESS than a couple of decades ago, few would have imagined that solar power would evolve as a significant source of alternative, clean energy. Dating back to 1831, when the English scientist and physicist, Michael Faraday demonstrated the electromagnetic effect through the famous coil and magnet experiment, only a handful in the gathering could foresee what its implications would mean to the modern world. The applications are endless now; electric motors to turbine generators in large power plants utilize the above principle. It was discovered at a time when fossil fuels, predominantly coal and oil, were cheap and fuel supplies appeared inexhaustible. Today, rising prices of coal and oil and concurrent pollution hazards associated with major power generation technologies (nuclear, coal and gas) have all led us to follow solar power as a quiet, non-polluting and inexhaustible source of energy. In the voice of a fervent scientist–philanthropist: 'The Sun radiates about 10 trillion times the energy that humans consume worldwide. If we are able to extract a small portion of this energy, it would be sufficient to secure energy demands of our future' (A. P. J. Abdul Kalam, 10 January 2012; Anna University).

Photovoltaics, literally translated as light-electricity ('photo' in Greek for light and 'volt', the electric potential after the electricity pioneer, Alessandro Volta), is the art of converting light energy directly into electrical energy, since its discovery by French physicist Alexandre-Edmond Becquerel in 1839 (Figure 1). He found that certain materials would produce small amounts of electric current when exposed to light. The first photovoltaic module was built by Bell Laboratories in 1954. It was termed as a solar battery and served mostly as a curiosity model since it was too expensive to gain widespread use. In the 1960s, the space industry began to make the first serious use of the technology to provide power aboard spacecraft. Through several space programmes, the technology advanced, its reliability was established, and the cost began to decline. During the energy crisis in the 1970s, photovoltaic technology gained recognition as a source of power for non-space applications.

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Basic building blocks

Photovoltaic (PV) systems are already an important part of our daily lives. Simple ones provide power for small consumer items such as calculators and wristwatches. More complicated systems energize water pumps and

Figure 1. French physicist, Alexandre-Edmond Becquerel (1820–1891).
• Studied solar spectrum, magnetism, electricity and optics.
• Discovered the photovoltaic effect (1839).

lights, appliances in homes and workplaces, traffic signs and lights, off-shore rigs and communication satellites. In many specific cases, solar power is the least expensive form of electricity.

PV cells (commonly known as solar cells) are electricity-producing devices made of semiconductor materials. These constitute many sizes and shapes, from smaller than a postage stamp to as much as 6 inches across and are often connected together to form PV modules that may be up to 2 m long and 1 m wide (Figure 2).

PV modules are joined together in series and parallel configurations to form PV arrays of different sizes and power output. The modules of the array make up the major part of a PV system, along with the balance of system components that include mounting hardware, electrical connections, power-inverting and conditioning equipment, transformers, supervisory control and diagnostic tools, switch gear, switch yard with metering and protection devices and batteries that store solar energy for use in auxiliary systems when the Sun is not shining.

When sunlight shines on a PV cell, it may be reflected, absorbed, or pass right through. However, only the absorbed light generates electricity. The energy of the absorbed light is transferred to electrons in the atoms of the PV cell semiconductor material. With their newfound energy, these electrons escape from their normal positions in the atoms and become part of the electrical flow, or current, in an electrical circuit. A special electrical property of the PV cell – built-in electric field – provides the force, or voltage, needed to drive the current through an external load, such as a light bulb.

For solar cells, a thin semiconductor wafer is specially treated (doped) to create an in-built electric field, positive on one side and negative on the other. When light energy (photons) strikes the active surface, electrons are knocked loose from the atoms in the semiconductor material. If electrical connectors are attached to the positive and negative sides forming an electrical circuit, the electrons can be captured in the form of an electric current, that is, electricity. This electricity is utilizable to power a load, such as a light or a tool. Excess electricity generated can also be fed back into the utility grid by stepping up the voltage and frequency in a matching manner. This augments the line voltage and electric power transmitted from the conventional generating stations.

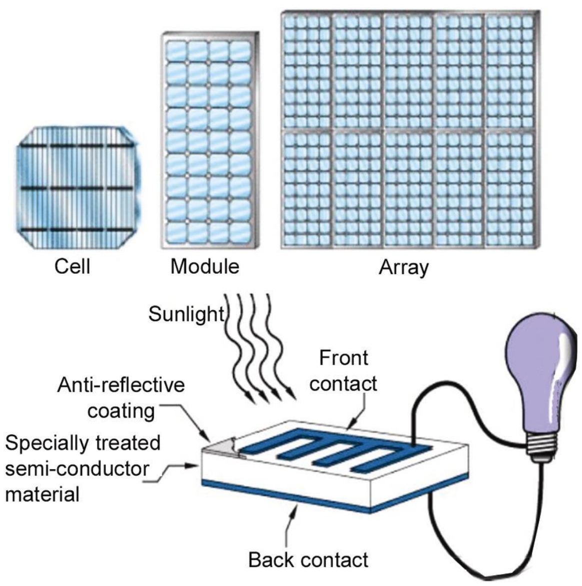

Figure 2. (Top) Building blocks of a solar photovoltaic array. (Below) Schematic representation of solar electricity generation.

The most common solar cell used today is of the crystalline silicon type. It is also the earliest successful photovoltaic device. Each silicon solar cell produces a small amount of power, typically 4.5 watts at 0.5 volt. To generate more power, several cells are interconnected to form modules (typical output of 24 volts, 250 watts), which are mounted in arrays to produce yet more power at higher voltage (415 volts). Owing to the modular nature, PV systems can be designed to meet any electrical load requirement, no matter how large or how small which forms the basis of mega-watt solar power plants.

The current produced is dependent on how much light strikes the PV module surface. It would mean that PV systems can still produce electricity on cloudy days, but not as much as on a sunny day. The performance of a solar cell is measured in terms of its efficiency at converting sunlight into electricity[1] (Figure 3).

Of the several solar cell materials available, two of the most popular wafer-based ones are mono-crystalline silicon (or single crystal) and multi-crystalline silicon (Figure 4). Other types of thin film cells are: cadmium telluride (CdTe), copper indium gallium selenide (CIGS) and germanium multi-junction thin film cell (Ge–GaAs–GaInP), all of which possess high absorption coefficients and suitable band gaps. The multi-junction thin film cell is used in spacecraft and has the highest solar conversion efficiency (28%) among all solar cells.

Building integrated photovoltaics

Solar cells have potential to enter the residential market in the form of roof-top integrated[2], roof-top mounted or, as building facades, skylights or glazed atria (Figures 5 and 6). Their main benefits are attractive integration into homes, good response in low ambient light and pollution-free electricity generator. However, their affordability and maintainability in comparison with conventional roofing and public utility system are yet to be proved.

Stand-alone PV systems

Here, the current generated by the PV system is connected directly to the equipment that it powers (load).

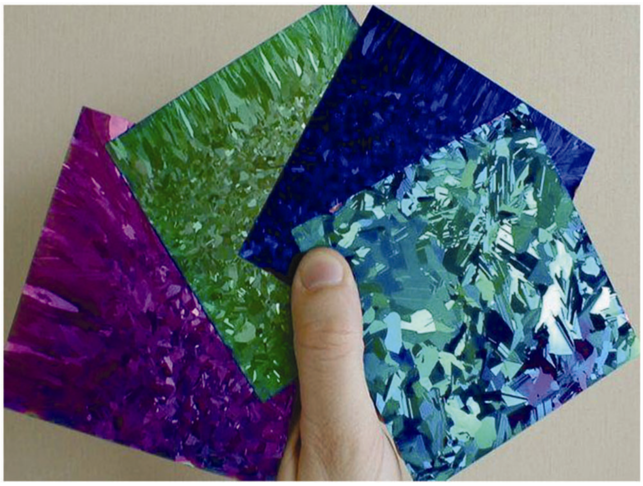

Figure 3. Multi-crystalline silicon solar cells with differently coated (thickness) anti-reflection films on them. Deep blue is the most commonly adopted colour for maximum light absorption. (Source: ref. 1; http://pveducation.org/pvcdrom/design/arc-color).

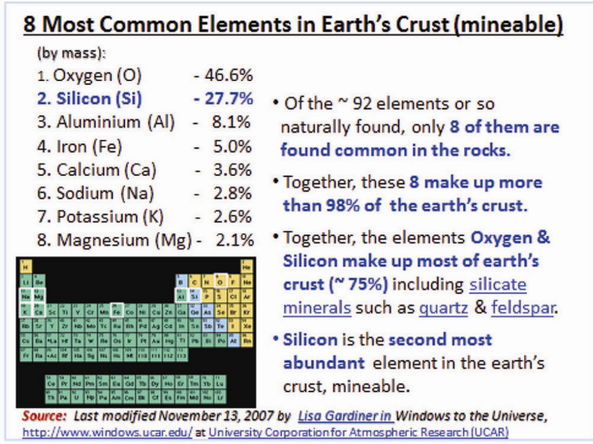

Figure 4. Silicon-based solar cell has the largest techno-marketable share among all solar cell types today. This is largely due to universal availability of the raw material, optimal semiconducting and light absorption properties and also, by virtue of the easily transferable process developments from the electronics industry.

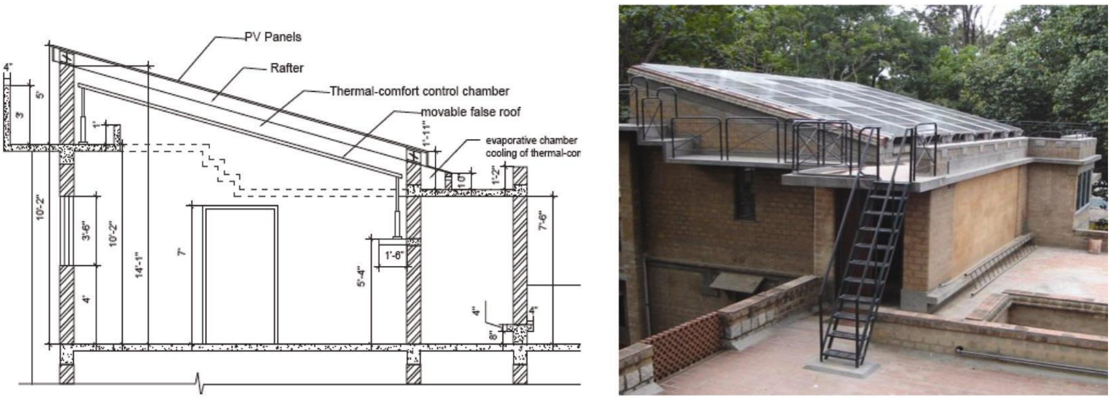

Figure 5. Design of climate-responsive building (left) with integrated PV roof (3 kW) at the Centre of Sustainable Technologies, Indian Institute of Science in Bangalore[2].

Figure 6. Smart house concept for localized power generation and efficient energy management and roof-mounted PV modules (right).

However, if one likes to store power for use when the system is not producing electricity, then one requires batteries and a charge controller. The cost of balance-of-system equipment (batteries, charge controller, power conditioning equipment, safety equipment and meters and instrumentation) for a stand-alone system could be half the total system costs.

Generally, lead-acid batteries are designed to provide electricity over long periods, and can repeatedly charge and discharge up to 80% of their capacity. The charge

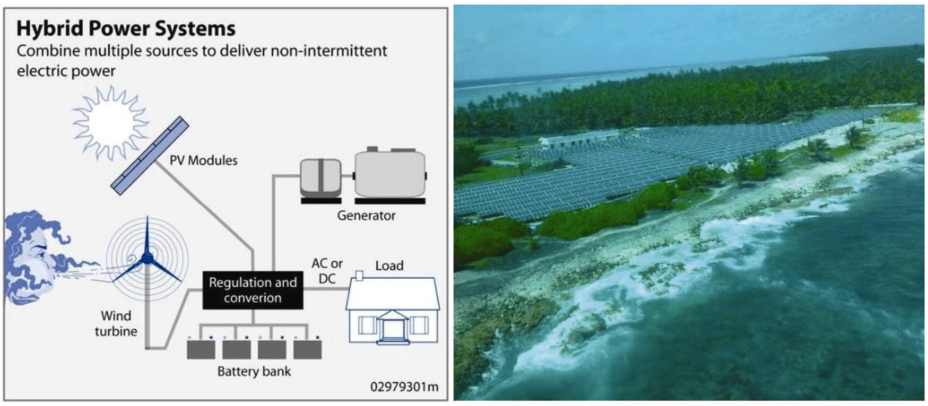

Figure 7. (Left) Schematic diagram of hybrid power system (wind–diesel–solar PV). (Right) Kavaratti island: Single largest solar plant among 11 Lakshadweep islands; 760 kWp solar PV-cum-diesel hybrid power plant; Eco-friendly; Diesel saving/day ~1000 liters; Commissioned: October 2011.

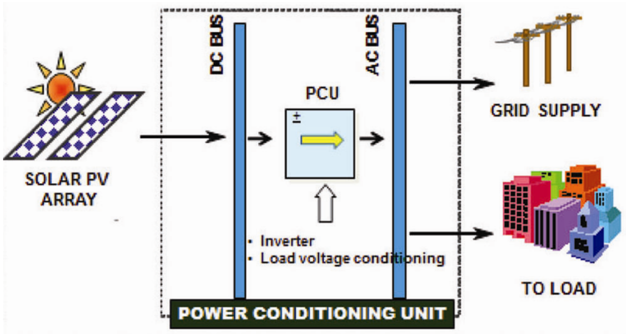

Figure 8. Design philosophy of a grid-connected PV system.

Figure 9. The 5 MWp solar PV power plant of Karnataka Power Corporation Limited.

controller regulates the rate of flow of electricity from the generation source to the battery and the load.

Hybrid (PV–wind–diesel) power systems

A 'hybrid' electric system that combines wind–diesel–solar PV technologies offers several advantages over any one (single) system (Figure 7). Where wind speeds are low at times and when Sun shines brightest and longest, or when the wind is strong but less sunlight is available (peak operating periods for wind and solar systems occur at different times of the day and year), hybrid systems are more likely to yield best results and the power when needed.

Many hybrid systems are stand-alone systems, which operate 'off-grid' – not connected to an electricity distribution system. For the period when neither wind nor solar PV system is producing, most hybrid systems provide power through batteries and/or an engine generator powered by conventional fuels such as diesel. If the batteries run low, the engine generator can provide power and recharge the batteries.

Grid-connected PV system

A grid-connected system allows you to power your home or small business with solar PV energy during those periods (daily as well as seasonally) when the Sun is shining and the excess electricity produced is fed back into the grid (Figure 8).

When Sun power is unavailable, electricity from the grid meets the energy needs, eliminating the expense of electricity storage devices such as batteries. Power providers (electric utilities) in many countries allow net metering, an arrangement by which the excess electricity generated by grid-connected PV system 'turns back' your electricity meter as it is fed back into the grid. If you use more electricity than your system feeds into the grid during a given month, you pay your power provider only for the difference between what you used and what you produced.

Today, design and installation of mega-watt size solar PV power plants facilitate directly feeding stable, conditioned power to the grid; as these are large in capacity, say 10 MW, 50 MW or even 100 MW, they are generally located in places where large tracts of land are available with access to grid transmission stations. These are also known as solar parks (Figure 9).

PV power generation, balance of system, safety and regulatory practices

There are several important factors that determine the amount of electric power generated by an SPV system and are generally accounted for in the design and sizing calculations of the power plant. The major ones are solar irradiance and incident angles of light on the PV array at the site. Other losses such as due to dust accumulation, ambient temperature, electrical cable drop, solar cell conversion efficiency, inverter/transformer efficiency and the grid stability and availability are considered (Table 1).

Apart from solar power system components, one requires more tools and equipment in order to safely transmit electricity to the transmission line (grid), and comply with utility and grid safety regulations. These deal with safety and power quality, contracts that may require liability insurance, metering and tariff. Safety components include switches to disconnect the PV system from the grid in the event of a power surge or power failure and custom-specific power conditioning equipment to ensure that the PV power transmitted exactly matches the voltage and frequency of the electricity flowing through the grid. Statutory clearances, including approval of the Central Electricity Authority for synchronization to the grid and that from the transmission company are pre-requisites.

Grid parity

A comparison of the conventional (coal-fired) and solar PV power plant is shown in Table 2. If the current levels of manufacturing and applications are anything to go by, the day is not far when solar photovoltaic energy will present more positives. Although the industrial and economic impact of such possibility is to be fully evaluated for reliability periods up to 25 years, it is quite optimistic to believe that this technology is here to stay.

The premium land area needed for a solar power plant raises concern, but vertical mounting design of solar panels and 'futuristic' concepts of ocean-float and satellite-borne PV systems provide key solutions. To the final question as to when parity will be achieved between conventional utility tariff (Rs per kWh) and solar electricity can be best answered by viewing the sharp fall in the rate of the latter in the cost trend curve (Figure 10).

It compels one to seriously consider adopting this renewable package in favour of the utility power for domestic use. Cost of power from large scale solar is already at par with imported coal[3]. Grid parity with domestic coal may not be too far.

Solar PV system reliability and potential

Long-term reliability of solar PV arrays is an important factor that governs the cost of solar systems and creates consumer acceptance. Solar cells that are 'solid-state' devices with no moving parts lend themselves to high degree of reliability and are long-lived. Therefore, reliability data of solar systems are usually focused not on solar cells but on modules and whole systems. Infant mortality can be lowered by process diagnostics and screening of solar cells and PV modules in production

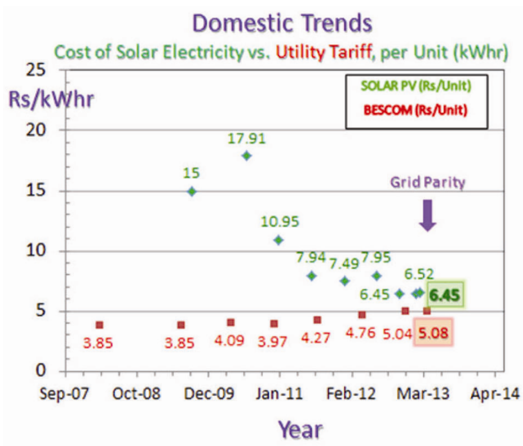

Figure 10. Cost trends of solar electricity versus utility power tariff.

Table 1. Factors determining the electric power generation in a SPV power plant.

Factors that determine PV Energy generation

FACTOR	RESPONSE
❑ Solar Radiation (Watt/m²)	Affected by cloud/rain/shadow
❑ Dust	A dust layer on PV modules lowers o/p power.
❑ Ambient Temperature	Silicon has a negative temperature coefficient of Power dP/dT = -0.45%; As temp rises, solar cell power o/p decreases, Typically, 1 Watt / 1 C rise in a 240-Wp PV module.
❑ Cable loss & Soil age	2% (typ) Losses due to cable drop lowers PV Module's o/p power. Hence copper cables.
❑ Conversion efficiency, ή	Solar Cell = 18 to 19% PV module = 15 to 16%
❑ Inverter efficiency	Typically 96%
❑ Transformer efficiency	98%
❑ Grid	In a grid-connected Solar PV Power Plant, availability of HT supply (grid) within desired range of voltage & frequency is essential. An express feeder is required.

Table 2. Comparison of conventional (fossil fuel) and solar PV power plants

A comparison : Conventional vs. Solar PV Power Plant

Feature	Thermal Power	Solar PV Power
Plant Area per MW (in Acres)	0.25	5
Cost or Power Plant per MW (in Rs. Cr)	5.5	6.5
Time to establish Power Plant (in Months)	24-36	6-9
Service Life of Power Plant (in Years)	20-25	20-25
Price of Electricity per unit-kWhr (in Rs.)	4.5-5.5	6.0-6.5
Fuel required	Coal, Water	Sunlight
Emission Level	Significant (SO_2, CO_2, CO, NO_2, SPM)	Nil
Maintenance Work	Significant	Relatively Less
Operating Personnel (per MW)	4 (typ for 1000 MW plant)	5 (typ for 5 MW plant
Abundance Value of Raw Material (Estimated Depletion Period in Years)	Coal >100	Silicon: Not estimable 2nd most abundant element in earth's crust
Plant Operational Hazards	Many	Few

Figure 11. A Stroke of Solar: 'We should put a solar power satellite into orbit. Such a satellite can supply clean power and it will be a solution to our power problem' – Bharat Ratna A. P. J. Abdul Kalam (2012).

and prior to final packing. Today's component failure rates are sufficiently low and facilitate product warranties of 25 years (end-of-life) with output power of 80% of the nominal rating.

The potential of PV technology seems enormous, but industrial and economic impact of such possibilities is to be fully evaluated for service periods up to 25 years. Nevertheless, it is explicit from current global data and annual growth rates that remaining commercial and technical challenges of large-scale deployment of solar PV systems are being addressed at extraordinary speeds. As long as 120 years ago, visionaries looking through soot and smoke of the early industrial world foresaw the need for a renewable, non-polluting source of energy (Figure 11). Appleyard wrote in 1981: 'Behold the blessed vision of the Sun, no longer pouring his energies unrequited into space, but, by means of photo-electric cells and thermo-piles, these powers gathered into electric storehouses, to the total extinction of steam engines, and the utter repression of smoke.'

In the small hamlet where this writer comes from, continuous supply of electricity is a luxury. With several power outages during lean periods, many domestic gadgets such as washing machine, refrigerator, television and cooking implements become non-functional. One is left with little choice but to suffer quietly and find ways to circumvent this problem. The state of Gujarat has made pioneering efforts in generation and application of solar power and consequently, its citizens have much to cheer about the quality of power. About 1000 mega-watts of solar power were installed in the state during the just concluded year (in a total of 2500 mega-watts in the country). This initiative not only brought self-reliance to the state power utility, but also helped to restore public morale through strong governance and service. Considering the dismal need for a stable power supply in many states, would the policy makers implement mega-watt scale solar power plants in conjunction with conventional utility power? The National Thermal Power Corporation has made much progress in this approach by deploying SPV plants along its various fossil fuel plants for clean energy generation. There is little doubt that this measure will stabilize the grid power to a great extent and, just as well, silence the nouveau-critics of solar. It also serves to orient societal furore towards capability-building initiatives.

Additionally, the gains from this initiative are likely to impact both education and employment sectors in the country. Solar cell production and applications worldwide are growing at a compound annual growth rate (CAGR) of 25–30%. This stems from intense R&D efforts taking place at dedicated global research institutions (Energy Research Centre of the Netherlands (ECN); Fraunhofer Institute of Solar Energy Systems ISE, Germany; University of Konstanz, Germany; National Renewable Energy Laboratory, USA; School of Photovoltaic and Renewable Energy Engineering UNSW, Australia) in tandem with equipment designers and solar cell production companies that continuously aim at higher and higher solar conversion efficiencies. Consequently, solar cell research and process industry knowledge have become very rewarding. A few universities have taken this forward to devise academic curriculum in renewable energy and in photovoltaic technologies leading to Master's and doctoral degrees. In this context, the example of School of Photovoltaic Engineering and Renewable Energy at the University of New South Wales, Australia is worth emulating. Our country's education departments and policy makers need to act in unison and enact this process in many of our academies and university centres. Opportunities created along this direction would be lauded by young researchers and academia.

Another telling aspect of solar electricity lies in mitigation of our concern for the environment. With crude oil and coal as the mainstay (besides unreliable hydro and questionable nuclear energy sources), the ambience is far from favourable. A marked change in environment in the state of Delhi amply justifies the switch from gasoline to compressed natural gas in public transport vehicles. The Clean Air Act in the state of California mandates that automobile companies manufacture 10% of their vehicles to run on non-fossil fuels. It shall be our endeavour to generate clean energy from renewable and indigenous resources. The Jawaharlal Nehru National Solar Mission and the National Climate Change Policy are key drivers to this philosophy: Reduce dependence on fossil fuels, bring about price parity between solar electricity and conventional utility power by the year 2022.

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