FACTA UNIVERSITATIS
Series: **Electronics and Energetics** Vol. 27, N° 2, June 2014, pp. 275 - 298
DOI: 10.2298/FUEE1402275S

WHY AND HOW PHOTOVOLTAICS WILL PROVIDE CHEAPEST ELECTRICITY IN THE 21ST CENTURY

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Abstract. *With the advent of solar panels and windmills, and our ability to generate and use electrical energy locally without the need for long-range transmission, the world is about to witness transformational changes in energy infrastructure. The use of photovoltaics (PV) as source of direct current (DC) power reduces the cost and improves the reliability of PV system. DC microgrid and nanogrid based on PV and storage can provide sustainable electric power to all human beings in equitable fashion. Bulk volume manufacturing of batteries will lead to cost reduction in a manner similar to the cost reduction experience of PV module manufacturing. Future manufacturing innovations and R & D directions are discussed that can further reduce the cost of PV system. If the current trends of PV growth continue, we expect PV electricity cost with storage to reach $0.02 per kWh in the next 8-10 years.*

Key words: *Photovoltaics, Direct Current, Local Electricity, Nanogrid, Energy Policy, Batteries*

1. INTRODUCTION

The world population is currently about 7 billion and by the end of the 21st century the world population is projected to reach nearly 11 billion people [1]. Providing green energy to all human beings in equitable fashion is one of the biggest technical challenges. The costs of generating, transmitting and utilizing energy must be decreased to ensure sustainability. For any energy technology to be truly sustainable it must be environmentally friendly, conserves water, and be affordable [2]. As a solid state device, silicon based integrated circuits popularly known as “computer chips” have brought revolution in the information technology that stated in the 20th century and is continuing to shape the future world of tomorrow [3]. The use of solid-state devices for power generation, power delivery and power utilization is bringing green energy revolution in a manner similar to the role played by solid-state devices in the field of global

Received February 6, 2014
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communication [4]. In particular, photovoltaics (PV) is playing the central role in the emerging green energy revolution [5], [6]. The objective of this paper is to demonstrate that the progress made in recent years in reducing the cost of the electricity generated by PV is phenomenal and in the very near future PV will emerge as the lowest cost and sustainable electricity generation technology. For achieving the goal of lowest cost, the importance of direct current (DC) generated by PV systems will be highlighted. In addition we will also provide manufacturing innovations, research directions and energy policies that will continue to further reduce the cost of electricity generated by PV systems.

2. ENERGY SOURCES

For equitable sustainable energy scenario, we must consider environmental concerns and conservation of water for future generations of mankind. In earlier publications we have stated that nuclear energy is not economical for any country and no more new nuclear reactors should be constructed [4]-[7]. Hydro-energy, biomass energy, and geothermal energy are partially renewable, but are not totally sustainable [2]. As of today, no cost effective technology exists for producing bio-fuels. Fundamental breakthrough is required to produce cost-effective bio-fuels [2]. Consideration of renewable and non-renewable energies (Figure 1) shows that only solar and wind energies are truly renewable and can provide the ultimate in sustainable energy to meet the global energy needs of the 21st century [2].

3. WHY PHOTOVOLTAICS?

There is no direct competition between solar and wind energy, since without storage solar energy can be used during the daytime and wind energy mostly during the nighttime. However, other than the larger amount of available solar energy, there are fundamental differences between solar energy and wind energy. As shown in Figure 2 and 3, solar energy is more uniformly distributed than wind energy. 98 % of world population receives more than 3 kWh/m^2 solar irradiance per day. The other difference relates to the cost and reliability of PV systems and wind energy systems. During the last several years the annual global installation of wind energy was much more than the PV systems. In 2010, one of us predicted that due to inherent advantages, PV will take over wind and eventually we will have PV as the dominant electricity generation technology [11]. Globally in 2013, 33.8 GW of new onshore wind farms plus 1.7 GW of offshore wind capacity will be installed [12]. The total wind capacity of 35.5 in 2013 is lower than the 36.7 GW PV installed in 2013 [12]. Since 2008, solar PV panel prices have fallen well over 70 percent, with the cost of wind turbines decreasing by 40 percent during that same time. Similar to the experience of semiconductor products, the cost of PV systems will continue to decrease in coming years.

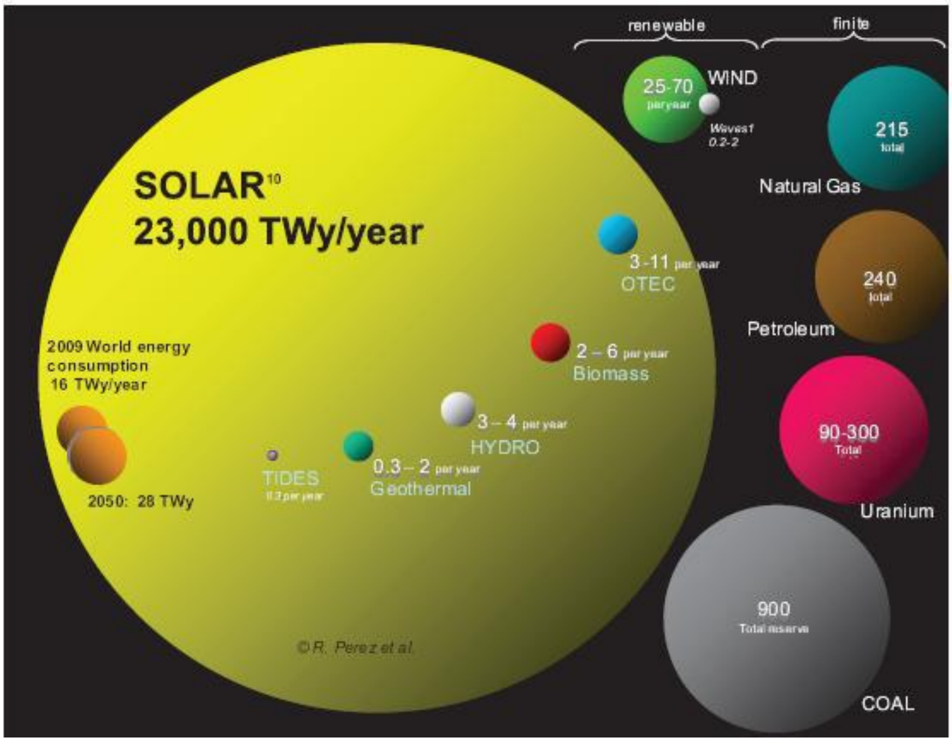

Fig. 1 Importance of Solar and Wind Energy in Global context [8]

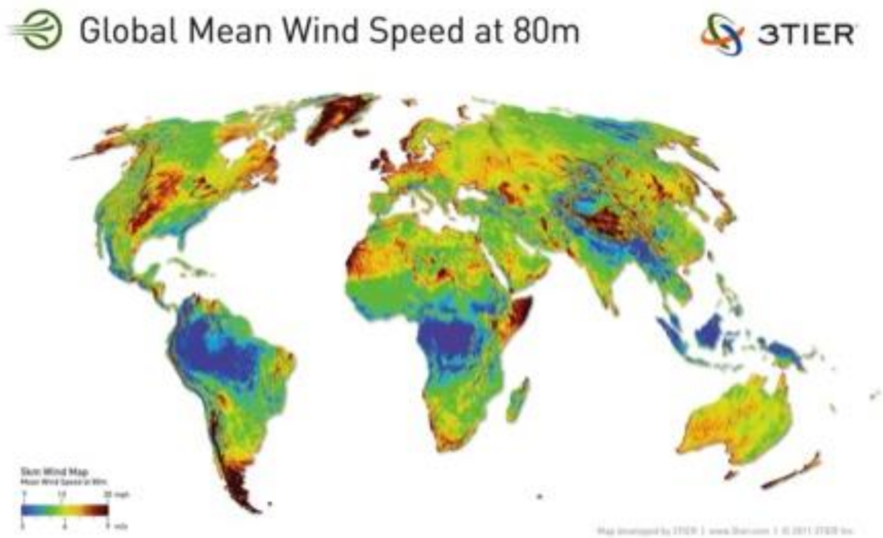

Fig. 2 Global mean wind speed at 80 m [9]

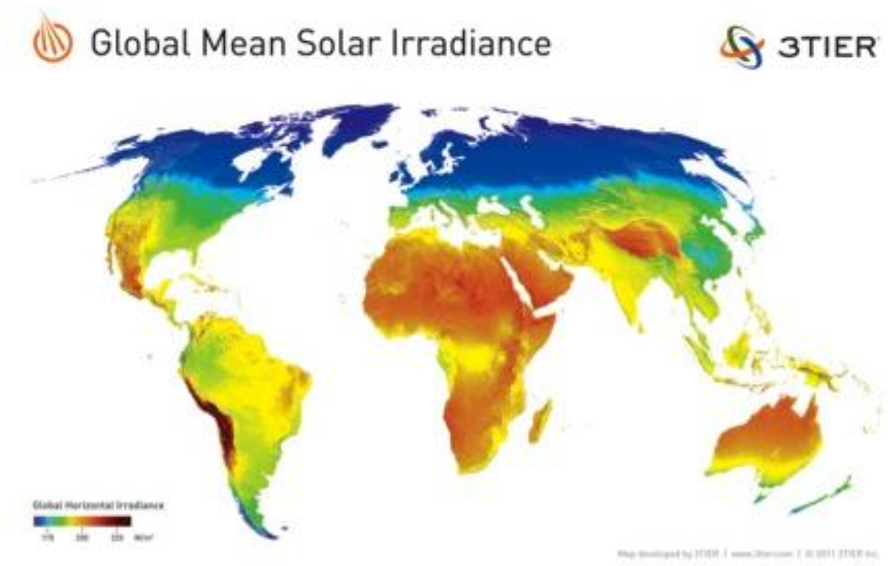

Fig. 3 Global mean solar irradiance [10]

Solar energy received on earth surface per year is about 89 PW (1 PW = 10^{15} W). 2009 global energy consumption is about 16 TW (1 TW = 10^{12}W) that is about 0.016 % of solar energy received on earth surface. The challenge is to convert the enormous amount of solar energy into electricity at lower cost than any other technique of generating electricity. Solar energy can be converted into electricity either by concentration solar power (CSP) or by photovoltaics. Due to a number of cost and reliability related factors the successful implementation of CSP is much lower than PV. As an example in 2012, installed capacity of CSP is 2.8 GW [13] while PV installed capacity is 28.4 GW [14]. In fact, between 2007 and 2012, only 7.44 GW of CSP was installed. The primary interest in CSP is due to the fact that other than optical system, the operation of CSP is similar to coal, nuclear and gas generation of electricity. Thus initially utilities were more interested in CSP than PV, however due to intrinsic cost advantages of PV over CSP the situation has changed now.

4. Important Role of PV as DC Source of Power and the Development of PV Based DC Nanogrid and DC Microgrid

Current global electric infrastructure is dominated by alternating current (AC). Due to the development of solid state dominated power electronics in the last 50 years, high voltage DC transmission has certain advantages [15] over high voltage long haul transmission and currently about 2 % of installed global generating capacity is handed by high voltage DC transmission [16]. However, except few applications, all loads around us (smart phone, lap top, refrigerator, air conditioner, light source etc.) need DC power source. Due to local generation of power by PV and the availability of power electronics to step up or step down DC voltages, it is important to visit Thomas Edison's original concept of local DC power generation [17]. In the context of 21st century power generation and utilization, Edison's concept can be extended in to two directions. Ideally the distance between electricity generation sources and loads must be at a minimum; however cost-effective solar and wind farms at a particular site also meet the requirements of the local DC power. Minimum conversion from DC to AC and or AC to DC must take place to conserve energy. According to US Energy Information Administration (EIA), local power generation is defined as electricity that is (i) self-generated, (ii) produced by either the same entity that consumes the power or an affiliate, and (iii) used in the direct support of a service or industrial process located within the same facility or group of facilities that house the generating equipment. Because of the novelty of direct use of the electricity, local electricity generation is on the rise in the United States. This increase is partly due to the compatibility of local DC electricity infrastructures, which can co-exist with existing electrical infrastructures that are based upon alternating current (AC). Regarding power storage, DC storage devices such as batteries, capacitors and fuel cells also meet the requirements of local DC electricity. In essence, the self-sufficient power network of energy generation and energy storage sources, known as the micro grid, is basically a smaller version of the larger power grid. In the absence of no external connectivity of the microgrid with the main grid, this self-sufficient PV based "Nanogrid" can generate, store and distribute its own power. Figure 4 show the structure of the proposed PV based Nanogrid. This concept is innovative in that it uses DC power generation sources, DC storage devices and minimum distance between power sources and the DC loads for the 21st century new electricity infrastructure. Rooftop PV with storage is a typical example of Nanogrid. PV based Nanogrid is also ideally suited for rural electrification where there is no existing grid.

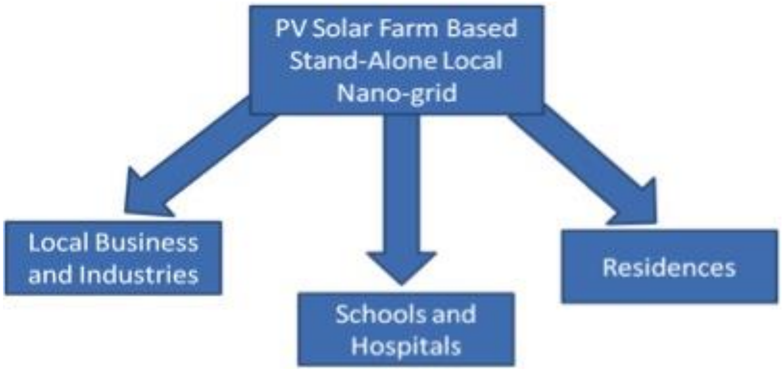

Fig. 4 PV based Nano grid for rural electrification

Though there are many components driving the growth of local DC electricity, we list the key points below:

(i) The traditional model of large base-load AC centralized electrical power generation and long haul distribution via high-voltage transmission and low voltage lines causes huge losses of energy and costs required to operate such systems. As clearly shown in Table 1, approximately 70% of electricity produced is lost in generation, transmission and distribution. Assuming that the cost of electricity is \$0.1/kWh, the annual energy loss amounts to about 40 trillion dollars.

(ii) Direct Current (DC) electricity locally generated by renewable energy sources such as solar panels and wind mills, and used with a minimum conversion (DC to AC or AC to DC) and minimum transmission can reduce energy losses by as much as 30% or more energy that is typically lost in AC generation, transmission, and distribution.

(iii) Unlike 20th century technologies, the cost of generating local power generated from solar PV and wind systems is decreasing daily, with the substitution of DC for AC power further reducing that cost. The cost of centralized AC power generation, however, has either increased or remained unchanged during that time. Wind and solar generated power is cheaper than coal-fired power plants when factoring the social costs of carbon. Some utilities are now using more PV as it has become more cost-competitive with natural gas. US companies are increasingly turning to solar panels and DC microgrid to offset energy costs. In Minnesota, for example, roof-top PV electricity cost 36-75% less than natural gas during peak delivery times. Steam generation by PVforso-called enhanced oil reserve projects costs about \$5 to \$7 per million British thermal units of energy, half of the \$12 to \$18 price for liquefied natural gas [18].

(iv) DC based PV and wind power systems are more reliable than AC based systems. While the inverter cost is less than about 20% of PV system cost, any system malfunction can shut the system down, with a total loss in energy production [19]. Wind turbines are more reliable in DC configurations, due to the greatly reduced complexity of the mechanical transmissions that are required for turbine AC generation [16].

(v) PV systems are extremely reliable. After almost 20 years of continuous outdoor exposure, silicon PV module average performance decay is only 4.42% for the whole period [20]. Reliability results guarantee safe investments, for the benefit of all PV users and stakeholders [20].

(vi) Batteries, capacitors, and fuel cells are used to store DC electricity. The use of AC in place of DC increases the cost of storage device, as with batteries in which AC based storage systems increase their cost to as much as 50 % [21].

(vii) Increase in energy efficiency translates to job creation and economic growth. According to the Energy Information Administration the electricity consumed in the US in 2011 was 3,839 Billion kWh and is expected to increase by 0.91% annually until 2040. Assuming that by 2015 the DC electricity is used for 10% of generation and distribution of the electricity consumed in US, more than 60,000 jobs will be created.

(viii) Integrated circuits and other solid state devices revolutionized virtually every facet of human life. Except very few cases, (e.g. certain motor-based systems), all other loads require DC power. For example, unlike old cathode-ray tube televisions, solid-state TVs do not use AC current. Similarly, though lighting consumes about 20% of the electricity produced worldwide, it too uses DC power. Also, unlike DC current, typical AC based cell phone chargers waste approximately 20-35% energy used [16]. Electrical vehicles do not require AC power for charging batteries. With revolution in the IT industry, more semiconductor-based electronics are being used, with a concurrent increase in DC loads and a decrease in AC loads.

(ix) Battery-based hybrid and electrical vehicles and solid-state based LED lighting are transforming the transportation and lighting industries, both of which are powered by direct current.

(x) Energy-efficient appliances use adjustable speed motor drives in which a rectifier converters the AC from the grid into an internal DC bus voltage. Though one option entails directly powering the appliances from a DC source, it is also possible to redesign appliances without these embedded rectifiers. Such redesigns may require a refit of manufacturing facilities, state and/or federal government subsidies and related financial incentives to the consumer can offset the costs. Globally, 268.1 million major appliances were sold in 2012. Developing public policies to offset the cost of retrofitting manufacturing factories and exporting this new technology will create many new jobs

(xi) A DC nanogrid is the key-enabler of the "zero energy building model." With minimum wastage in transmission and conversion, the use of locally generated DC electricity can provide 100% energy needs of a building.

Table 1 2008 World Energy Consumption by Sector
[Source: US Energy Information Administration (EIA)]

End-Use Sectors	Energy End-Use includes end-use of electricity but excludes losses (quadrillion Btu)	Electricity Losses includes generation, transmission, and distribution losses (quadrillion Btu)	Total Energy Use includes electricity losses (quadrillion Btu)	Share of Total Energy Use (quadrillion Btu)
Commercial	28	32	60	12%
Industrial	191	64	255	51%
Residential	52	37	89	18%
Transportation	98	2	100	20%
Total End-Use Sectors	369			
Electric Power Sector	194			39%
Total Electricity losses	135			
Total Energy Use	505			

5. Global Manufacturing Advantages of PV Generated DC Electricity

Cutting energy costs increases the competiveness of manufacturing industry and saves jobs worldwide, the energy cost of which in some cases is as great as one-third of the operating cost of the manufacturing plant. This is typically true for aluminum plants and many other high energy consuming manufacturing industries. As shown in Table 2 [22], aluminum plants lose 6.3% of the total energy due to conversion from AC to DC current, a process that cannot be avoided today. Based on World Aluminum data, 93,576thousand metric tons of aluminum was produced in 2012. Using the average data of Table 2 and an electricity cost of $0.1/kWh, a net saving of $9.6 Billion is possible through the use of DC instead of AC power. Similarly, other high energy consuming industries (such as the pulp and paper industries) can also be retrofitted for DC current.

Table 2 2012 Data of Energy Consumed in Producing One Ton of Aluminum [22]

Nation or Region	DC Energy (kWh)	AC Energy (kWh)	% Loss in Current Plants
North America	14,540	15,458	6.31
World	13,756	14,639	6.42
China	13,014	13,844	6.38

As clearly indicated in Table 3 [23], different AC standards of voltage and frequency are used in different countries. Japan, however, is an exception in that two sets of frequency standards are used in that nation. The worldwide adoption of DC power can prevent such a redundancy of effort by providing uniform voltage standards worldwide, thus reducing the cost of related power electronics to yield an overall lower manufacturing cost of every DC based electrical system.

Table 3 Voltage and Frequency Standards of 16 Developing/Developed Nations [23]

Country	Voltage (V)	Frequency (Hz)
Australia	230	50
Brazil	110 and 220	60
Canada	120	60
China	220	50
Cyprus	240	50
Egypt	220	50
Guyana	240	60
South Korea	220	60
Mexico	127	60
Japan	100	50 and 60
Oman	240	50
Russian Federation	220	50
Spain	230	50
Taiwan	110	60
United Kingdom	230	50
United States	120	60

6. CURRENT STATUS OF PHOTOVOLTAICS

As shown in Fig. 5, by the end of year 2012 the cumulative installed solar PV electricity generation capacity has exceeded 100 GW and is expected to double from about 100GW in 2012 to 200GW in 2015 [24]. The installed capacity of PV is expected to reach 36 GW and 49 GW by the end of year 2013 and 2014 respectively [25]. The large-scale solar PV market that is comprised of rooftop projects above 100 kilowatts (kW) in size and ground-mounted solar PV projects is about 26 GW in 2013 [26]. Based on manufacturing considerations discussed at length in earlier publications [5], [27]-[29] silicon based PV modules will continue to dominate PV market. Fundamentally, there is nothing wrong in assuming that concentration photovoltaic (CPV) systems should provide lower cost compared to non-concentration solar cells. However the engineering problems that include the thermal and optical challenges have not permitted the large-scale commercialization of concentration solar cells (Fig. 6). The average cost of installed PV system for various segments of US market is shown in Fig. 7 [31]. Average solar PV system coast for various sizes and locations in Australia is given in Table 4 [32]. The cost of PV modules for various countries is shown in Fig. 8 [33]. The data of Fig. 7, Fig. 8 and Table 4 clearly indicate that we are reaching towards PV module and installed PV system cost of $\$0.50/W_p$ and $\$1.00/W_p$ respectively. As shown in Fig. 9 and Fig. 10 European Union (EU) has dominated the PV market in the past and China, Japan and US are currently dominating the PV market. PV module manufacturing share in 2013 is dominated by companies based in China and Taiwan [34]. In 2013, only one US based PV Company (First Solar) is in top 10 PV manufacturers list [34]. However, PV growth in US is significant, since water conservation advantages of PV are quite important [35].

Table 4 Installed Cost of PV system in Australia (1 Australian $~$0.87 US $) [32]

Solar Choice: Solar PV system price, $/Watt - Jan 2014							
		1.5kW	**2kW**	**3kW**	**4kW**	**5kW**	**10kW**
Adelaide, SA	Average	$2.68	$2.37	$2.00	$1.88	$1.78	$1.65
	High	$3.53	$3.25	$2.36	$2.10	$2.06	$1.95
	Low	$2.12	$1.94	$1.64	$1.65	$1.58	$1.39
Brisbane, QLD	Average	$2.20	$2.19	$1.90	$1.77	$1.64	$1.70
	High	$3.86	$2.99	$2.67	$2.25	$2.20	$1.95
	Low	**$1.33**	$1.65	$1.33	$1.27	$1.21	$1.45
Canberra, ACT	Average	$2.89	$2.37	$2.14	$2.08	$1.98	$1.98
	High	$3.99	$2.79	$2.53	$2.40	$2.28	$2.01
	Low	$2.28	$2.14	$1.91	$1.83	$1.71	$2.01
Melbourne, VIC	Average	$2.91	$2.45	$2.12	$1.92	$1.80	$1.77
	High	***$4.46***	***$3.34***	***$2.68***	***$2.47***	***$2.36***	***$2.13***
	Low	$2.22	$2.00	$1.68	$1.57	$1.42	$1.35
Sydney, NSW	Average	$2.13	$1.94	$1.73	$1.63	$1.59	$1.53
	High	$2.97	$2.72	$2.26	$2.01	$1.95	$1.95
	Low	$1.43	**$1.36**	$1.43	$1.39	$1.37	$1.06
Perth, WA	Average	$1.77	$1.74	$1.57	$1.54	$1.52	$1.79
	High	$2.06	$1.88	$1.99	$1.85	$1.94	$1.85
	Low	$1.50	$1.40	**$1.18**	**$1.06**	**$1.03**	**$1.73**
All	**Average**	**$2.65**	**$2.35**	**$2.07**	**$1.94**	**$1.84**	**$1.80**
	High	**$4.46**	**$3.34**	**$2.68**	**$2.47**	**$2.36**	**$2.13**
	Low	**$1.33**	**$1.36**	**$1.18**	**$1.06**	**$1.03**	**$1.06**

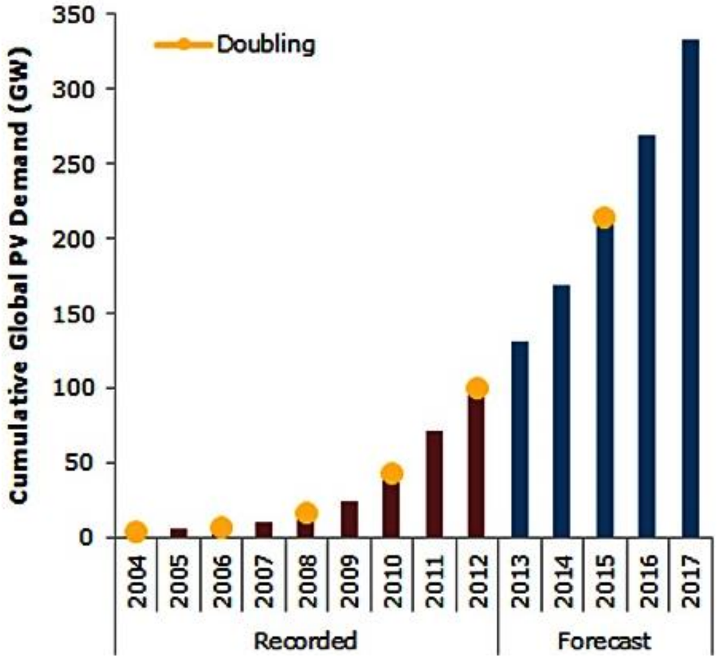

Fig. 5 Global Growth in PV electricity generation capacity worldwide [24]

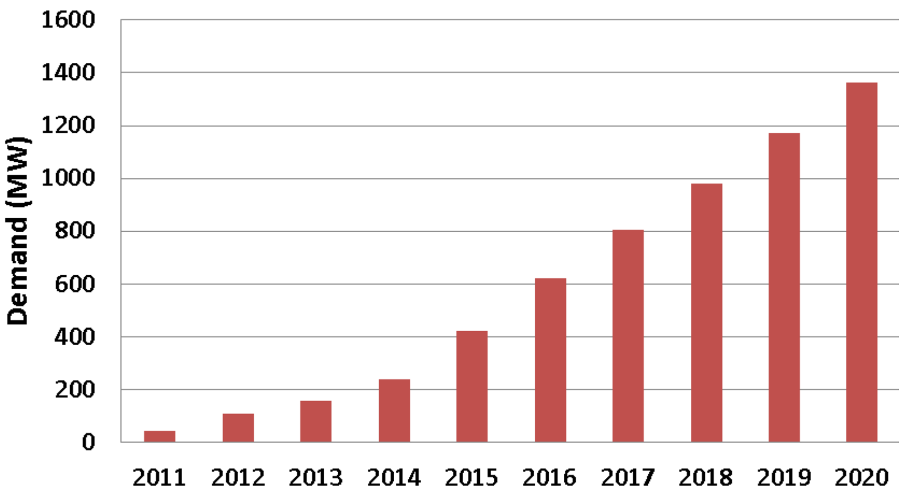

Fig. 6 Past, current and projected market of CPV [30]

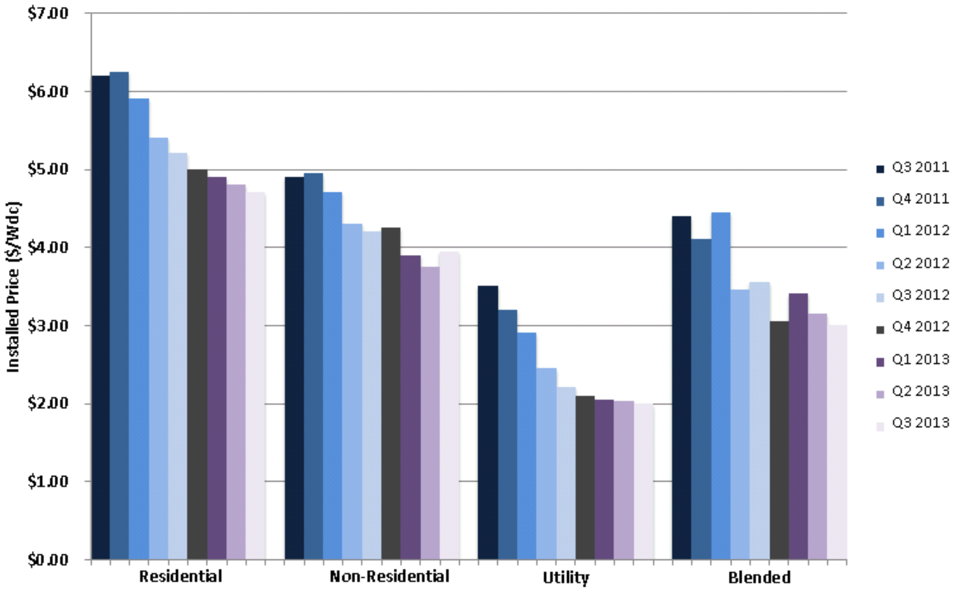

Fig. 7 Average installed prices of PV system in US for various market segments [31]

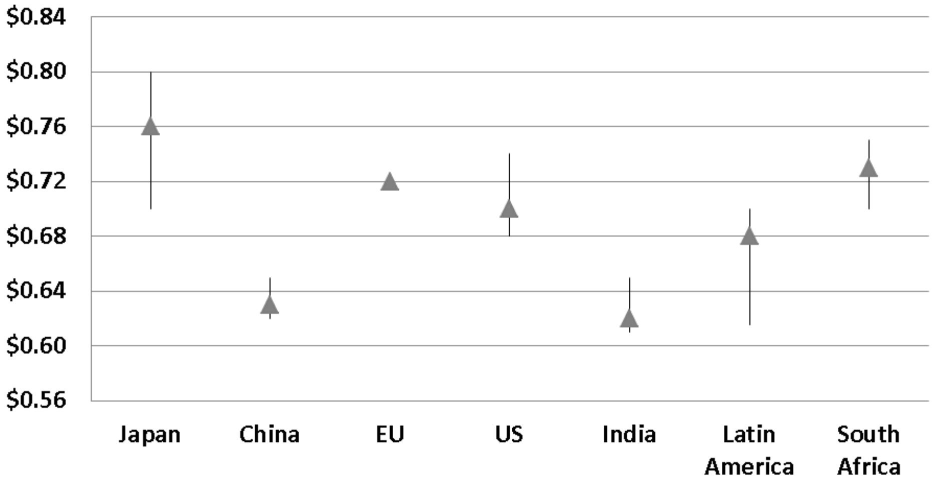

Fig. 8 Silicon PV module prices for various countries [33]

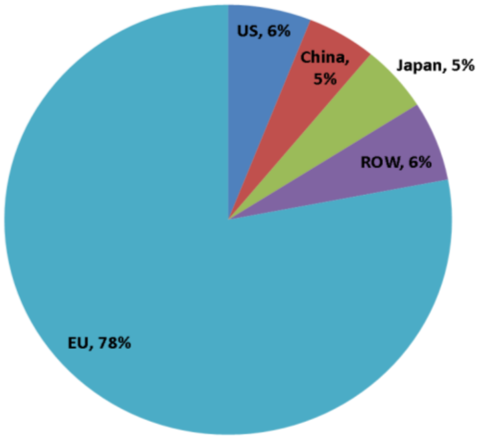

Fig. 9 Dominance of European Union PV market between 2007-2011 [33]

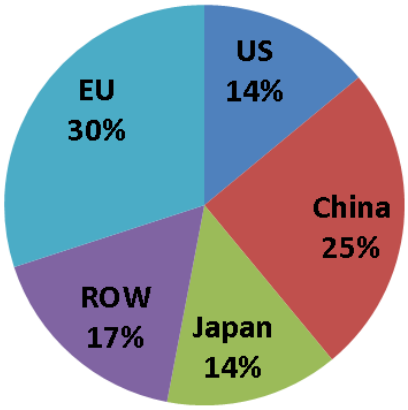

Fig. 10 Dominance of China, Japan and US PV market between 2012-2016 [33]

7. Manufacturing Innovations Leading to Constant Reduction of PV System Cost

As we have stated before more than 90% of the installed PV capacity employs bulk-silicon solar cells. The rise in PV market (Fig. 5) and innovation in materials and processing leads to reduced cost of silicon solar cells (Fig. 11). The highest reported AM 1.5G efficiency of silicon solar cells and silicon PV modules are 25 % and 21.5 % respectively [29]. Except some minor improvements, no major improvement is expected in increasing the efficiency of silicon solar cells. Further cost reduction will be achieved by using thinner wafers, building new process equipment with higher throughput, lower defect density and reduced foot print. All the new tools must provide lower cost of ownership [29] than current manufacturing tools. In a recent publication [37] we have shown that as compared to conventional furnace processing and rapid thermal processing, the use of ultra violet (UV) and or vacuum ultra violet (VUV) photons enhances the diffusion coefficient of dopants by many orders of magnitudes. As shown in Figure 12, for wavelength below about 0.3 micrometer, the diffusion coefficient is higher by two to four order of magnitudes Thus in case of rapid photothermal processing (RPP), other than thermal energy, the VUV photons are used as an additional source of optical energy. The principal advantages of RPP over other thermal processing techniques are (i) lower density of defects, (ii) minimum process variation, (iii) higher throughput, and (iv) lower deposition temperature. Based on a conservative estimate, we expect that the throughput of RPP based diffusion and annealing tools will be at least an order of magnitude higher than current thermal processing tools.

Similar to silicon integrated circuit (IC) manufacturing (Fig. 13), PV manufacturers can use larger size substrate to further reduce the cost of silicon solar cells. Gigawatt PV system manufacturing shown in Fig. 14 will provide the ultimate lowest cost of PV system.

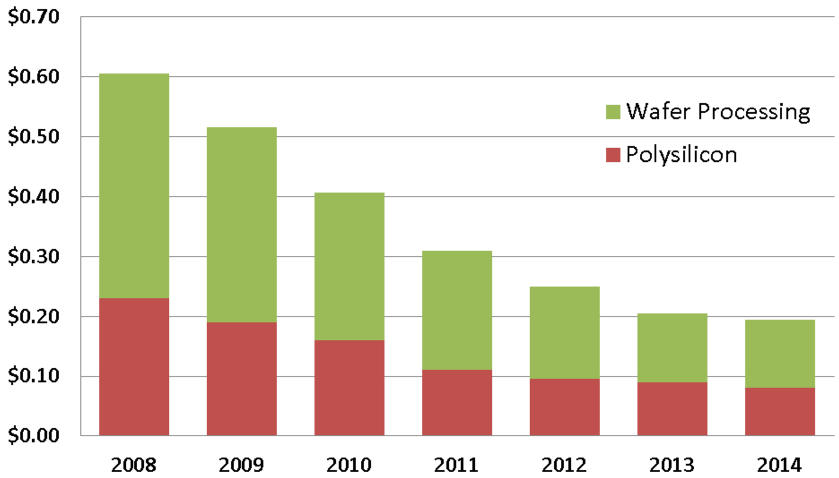

Fig. 11 Innovations and supply-chain advantages leading to low-cost of silicon solar cells [36]

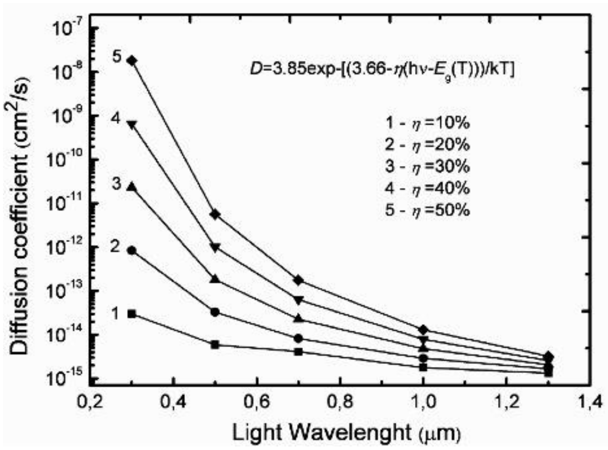

Fig. 12 Diffusion coefficient under vacuum ultra violet (VUV) photons [37]

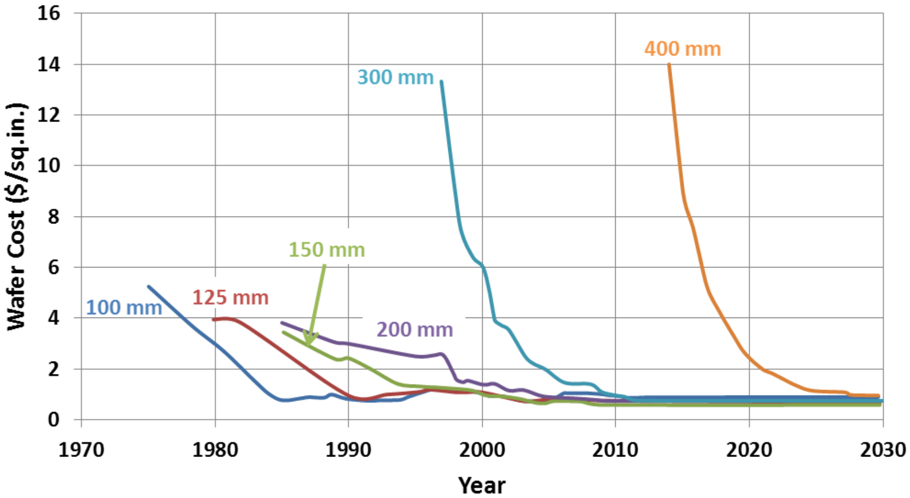

Fig. 13 Use of larger wafer size by silicon IC manufacturers to reduce the cost of silicon based ICs [38]

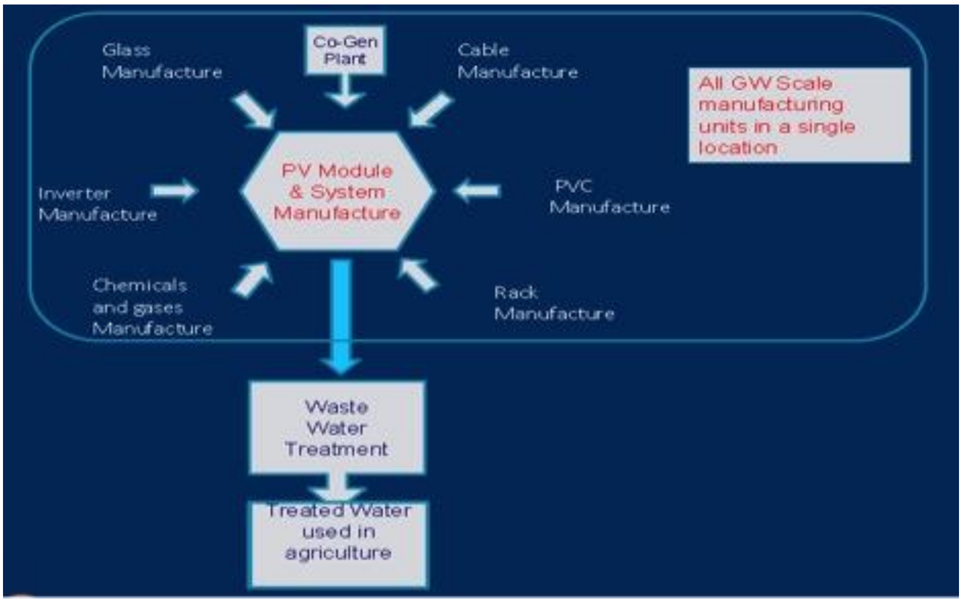

Fig. 14 Giga Watt Scale PV system manufacturing will lead to ultimate lowest cost of PV system

8. R & D DIRECTIONSTHAT CAN LEAD TO FURTHER REDUCTIONS OF COST OF PV SYSTEM AND LEAD TO NEW APPLICATIONS OF PV

In a recent publication [29] we have shown that most of the research community is working in areas that either has fundamental flaws or does not meet fundamental manufacturing requirements. Interested reader should read reference [29]. Since the publication of reference [29], lead halide perovskite solar cell [39] has received lot of publicity. Following are the main reasons that this type of solar cell will never be manufactured:

(i) As a single junction solar cell, silicon cannot be replaced by other solar cells, unless the abundant materials based solar cell has at least 30 % efficiency of large area cells.

(ii) The use of lead in the solar cell reported in reference [39] does not meet the manufacturing requirements.

(iii) The area of the high efficiency solar cell reported in ref. [39] is less than 0.1 cm^2. The authors of reference [40] reported that any silicon solar cell with area less than 0.25 cm^2 would not show the efficiency degradation due to series resistance effects. In other words, simply scaling to larger size of area less than this critical size will lead to significant reduction in efficiency. Using AM 1.5G spectrum and other data as used in theoretical calculations in ref. [29], we have used method of reference [40] to calculate the minimum solar cell area that should be used in reporting any new type of solar cells. These results are shown in Fig. 14.

(iv) The band gap of lead halide perovskite of 1.5 eV is not optimum for multi-junction multiterminal solar cells [29].

(v) The use of graphene in lead halide perovskite solar cell will lead to significant process variability and the performance of module will be worse than other thin film materials (CdTe, CIGS and a-Si) used in manufacturing thin film PV modules [29]. Thus module based on lead halide perovskite solar cells will not be able to complete with existing thin film PV modules.

Based on solid scientific and engineering principles, following are productive R &D directions that can lead to advancement of PV module manufacturing:

(a) Multiterminal multijunction solar cells

The next major improvement in the performance and cost reduction of silicon solar cells can be achieved by taking advantage of both bulk silicon and thin film solar cells. In reference [29] we have introduced the concept of multiterminal multijunction solar cells. Fig. 15 shows the concept for two terminals four junctions device. The optimal band gap of top junction should be about 1.8 eV.

(b) Thin Film Solar Cells For Building Integrated Photovoltaics (BIPV)

Enormous opportunity exists to convert glass used in the construction of every building for generating PV electricity. The low efficiency leading to high cost of existing commercial thin film for BIPV application is the major barrier. Reliability of BIPV must be very high, since glass does not degrade under normal weather conditions.

(c) Use of PV in Transport Sector

All kind of vehicles used in transport sector can use PV for power generation [7]. Limited surface area of the vehicle requires high efficiency and low-cost of PV modules. Mounting of PV modules on surface of the vehicle requires innovative design concepts.

(d) Integration of PV and Consumer Products

With rise in the number of consumer products used by modern man, there is need to use ambient light to convert into electricity. This will require innovation in the integration of PV and consumer products. Recent patent filed by Apple demonstrate the importance of this area [41].

(e) Use of PV Electricity for Desalination

PV electricity can be used for desalination. However, to reduce the cost of drinkable water the design of PV system and desalination must be reconsidered to conserve energy.

(f) PV as Source of Combined Heat and Power

The unused part of the spectrum by PV can be used to collect heat generated by the PV system. However, cost effectiveness of such a CHP system has not been proven.

(g) Solid State Capacitor as Energy Storage Device

The fundamental problem of the current capacitor technology is the low value of capacitance density.Based on ultra-high dielectric constant (k) materials ($k > 10^6$) solid-state capacitors have the potential of providing high energy and high power density. Unfortunately, currently, due to defects in the material the dielectric constant degrades with both electric field and temperature and the leakage current is very high. Finding a solution to all these problems can provide a cost effective large-scale solution of storing electric energy

(h) Use of Nanostructures in the Fabrication of Solar Cells

For almost two decades, the buzzword "nanotechnology" has been advocated by a large group of researchers to improve the efficiency of solar cells. However, to date there is not a single work where the efficiency of nanostructure based solar cells for terrestrial applications has exceeded the efficiency of bulk solar cells. In previous publications we have critically examined the role of nanostructures for solar cell applications [29],[42]-[44] and the summary of our findings is reported here.

Figure 16 shows the quantization of properties as the dimension changes from "3-D" to "0-D".The 2-D properties of quantum wells have been exploited very well in the fabrication of III-V solar cells. The use of self-assembly for 2-D and 1-D nanostructures may provide properties of isolated structures as expected theoretically. However, when self-assembly is used in device fabrication, the process variation results into lower efficiency devices. Further when such devices are used in module manufacturing, the lowest performance device will dictate the efficiency of the modules. As shown in Figure 17 [46], the quantum dot or "0-D" devices shows increase in the value of energy gap in the quantum confinement region. Below 8 nm, the band gap of silicon quantum dots increases (Figure 18). There is no experimental proof that at any given wavelength quantum dots can provide quantum efficiency greater than one. Similarly there is no experimental proof that hot electrons can provide higher efficiency than normal operating devices. As discussed at length in reference 29, the concept of intermediate band gap is flawed and one cannot get higher conversion efficiency than the normal bulk material solar cell.

There is need to invent new control processes so that the unique properties of nanostructures can provide tolerable process variation. In the absence of such processing tools, no practical devices can be made where one can exploit the unique properties offered by the nanostructures.

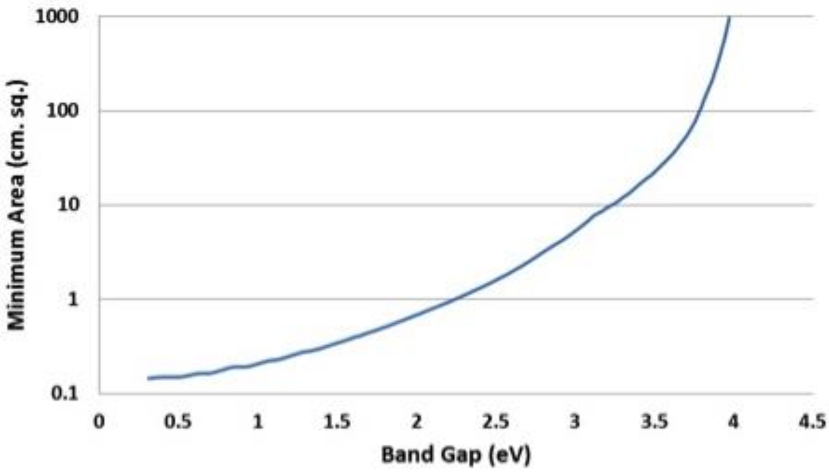

Fig. 15 Minimum solar cell area as a function of band gap to observe the degradation of efficiency of solar cell.

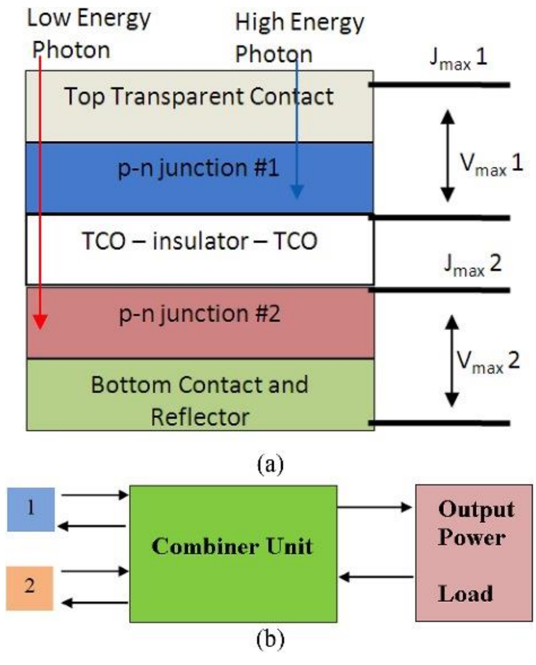

Fig. 16 (a) Schematic of the proposed two-junction four-terminal solar cell. (b) External electric circuitry to combine the electricity generated separately by the two junctions.

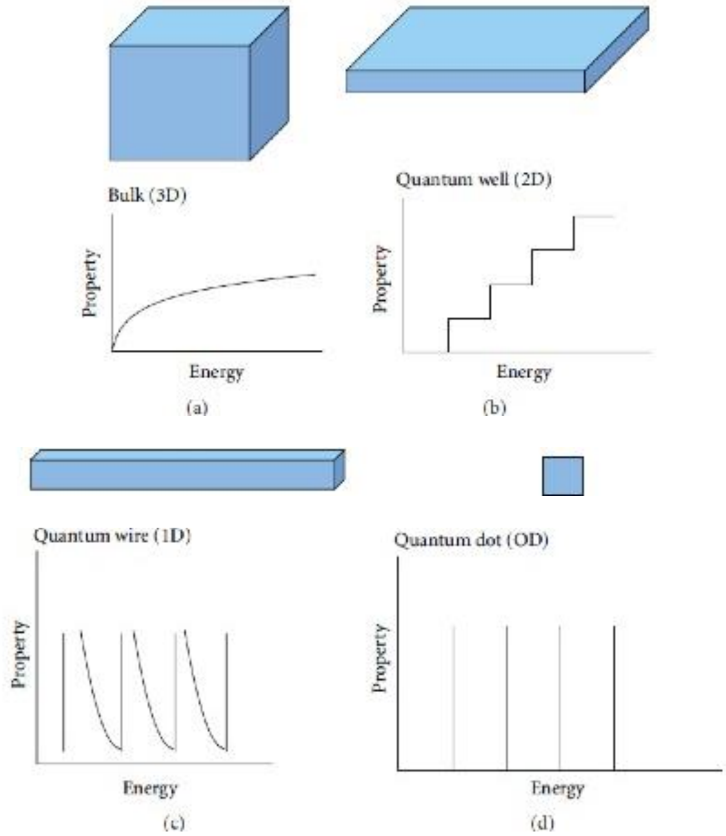

Fig. 17 Quantization of properties with scaling of dimensions [45]

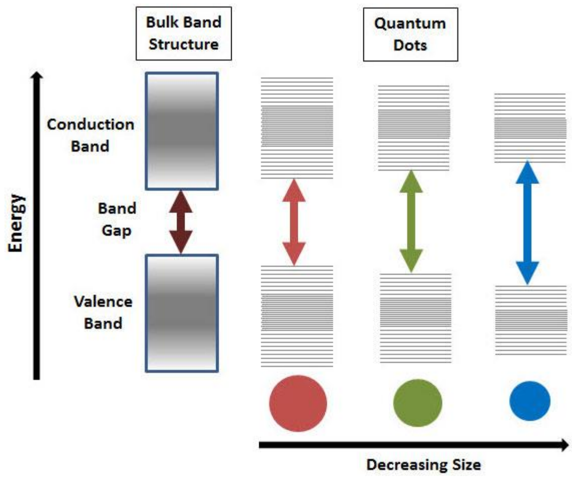

Fig. 18 Increase in energy gap with decrease in the size of quantum dot [46]

9. STORAGE OF ELECTRICITY GENERATED BY PV

Batteries [21], ultracapacitors [48] and fuel cells [49] are all useful for storing DC electricity. Other than safety issue, fuel cells are expensive. Significant progress has been made in recent years to reduce the cost of batteries. Also the increasing use of EVs [50] and large-scale grid storage [51]-[53] will increase the demand of batteries. Similar to the experience of cost reduction of PV by volume manufacturing (Fig. 19), the cost reduction of battery prices will continue. Indeed, utility scale battery storage is now competitive with natural gas in the US; EOS Energy storage Inc. has developed a battery system that costs approximately $160/kWh [21]. Semiconductor manufacturing techniques can also further reduce the cost of batteries. Similar to solar cells [29], the use of a series and parallel combination of various cells in batteries yield the desired watt-hours of the battery. The equipment used in battery manufacturing is generally based on statistical process control, and the resultant process variations leads to variations in the output of various cells of the battery. Advanced process control can reduce this process variation resulting higher power out from the same battery. In addition, large scale manufacturing of batteries in a single location will provide tight control on supply chain and further reduce the cost of batteries.

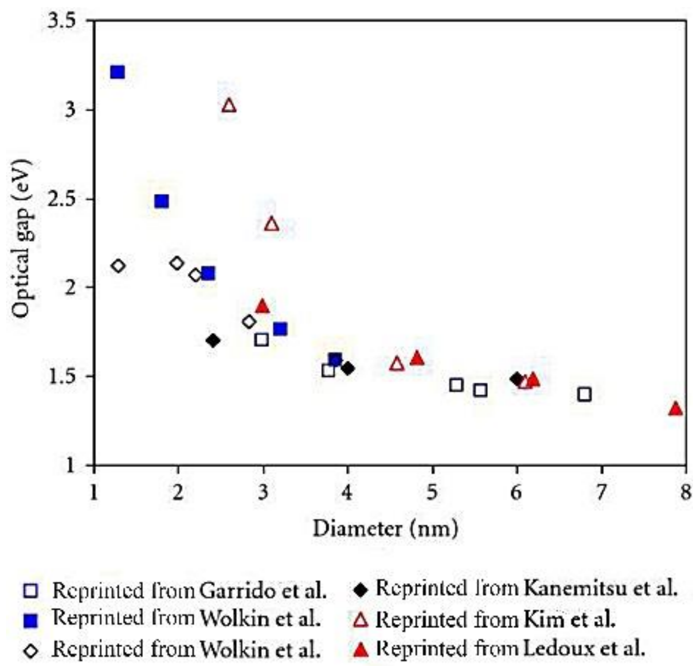

Fig. 19 Experimental results on the variation of optical bandgap of nanostructured silicon with diameter of silicon nanograins [47]

10. MISCONCEPTION ABOUT SUBSIDIES

In the context of PV, wind energy and other renewables, there are many misconceptions regarding the concept of energy subsidies, a review of which is provided elsewhere [55]. Globally, fossil fuel industries receive nearly $1 trillion a year in subsidies, approximately twelve times of that allocated to the renewables industry [56]. Most alarmingly, nearly 43% of subsidies to fossil fuel industries in the developing world end up in the pockets of the richest 20%; only 7% go to the bottom 20% of households [57]. Eliminating subsidies for oil, gas, coal and other fossil fuels would make a significant dent in curbing global warming pollution [56]. In Table 5 we provide a historical average of US federal energy subsidies. Similar situation exists in other parts of the world.

Table 5 Historical Average of Average Federal Energy Subsidies in US [55]

Energy Source	Subsidies 2010 $Billion
Oil and Gas	4.86
Nuclear	3.50
Biofuels	1.08
Renewables	0.37

11. PHOTOVOLTAICS AND THE FUTURE OF UTILITIES

The traditional business model of the utility “investing in equipment, turning meters, and earning steady profits” is undergoing a transformational change with the emergence of rooftop PV leading to new business models [58]. Rooftop PV dominated concept of the DC microgrid poses no threat to a utility industry that is willing to adapt to rapid technological changes in the power industry that PV, storage, power electronics and wind technologies will accelerate. If the utility fails to adapt to these all but certain developments, they will become as archaic as the Sears Catalog business of the 20^{th} century.

13. ENERGY POLICY ISSUES

The worldwide adoption of PV generated DC power is a wise global public policy move in terms of sustainability and economic growth of developed, developing and underdeveloped economies PV trade war between any two countries is not in the best interest of any nation [59]. A new business model that capitalizes the buying power of a nation or group of nations further reduce the cost of implementing PV generated DC power. The real or virtual vertical business model [2] will lead to the lowest cost of PV electricity generated by either the DC microgrid or DC nanogrid.

14. PHOTOVOLTAICS FOR UNDERPRIVILEGED PEOPLE (PUP)

Economic disparity is a serious issue, since the 85 richest people are as wealthy as poorest half of the world [60]. Globally, 2.5 billion people in the developing world rely on biomass (fuel from wood, charcoal and animal dung) to meet their energy needs for cooking and other daily necessities. The continuous decrease in cost of PV generated electricity is now making it possible to provide electrical energy to those populations who can be served entirely by PV generated DC electricity. Similar to the explosive growth of cell phones (no need of land lines), PV combined with a DC energy distribution system will provide badly needed clean alternatives to dirty sources of fuel. Unlike developed economies, in which replacing an aging electricity infrastructure is a challenge, implementing a new low-cost DC power system infrastructure in developing economies that have no such infrastructures is a much easier proposition. A PV based DC Nanogrid (Figure 4) is the most practical low-cost method of providing cost effective electricity to such developing societies worldwide. Indeed, the market size is huge and the societal implications are monumental. United Nations, World Bank, developed, developing and underdeveloped countries need to work together and invent new real or virtual business model as shown in Fig. 20. Underdeveloped countries do not have the technology or capital to manufacturer PV systems, new business model must be developed where the combined purchasing power of the underdeveloped countries must be considered as a single entity and the developed economies or developing economies gets a huge market share without investment on marketing. The power situation in emerging and underdeveloped countries is a serious issue. As an example shortage of electricity in India is a significant hindrance in economic growth [7]. Although not an optimal low-cost engineering solution, under desperation India is running a pilot project where each customer will get uninterrupted 100 W DC power that will be obtained from each substation and run on a separate lime and separate meter [61]. Nanogrid for underprivileged people is also a solution of national security [62], [63]

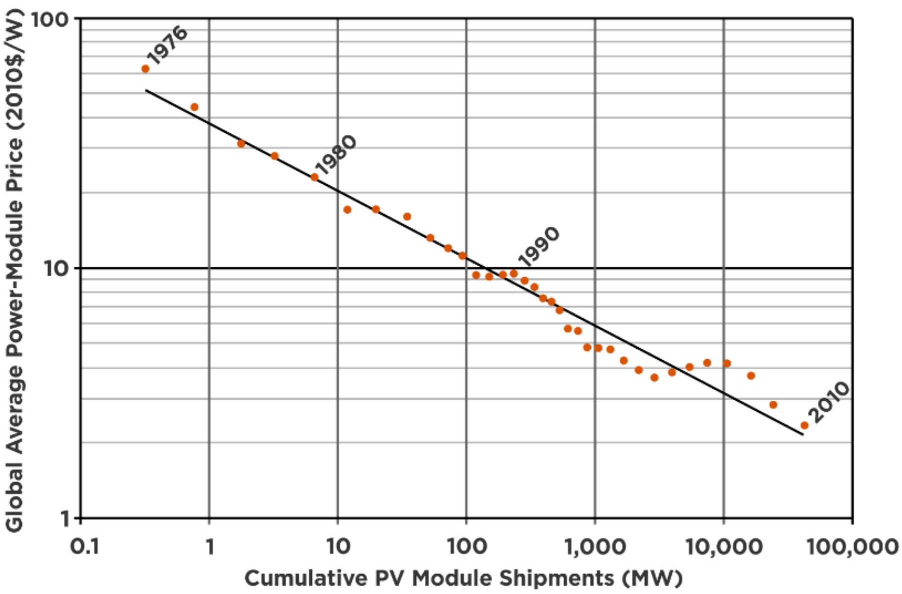

Fig. 20 Doubling the volume manufacturing reduces the PV module prices by 20 % [54]

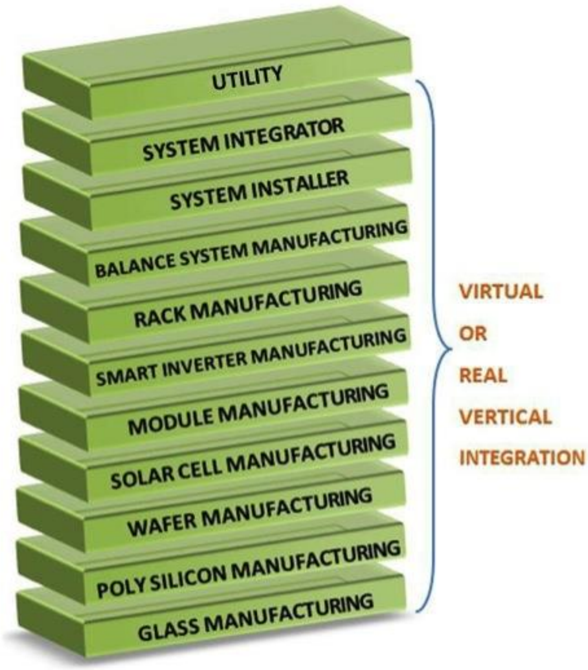

Fig. 21 Proposed virtual or real vertical integrated business model will provide lowest cost of solar electricity

15. Concluding Remarks

In this paper we have provided an in depth review of Photovoltaics for generating sustainable green electricity in the 21st century. The importance of PV is examined from global perspective. Without storage the cost of PV system is approaching less than about \$1per peak watt, which can provide DC electricity generation cost of about \$0.02- \$0.03 per kWh for most of the World's population. We have identified future manufacturing innovations and R & D directions that can further reduce the cost of PV system. Bulk volume manufacturing of batteries will lead to cost reduction in a manner similar to the cost reduction experience of PV module manufacturing. For underprivileged people, United Nations and World Bank need to seriously think about PV and develop a new vertically integrated business model that can capitalize the buying power of the underprovided people living all over the world. Current trends of PV market growth are such that in about two years the market size doubles. If this trend continues, we expect Terawatt (1,000 GW) PV installations by the end of this decade. Under this scenario we expect PV electricity cost with storage to reach \$0.02 per kWh in the next 8-10 years.

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