PHOTOVOLTAICS IN A TRANSITION WORLD TOWARD RENEWABLE ENERGIES

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1. INTRODUCTION

Our sun is the only sustainable energy source large enough to supply carbon-neutral energy to meet humanity's entire energy demand. Since the fabrication of the first GaAs cell in 1956, with an efficiency of 4%, a steady effort to improve the efficiency of the cells has been undertaken achieving efficiencies in the range of 30-40% (Figure 1). The phase diagram in Figure 2 shows the relation of the bandgap and lattice constant for several III-V ternary and quaternary compounds, and the transitions between them for variations in the relative proportions in their elements, e.g. $Al_xGa_{1-x}As$. An interesting idea is the insertion of a half-filled energy band inside the energy gap of a semiconductor, in order to allow also subgap photons to be absorbed in a double step process [1]. Superlattices of quantum dots can provide an effective formation of an intermediate band, and the first devices operating with the double photon absorption process have been demonstrated [2, 3]. Plasmonics is an emerging field in optical science, based on the resonance of light and charge oscillation modes on the surface of metallic micro- or nanoparticles. With different designs it allows to trap light, to enhance the electric field, or to guide it inside a semiconductor absorbing film, like a solar cell [4]. In this way just very thin layers of expensive but efficient semiconductors like GaAs can be used to produce cost-effective solar cells.

Among renewable energies, the conversion of sunlight into electricity by photovoltaic (PV) devices is a reliable choice to tackle the growing global energy demand. From the beginning, the PV market was dominated by inorganic materials. Organic PV devices are instead in the state of advanced development and pilot production. Even if their commercialization started for indoor and low-power applications, they show efficiency, stability, and lifetime not yet comparable with inorganic devices [5].

In the last decade, the fast increase of the global energy consumption, mainly related to the strong economic growth in the Far East, and the progressive depletion of the fossil fuels induced a run-up in the world oil price. Both these economic concerns and the growing global pollution pointed out that a transition toward renewable energies is mandatory. Among renewables, the conversion of sunlight into electricity by photovoltaic (PV) devices is a reliable choice to cope the growing energy consumption, due to the huge potentially extractable power (up to 120000 TW).

Harvesting solar energy using photovoltaic devices is being increasingly recognized as an essential component of future global renewable energy generation. The key economic factor for the production of conventionally used photovoltaic cells is the expensive investment in costly semiconductor processing technologies. The concept of fabricating photovoltaic elements on thin plastic substrates, manufactured by techniques such as roll-to-roll (R2R) printing, coating and lamination, is highly attractive from an economic standpoint. Thin film PV technologies have been under development in the last decades as a low-cost alternative to bulk c-Si. Incidentally, this technology is the most suitable for large-scale production since the module is the final stage of an in-line process that does not require the assembly of discrete smaller cells [6].

Today, the vast majority of PV modules (85% to 90% of the global annual market) are based on wafer-based crystalline silicon (c-Si). Crystalline silicon PV modules are expected to remain a dominant PV technology until at least 2020, with a forecasted market share of about 50% by that time. It is expected that a broad variety of technologies will continue to characterise the PV technology portfolio, depending on the specific requirements and economics of the various applications [7].

We’re continuing to see silicon as a significant technology, and thin film technologies are growing, but there are a number of other technologies are brewing, and we're starting to see them show promise for use later in this decade.

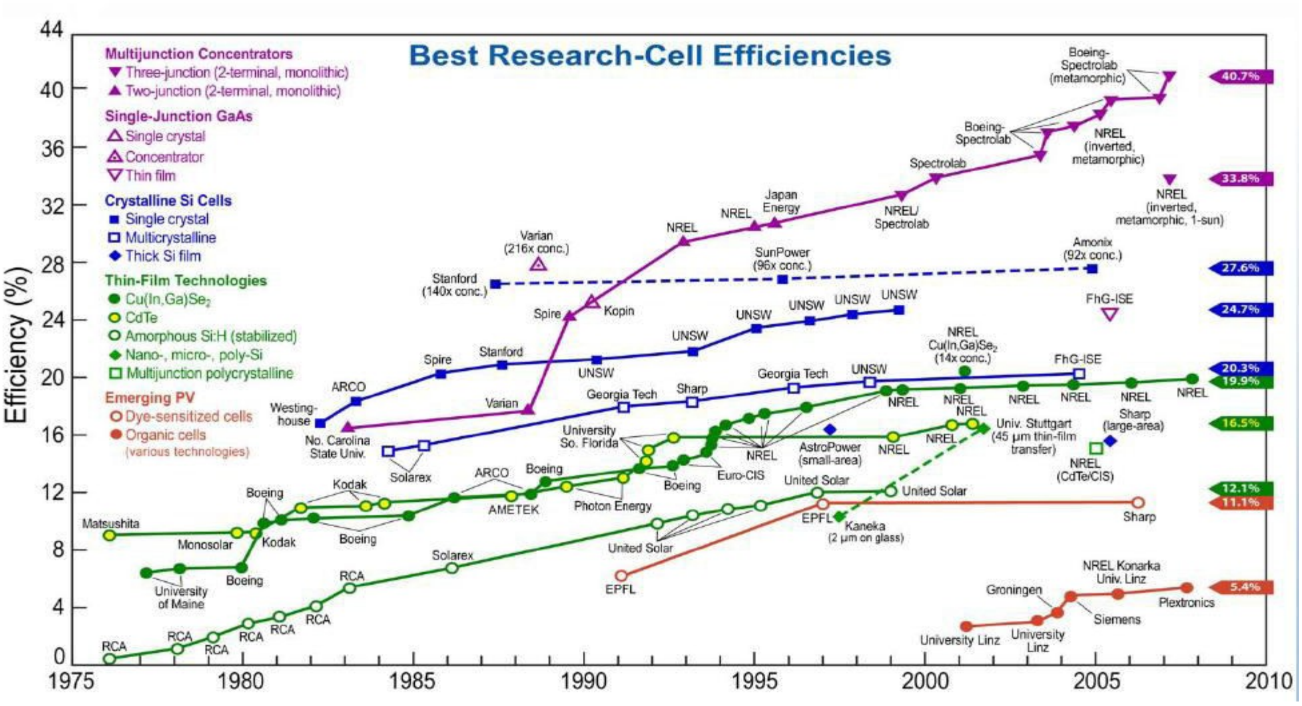

Figure 1. Best research-cell efficiency (after [8]).

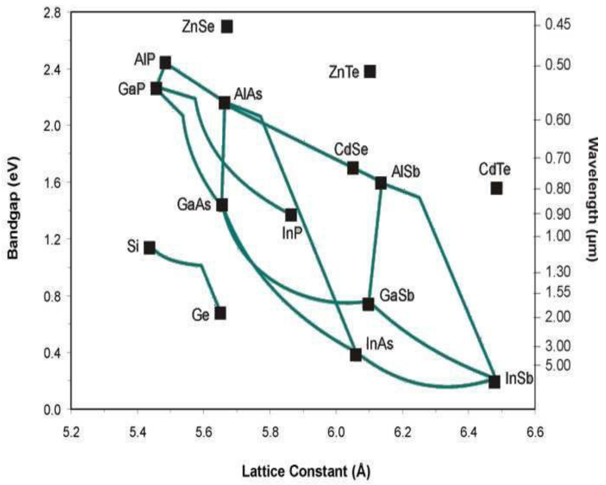

Figure 2. Ternary and quaternary III-V compounds relation between lattice constant and bandgap (after [9]).

Already carbon nanotubes (CNTs), nanowires, and quantum dots are showing promising results at the device-level, improving photovoltaic response. But there are less well-known nanoscale technologies that are just as exciting, such as quantum wells and 3D nano-composites.

Global power consumption currently stands at approximately 15 TW (1 TW = 10^{12} W), the vast majority of which is generated by the combustion of fossil fuels. The associated release of CO_2 from these anthropogenic sources has dramatically altered the composition of the atmosphere and may detrimentally impact global temperature, sea levels, and weather patterns. All renewable resources will be utilized, but only solar can meet this level of demand. The practical global potential of other renewable energy sources such as wind, hydroelectric, biomass and geothermal is estimated to be less than 10 TW.

Solar photovoltaics have great promise for a low-carbon future but remain expensive relative to other technologies. An affordable electricity supply is essential for meeting basic human needs, and yet 30% of the world population remains effectively without reliable or sufficient electricity [10]. With forecasts of over 30 TW of new power needed by 2050, the carbon emissions associated with the expansion, or even continuation, of current fossil-fuel-based electricity generation would make maintaining atmospheric CO_2 concentrations near their current levels of 379 ppm an insurmountable challenge [10-12]. Solar photovoltaics (PV) are frequently cited as a promising but an economically unrealistic large-scale supply option for a low-carbon future [13]. The clear expression of the value of PV energy, in terms of climate protection and other development challenges such as rural electrification is important for accelerated PV deployment. Benefits in terms of innovation, employment and environmental protection should be accurately quantified and shared with developing economy partners, particularly in terms of their ability to contribute towards the fundamental questions of adequate energy provision and poverty alleviation.

The global PV market has experienced vibrant growth for more than a decade with an average annual growth rate of 40%.

A typical polycrystalline silicon PV cell produces electricity, amortized over a 20 year lifetime, at above 20¢/kWh (but variations in insolation may lead to costs as low as 16¢/ kWh) with life-cycle carbon emissions as low as 32 g CO_2/kWh[1] [9, 10].

2. KEY COMPONENTS OF A PV POWER SYSTEM

The key components of a photovoltaic power system are various types of photovoltaic cells (sometimes also called solar cells; the conversion of sunlight into electricity is a clean, abundant and renewable energy source (Figure 3) interconnected and encapsulated to form a photovoltaic module[2] – Figure 4 – (the commercial product), the mounting structure for the module or array, the inverter (essential for grid-connected systems and required for most off-grid systems), the storage battery and charge controller (for off-grid systems but also increasingly for grid connected ones). PV cells represent the smallest unit in a photovoltaic power producing device, typically available in 12,5 cm, 15 cm and up to 20 cm square sizes. In general, cells can be classified as either wafer-based crystalline[3] (single crystal and multicrystalline silicon, compound semi-conductor) thin film or organic. A PV array consists of a number of modules connected in series (strings), then coupled in parallel to produce the required output power.

There are six primary applications for PV power systems starting from small pico systems of some watts to very-large-scale PV plants of hundreds of MW: *(i)* Pico PV systems have experienced significant development in the last few years, combining the use of very efficient lights (mostly LEDs) with sophisticated charge controllers and efficient batteries. *(ii)* Off-grid domestic systems provide electricity to households and villages that are not connected to the utility electricity network (also referred to as the grid). *(iii)* Off-grid non-domestic installations were the first commercial application for terrestrial PV systems. *(iv)* Hybrid systems combine the advantages of PV and Diesel hybrid in mini grids. *(v)* Grid-connected distributed PV systems are installed to provide power to a grid-connected customer or directly to the electricity network. *(vi)* Grid-connected centralized systems perform the functions of centralized power stations.

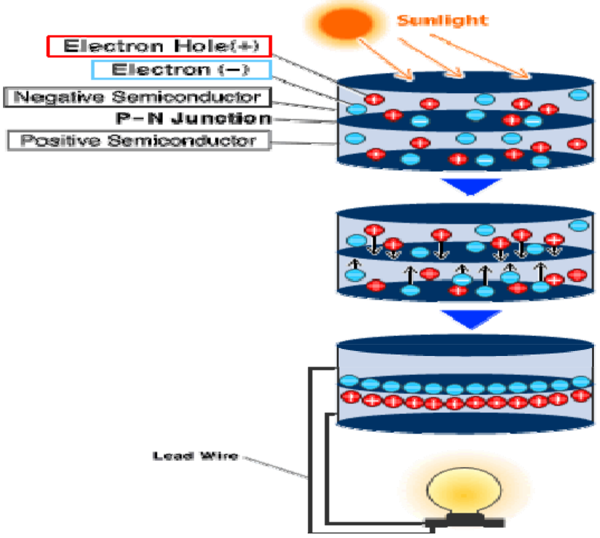

Figure 3. Generation of PV electricity (after [4]).

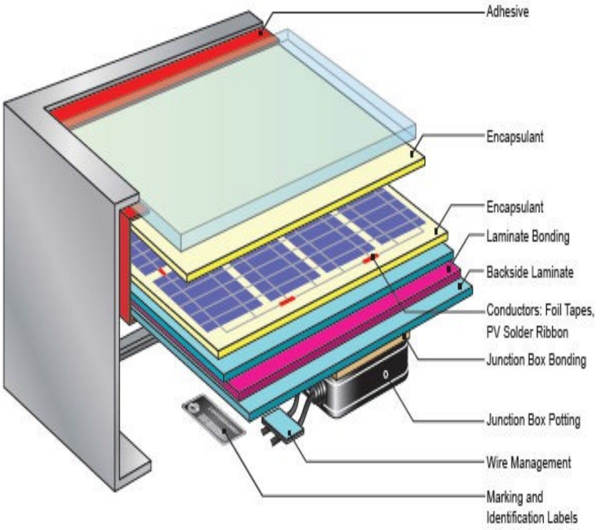

Figure 4. Silicon PV module contains many commoditized raw materials including silicon, glass, and aluminium. The challenge will be to reduce the costs or utilization of these materials while improving module efficiency. (Graphic source: Hisco).

Further research and development is being carried out to improve the efficiency of all the basic types of cells with laboratory efficiency levels of

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[1] This is more than twice the average cost of the two fastest growing alternatives, namely, wind at 4-10¢/kWh (~20 g CO_2/kWh) and natural gas at 5-7¢/kWh (~400 g CO_2/kWh) [9, 19].

[2] Photovoltaic modules are typically rated between 50 W and 300 W with specialized products for building integrated PV systems at even larger sizes. Quality PV modules are typically guaranteed for up to 25 years by manufacturers.

[3] Currently, crystalline silicon technologies account for about 80% of the overall cell production.

25% for single crystal cells, and 20% for thin film technologies being achieved [15].

Looking at recent developments, the role of solar photovoltaic electricity in the future energy supply can be observed to increase constantly in present energy scenarios, policies and – above all – the real market[4]. The recent rapid growth of photovoltaic markets all around the world, together with dramatically reduced costs, provides the confidence that photovoltaics will be able to play the expected role. These times are thus crucial for the future development of this young energy technology which is facing the challenges of rapid implementation, fast industry growth, increasing market dynamics and fierce global competition.

Very Large Scale Photovoltaic Power Generation (VLS-PV) systems have capacities ranging from several megawatts to gigawatts, and develop strategies toward implementing the VLS-PV systems in the future.

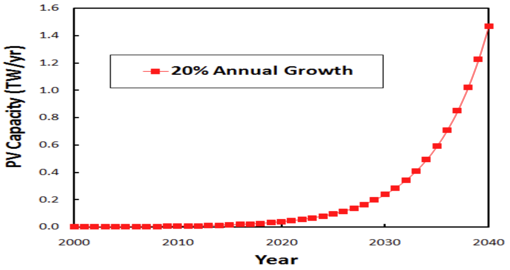
Ban Ki-Moon has right to say: “Energy will be a determining factor in whether the world can avoid dangerous climate change and make a transition to a sustainable, more inclusive global economy” [16].

The two main challenges to high penetration rates of PV systems are *variability* and *uncertainty*, i.e. the fact that PV output exhibits variability at all timescales (from seconds to years) and the fact that this variability itself is difficult to predict.

The EU is expected to continue dominating the distributed solar PV market through 2015. India and China show strong growth potential due to their vast populations without electricity access. In the four-year period ending 2015, the distributed solar PV value chain is expected to represent close to $600 billion in revenue [17]. While other countries around the world have reached various PV installations levels (Figure 5), the total of these remains hard to quantify with certainty. Some could argue the 100 GW mark worldwide has been passed, but evidence remains limited [15].

With the current rate of progress, the cost of a utility - sized photovoltaic (PV) system is likely to reach $2.20/watt by 2016, and $2.50/watt and $3.50/watt, for commercial scale and residential scale systems respectively. Reductions significantly beyond that in the next four to eight years are unlikely absent dramatically new ideas and significant investment [18].

3. GROWTH OF PV MARKET



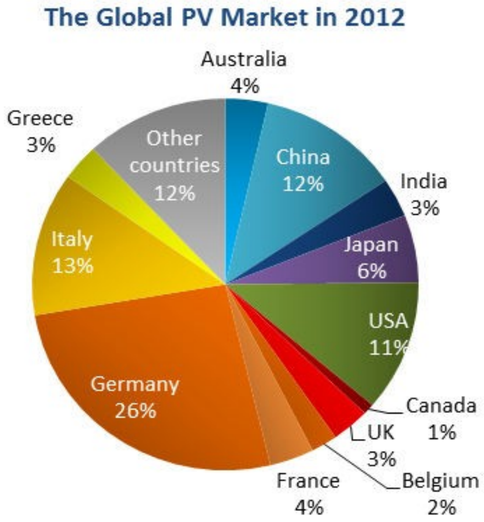


Figure 5. The global PV market in 2012 (after [15]).

With current market trends and cost reduction opportunities, utility scale system costs are expected to reach $2.20/watt by 2016 if no new program is launched. The $1/watt goal will require a major change in the rate of innovation (see Table 1).

A major theme of 2012 was a further, significant reduction in the costs of solar photovoltaic technology. The levelised cost of generating a MWh of electricity from PV was around one third lower in 2012 than the 2011 average. This took small-scale residential PV power, in particular, much closer to competitiveness. PV markets have significantly progressed outside Europe for the first time in 2012. While the market stabilized globally, the PV industry was put under heavy cost pressure. The price decrease of PV modules and system is opening new opportunities [15].

China was the dominant performer among the developing economies, raising its investment by 22% to $64.7 billion, thanks to a take-off in its solar market. The surge in China’s solar development came as Beijing trimmed its national feed-in tariff,

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[4] When the project Photovoltaic Power Systems (PVPS) of International Energy Agency (IEA) started in 1999, very large scale photovoltaic power systems were seen as a futuristic, long-term concept which many doubted would ever become reality. Today, only 15 years later, we can see many examples of large and very large scale photovoltaic power systems being planned and realized. The vision of Professor Kosuke Kurokawa who inspired the work of IEA PVPS Task8 has become reality much faster than expected.

but falling system costs enabled developers still to see a return. Also, manufacturers, faced with oversupply in the industry worldwide, opted to develop PV projects in their own country to take up some of the slack. Germany remained the third largest investing country in renewable energy worldwide. The country installed some 7.6 GW of solar capacity in 2012, the largest for any country, and most of it small-scale [19].

In 2012, global investment in research and development in renewable energy held up surprisingly well in difficult circumstances.

4. NEW PROJECTS FOR PV CELL

Massachusetts Institute of Technology developed a thin-film photovoltaic cell based on thin sulphide, which could cut costs because both tin and sulphur are abundant and can be processed at temperatures below 400°C. Another project at University of California Irvine has built a prototype cell from iron pyrite which the developers claim offers a clear pathway to meeting SunShot targets on cost, efficiency and terawatt scalability; and another by commercial developer Bandgap Engineering to produce a 36% efficient silicon cell using nanotechnology.

Table 1. Potential utility scale system cost breakdown to reach $1/watt (note capacity factors assumed are 26% in 2010 and 28% in 2016). BOS: Balance of systems; O&M: Operation and maintenance (after [18]).

Installed system price ($/W)

	2010	*2016*	*$1/W*
Module	1.70	1.05	0.50
BOS/Installation	1.48	0.97	0.40
Power Electronics	0.22	0.18	0.10
	3.40	2.20	1.00

Cost of Energy ($/kwh)

	2010	*2016*	*$1/W*
Module	0.063	0.037	0.018
BOS/Installation	0.055	0.034	0.014
Power Electronics	0.008	0.006	0.004
O&M	0.013	0.009	0.003

Historically, conventional solar cells were built from inorganic materials such as silicon. Although the efficiency of such conventional solar cells is high, very expensive materials and energy intensive processing techniques are required.

Hybrid and photoelectrochemical (dye sensitized) solar cells have been the cheap alternatives for conventional silicon solar cells. A hybrid solar cell consists of a combination of both organic and inorganic materials therefore, combines the unique properties of inorganic semiconductors with the film forming properties of the conjugated polymers. Organic materials are inexpensive, easily processable and their functionality can be tailored by molecular design and chemical synthesis. On the other hand, inorganic semiconductors can be manufactured as nanoparticles and inorganic semiconductor nanoparticles offer the advantage of having high absorption coefficients and size tunability. By varying the size of the nanoparticles the bandgap can be tuned therefore the absorption range can be tailored[5].

A broad range of solar cell technologies are currently being developed, including dye-sensitized nanocrystalline photoelectrochemical solar cells, polymer/fullerene bulk heterojunctions, small molecule thin films and organic–inorganic hybrid devices.

Hybrid solar cell research shall combine the advantages of organic semiconductors and nanoparticles with the properties of the inorganic semiconductors and nanoparticles. The parameter space to choose from is large and only a fraction of possible combinations has been realized. Even such limited efforts have attracted much attention due to the simple processability and low cost processing. Their power conversion efficiencies are still low compared with the conventional inorganic solar cells. Further research and development for optimization is required for different types of hybrid solar cell devices [20].

5. THIN FILMS [7]

Thin films are made by depositing extremely thin layers of photosensitive materials in the μm range on a low-cost backing such as glass, stainless steel or plastic. The first thin film solar cell produced was a-Si. Based on early a-Si single junction cells, amorphous tandem and triple cell configuration have been developed. To reach higher efficiencies, thin amorphous and microcrystalline

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[5] All of the novel devices efficiency boosted by the presence of nanostructures have to deal with the problem of the additional costs needed by the fabrication of the nanostructures themselves. Of course self-assembly of quantum dots should be preferred to nanolithography in terms of time and steps of fabrication, and the same is for plasmonic antennas.

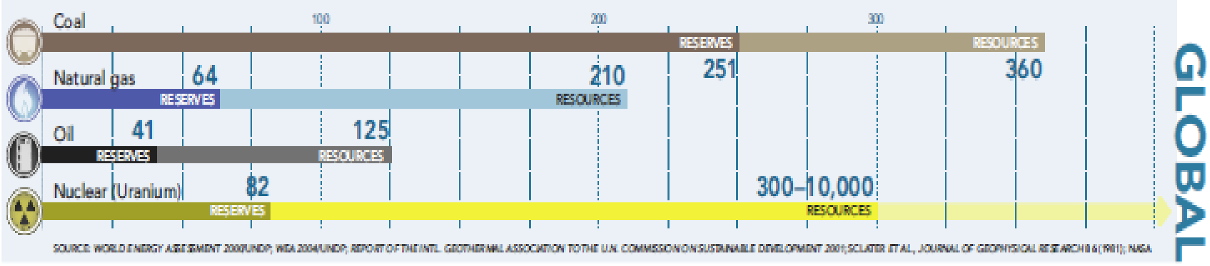
silicon cells have been combined to form micromorph cells (also called thin hybrid silicon cells) [13]. In the area of II-VI semiconductor compounds, other thin film technologies have been developed, including Cadmium Telluride (CdTe) and Copper-Indium-Gallium-Diselenide (CIGS).

Table 2. Prospects and key R&D issues for CPV, emerging and novel technologies (after [7]).

	CPV	*Emerging technologies*[6]	*Novel technologies*[7]
Type of cell	High cost, super high efficiency	Low cost, moderate performance	Very high efficiency Full spectrum utilization
Status & potential	23% AC system efficiency demonstrated	Demonstrated level (e.g. polymer PV, dye PV, printed CIGS)	Wide variety of new conversion principle & device concepts at lab level
	Potential to reach over 30% in the medium-term	First applications expected in niche market applications	Family of potential breakthrough technologies
Selected R&D areas	Reach super high efficiency over 45%	Improvement of efficiency and stability to the level needed for first commercial applications	Proof-of-principle of new conversion concepts
	Achieve low cost, high-performance solutions for optical concentration and tracking	Encapsulation of organic-based concepts	Processing, characterization and modelling of especially nano-structured materials & devices

6. CONVENTIONAL ENERGY RESOURCES: HOW MUCH IS LEFT? [21]

Oil: 40 –125 years
Natural Gas: 65 -210 years
Coal: 250 –360 years
Nuclear: 80 –300 years



SOURCE: WORLD ENERGY ASSESSMENT 2000/UNDP; WEA 2004/UNDP; REPORT OF THE INTL. GEOTHERMAL ASSOCIATION TO THE U.N. COMMISSION ON SUSTAINABLE DEVELOPMENT 2001; SCLATER ET AL., JOURNAL OF GEOPHYSICAL RESEARCH 86 (1981); NASA

7. RENEWABLE ENERGY RESOURCES

Hydroelectric
Wind
Biomass
Geothermal
Ocean / tides
Solar

Global potential: Current ~2 TW; Practical: ~10 TW.

→ Solar energy potential: Solar flux = 1.1 x 10^5 TW; practical potential: 600 TW; 1 h sunlight = annual global consumption. Infinite supply.

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[6] Comprise advanced inorganic thin film technologies (e.g. Si, CIS) as well as organic solar cells. Within the organic cells area, there are different technology branches such as the dye sensitised solar cell (a hybrid approach of an organic cell retaining an inorganic component) and fully organic approaches.

[7] Novel PV concepts aim at achieving ultra-high-efficiency solar cells by developing active layers which best match the solar spectrum (or which modify the incoming solar spectrum), utilizing nanotechnology and nanomaterials. Quantum wells, quantum wires and quantum dots are examples of structures introduced in the active layer.

8. SOME TRENDS IN PV INDUSTRY [15]

Most of major manufacturers adopt conventional technologies such as Siemens and FBR processes, which were used to supply silicon for the semiconductor industry. To address lowering price, major manufacturers are working on improvement of production efficiency. New technology such as metallurgical process has not yet become a major technology, mainly due to impurity issues. Some companies in IEA PVPS member countries that worked on new process closed their plant or exited from the business because of the overcapacity in 2012.

In 2012, polysilicon for PV cells was mainly manufactured in China, the USA, Korea, Germany and Japan. Canada and Norway also reported activities of polysilicon producers. China produced 71,000 tons of polysilicon, with 190,000 tons/year of production capacity in 2012. The production volume in China accounts for about 30% of global polysilicon production. Meanwhile, China imported 8,700 tons of polysilicon in 2012, a 28% increase from the previous year. Affected by the polysilicon price falling in the global market, most of Chinese enterprises with smaller production capacity have stopped production in 2012.

9. STORAGE PROBLEM

EnStorage flow batteries [22] utilize HBr and H_2 as storage chemicals. Abundance of these materials reduces the chemical cost by 95% compared to other batteries, making it the most affordable flow battery in the market. Moreover, the battery’s proprietary conversion stacks has demonstrated over 3 times the power densities compared to other batteries, making it smaller and lower in cost. Following the recent success of the 50 KW unit, *EnStorage* is now moving forward with the next milestone of a 150 KW, 6 hours of storage, commercial unit.

10. CONCENTRATOR TECHNOLOGIES (CPV)

As an alternative to flat-plate technologies – which use the naturally available sunlight – direct solar radiation can be concentrated by optical means and used in concentrator solar cell technologies[8]. Low and medium concentration systems work with high efficiency silicon solar cells. Beyond 500 suns, III-V compound semiconductors are being used for the CPV solar cells and efficiencies beyond 40% have been achieved in the laboratory. The prospects and key R&D issues for CPV as well as emerging and novel technologies are summarized in Table 2.

11. WHAT WE NEED

We need new materials and a better optics, a better use of sunlight, and a easier cell fabrication.

With this end in view, we must have a smarter optics, self-healing materials, self assembling procedures and solar paint.

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[8] Considerable research has been undertaken in this high-efficiency approach because of the attractive feature of the much smaller solar cell area required.

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