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International Renewable Energy Agency

Solar Photovoltaics

Technology Brief

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Insights for Policy Makers

Solar photovoltaic (PV) cells convert sunlight directly into electricity. Currently, crystalline silicon (c-Si) and the so-called thin-film (TF) technologies dominate the global PV market. In a c-Si PV system slices (wafers) of solar-grade (high purity) silicon are made into cells that are assembled into modules and electrically connected. TF PV technology consists of thin layers of semiconducting material deposited onto inexpensive, large-size substrates such as glass, polymer or metal. Crystalline silicon PV is the oldest and currently dominant PV technology with approximately 85-90% of the PV market share.

The manufacture of solar PV systems basically comprises of four phases: production of the semiconducting material (90% of polysilicon is supplied by a handful of companies in the United States, Japan, Europe, and China); production of the PV cells, which often requires sophisticated manufacturing (most solar cells are produced in China, Germany, the US and Japan); production of PV modules, a labour-intensive process whereby the cells are encapsulated with protective materials and frames to increase module strength (around 1,200 companies worldwide currently produce solar PV cells and modules); and installation of PV modules, including the inverter to connect the PV system to the grid, the power control systems, energy storage devices (where appropriate) and the final installation in residential or commercial buildings or in utility-scale plants. The cost of a PV module typically ranges between 30-50% of the total cost of the system. The remaining costs include the balance of system and the installation - which can be as low as 20% for utility-scale PV plants, 50-60% for residential applications, and as a high as 70% for off-grid systems, including energy storage (usually batteries) and back-up power.

PV power has an enormous energy potential and is usually seen as an environmentally benign technology. Over the years a good number of countries have implemented specific policies and incentives to support PV deployment. This has led to a rapid increase in the total installed capacity of PV from 1.4 GW in 2000 to around 70 GW at the end of 2011, with about 30 GW of capacity installed in that year alone. The associated industrial learning and market competition have resulted in very significant and rapid cost reductions for PV systems. Continued cost reductions for PV systems are an essential requirement for accelerating the attainment of grid-parity of electricity generated using on-grid solar PV systems. In countries with good solar resources and high electricity tariffs, residential solar PV systems have already reached parity with electricity retail prices, whilst in general PV is now fully competitive with power generated from diesel-based on- and off-grid systems.

The choice of solar PV technology for installation is often based on a trade-off between investment cost, module efficiency and electricity tariffs. Compared with c-Si-based PV systems, the production of TF PV system is less energy-intensive and requires significantly less active (semiconducting) material. TF solar PV is therefore generally cheaper, though significantly less efficient and requires substantially more surface area for the same power output, than c-Si-based systems. The module cost of c-Si PV systems have fallen by more than 60% over the last two years; in September 2012, Chinese-made modules averaged USD 0.75/watt, while TF PV modules. Consequently, even though TF PV has experienced tremendous growth a few years ago, more recently its market share is decreasing and the current outlook for further growth in the deployment of this technology is uncertain and will depend heavily on technology innovation.

Solar PV, as a variable renewable electricity source, can be readily integrated into existing grids up to a penetration level of about 20% depending on the configuration of the existing electricity generation mix and demand profiles. Increasing the integration of a high level of variable renewable power from PV systems into electricity grids requires, in general, re-thinking of grid readiness with regards to connectivity, demand-side response and/or energy storage solutions. However, the on-going reduction of financial incentives in many leading markets, together with the overcapacity of the PV manufacturing industry, suggest that module prices will continue to decline, leading to parity in off- and on-grid PV. It is noteworthy that, since 2001, the global PV market has grown faster than even the most optimistic projections. However, it is not clear whether the deployment of PV will slow down or continue to grow at the same as in the recent past years.

Highlights

- **Process and Technology Status –** Photovoltaic (PV) solar cells directly convert sunlight into electricity, using the *photovoltaic effect*. The process works even on cloudy or rainy days, though with reduced the production and conversion efficiency. PV cells are assembled into modules to build modular PV systems that are used to generate electricity in both grid-connected and off-grid applications, such as residential and commercial buildings, industrial facilities, remote and rural areas and power plants (i.e. utility PV systems). Over the past decades PV technology has been constantly improving performance and reducing costs. Most recently, rapid cost reductions are enabling PV plants to become economically competitive not only in niche markets such as off-grid installations, but also for on-grid applications. As a result, PV power is expanding rapidly in many countries, even though governmental support policies and incentives (feed-in tariffs) are being reduced. In countries with good solar resources and high electricity tariffs, residential solar PV systems have already reached parity with electricity retail prices, whilst in general PV is now fully competitive with power generated from diesel-based on- and off-grid systems.The global cumulative installed PV capacity grew from 1.4 GW in 2000 to about 70 GW at the end of 2011, with around 30 GW added in 2011 alone. Global annual investment totalled some USD 93 billion in 2011 (NPD Solarbuzz, 2012). Italy, Germany, China, the United States, France and Japan are the leading countries in terms of cumulative capacity, annual installed capacity and/or production of PV modules and systems. European countries accounted for 70% of the newly installed capacity in 2011. Commercial PV technologies include wafer-based crystalline silicon (c-Si) (either mono-crystalline or multi-crystalline silicon) and thin-films (TF) using amorphous Si (a-Si/μc-Si), cadmium-telluride (CdTe) and copper-indium-[gallium]-[di]selenide-[di]sulphide (CI[G]S). The c-Si systems accounted for 89% of the market in 2011, the rest being TF.

- **Performance and Costs –** Crystalline silicon (c-Si) cells have reached a record efficiency of around 25%. The efficiency of the best current commercial modules is around 19-20% (with a target of 23% by 2020). The majority of commercial c-Si modules, however, have efficiencies in the range of 13-19% with more than a 25-year lifetime. Commercial TF modules offer lower efficiency between 6-12% (with a target of 12-16% by 2020). In addition to the commercial options, a number of new PV technologies is under development (e.g. concentrating PV, organic PV cells, advanced thin films and novel concepts and materials) and hold out the promise of high performance and low costs in the medium-term. Today's PV systems are fully competitive for off-grid electricity generation and with diesel-based on-grid systems in countries with good solar resources. In an increasing number of countries with high cost of electricity and good solar resources, small PV systems are also achieving the so-called *grid-parity* between the PV electricity cost and the residential retail prices for householders. For instance, in 2011, electricity prices for householders in the EU-27 ranged between USD 83-291/MWh, excluding taxes (Eurostat), while the average cost of PV electricity for large ground-mounted systems ranged from USD 160- 270/MWh in southern and northern Europe, respectively. Furthermore, advantages of PV electricity are that it is usually produced close to the consumption site and can match peak demand profiles. Owing to their low capacity factors, PV systems are not yet cost competitive for base-load electric power generation. However, PV capital costs are declining very rapidly due to technology learning, increasing industrial production and improved efficiency. With a learning rate between of between 18-22% for each doubling of installed capacity, PV module prices have dramatically dropped over the past two decades. A 60% reduction has been achieved over the last two years and more than a 40% reduction is likely to occur by 2020. In September 2012, Chinese c-Si module prices had fallen to an average of USD 0.75/W, although the rate of decline has slowed. In Germany, the costs of installed rooftop PV system had fallen to USD 2.2/W by mid-2012. PV system costs have been declining so rapidly that past projections of cost reductions have become obsolete in a very short time. The latest industry projections (EPIA, 2012) suggest a slowdown in cost reductions of PV systems, with residential rooftop systems in the most competitive European markets falling to between USD 1.8-2.4/W by 2020. The recent cost reductions for c-Si modules have squeezed TF technologies increasingly into niche markets while novel PV concepts are expected to reach the market in the medium- to long-term.

- **Potential and Barriers –** PV power has a virtually unlimited energy potential with no environmental constraints to market expansion. A main issue is the limited capacity factors that translate into higher electricity costs than most base-load electricity generation technologies. To drive cost reductions through deployment, many governments offer financial incentives (such as feed-in tariffs and tax incentives). The variable nature of the solar source also means that appropriate grid management and technology (i.e. smart grids) and energy storage are required for high PV penetration. Where feed-in tariffs and incentives are in place, PV is attractive to investors and consumers and contributes significantly to energy production and the mitigation of greenhouse gas emissions. PV technology is perceived as a sustainable business with jobs creation opportunities, and is usually the least-cost solution when integrated with storage and/or backup generation to provide electricity to remote areas. Scenarios analysed by the European PV Industry Association (EPIA, 2012) project that PV power could reach between 4.9-9.1% of the global electricity generation by 2030 (depending on PV growth and electricity demand) and up to 17-21% of electricity share by 2050. The World Energy Outlook of the International Energy Agency (IEA, 2012) presents a more conservative outlook that projects PV power to provide between 2-3.3% of the global electricity by 2030 assuming continued policy support and cost reductions. It is noteworthy that since 2001 the global PV market has grown faster than the most optimistic projections.

Basic Process and Technology Status

Based on the *photovoltaic (PV) effect*[1], PV solar cells can convert solar energy directly into electricity. PV electricity was discovered in the 19th century, but the first modern PV cells for electricity generation based on silicon (Si) semi-conductors were developed only in the 1950s. The large-scale commercialisation of PV devices started only after 2000, following financial incentives in many countries that are part of government policies to mitigate CO_2 emissions and improve energy security. PV electricity is environmentally friendly[2] and has virtually unlimited potential. Currently, PV power provides only a small percentage of global electricity supply, but the market is expanding rapidly, driven by financial incentives and rapid cost reductions. Over the past decade, the global cumulative installed PV capacity has grown from 1.4 GW in 2000 to around 70 GW at the end of 2011 (Figure 1), with some 30 GW of new capacity installed in 2011 alone and annual revenues that are estimated at around USD 93 billion[3]. In terms of newly installed capacity, the leading countries in 2011 were Italy (9.3 GW), Germany (7.5 GW), China (2.2 GW), the United States (1.9 GW) and Japan (1.3 GW). In terms of total installed capacity, Europe has around three-quarters of the global total with the leading countries

1 In the PV effect, two different (or differently doped) semi-conducting materials (e.g. silicon, germanium), in close contact each other, generate an electrical current when exposed to sunlight. Sunlight provides electrons with the energy to move cross the junction between the two materials more easily in one direction than in the other. This gives one side of the junction a negative charge with respect to the other side (i.e. p-n junction) and generates a voltage and a direct current (DC). PV cells work with direct and diffused light and generate electricity even during cloudy days, though with reduced production and conversion efficiency.

2 No GHG emissions during operations and negligible environmental impact.

3 All investment and cost figures are expressed in 2010 USD or converted from EUR into USD using the conventional exchange rate of 1E=1.3 USD.

being Germany, Italy and Spain. Outside of Europe, China, the United States, Japan, Australia, Canada and India constitute the largest markets. China, Germany, the US and Japan are the leading producers of PV components and systems.

PV power can be used for either grid-connected applications (e.g. residential, commercial, utility systems) or off-grid installations. In fact, more than 90% of the installed capacity consists of grid-connected systems. Primary applications are systems for residential and commercial buildings, with unit sizes of up to 10 kWp and 100 kWp, respectively, followed by utility systems (size greater than 1 MWp), and off-grid applications (e.g. telecommunication towers, rural supply, consumer goods). The current share of the residential sector is 60%. There are currently no material availability or industrial constraints to the growth of the share PV power in the global energy mix. The PV Industry has quickly increased its production capacity to meet growing demand. At present, supply exceeds demand by a large margin. Although there are over 1,000 companies that currently produce PV products worldwide (e.g. PV cells, modules and systems), 90% of the basic material (polysilicon) is produced by only a few companies, mostly in the United States, Japan, Europe and China.

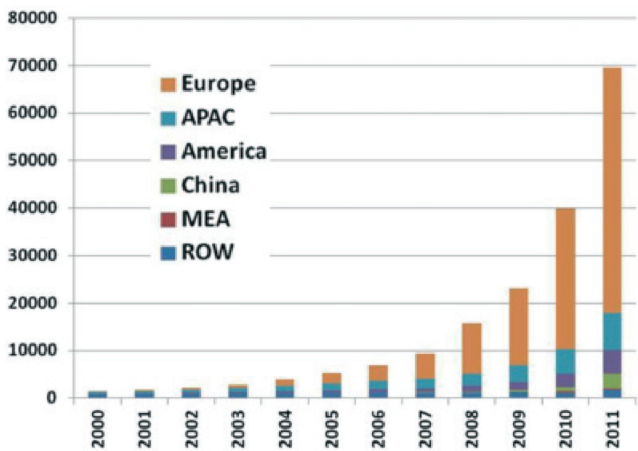

Figure 1 – Global installed PV capacity (MW) – Source EPIA, 2012

PV Technologies and Performance

The basic element of a PV system is the PV solar cell that converts solar energy into direct-current (DC) electricity. PV cells are assembled and electrically interconnected to form PV modules. Several PV modules are connected in a series and/or in parallel to increase voltage and/or current, respectively. An inverter is needed to convert DC into AC for grid integration and use with most electrical appliances. Modules and balance of system (i.e. inverter, racking, power control, cabling and batteries, if any) form a modular PV system with a capacity ranging from a few kW to virtually hundreds of MW. PV systems can be integrated into building-structures (i.e. building-adaptive or integrated PV systems, BAPV or BIPV), placed on roofs or ground-based. A number of PV technologies are either commercially available or under development. They can be grouped into three categories that are also referred to as 1st, 2nd and 3rd generation: 1) wafer-based crystalline silicon (**c-Si**); 2) thin-films (**TF**); and 3) emerging and novel PV technologies, including concentrating PV, organic PV, advanced thin films and other novel concepts. Over the past two decades, PV technologies have dramatically improved their performance (i.e. efficiency[4], lifetime, energy pay-back time[5]) and reduced their costs, and this trend is expected to continue in the future. Research aims to increase efficiency and lifetime, as well as reduce the investment costs so as to minimise the electricity generation cost. Several studies have analysed the development of PV performance and costs over time. A broad overview of current PV technologies and their performance is provided in Table 1. Current commercial technologies include wafer-based crystalline silicon (**c-Si**) and thin-films (**TF**). The c-Si technology includes three variants: mono crystalline silicon (mono**-c-Si**), multi-crystalline silicon (**multi-c-Si**) and ribbon-sheet grown silicon. The TF technology currently includes four basic variants: 1) amorphous silicon (**a-Si**); 2) amorphous and micromorph silicon multi-junctions (**a-Si/μc-Si**); 3) Cadmium-Telluride (**CdTe**); and 4) copper-indium-[gallium]-[di]selenide-[di]sulphide (**CI[G]S**). It is worth noting that module efficiencies are lower than commercial cell efficiencies and commercial cell efficiencies are lower than the best efficiency performance of cells in laboratories. Besides current commercial technologies, Table 1 includes 3rd generation PV technologies that promise significant advances in terms of performance and costs. Crystalline silicon (c-Si) accounted for 89% of the global market in 2011. The TF technology currently accounts for the remaining 11%. Among TF, the market is

4 Efficiency is the ratio of the electrical power to the incident solar power.

5 The time needed for the PV system to produce the energy needed for its manufacture, i.e. approximately 1-3 years, depending on location and materials, against a lifetime of at least 25 years. PV systems are durable as they have no moving or rotating components.

Table 1 – Performance of Commercial PV Technologies (Data from EPIA, 2011)

	Cell effic. (%)	Module effic. (%)	Record commercial and (lab) efficiency, (%)	Area/kW (m2/KW)[a)]	Life-time (yr)
c-Si					
Mono-c-Si	16 - 22	13 - 19	22 (24.7)	7	25 (30)
Multi-c-Si	14 -18	11 - 15	20.3	8	25 (30)
TF					
a-Si	4 – 8		7.1 (10.4)	15	25
a-Si/μc-Si	7 – 9		10 (13.2)	12	25
CdTe	10 - 11		11.2 (16.5)	10	25
CI(G)S	7 - 12		12.1 (20.3)	10	25
Org.Dyes	2 – 4		4 (6-12)	10 (15)	na
CPV	na	20 - 25	>40	na	na

a) A module efficiency of 10% corresponds to about 100 W/m^2

shifting to CdTe and CIGS. Among emerging technologies, concentrating PV and organic solar cells are just entering the market and are expected to capture some percentage points by 2020. Table 2 provides the evolution of performance over time for commercial PV modules. Individual PV technologies are discussed in the following sections.

- **Wafer-based Crystalline Silicon Technology –** The manufacturing process of c-Si modules includes: 1) purification of metallurgical silicon to solar grade polysilicon; 2) melting of polysilicon to form ingots and slicing these ingots into wafers[6]; 3) wafer transformation into cells (typically 15x15 cm, 3-4.5 W) by creating *p-n junctions,* metal (silver) contacts and back-coating (metallisation); and 4) cell assembly, connection and encapsulation into modules with protective materials (e.g. transparent glass, thin polymers) and frames to increase module strength. Silicon is used in the three forms of single-crystal (sc-Si), block crystals (multi-crystalline silicon, mc-Si) and ribbon-sheet grown c-Si. Unlike sc-Si cells offer high efficiency (Tables 2 and 3), mc-Si cells

6 Slicing the wafer by wire saw produces up to 40% silicon wastage. This can be reduced by using a laser cutter and ribbon/sheet-grown c-Si.

Table 2 – Performance and Targets for PV Technology (Data from EU SRA 2008, IEA 2010a, EPIA 2011)

	1980	2007	2010	2015-20	2030+
Module effic., %					
Mono-c-Si	≤8	13-18	13-19	16-23	25-40
Mult-c-Si			11-15	19	21
TF	na	4-11	4-12	8-16	na
c-Si material use, g/Wp			7	3	<3
c-Si wafer thick, mm			180-200	<100	na
Lifetime, yr	na	20-25	25-30	30-35	35-40
En. payback, yr	>10	3	1-2	1-0.5	0.5

have lower efficiency owing to their random atomic structure which affects the flow of electrons. However, they are less expensive than sc-Si cells.. The efficiency of mc-Si cells is lower owing to their random atomic structure which affects the flow of electrons. However, they are less expensive than sc-Si cells. A standard c-Si module is typically made up of 60-72 cells, has a nominal power of 120-300 Wp and a surface of 1.4-1.7 m^2 (up to 2.5 m^2 maximum). Factory production capacities of 500-1000 MWp per year are currently common to achieve economies of scale and reduce manufacturing costs. Special processes for high-efficiency commercial cells include *Buried Contacts* (by laser-cut grooves)*; Back Contacts* (that currently achieve the highest commercial efficiency of 22%); specialised surface texturing to improve sunlight absorption (Suntech, 19%), and *HIT* (heterojunction with an intrinsic thin layer, consisting of a sc-Si wafer between ultra-thin a-Si layers to improve efficiency - Sanyo Electrics, 19.8%). The record cell efficiency for simple c-Si cells (24.7%) belongs to SunPower. Higher efficiencies have been achieved using materials other than silicon and multi-junction cells by Sharp, (35.8%, without concentration) and Boeing Spectrolab (41.6%, with 364 times concentration).

A standard c-Si module is typically made up of 60-72 cells, has a nominal power of 120-300 Wp and a surface of 1.4-1.7 m^2 (up to 2.5 m^2 max). Factory production capacities of 500-1,000 MWp per year are currently common to achieve economies of scale and reduce manufacturing costs. Special processes for high-efficiency commercial cells include *Buried Contacts* (by laser-cut grooves)*; Back Contacts* (that currently achieve the highest commercial efficiency of 22%); *Pluto process* to improve sunlight absorption (Suntech, 19%), and *HIT* (hetero-junction with an intrinsic thin layer consisting of a sc-Si wafer between ultra-thin a-Si layers to improve efficiency—Sanyo Electrics, 19.8%).

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The main manufacturing challenge for c-Si cells is to improve efficiency and reduce costs through learning-by-doing and reducing material use. High silicon prices in 2006 spurred a 30% reduction of in the amount of silicon in the manufacturing process to just 5-10 g/Wp today. This has been made possible by the use of thinner wafers, process automation and waste recycling. The target is to reach the level of 3 g/Wp or less between 2030 and 2050. Today's wafers have a typical thickness of 180-200 μm. Cell interconnection and assembly using glass, polymer and aluminium structures, and techniques (e.g. metallisation, back-contacts and encapsulation) are continuously improved to reduce costs and enhance performance. The reduction or substitution of high-cost materials used in the manufacturing process (e.g. silver, currently 80-90 mg/Wp) also is a key objective. As far as efficiency is concerned, the maximum theoretical efficiency for c-Si is currently estimated at around 29%. Record cell efficiencies have been obtained using expensive laboratory processes (e.g. clean rooms, vacuum technologies), but only a few commercial cells have efficiencies above 20%. Current commercial sc-Si modules efficiencies, which are lower than for cells, range between 13-19%. They could reach 23% by 2020 and up to 25% in the longer term. The majority of commercial modules, however, are based on multi-crystalline silicon and low-cost manufacturing (screen-printing) and offer efficiencies between 12-15% (17% in the best cases), with prospects for reaching a 21% target in the long term.

- **Thin-film Technologies –** The TF technology is based on the deposition of a thin (μm) layer of active materials on large-area (m^2-sized or long foils) substrates of materials such as steel, glass or plastic. TF technologies use small amounts of active materials and can be manufactured at a lower full cost than c-Si. They have short energy pay-back times (i.e. <1yr in southern Europe) despite their lower efficiency, good stability and lifetimes comparable to c-Si modules. Plastic TF are usually frameless and flexible and can easily adapt to different surfaces. Standard TF modules have a typical 60-120 Wp capacity and a size between 0.6-1.0 m^2 for CIGS and CdTe, and 1.4-5.7 m^2 for silicon-based TF. In comparison with c-Si modules, TF module efficiency (i.e. 4-12%) is significantly lower. The operational experience is also lower. A typical TF manufacturing process includes: 1) coating of the substrate with a transparent conducting layer (TCO); 2) deposition of the active layer by various techniques (e.g. chemical/physical vapour deposition); 3) back-side metallisation (contacts) using laser scribing or traditional screen-printing;

and 4) encapsulation in a glass-polymer casing. Roll-to-roll (R2R) techniques are often used with flexible substrates to reduce production time and costs.

Research efforts focus on materials with higher absorption and efficiency, thin polymer substrates, high-stability TCO, deposition techniques (e.g. plasma-enhanced chemical vapour deposition, PECVD), hetero-structures, electrical interconnection, low-cost manufacturing (i.e. R2R coating, sputtering, cheap and durable packaging), quality control and aging tests. In a few years, the typical manufacturing plant-scale has increased from less than 50 MW to hundreds of MW per year. However, the TF manufacturing industry is undergoing significant changes at the moment and the outlook is quite uncertain because TF's share in the PV market is being challenged by the current low costs of c-Si modules. Four types of commercial TF modules are described below, with typical efficiencies as given in Table 3.

- **Amorphous Silicon (a-Si) films** consist typically of 1μm-thick amorphous silicon (good light absorption, but low electron flow) deposited on very large substrates (5-6 m^2), with low manufacturing costs but also low efficiency

Table 3 – Performance and Targets for TF Technologies (Data from IEA 2010a, EPIA 2011)

a-Si	**2010**	**2015-2020**	**2030-**
Max. effic., %	9.5-10	15	Na
Commercial effic., %	4-8	10-11	13
a-Si/μc-Si			
Max. effic., %	12-13	15-17	Na
Commercial effic., %	7-11	12-13	15
Cd-Te			
Max. effic., %	16.5	na	Na
Commercial effic., %	10-11	14	15
CI(G)S			
Max. effic., %	20	na	Na
Commercial effic., %	7-12	15	18

Key R&D targets: Optimise CVD and plasma deposition process; new roll-to-roll processes; low-cost packaging; new materials (i.e. μc-SiGe, SiC, nano-diamond, cheaper TCO and substrates); replace/re-cycle scarce materials; better understanding of the physics of advanced concepts (e.g. multi-junctions, doping, quantum dots, up/down converters, photonic crystals)

(4-8%). The best laboratory efficiencies are currently in the range of 9.5-10%. Among TF technologies, a-Si TF is perhaps the most challenged by the current low-cost c-Si. Its future is rather uncertain. Some producers have recently retired part of manufacturing capacity.

- **Multi-junction Silicon (a-Si/μ-Si) films** offer higher efficiency than a-Si films. The basic material is combined with other active layers, e.g. microcrystalline silicon (μc-Si) and silicon-germanium (μc-SiGe), to form a-Si/μc-Si tandem cells, micro-morph and hybrid cells (even triple junction cells) that absorb light in a wider range of frequency. An a-Si film with an additional 3μm layer of μc-Si absorbs more light in red and near-infrared spectrum, and may reach an of efficiency up to 10%. Best laboratory efficiencies are currently in the range of 12-13% for a-Si/μc-Si tandem cells and triple junction SiGe cells. Commercial module efficiencies are between 6.5-9%, but prototype module efficiencies of up to 11% have been demonstrated for best multi-junctions (Bailat, 2010). Short-term targets (Table 4) include the demonstration of cell efficiencies of 15% (17% by 2020) and module efficiency of 12%. Research has also been exploring further material options such as sc-Si (hetero-junctions, HIT), SiC, nanocrystalline-diamond, layers with quantum dots, and spectrum converters, improved TCO and substrates, and alternative low-cost deposition techniques (e.g. using no plasma)

- **Cadmium-telluride (CdTe) films** are chemically stable and offer relatively high module efficiencies (i.e. up to 11%). They are easily manufactured at low costs via a variety of deposition techniques. The efficiency depends significantly on deposition temperatures, growth techniques and the substrate material. The highest efficiencies (i.e. up to 16.5%) have been obtained from high temperature (600°C) deposition on alkali-free glass. The theoretical efficiency limit is around 25%. Approaches to increase the efficiency include inter-mixing elements, hetero-junctions, activation / annealing treatments and improved electrical back contacts. In most efficient CdTe films, the substrate faces the sun. In such a configuration, TCO properties are crucial for module efficiency. Thinner CdTe layers are also key to minimising the use of tellurium, given that its long-term availability may be a concern.

- **Copper-indium-[gallium]-[di]selenide-[di]sulphide film (CI[G]S)** has the highest efficiency among TF technologies (i.e. 20.1% lab efficiency; 13-14% for prototype modules and 7-12% for commercial modules). However, the manufacturing process is more complex and costly than the other TF technologies. Replacing indium with lower-cost materials or reducing indium use could help reduce costs (indium is used in liquid crystal displays as well). Cost reduction and module efficiencies of up to 15% can be achieved using better basic

Table 4 – Performance and Targets for Emerging PV Options (data from IEA 2010a, EPIA 2011)

	2010	2015-2020	2030-
CPV			
Effic.(lab-effic.),%	20-25 (40)	36 (45)	>45
Major R&D areas and targets	lifetime; optical efficiency (85%), sun-tracking, high concentration, up-scaling;		
Inorganic TF (spheral cells, poly-c Si cells)			
Effic.(lab-effic.),%	(10.5)	12-14 (15)	16-18
Major R&D areas and targets	deposition, interconnection, ultra-thin films; up-scaling, light tailoring		
Organic cells (OPV, DSSC)			
Effic.(lab-effic.),%	4 (6-12)	10 (15)	na
Major R&D areas and targets	Lifetime (>15 yr), industrial up-scaling		
Novel active layers			
Effic.(lab-effic.),%	Na	(>25)	40
Major R&D areas and targets	Materials, deposition techniques, understanding quantum effects, up-scaling from lab production		
Up/down converters			
Module effic., %	+10% over ref. Material		
Major R&D areas and targets	(nano) materials, physical stability, up-scaling		

processes (e.g. interface and grain boundary chemistry, thin-film growth on substrates), novel materials (e.g. new chalcopirytes, wide band-gap materials for tandem cells), material band-gap engineering (e.g. spectrum conversion, quantum effects), non-vacuum deposition techniques, electro-deposition, nano-particle printing and low-cost substrates and packaging.

- **Emerging and Novel PV Technologies –** A number of emerging and novel PV technologies are under investigation with a potential for higher efficiency and lower cost than c-Si and thin films. They include concentrating PV (CPV), organic solar cells, advanced inorganic thin-films, thermo-photovoltaics (TPV) and novel concepts that aim at either tailoring the active layer for better matching to the solar spectrum or modifying the solar spectrum to improve the energy capture. Typical efficiencies and R&D targets are provided in Table 4. Some of these technologies are beginning to emerge in the marketplace for niche applications. The feasibility of other options depends on breakthroughs in material science, nano-technology, plastic electronics and photonics.

- **Concentrating Photovoltaics (CPV)** is the most mature emerging technology. In CPV systems, optical sun-tracking concentrators (i.e. lens) focus the *direct* sunlight on highly efficient solar cells. This high efficiency reduces the need for costly active materials and helps offset to some extent the additional cost of the concentration system. The CPV technology is currently moving from pilot and demonstration plants to commercial applications, but further R&D is needed, particularly to reduce costs. A variety of options for cell materials and concentrators (with concentration factors from 2-100 and even up to 1,000 suns) is being tested.

  In general, c-Si modules with efficiencies of 20-25% are used with low-medium sunlight concentration while III-V semi-conductors and multi-junction solar cells (e.g. triple junction GaInP/GaInAs/Ge obtained from metal-organic CVD) are used for high concentrations (> 250). These high-quality cells can reach lab efficiencies above 40% (and even higher, when adding further junctions). CPV research efforts focus on low-cost. multi-junction cells with efficiency of around 35% and even high-cost, ultra-efficient cells. Concentration systems include lenses, reflection and refraction systems. High concentration factors require high accuracy in optical and sun-tracking systems (0.1 degree) and heat dissipation. Unlike other PV technologies, CPV uses only the direct sunlight component and will make the most sense in Sun Belt regions.

- **Organic Solar Cells** are based on active, organic layers that are also suitable for liquid processing. This technology is based on the use of very low-cost materials and manufacturing processes, with low energy input and easy up-scaling. It might be feasible to achieve costs below USD 0.5/Wp. Major challenges relate to the low efficiency and stability over time. Organic cells include hybrid dye-sensitised solar cells (DSSC) - which retain inorganic elements - and fully-organic cells (OPV). While in 2009, DSSC production amounted to 30 MW, production in 2012 is estimated on the order of few hundred MW. Lab efficiency is in the range of 8-12%, while commercial applications still have efficiency of around 4%. OPV production totalled 5 MW in 2009, with cell efficiencies of 6% for very small areas and below 4% for larger areas. Both technologies use R2R techniques and standard printing to reduce manufacturing costs to USD 0.6-0.7/W in a few years, which means that they still will not compete with c-Si. The demonstration of lab cell efficiencies of 10% (15% by 2015) and a lifetime of 15 years is needed to confirm feasibility. This involves a thorough understanding of the basic physics and synergies with organic LED and organic electronics. OPV cells are currently used for niche applications and their competitiveness has yet to be proven.

- **Advanced Inorganic Thin Films** include evolutionary TF concepts, such as the spheral CIS approach (i.e. glass beads covered by a thin multi-ycrystalline layer with a special interconnection between spheral cells) and the multi-crystalline silicon thin films obtained from the high-temperature (> 600 °C) deposition process, which promises lab efficiencies of up to 15% (10.5% achieved by CSG Solar).

- **Other Novel PV Concepts** are in a very early stage and their technical feasibility has yet to be proved. They rely on nanotechnology and quantum effects to provide high-efficiency solar cells that either match the solar spectrum using novel and tailored active materials or modify it to increase the energy absorption of current active materials. In the first approach, quantum effects[7] and nano-materials enable a more favourable trade-off between output current and voltage of the solar cell[8]. R&D efforts aim to demonstrate cell efficiency above 25% by 2015 and to characterise nano-materials and cells with a theoretical efficiency limit as high as 60%. The second approach relies on up/down-converters[9] to tailor the solar radiation and maximise the energy capture in existing solar cells. Photon absorption and re-emission may shift the sunlight wave-length and increase the energy capture (i.e. plasmonic excitation). The target is a 10% increase in the efficiency of existing c-Si cells and TF. However, a full understanding of these processes will take some years.

- **Balance of System (BoS) –** The balance of the system (BoS) includes components other than the PV modules (e.g. the inverter to convert DC into AC, the power control systems, cabling, racking and energy storage devices, if any). The BoS consists of rather mature technologies and components, but in recent years the BoS cost has declined in line with the price of PV module in most competitive PV markets. However, it remains to be seen whether this trend can be maintained in the future. Apart from reducing costs, the main targets for the inverter are improved lifetime and reliability, and control of

7 Note that quantum wells or quantum dots consist of low-band gap semi-conductors within a host semi-conductor with a wider band gap to enable increased current with high output voltage).

8 In PV cells, current and voltage depend on band gap with opposite trends.

9 Down-converters convert high-energy (e.g. violet) photons into two lower-energy (near infrared) photons for more efficient sunlight absorption. Up-converters convert two low-energy photons into a higher energy photon.

reactive power in grid-connected systems (this may help grid integration). Inverters are available with capacities from a few kW to as much as 2 MW for use in large-scale systems. Either single or numerous inverters can be used for a single PV system, depending on design requirements.

The BoS can also include electricity storage. As far as storage is concerned, in addition to lead-acid batteries and traditional pumped hydro storage systems (suitable for large-scale only), a number of new energy storage devices are being developed. These include new batteries technologies, electric capacitors, compressed air systems, superconducting magnets and flywheels. Apart from pumped hydro, none of these technologies is currently mature and cost-effective for large-scale commercialisation. Cost-effective electricity storage could significantly boost the market penetration of PV power by helping to manage the variability of the solar energy. For batteries, current R&D efforts focus primarily on performance, lifetime and cost of electrical batteries (i.e. Ni-MH and Li-ion batteries), but a number of other options are also under consideration. In particular, NaS batteries could represent a competitive long-term, large-scale solution. Off-grid PV systems must also be equipped with back-up power (e.g. diesel generators, biomass-fired generators, wind power) to supply energy when sunlight is not available.

Current Costs and Cost Projections

At present, providing up to date PV prices is a challenging task as the market is evolving on a monthly basis due to increased competition among suppliers, changing policy incentives in many countries, continuous material and technology innovation, growing economies of scale and dramatic cost reductions. PV power is currently economically competitive for off-grid applications, but recent PV cost reductions mean that residential and commercial grid-connected systems have significantly increased their economic attractiveness in the most favourable geographical locations, even without policy incentives and are likely to become competitive in the near future. The financial incentives that many governments - notably those in developed countries – have been offering to promote PV installations as a part of policies to combat climate change have helped significantly to spur PV deployment and reduce costs by mass production of components and systems. The so-called *grid parity* (i.e. the parity between the PV *generation cost* for residential and commercial systems and the *electricity retail price* for householders) has been achieved or is nearing that goal in the most favourable locations. For instance, in 2011, electricity prices for householders in the EU-27 ranged between USD 83-291/MWh, excluding taxes (Eurostat) while the average cost of PV electricity for large ground-mounted systems ranged from USD 160-270/MWh in southern and northern Europe, respectively.

From the utility perspective, in the absence of incentives, the PV generation cost is not yet competitive with the generation cost of conventional base-load power technologies (except in some countries with excellent solar resources and high fossil fuel prices) because of the relatively high investment cost and the limited capacity factor[10] of PV plants. However, this simple comparison does not take into account the fact that PV systems generally produce during daily peak-demand hours when the marginal cost of electricity is higher. Following this trend, producers of PV systems envisage that large-scale utility systems (i.e. the most competitive PV installations in terms of investment and electricity costs) will lead to the reduction of the levelised cost of electricity (LCOE) from PV systems by between USD 90-200/MWh by 2020 in southern and northern Europe, and USD 50-70/MWh by 2030 in Sun Belt countries (Note that, by definition, the LCOE is the cost per unit of electricity required to cover all investment and operational costs over the system's lifetime without profits). These projections account for the annual solar irradiance variability (e.g. 1,000 kWh/m^2 in Scandinavia, 1,900 kWh/m^2 in southern Europe and 2,200 kWh/m^2 in the Middle East). Residential PV prices will also decline sharply but will remain more expensive than large ground-mounted systems. The PV costs have to be compared with the rising costs of gas- and coal-fired power, taking into account that in many countries governments still subsidise conventional power and fossil fuels.

The investment cost of PV systems is rapidly declining. Over the past three decades, the PV industry has been reducing the price of PV modules by between 18-22% with each doubling of the cumulative installed capacity (EPIA 2011). More recently, prices have dropped even faster as increased competition and a supply surplus have pushed down PV module prices. Further reductions of 40-60% by 2020 are feasible. The increased efficiency of PV modules is an important component of this cost reduction.

10 The capacity factor of a power plant is defined as the ratio of the actual electricity produced per year to the electricity that could in theory be produced based on the nominal peak power and technical availability of the PV system.

The current costs of small PV systems in Germany fell to just USD 2,200/kW in the second quarter of 2012 from an average of USD 3,800/kW in 2010 (IRENA, 2012). However, not all PV markets are as competitive as Germany's. In some countries, small-scale systems (i.e. <10kW) may cost twice as much as in Germany (Seel, 2012). The EPIA forecasts that small-scale rooftop PV system costs in the most competitive markets could decline to between USD 1,750-2,400/kW by 2020. Large, utility-scale PV projects could see their average costs decline to between USD 1,300-1,900/kW by 2020 (EPIA, 2012).

- **Cost of PV Modules –** Due to significant overcapacity, current prices for wafer-based **c-Si modules** fell to around USD 800/kW in September 2012. In addition to overcapacity, the 60% price decline in just two years was due to the reduced use of silicon, higher efficiency (i.e. 5-7% cost reduction per 1% efficiency increase) and industrial learning driven by deployment policies. **Thin film** prices are slightly lower than c-Si module prices, but the projected TF growth in market share, due to lower cost structures than for c-Si, has yet to materialise in today's highly competitive market. In the long-term, the differences between TF technologies are projected to converge, but TF's future is uncertain in the current climate and will depend heavily on technology innovation. **CdTe modules** with efficiency of 11% can compete economically with the cheapest c-Si modules. They are expected to increase efficiency by up to 15% while cost reductions should keep them competitive with c-Si modules. Important steps towards this target include a full understanding of CdTe's basic properties and the use of lower temperature deposition processes. A better understanding of the basic physics can also reduce the cost of **CI(G)S modules** by introducing novel materials, concepts and manufacturing (e.g. new chalcopirytes, polymers, metal substrates, quantum effects, spectrum conversion, electro-deposition and nano-particle printing).

- **Cost Breakdown of PV Systems –** The typical cost of a c-Si module includes about 45-50% for silicon, 25-30% for cell manufacturing and 20-25% for cell assembling into modules. The cost breakdown for a commercial PV system includes 50-60% for PV modules (TF and c-Si, respectively), 10% for the inverter, 23-32% for installation of BoS and about 7% for engineering and procurement (EPIA, 2011). In the past five years, PV modules' share has declined from about 60-75% to 40-60%, depending on the technology. As a consequence —and important for PV competitiveness—is the cost reduction of inverter and BoS prices. Markets like Germany have seen these costs decline in line with module costs, but others have stickier soft-costs, particularly for residential installations, and BoS costs have not come down as rapidly. In Europe, BoS prices have fallen to as little as USD 1,300/kWp for residential roof installations but tend to be lower for ground-based, utility-scale systems.

Potential and Barriers

PV technology is well-positioned to exploit the huge solar energy potential. Estimates suggest that, in principle, if about 4% of the world's deserts were covered by PV modules, this could meet the global primary energy demand, and that 0.34% of the European landmass if covered with solar PV modules would meet the entire European electricity demand (EPIA). Based on solar irradiance and electricity consumption, and assuming a 14% PV efficiency, the surface needed to meet the annual electricity demand of a typical house ranges from 14 m^2 in Rome (i.e. 2,700 kWh/yr/household of electricity) to 33 m^2 in Copenhagen (i.e. 4,400 kWh/yr/household) up to 45 m^2 in New York (i.e. 11,000 kWh/yr/household). This supply would, in principle, meet the average annual electricity demand, taking into account excess production in spring and summer, while additional power would be needed from the grid in most regions during the winter.

There are no technical constraints (e.g. material availability, energy payback time) to the full expansion of the PV market. The main issues remain the relatively high electricity costs (although grid-parity for residential systems will soon be the norm rather than the exception) and the need for advanced grid management and energy storage (or back-up power in off-grid installations) to deal with the intermittent nature of PV power. Recent studies suggest that more than 20% of intermittent power could be integrated into existing large grids without significant difficulty while a more sizeable integration would require re-thinking grid management, larger interconnections, mid-load power plants and energy storage. At present, many countries are preparing for new grid regulations and technologies[11] to accommodate an increasing amount of renewable, non-dispatchable electricity. More challenging is the development of cost-effective energy storage, a key component when the intermittent electricity reaches a certain share, depending on grid size and inter-connection.

As a part of the policies to promote local socio-economic development, combat climate change and increase energy security a good number of countries have **financial incentives** in place (e.g. investment subsidies, fiscal allowances, portfolio standards and feed-in tariffs) aimed at promoting the deployment of PV systems and providing a level playing field for PV power. **Feed-in tariffs** (FiT) is the most common and effective mechanism for PV promotion when accurately set. Under the FiT mechanism, PV electricity producers are granted the right to feed elec-

11 **Smart grids**, e.g. with bi-directional flow and metering between grids and users/producers, and **super grids**, with international interconnection to complement e.g. wind power from windy countries with solar power from sunny countries.

tricity into the grid and receive a premium tariff per kWh over a fixed period of time. This compensates for the high investment cost of PV systems and reflects the social and environmental benefits of solar power. The FiT cost is typically covered by utilities and recovered from electricity consumers. One advantage of a FiT mechanism is that it rewards electricity generation rather than capacity additions. To ensure continued pressure on investment cost reduction, well-designed FiT should plan for gradual decrease over time, based on the PV cost decline (i.e. the "corridor" mechanism). In line with this principle, many European countries (e.g. Germany, Italy, Spain) are significantly reducing their FiT tariffs. In the United States, FiT, energy credits, loans and other mechanisms are in place in some 19 states while, at the federal level, a 30% tax credit is granted to commercial and residential PV systems. China is currently the largest PV module producer and until recently had a small national market. With feed-in tariff incentives introduced in 2011, China is fast becoming the largest PV market. Other countries with incentives include Israel, Turkey, Thailand, South Africa, India, Indonesia, Uganda, Canada and Australia.

PV power benefits from a **good social acceptance**. It is perceived as an environmentally benign technology, a sustainable business and labour opportunity, and an easy and cost-effective way to provide access to electricity in remote rural areas. While today's incentive schemes focus mostly on grid-connected PV systems, special financing mechanisms are needed for off-grid rural electrification in developing countries. According to New Energy Finance (2009), private venture capital investment in solar energy, notably PV, more than doubles each year while public R&D funds increase at a slower pace. In terms of applications, residential systems will continue to dominate in the coming decade, but commercial and utility systems will increase their share. Since 2009, **a number of large PV plants** has been completed and started operation. As of November 2012, about 40 PV power plants with capacities between 40-75 MW are in operation or about to open all over the world (i.e. mostly in Germany, Italy, the USA and Spain, but also in Canada, France, India and the Ukraine).

In terms of market potential, assuming continued policy support and cost reductions, the World Energy Outlook published by the International Energy Agency (IEA, 2012) projects that PV power will provide between 2-3.3% of the global electricity by 2030, depending on the scenario. The most ambitious projections by the European PV Industry Association (EPIA) and Greenpeace predict that PV power could reach between 4.9-5.7% and 7.8-9.1% of the global electricity generation by 2030 (depending on PV growth and electricity demand) and up to 17-21% by 2050 (EPIA, 2012b). The EPIA's analysis assumes a global average capacity factor increasing from today's 12-17% by 2050 with moderate progress in energy storage.

It should be noted that, since 2001, the global PV market has been growing faster than even the most optimistic projection.

PV benefits and impacts have been analysed and monetised by the *SET For 2020* study for the European Union. The benefit of reducing GHG emissions in Europe by producing PV electricity has been estimated at €12/MWh, compared with €23/MWh at the global scale. This is based on a global average GHG emission factor from electricity production of 0.6 kgCO_2/kWh, which includes 12-25 gCO_2/kWh emitted from the PV lifecycle and assumes a CO_2 abatement cost of €20/tCO_2. This estimate is actually a conservative one because the cost of CO_2 abatement in fossil fuel power plants is likely to be well above €20/tCO2 in the long term. All this means that the real external costs of fossil fuel-based power are not included in the current electricity prices. Other benefits in terms of external costs include the reduction of grid losses due to distributed generation (on the order of €5/MWh); the positive impact on energy security (€15-30/MWh, depending on fossil fuel prices) and on electricity demand peaks (i.e. peak shaving), thus reducing the need for additional peak capacity (€10/MWh).

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Table 8 – Summary Table - Key Data and Figures for PV Technologies

Technical performance	Typical current international values and ranges					
Energy input/output	Sunlight/ Electricity					
Current PV technologies	**Crystalline Si**		**Thin Film**			**CPV**
	sc-Si	**mc-Si**	**a-Si/m-Si (m-SiGe)**	**CdTe**	**CI(G)S**	
Max. (record) cell efficiency, %	22 (24.7)	18 (20.3)	10 (13.2)	11.2 (16.5)	12.1(20.3)	(>40)
Max. module efficiency, %	19-20	15-16	9	na	na	na
Commercial modules effic., %	13-19	11-15	7-9	10-11	7-12	20-25
Land use, m^2/kW	6-8	7-9	11-15	9-10	9-15	na
Lifetime, yr	25 (30)		25			na
Energy payback time, yr	1-2		1-1.5			na
Material use, g/W	5-7		na			na
Wafer thickness, µm	<180-200		na			na
Market share, %	~85		~15			na
Typical size (capacity), kW	Residential < 10 kWp; Commercial < 100 kWp; Industry 100Kwp -1MWp; Utility > 1MWp					
Total cumulative capacity	1.4 GW (2001), 23 GW (2009), 40 GW (2010), 70 GW (2011)					
Annual installed capacity	2.8 GW (2007), 5.9 GW (2008), 7.2 GW (2009); 15 GW (2010); 30 GW (2011)					
Capacity factor, %	From 9-16% (in most favourable locations), based on annual electricity production					
CO2 emissions, gCO_{2eq}/kWh	Occurring during manufacturing only - between 12-25 gCO_{2eq}/kWh					
Avoided CO_2 emissions	~ 600 gCO_{2eq}/kWh (based on electricity mix in developed countries); up to 900 gCO_{2eq}/kWh in countries with coal-based power generation.					

Costs By technology	Typical current international values and ranges (2012 USD, 1EUR = 1.3 USD)				
	Crystalline Si	Thin Film			CPV
	c-Si	a-Si/μ-Si; (μ-SiGe)	CdTe	CI(G)S	
Module cost, $/kW (2012)[1]	880-1140	650-750	770-1000 (1500)	770-1000(1500)	3100-4400
BoS cost, $/kW (2012)	820-1660 (best practice to global average)				
O&M cost	Estimated at 1% of the investment cost per year				
Typical cost breakdown	PV module 50-60% (TF-c-Si); Inverter 10-11%; BoS & Installation 32-23%; E&P 7%				
By applications	Residential systems		Commercial systems	Utility systems	
System cost, $/kW	2200 – 4500		1900 - 2500	1700 – 2100	
Electricity cost[2], $/MWh	190-200[3]		130-160[4]	100 -150[5]	
Cost projections 2016	Residential systems		Commercial systems	Utility systems	
Module cost, $/kW	920 (c-Si) -950 (TF)				
BoS cost, $/kW	1200-1600 (global average)				
Electricity cost, $/MWh	150		110-130	80-140	
Market share projection	2030			2050	
Global electricity share, %	2-3.3% (IEA,2012); 4.9-5.7% to 7.8-9.1% (EPIA,2012)			17-21% (EPIA,2012)	

1 Sources: www. Sologico.com – 2012; Photon Consulting 2012; (overall TF module cost)
2 25-year lifetime, 10% interest rate, 1%/yr O&M cost
3 With reference to the US and Japan markets,
4 With reference to Italian and German market
5 With reference to Chinese and US markets

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