Photovoltaic Solar Power

INSIGHTS FOR POLICY MAKERS

Solar photovoltaic (PV) cells convert sunlight directly into electricity. Currently, crystalline silicon (c-Si) and the so-called thin-fi lm (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 poly-silicon 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 labor-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 100 GW at the end of 2012, with about 30 GW of capacity installed per year in 2011 and 2012. 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 tariff s, 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 tariff s. 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 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 same as in the recent past years.

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TECHNICAL HIGHLIGHTS

■ **PROCESS AND TECHNOLOGY STATUS -** Photovoltaic (PV) solar cells convert directly sunlight into electricity, using the *photovoltaic effect*. The process works even on cloudy or rainy days, though with reduced conversion efficiency. PV cells are assembled into modules to build modular PV systems that are used to generate electricity in both on-grid and off-grid applications, e.g. residential and commercial buildings, industrial facilities, and utility PV systems. Over the past decades PV technology has been constantly improving performance and reducing costs. Most recently, rapid cost reductions have enabled PV power to become economically competitive not only in niche markets such as off-grid systems, but also for on-grid use. As a result, PV power is expanding rapidly in many countries, fostered by governmental incentives such as *feed-in tariffs*. In countries with good solar resources and high electricity prices, the electricity generation cost of residential PV systems is already competitive with the electricity retail price, whilst in general PV power is not yet competitive with base-load power generation. The global cumulative PV capacity (only 1.4 GW in 2000) has reached the level of about 100 GW at the end of 2012, with about 30 GW of new capacity per year added in 2011 and 2012. In 2011, the total annual investment in PV systems amounted to about USD 93 billion, and the European countries accounted for 70% of the newly installed capacity. In recent years, leading countries in terms of annual installed PV capacity, cumulative capacity, and/or production of PV modules have been Germany, Italy, the United States, China and Japan. Current 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/c-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. Novel PV concepts such as concentrating PV and organic PV are under development.

■ **PERFORMANCE AND COSTS –** While **c-Si** cells have reached a record efficiency of around 25%, the best commercial modules offer today's efficiencies of 19-20% (with a 23% target by 2020), and the majority of commercial c-Si modules have efficiencies of 13-19%, with more than a 25-year lifetime. Commercial **TF** modules offer lower efficiency between 6% and 12%, with a target of 12-16% by 2020. Today's PV systems are fully economically competitive for off–grid electricity generation and with diesel-based on-grid systems in countries with good solar resources. In these countries, small PV systems are also achieving the so-called *grid-parity* between the PV electricity generation 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 USD160-270/MWh in southern and northern Europe, respectively. Advantages of PV power also include that production is usually close to the consumption site and that supply often matches peak demand profiles. If compared with cheapest conventional power technologies, current PV systems still involve higher investment cost and significantly lower capacity factor, which translate into relatively higher costs of electricity. However, PV capital costs are declining very rapidly due to increasing industrial production and high learning rate. More than a 60% reduction has been achieved over the last two years and more than a 40% reduction is likely to occur by 2020. Although the rate of decline is now slowing, in September 2012 the Chinese c-Si module prices had fallen to an average of USD 0.75/W, and in Germany the costs of installed rooftop PV systems has fallen to USD 2.2/W by mid-2012. The recent decline of PV costs has been so rapid that all past cost projections have become obsolete. In particular, the cost reduction of c-Si modules has squeezed TF technologies increasingly into niche markets. Latest industry studies (EPIA, 2012) suggest a slowdown in PV cost reduction, with residential systems falling to USD 1.8-2.4/W by 2020 in most competitive markets.

■ **POTENTIAL & BARRIERS –** PV power has a virtually unlimited energy potential with no environmental constraints. 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 (e.g. feed-in tariffs, tax incentives). The variable nature of the solar source 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 to provide electricity to remote areas if integrated with storage and/or backup generation. Scenarios by the European PV Industry Association (EPIA, 2012) project that PV power could reach from 4.9 to 9.1% of the global electricity generation by 2030 and up to 17-21% by 2050. Assuming continued policy support and cost reductions, the World Energy Outlook of the International Energy Agency (IEA, 2012) presents a more conservative outlook where PV power provides about 2-3.3% of the global electricity by 2030. It is noteworthy that since 2001 the global PV market has grown faster than the most optimistic projections.

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BASIC PROCESS AND TECHNOLOGY STATUS

Based on the *photovoltaic (PV) effect*[1], PV solar cells can convert directly solar energy into electricity. PV electricity was discovered in the 19th century, but first modern PV cells for electricity generation based on silicon (Si) semiconductors were developed in the 1950s. The large-scale commercialisation of PV devices started only after 2000, following financial incentives that in many countries are part of government policies to mitigate CO_2 emissions and improve energy security. The PV electricity is environmentally friendly[2] and has virtually unlimited potential. Currently, PV power provides a small percentage of global electricity supply, but the market is expanding very rapidly driven by financial incentives and rapid cost reductions. Over the past decade, the global cumulative installed PV capacity has been growing from 1.4 GW in 2000 to around 100 GW at the end of 2012 (Figure 1), with some 30 GW/y of new capacity installed in 2011 and 2012, and an annual investment that in 2011 was estimated at around USD 93 billions[3]. In terms of new installed capacity, leading countries in 2011 were Italy (9.3 GW), Germany (7.5 GW), China (2.2 GW), United States (1.9 GW) and Japan (1.3 GW). In terms of total installed capacity, Europe accounts for around three-quarters of the global total, with the leading countries being Germany, Italy and Spain. Outside of Europe, China, the United States, Japan, Australia, Canada and India are the largest markets. China, Germany, the US and Japan are leading producers of PV components and systems.

While PV power can be used for either grid-connected applications (residential, commercial and utility systems) and off-grid installations, more than 90% of the installed capacity consists of grid-connected systems. Primary applications are systems for residential and commercial buildings, with unit size of up to 10 kWp and 100 kWp, respectively, followed by utility systems (size> 1 MWp), and off-grid applications (telecommunication devices, rural supply, consumer goods). The current share of the residential sector is 60%.

There are currently no technical (e.g. material availability) or industrial constraints to the growth of the share of PV power in the global energy mix. The PV industry has quickly increased its production capacity to meet the growing demand. At present, supply capacity exceeds the demand by a large margin. Although there

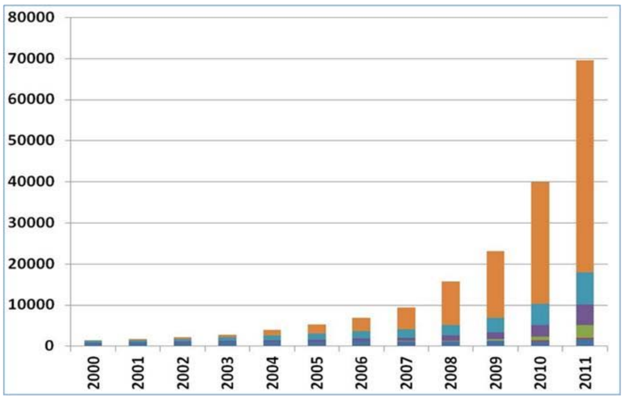

Figure 1 - Global installed PV capacity (MW) – EPIA, 2012

are over 1,000 companies that currently produce PV products worldwide (PV cells, modules, systems, etc.), 90% of the basic material (polysilicon) is produced by a few companies mostly in the United States, Japan, Europe and China.

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 (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 reducing the investment costs so as to minimise the electricity

[1] In the PV effect, two different (or differently doped) semiconducting materials (e.g. silicon, germanium), in close contact each other, generate an electrical current when exposed to sunlight. Sunlight provides energy to electrons to cross the junction (p-n junction) between the two materials more easily in one direction than in the other one. This generates a voltage and a direct electrical 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 emission during operation and small environmental impact.

[3] All costs are expressed in 2010 USD or converted from EUR in USD using the conventional exchange rate of 1E=1.3 USD.

[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 to 3 years depending on location; to compare with a lifetime of at least 25 year. PV systems are durable as they have no moving or rotating components.

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: single (or mono) crystalline silicon (s**c-Si**), multi-crystalline silicon (**mc-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/_c-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. In 2011, crystalline silicon (c-Si) accounted for 89% of the global market and TF technology accounted for the remaining 11%. Among TF, the market is mostly shifting to CdTe and CIGS. Among emerging technologies, concentrating PV and organic solar cells are just entering the market and expected to capture some percentage points in the next years. Table 2 provides the evolution of performance over time for commercial PV modules. Individual PV technologies are discussed in the following sections,

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

	Cell effic. (%)	Module effic. (%)	Record commercial and (lab) efficiency, (%)	Area/kW (m^2/KW) (a)	Life-time (yr)
c-Si					
sc-Si	16 - 22	13 - 19	22 (24.7)	7	25 (30)
mc-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		na	na	na
CPV	na	20 - 25	>40	na	na

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

Table 2 - Performance & Targets for PV Technology (EU SRA 2008, IEA 2010, EPIA 2011)

	1980	2007	2010	2015-20	2030+
Module effic., %					
▪ c-Si	≤8	13-18	13-19	16-23	na
▪ mc-Si			11-15	19	na
▪ TF	na	4-11	4-12	8-16	na
c-Si material use, g/W			7	3	<3
c-Si wafer thickn, μm			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

■ **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 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 (transparent glass, thin polymers), and frames to increase modules 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. The sc-Si cells offer higher efficiency (Table 2 & 3) while mc-Si cells are less efficient because of the disorder of their 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 to 1.7 m² (up to 2.5 m² 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, and *HIT* (hetero-junction with intrinsic thin layer, consisting of a sc-Si wafer between ultra-thin a-Si layers to improves efficiency. The record cell efficiency for simple c-Si cells (24.7%) belongs to SunPower. Higher efficiency have been achieved using materials other than silicon and multi-junction cells (i.e. Sharp: 35.8% without concentration; Boeing Spectrolab: 41.6%, with 364 times concentration).

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 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 to

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

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200 μm. Cell interconnection (metallisation, back-contacts), encapsulation and assembly techniques using glass, polymer and aluminium structures are continuously improving to reduce costs and increase performance. The reduction or the substitution of high-cost materials used in the manufacturing process (e.g. silver, currently 80-90 mg/W_p) also is a key objective. As far as efficiency is concerned, the maximum theoretically efficiency for c-Si is currently estimated at around 29%. Record cell efficiencies have been obtained using expensive laboratory processes (clean rooms, vacuum technologies, etc.), but only a few commercial cells have efficiency above 20%. Current commercial sc-Si modules efficiencies, which are lower than for cells, range between 13% and 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, with low-cost manufacturing (screen-printing), and lower efficiencies between 12% and 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 low-cost materials such as steel, glass or plastic. TF technologies use small amounts of active materials and require low manufacturing energy and costs. Despite their lower efficiency, they have short energy pay-back times (less than 1yr in Southern Europe), good stability and lifetime 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 m² for CIGS and CdTe, and 1.4-5.7 m² for silicon-based TF. In comparison with c-Si modules, TF modules have a significantly lower efficiency (4% to 12%). 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; 4) encapsulation in a glass-polymer casing. Roll-to-roll (R2R) techniques are often used with flexible substrates to reduce production time and costs. The operational experience with TF systems is also lower than with c-Si systems.

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 (R2R coating, sputtering, cheap and durable packaging), quality control and ageing 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 currently undergoing significant changes because its market is being challenged by the low costs of c-Si modules. Four types of commercial TF modules are described below. Typical efficiency is 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 m²), with low manufacturing costs but also low efficiency (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. 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 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% and 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

Table 3 – Performance and Targets for TF technologies (IEA 2010, 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 (μc-SiGe, SiC, nano-diamond, cheaper TCO and substrates); Replace/recycle scarce materials; better understanding of physics of advanced concepts (multi-junctions, doping, quantum dots, up/down converters, photonic crystals)

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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 (up to 11%). They are easily manufactured at low-cost via a variety of deposition techniques. The efficiency depends significantly on deposition temperature, growth techniques and the substrate material. The highest efficiencies (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 the key to minimise 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 (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 up to 15% can be achieved using better basic 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 (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 and novel concepts that aim at either tailoring the active layer for better matching 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 such technologies (CPV, organic cells) are beginning to emerge in the marketplace for niche applications. The feasibility of other options depend on breakthroughs in material science, nano-technology, plastic electronics, photonics.

Concentrating Photovoltaics (CPV) is the most mature emerging technology. In CPV systems, optical sun-tracking concentrators (lens) focus the *direct* sunlight on highly-efficient solar cells. The high efficiency reduces

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

	2010	2015-2020	2030-
CPV			
Effic.(lab-effic.),%	20-25 (40)	36 (45)	>45
R&D targets	25-yr lifetime; 85% optical effic., sun-tracking, high concentration, up-scaling.		
Inorganic TF (spheral cells, poly-c Si cells)			
Effic.(lab-effic.),%	(10.5)	12-14 (15)	16-18
R&D targets	deposition, interconnection, ultra-thin films industrial up-scaling, light tailoring		
Organic cells (OPV, DSSC)			
Effic.(lab-effic.),%	4 (6-12)	10 (15)	na
R&D targets	Lifetime>15 yr, industrial up-scaling		
TPV			
Effic.(lab-effic.),%	na	(8)	15
R&D targets	lifetime >15 yr, industrial up-scaling		
Novel active layers			
Effic.(lab-effic.),%	na	(>25)	40
R&D targets	deposition, nano-mat. & opto-electronics, q-wells, q-wires, q-dots, up-scaling		
Up/down converters			
Module effic., %	+10% over ref. material		
R&D targets	nano-materials, stability, up-scaling		

the need for costly active material 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 (concentration factors from 2 to 100, and even up to 1000 suns) are being tested.

In general, c-Si modules with efficiency 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 concentration (> 250). These high-quality cells can reach lab efficiencies above 40% (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 mostly make sense in sun-belt countries.

● **Organic solar cells** are based on active, organic layers that are also suitable for liquid processing. This

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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 able to achieve costs below USD0.5/Wp. Major challenges relates to the low efficiency and the stability over time. Organic cells include either hybrid dye-sensitised solar cells (DSSC) - which retain inorganic elements - and fully-organic cells (OPV). DSSC production is currently (2012) estimated at several tens of MW, with lab efficiency in the range of 8-12% and commercial efficiency of around 4%. OPV cells have 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 USD0.6-0.7/W in a few years, which means 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 good understanding of the basic physics, and synergies with the development of organic electronics (e.g. LED). OPV cells are currently used for niche applications and their competitiveness is 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 polycrystalline layer, with a special interconnection between spheral cells) and the polycrystalline silicon thin films obtained from 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 of development, with technical feasibility 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, tailored active materials, or modify it to increase the energy absorption of current active materials. In the first approach, quantum effects and nano-materials enable a more favourable trade-off between output current and voltage of the solar cell[7]. 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[8] 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 (plasmonic excitation). The target is a 10% increase of 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 direct current 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 continue in the future. Apart from reducing costs, the main targets for the inverter are improved lifetime and reliability, and control of 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 devices. In addition to pumped-hydro storage (which is suitable for large-scale storage only) and traditional lead-acid batteries, a number of electricity storage devices are being developed (ETSAP E18). 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 managing the variability of the solar energy. Large R&D efforts focus primarily on performance, lifetime and cost of batteries (Ni-MH, Li-ion, NaS, and a number of novel concepts.).

CURRENT COSTS AND COST PROJECTIONS

Providing up to date PV prices is currently 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 reduction. PV power is currently fully competitive for off-grid applications, but recent cost reductions mean that, in sunny regions, residential and commercial grid-connected PV systems are more economically attractive, even with no policy incentives, or are likely to become so in the near future. The financial incentives that many governments - notably 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.

Electricity generation cost - The so-called *grid parity,* i.e. the parity between the PV electricity generation cost for residential and commercial systems and the *electricity retail price* for householders, has been achieved or is about to be achieved in most favourable

[7] In PV cells, current and voltage depend on band gap with opposite trends.
[8] Down-converters convert high-energy (e.g. violet) photons in two low-energy (near infrared) photons for more efficient sunlight absorption. Up-converters convert two low-energy photons in a high-energy photon.

locations. In 2011 for example, electricity prices for householders in the EU-27 ranged between USD 83/MWh and 291/MWh excluding taxes (Eurostat) while the average cost of PV electricity for large ground-mounted systems ranged from USD 160/MWh to 270/MWh in South and North 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 because of the relatively high investment cost and the limited capacity factor[9] of PV plants. However, this simple comparison doesn't take into account that PV systems generally produce during daily peak-demand hours when the marginal cost of electricity is higher. Following this trend, PV producers envisage that large-scale utility systems – the most competitive PV installations – will lead the reduction of the levelised cost of electricity (LCOE) for PV plants to about USD 90-200/MWh by 2020 (South and North Europe, respectively), and to USD50-70/MWh by 2030 in Sun-Belt countries. These projections account for the solar irradiance variability (e.g. 1000 kWh/m² in Scandinavia, 1900 kWh/m² in South Europe, 2200 kWh/m² in 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 increasing costs of the gas- and coal-fired power, taking into account that in many countries governments still subsidise fossil fuels and that prices are currently low due to the economic crisis.

Investment cost - The investment cost of PV systems is also rapidly declining. Over the past three decades, the PV industry has been reducing the price of PV modules by an average 18-22% each time the cumulative installed capacity has doubled (EPIA 2011). More recently, prices have dropped even faster (60% in the past two years) because of the increased competition and supply surplus. Further reductions of more than 40% are thought to be feasible by 2020. The increased efficiency of PV modules is an important component of this cost reduction.

The current costs of small PV systems in Germany fell to just USD2200/kW in the second quarter of 2012, from an average of USD3800/kW in 2010 (IRENA, 2012). However, not all PV markets are so competitive. In some countries, small-scale systems (<10kW) may cost twice the cost in Germany (Seel, 2012). The EPIA projects that small-scale rooftop PV system costs in the most competitive markets could decline to between USD 1750 and 2400 per kW by 2020 and that large, utility-scale PV projects could see costs to decline to between USD 1270 and 1920 per kW by 2020 (EPIA, 2012)

Cost of PV modules – Due to significant overcapacity, current prices of wafer-based **c-Si modules** have fallen to around USD 800/kW in September 2012. In addition to the over capacity, the strong price decline (60% in two years) was due to the reduced use of silicon, the higher efficiency (i.e. 5-7% cost reduction per 1% efficiency increase), and the industrial learning driven by the deployment policies. **Thin films** module prices are slightly lower than c-Si module prices, but the projected growth of TF market has not yet materialised because of the strong reduction of c-Si modules prices. **CdTe modules** with efficiency of 11% can still economically compete with the cheapest c-Si modules, but the future of TF will depend significantly on technology innovation and the ability to increase the efficiency and reduce prices. An important step is a full understanding of CdTe basic properties and the use of lower temperature deposition processes. Better understanding of the basic physics is also the key to reduce the cost of **CI(G)S modules** by introducing new materials and manufacturing (e.g. new chalcopirytes, polymers, metal substrates, quantum effects, spectrum conversion, electro-deposition, 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% to 60% for PV modules (TF and c-Si, respectively), 10% for the inverter, 32% to 23% for installation and BoS, and about 7% for engineering and procurement (EPIA, 2011). In the past 5 years, the share of the PV modules has declined from about 60-75% to 40-60%, depending on the technology. As a consequence, cost reductions of inverter and BoS are also important for PV competitiveness. In some markets (e.g. Germany), these costs have been declining in line with module costs, but other markets have stickier soft-costs for BoS, particularly for residential installations. In Europe, BoS prices have fallen to as little as USD 1300/kWp for residential roof installations, but tend to be lower for ground-based systems, utility-scale systems.

POTENTIAL AND BARRIERS

PV technology is well-positioned to exploit the huge solar energy potential. In principle, about a 4% of the world's deserts covered by PV modules could meet the global primary energy demand, and about 0.34% of the European landmass covered with PV modules could meet the entire European electricity demand (EPIA). Based on a 14% PV efficiency and local electricity consumption, 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/y per household) to 33 m^2 in

[9] The capacity factor of a power plant is usually defined as the number of hours the power plant can work at nominal power, taking into account technical availability (i.e. maintenance needs). In PV systems, the capacity factor takes into account the sun availability over the year and the fact that the power level with a cloudy sky is lower than the nominal power. Therefore, the PV capacity factor is defined as the ratio of the electricity produced per year to the electricity that could in theory be produced based on nominal (peak) power and technical availability.

Copenhagen (4,400 kWh/y) up to 45 m^2 in New York (11,000 kWh/y). This supply would meet in principle 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 such as material availability and energy payback time to the full expansion of the PV market. Main issues remain the relatively high electricity costs (although grid-parity for residential systems will soon be the norm rather than an exception) and the need for advanced grid management and energy storage (or backup 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 larger integration would require new grid management approaches, larger grid interconnection, mid-load power plants and energy storage. At present, many countries are preparing for new grid regulations and technologies[10] 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 electricity share, depending on grid size and interconnection.

As a part of the policies to combat the climate change, a number of countries have **financial incentives** in place (e.g. investment subsidies, fiscal allowances, portfolio standards, and feed-in tariffs) aimed to promote the deployment of PV systems and provide a level playing field for PV power. **Feed-in tariffs** (FiT) is the most used and effective mechanism for PV promotion when accurately set. Under the FiT mechanism, PV electricity producers are granted the right to feed electricity 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. An advantage of a FiT mechanism is that it rewards the electricity generation, rather than capacity additions. To ensure continued pressure on capital cost reduction, well-designed FiT should plan for gradual decrease over time, based on PV cost decline (corridor mechanism). In line with this principle, many European countries such as Germany, Italy, Spain are significantly reducing their FiT tariffs. In the United States, FiT, energy credit, loans etc. are in place many States while, at federal level, a 30% tax credit is granted to commercial and residential PV systems. China, the largest PV producer, has introduced FiT in 2011 and is rapidly 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 environmental benign technology, a sustainable business and labour opportunity, and an easy and cost-effective way to provide access to electricity in rural, remote 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. In the last three years **a number of large PV plants** have been completed and started operation. As of November 2012, about 40 PV power plants with capacity between 40 and 75 MW are in operation or are about to start operation all over the world, (mostly in Germany, Italy, USA, Spain, but also in Canada France India, Ukraine).

In terms of market potential, assuming continued policy support and cost reduction, the International Energy Agency (IEA, 2012) projects that PV power will provide between 2% and 3.3% of the global electricity by 2030. More ambitious projections by the European PV Industry Association (EPIA) and Greenpeace project 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% to 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 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 (€23/MWh on global basis). This is based on a global average GHG emission factor from electricity production of 0.6 $kgCO_2$/kWh, includes 12-25 gCO_2/kWh emitted from the PV lifecycle, and assumes a CO_2 abatement cost of €20/tCO_2). This is actually a conservative estimate because the cost of CO2 abatement in fossil fuel power plants may be well above USD 20/tCO2. 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

10 smart grids (e.g. bi-directional flow and metering between grids and distributed users/producers, intelligent demand side management, large grid interconnection and energy storage to compensate for the variability of renewable sources.

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costs include the reduction of grid losses due to distributed generation (in the order of €5/MWh); the positive impact on energy security (€15-30/MWh, depending on fossil fuels price) and on electricity demand peaks (peak shaving), thus reducing the need for additional peak capacity (€10/MWh).

The impact of PV industry and deployment on employment is estimated at about 30 full-time jobs per MW of PV power installed. Phoenix Solar AG and A. T. Kearney have also calculated that the impact of FiT incentives on the electricity price in Germany is in the order of €13/MWh. This represents about 5% of the current electricity price.

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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 Films			CPV
	sc-Si	mc-Si	a-Si/µ-Si (µ-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) 100 GW (2012)					
Annual installed capacity,	2.8 GW (2007), 5.9 GW (2008), 7.2 GW (2009); 15 GW (2010); 30 GW (2011, 2012)					
Capacity factor, %	From 9% to 16% (in most favourable locations), based on annual electricity production					
CO2 emissions, gCO_{2eq}/kWh	Occurring during manufacturing only - between 12 and 25 gCO_{2eq}/kWh					
Avoided CO_2 emissions	~ 600 gCO_{2eq}/kWh (based on electricity mix in developed countries); up to 900 in other areas					
Costs	Typical current international values and ranges (2012 USD, 1EUR = 1.3 USD)					
By technology	Crystalline Si	Thin Film				CPV
	c-Si	a-Si/µ-Si;(µ-SiGe)		CdTe	CI(G)S	
Module cost, $/kW (2012)[11]	880-1140	650-750		770-1000 (1500)	770-1000(1500)	3100-4400
BoS cost, $/kW (2012)	820 to 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[12], $/MWh	190-200[13]		130-160[14]		100 -150[15]	
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% to 3.3% (IEA,2012); 4.9-5.7% to 7.8-9.1% (EPIA,2012)				17% to 21% (EPIA,2012)	

[11] Sources: www. Sologico.com – 2012; Photon Consulting 2012; (overall TF module cost)
[12] 25-year lifetime, 10% interest rate, 1%/yr O&M cost
[13] With reference to the US and Japan markets,
[14] With reference to Italian and German market
[15] With reference to Chinese and US markets

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