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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation dedicated to renewable energy.

In accordance with its Statute, IRENA's objective is to "promote the widespread and increased adoption and the sustainable use of all forms of renewable energy". This concerns all forms of energy produced from renewable sources in a sustainable manner and includes bioenergy, geothermal energy, hydropower, ocean, solar and wind energy.

As of May 2012, the membership of IRENA comprised 158 States and the European Union (EU), out of which 94 States and the EU have ratified the Statute.

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This working paper is available for download from www.irena.org/Publications

Preface

Renewable power generation can help countries meet their sustainable development goals through provision of access to clean, secure, reliable and affordable energy.

Renewable energy has gone mainstream, accounting for the majority of capacity additions in power generation today. Tens of gigawatts of wind, hydropower and solar photovoltaic capacity are installed worldwide every year in a renewable energy market that is worth more than a hundred billion USD annually. Other renewable power technology markets are also emerging. Recent years have seen dramatic reductions in renewable energy technologies' costs as a result of R&D and accelerated deployment. Yet policy-makers are often not aware of the latest cost data.

International Renewable Energy Agency (IRENA) Member Countries have asked for better, objective cost data for renewable energy technologies. This working paper aims to serve that need and is part of a set of five reports on solar pholtovoltaics, wind, biomass, hydropower and concentrating solar power that address the current costs of these key renewable power technology options. The reports provide valuable insights into the current state of deployment, types of technologies available and their costs and performance. The analysis is based on a range of data sources with the objective of developing a uniform dataset that supports comparison across technologies of different cost indicators - equipment, project and levelised cost of electricity – and allows for technology and cost trends, as well as their variability to be assessed.

The papers are not a detailed financial analysis of project economics. However, they do provide simple, clear metrics based on up-to-date and reliable information which can be used to evaluate the costs and performance of different renewable power generation technologies. These reports help to inform the current debate about renewable power generation and assist governments and key decision makers to make informed decisions on policy and investment.

The dataset used in these papers will be augmented over time with new project cost data collected from IRENA Member Countries. The combined data will be the basis for forthcoming IRENA publications and toolkits to assist countries with renewable energy policy development and planning. Therefore, we welcome your feedback on the data and analysis presented in these papers, and we hope that they help you in your policy, planning and investment decisions.

Dolf Gielen

Director, Innovation and Technology

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Key findings

1. **At the beginning of 2012,** thin-film module prices (factory gate or spot) had fallen below USD 1/watt (W), with prices between USD 0.84 and USD 0.93/W available. The prices of crystalline silicon (c-Si) modules are more varied, but were typically in the range USD 1.02 to USD 1.24/W for the most competitive markets. PV module costs have a learning rate of 22%, implying that costs will decline by just over a fifth with every doubling of capacity. Continued rapid cost reductions are likely due to the rapid growth in deployment, given that cumulative installed capacity grew by 71% in 2011 alone.

2. **The total installed cost of PV systems** can vary widely within individual countries, and between countries and regions. These variations reflect the maturity of domestic markets, local labour and manufacturing costs, incentive levels and structures, and a range of other factors. At an average of USD 3.8/W for c-Si systems, Germany has the lowest PV system costs in the small-scale residential market (<5 kW). In comparison, the average installed cost in 2011 in Italy, Spain, Portugal and the United States was between USD 5.7 to USD 5.8/W.

3. **Utility-scale systems using thin-film** amorphous silicon, Cadmium Telluride (CdTe) and Copper-Indium-Gallium-Diselenide (CIGS) PV modules tend to have lower capital costs than residential systems in a given market, but this is not always the case if tracking is included. Thin-film utility-scale systems had an average cost of around USD 3.9/W in 2010, not substantially cheaper than the average cost of a residential c-Si system in Germany in 2011.

TABLE 1: TYPICAL COST AND PERFORMANCE VALUES FOR SOLAR PV SYSTEMS

	Module cost, factory gate or spot (2010 USD/W)	Installed cost (2010 USD/W)	Efficiency (%)	Levelised cost of electricity (2010 USD/kWh)
Residential				
c-Si PV system	1.02 – 1.24	3.8 – 5.8	14	0.25 – 0.65
c-Si PV system with battery storage	1.02 – 1.24	5 – 6	14	0.36 – 0.71
Utility-scale				
Amorphous Si thin film	0.84 – 0.93	3.6 – 5.0	8 – 9	0.26 – 0.59

Note: Assumes a 10% cost of capital.

4. **Despite the impressive declines in PV system costs,** the levelised cost of electricity (LCOE) of PV remains high. The LCOE of residential systems without storage assuming a 10% cost of capital was in the range USD 0.25 and USD 0.65/kWh in 2011. When electricity storage is added, the cost range increases to USD 0.36 and USD 0.71/kWh. The LCOE of current utility-scale thin-film PV systems was estimated to be between USD 0.26 and USD 0.59/kWh in 2011 for thin-film systems.

5. **Despite the large LCOE range,** PV is often already competitive with residential tariffs in regions with good solar resources, low PV system costs and high electricity tariffs for residential consumers. In addition, PV with storage is now virtually always cheaper than diesel generators for the provision of off-grid electricity.

6. **The prospects for continued cost** reductions are very good. However, the rate at which PV costs will decline is highly uncertain due to the very rapid growth in the PV market compared to the installed base and the high learning rate for PV. As a result, even small differences in scenarios for PV growth can have a big impact on the projected decline in module prices. Leaving aside this uncertainty, the installed costs of a c-Si residential system may decline from between USD 3.8 to USD 5.8/W in 2011 to between USD 2.9 to USD 4.1/W in 2015 if current trends continue.

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1. Introduction

Renewable energy technologies can help countries meet their policy goals for secure, reliable and affordable energy to expand electricity access and promote development. This paper is part of a series on the costs and performance of renewable energy technologies produced by IRENA. The goal of these papers is to assist government decision-making and ensure that governments have access to up-to-date and reliable information on the costs and performance of renewable energy technologies.

Without access to reliable information on the relative costs and benefits of renewable energy technologies it is difficult, if not impossible, for governments to arrive at an accurate assessment of which renewable energy technologies are the most appropriate for their particular circumstances. These papers fill a significant gap in information availability because there is a lack of accurate, comparable, reliable and up-to-date data on the costs and performance of renewable energy technologies. The rapid growth in installed capacity of renewable energy technologies and the associated cost reductions mean that even data one or two years old can significantly overestimate the cost of electricity from renewable energy technologies. There is also a significant amount of perceived knowledge about the cost and performance of renewable power generation that is not accurate or even misleading. Conventions on how to calculate costs can influence the outcome significantly and it is imperative that these are well-documented.

The absence of accurate and reliable data on the cost and performance of renewable power generation technologies is therefore a significant barrier to the uptake of these technologies. Providing this information will help governments, policy-makers, investors and utilities make informed decisions about the role renewable energy can play in their power generation mix. This paper examines the fixed and variable cost components of solar photovoltaics (PV), by country and region and provides the levelised cost of electricity from solar PV, given a number of key assumptions. This up-to-date analysis of the costs of generating electricity from solar PV will allow a fair comparison of solar PV with other generating technologies.[1]

1.1 DIFFERENT MEASURES OF COST

Cost can be measured in a number of different ways, and each way of accounting for the cost of power generation brings its own insights. The costs that can be examined include equipment costs (e.g. PV modules), financing costs, total installed cost, fixed and variable operating and maintenance costs (O&M), fuel costs and the levelised cost of energy (LCOE).

The analysis of costs can be very detailed, but for comparison purposes and transparency, the approach used here is a simplified one. This allows greater scrutiny of the underlying data and assumptions, improving transparency and confidence in the analysis, as well as facilitating the comparison of costs by country or region for the same technologies in order to identify what are the key drivers in any differences.

The three indicators that have been selected are:

» Equipment cost (factory gate FOB and delivered at site CIF);

» Total installed project cost, including fixed financing costs[2]; and

» The levelised cost of electricity.

The analysis in this paper focuses on estimating the cost of solar PV energy from the perspective of a private investor, whether they are a state-owned electricity generation utility, an independent power producer or an individual or community looking to invest in small-

[1] IRENA, through its other work programmes, is also looking at the costs and benefits, as well as the macroeconmic impacts, of renewable power generation technologies. See WWW.IRENA.ORG for further details.

[2] Banks or other financial institutions will often charge a fee, such as a percentage of the total funds sought, to arrange the debt financing of a project. These costs are often reported separately under project development costs.

scale renewables (Figure 1.1). The analysis excludes the impact of government incentives or subsidies, system balancing costs associated with variable renewables and any system-wide cost-savings from the merit order effect[3]. Further, the analysis does not take into account any CO_2 pricing, nor the benefits of renewables in reducing other externalities (e.g. reduced local air pollution, contamination of the environment). Similarly, the benefits of renewables being insulated from volatile fossil fuel prices have not been quantified. These issues are important, but are covered by other programmes of work at IRENA.

It is important to include clear definitions of the technology categories, where this is relevant, to ensure that cost comparisons are robust and provide useful insights (e.g. off-grid PV vs. utility-scale PV). Similarly, it is important to differentiate between the functionality and/or qualities of the renewable power generation technologies being investigated (e.g. PV with and without battery storage). It is important to ensure that system boundaries for costs are clearly set and that the available data are directly comparable. Other issues can also be important, such as cost allocation rules for combined heat and power plants, and grid connection costs.

The data used for the comparisons in this paper come from a variety of sources, such as business journals, industry associations, consultancies, governments, auctions and tenders. Every effort has been made to ensure that these data are directly comparable and are for the same system boundaries. Where this is not the case, the data have been corrected to a common basis using the best available data or assumptions. It is planned that this data will be complemented by detailed surveys of real world project data in forthcoming work by the agency.

An important point is that, although this paper tries to examine costs, strictly speaking, the data available are actually prices, and not even true market average prices, but price indicators. The difference between costs and prices is determined by the amount above, or below, the normal profit that would be seen in a competitive market. The rapid growth of renewables markets from a small base means that the market for renewable power generation technologies is rarely well-balanced. As a result, prices can rise significantly above costs in the short-term if supply is not expanding as fast as demand, while in times of excess supply, prices may too low to earn a normal return on capital and losses can occur if prices are below production costs. This makes analysing

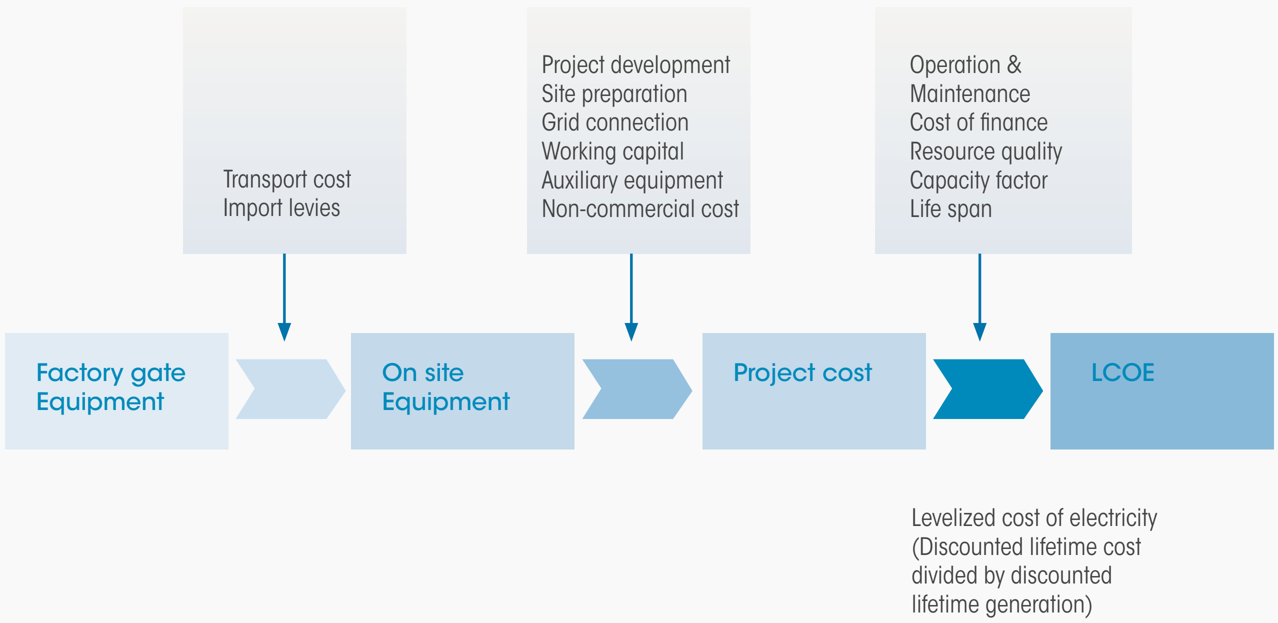

Figure 1.1: Renewable power generation cost indicators and boundaries

[3] *See EWEA, Wind Energy and Electricity Prices, April 2010 for a discussion*

the cost of renewable power generation technologies challenging and every effort is made to indicate whether current equipment costs are above or below their long-term trend.

The cost of equipment at the factory gate is often available from market surveys or from other sources. A key difficulty is often reconciling different sources of data to identify why data for the same period differ. The balance of capital costs in total project costs tends to vary even more widely than power generation equipment costs, as it is often based on significant local content, which depends on the cost structure of where the project is being developed. Total installed costs can therefore vary significantly by project, country and region depending on a wide range of factors.

1.2 LEVELISED COST OF ELECTRICITY GENERATION

The LCOE of renewable energy technologies varies by technology, country and project based on the renewable energy resource, capital and operating costs, and the efficiency / performance of the technology. The approach used in the analysis presented here is based on a discounted cash flow (DCF) analysis. This method of calculating the cost of renewable energy technologies is based on discounting financial flows (annual, quarterly or monthly) to a common basis, taking into consideration the time value of money. Given the capital intensive nature of most renewable power generation technologies and the fact that fuel costs are low, or often zero, the weighted average cost of capital (WACC), often also referred to as the discount rate, used to evaluate the project has a critical impact on the LCOE.

There are many potential trade-offs to be considered when developing an LCOE modelling approach. The approach taken here is relatively simplistic, given the fact that the model needs to be applied to a wide range of technologies in different countries and regions. However, this has the additional advantage that the analysis is transparent and easy to understand. In addition, more detailed LCOE analyses result in a significantly higher overhead in terms of the granularity of assumptions required. This often gives the impression of greater accuracy, but when it is not possible to robustly populate the model with assumptions, or to differentiate assumptions based on real world data, then the "accuracy" of the approach can be misleading.

The formula used for calculating the LCOE of renewable energy technologies is:

$$\text{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Where:

LCOE = the average lifetime levelised cost of electricity generation;
I_t = investment expenditures in the year **t**;
M_t = operations and maintenance expenditures in the year **t**;
F_t = fuel expenditures in the year **t**;
E_t = electricity generation in the year **t**;
r = discount rate; and
n = economic life of the system.

All costs presented in this paper are real 2010 USD; that is to say, after inflation has been taken into account, unless otherwise stated.[4] The LCOE is the price of electricity required for a project where revenues would equal costs, including making a return on the capital invested equal to the discount rate. An electricity price above this would yield a greater return on capital, while a price below it would yielder a lower return on capital, or even a loss.

As already mentioned, although different cost measures are useful in different situations, the LCOE of renewable energy technologies is a widely used measure by which renewable energy technologies can be evaluated for modelling or policy development. Similarly, more detailed DCF approaches taking into account taxation, subsidies and other incentives are used by renewable energy project developers to assess the profitability of real world projects.

[4] An analysis based on nominal values with specific inflation assumptions for each of the cost components is beyond the scope of this analysis. Project developers will develop their own specific cash-flow models to identify the profitability of a project from their perspective.

2. Solar photovoltaic technologies

Photovoltaics, also called solar cells, are electronic devices that convert sunlight directly into electricity[5]. The modern form of the solar cell was invented in 1954 at Bell Telephone Laboratories. Today, PV is one of the fastest growing renewable energy technologies and it is expected that it will play a major role in the future global electricity generation mix. Solar PV systems are also one of the most "democratic" renewable technologies, in that their modular size means that they are within the reach of individuals, co-operatives and small-businesses who want to access their own generation and lock-in electricity prices.

PV technology offers a number of significant benefits, including:

» Solar power is a renewable resource that is available everywhere in the world.

» Solar PV technologies are small and highly modular and can be used virtually anywhere, unlike many other electricity generation technologies.

» Unlike conventional power plants using coal, nuclear, oil and gas; solar PV has no fuel costs and relatively low operation and maintenance (O&M) costs. PV can therefore offer a price hedge against volatile fossil fuel prices.

» PV, although variable, has a high coincidence with peak electricity demand driven by cooling in summer and year round in hot countries.

A PV system consists of PV cells that are grouped together to form a PV module, and the auxiliary components (i.e. balance of system - BOS), including the inverter, controls, etc. There are a wide range of PV cell technologies on the market today, using different types of materials, and an even larger number will be available in the future. PV cell technologies are usually classified into three generations, depending on the basic material used and the level of commercial maturity:

» **First-generation PV systems** (fully commercial) use the wafer-based crystalline silicon (c-Si) technology, either single crystalline (sc-Si) or multi-crystalline (mc-Si).

» **Second-generation PV systems** (early market deployment) are based on thin-film PV technologies and generally include three main families: 1) amorphous (a-Si) and micromorph silicon (a-Si/μc-Si); 2) Cadmium-Telluride (CdTe); and 3) Copper-Indium-Selenide (CIS) and Copper-Indium-Gallium-Diselenide (CIGS).

» **Third-generation PV systems** include technologies, such as concentrating PV (CPV) and organic PV cells that are still under demonstration or have not yet been widely commercialised, as well as novel concepts under development.

2.1 FIRST-GENERATION PV TECHNOLOGIES: CRYSTALLINE SILICON CELLS

Silicon is one of the most abundant elements in the earth's crust. It is a semiconductor material suitable for PV applications, with energy band gap[6] of 1.1eV. Crystalline silicon is the material most commonly used in the PV industry, and wafer-based c-Si PV cells and modules dominate the current market. This is a mature

[5] The Photovoltaic effect is when two different (or differently doped) semiconducting materials (e.g. silicon, germanium), in close contact with each other generate an electrical current when exposed to sunlight. The sunlight provides the electrons with the energy needed to leave their bounds and cross the junction between the two materials. This occurs more easily in one direction than in the other and gives one side of the junction a negative charge with respect to the other side (p-n junction), thus generating 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. Electricity production is roughly proportional to the solar irradiance, while efficiency is reduced only slowly as solar irradiance declines.

[6] The energy needed to produce electron excitation and to activate the PV process.

technology that utilises the accumulated knowledge base developed within the electronic industry. This type of solar cell is in mass production and individual companies will soon be producing it at the rate of several hundred MW a year and even at the GW-scale. The manufacturing process of wafer-based silicon PV modules comprises four steps:

1. Polysilicon production;
2. Ingot/wafer production;
3. Cell production; and
4. Module assembly.

Crystalline silicon cells are classified into three main types depending on how the Si wafers are made. They are:

- **Monocrystalline** (Mono c-Si) sometimes also called single crystalline (sc-Si);
- **Polycrystalline** (Poly c-Si), sometimes referred to as multi-crystalline (mc-Si); and
- **EFG ribbon** silicon and silicon sheet-defined film growth (EFG ribbon-sheet c-Si).

Commercial production of c-Si modules began in 1963 when Sharp Corporation of Japan started producing commercial PV modules and installed a 242 Watt (W) PV module on a lighthouse, the world's largest commercial PV installation at the time (Green, 2001). Crystalline silicon technologies accounted for about 87% of global PV sales in 2010 (Schott Solar, 2011). The efficiency of crystalline silicon modules ranges from 14% to 19% (see Table 2.1).[7] While a mature technology, continued cost reductions are possible through improvements in materials and manufacturing processes, and from economies of scale if the market continues to grow, enabling a number of high-volume manufacturers to emerge.

2.2 SECOND-GENERATION PV TECHNOLOGIES: THIN-FILM SOLAR CELLS

After more than 20 years of R&D, thin-film solar cells are beginning to be deployed in significant quantities. Thin-film solar cells could potentially provide lower cost electricity than c-Si wafer-based solar cells. However, this isn't certain, as lower capital costs, due to lower production and materials costs, are offset to some extent by lower efficiencies and very low c-Si module costs make the economics even more challenging. Thin-film solar cells are comprised of successive thin layers, just 1 to 4 µm thick, of solar cells deposited onto a large, inexpensive substrate such as glass, polymer, or metal. As a consequence, they require a lot less semiconductor material to manufacture in order to absorb the same amount of sunlight (up to 99% less material than crystalline solar cells). In addition, thin films can be packaged into flexible and lightweight structures, which can be easily integrated into building components (building-integrated PV, BIPV). The three primary types of thin-film solar cells that have been commercially developed are:

- Amorphous silicon (a-Si and a-Si/µc-Si);
- Cadmium Telluride (Cd-Te); and
- Copper-Indium-Selenide (CIS) and Copper-Indium-Gallium-Diselenide (CIGS).

Amorphous silicon solar cells, along with CdTe PV cells, are the most developed and widely known thin-film solar cells. Amorphous silicon can be deposited on cheap and very large substrates (up to 5.7 m^2 of glass) based on continuous deposition techniques, thus considerably reducing manufacturing costs. A number of companies are also developing light, flexible a-Si modules perfectly suitable for flat and curved surfaces, such as roofs and facades. Currently, amorphous silicon PV module efficiencies are in the range 4% to 8%. Very small cells at laboratory level may reach efficiencies of 12.2% (Mehta, 2010). The main disadvantage of amorphous silicon

[7] It is important to be aware of the hierarchy of efficiency in PV, as a number of efficiencies can be quoted. The highest efficiency for a PV material is usually the "laboratory" efficiency, where optimum designs are tested. PV cell efficiencies are less than this, because compromises are often required to make affordable cells. Module efficiency is somewhat lower than cell efficiency, given the losses involved in the PV module system.

solar cells is that they suffer from a significant reduction in power output over time (15% to 35%), as the sun degrades their performance. Even thinner layers could increase the electric field strength across the material and provide better stability and less reduction in power output, but this reduces light absorption and hence cell efficiency. A notable variant of amorphous silicon solar cells is the **multi-junction thin-film silicon** (a-Si/µc-Si) which consists of a-Si cell with additional layers of a-Si and micro-crystalline silicon (µc-Si) applied onto the substrate.[8] The advantage of the µc-Si layer is that it absorbs more light from the red and near infrared part of the light spectrum, thus increasing the efficiency by up to 10%. The thickness of the µc-Si layer is in the order of 3 µm and makes the cells thicker and more stable. The current deposition techniques enable the production of multi-junction thin-films up to 1.4 m^2.

Cadmium Telluride thin-film PV solar cells have lower production costs and higher cell efficiencies (up to 16.7% [Green, 2011]) than other thin-film technologies. This combination makes CdTe thin-films the most economical thin-film technology currently available, with manufacturing costs of under USD 0.75/W achieved by at least one producer (First Solar, 2011). The two main raw materials are cadmium and tellurium. Cadmium is a by-product of zinc mining and tellurium is a by-product of copper processing. A potential problem is that tellurium is produced in far lower quantities than cadmium and availability in the long-term may depend on whether the copper industry can optimise extraction, refining and recycling yields. Cadmium also has issues around its toxicity that may limit its use.

Copper-Indium-Selenide (CIS) and Copper-Indium-Gallium-Diselenide (CIGS) PV cells offer the highest efficiencies of all thin-film PV technologies. CIS solar cell production has been successfully commercialised by many firms in conjunction with universities (e.g. Wurth Solar, Solibro, Miasole, Nanosolar, Avancis, SolarFrontier and Honda Soltec). Current module efficiencies are in the range of 7% to 16%, but efficiencies of up to 20.3% have been achieved in the laboratory, close to that of c-Si cells (ZSW, 2010 and Green, 2011). The race is now on to increase the efficiency of commercial modules. By 2010, CIGS producer Solar Frontier has reached an annual production capacity of 1 GW (Bank Sarasin, 2010).

2.3 THIRD-GENERATION PV TECHNOLOGIES

Third-generation PV technologies are at the pre-commercial stage and vary from technologies under demonstration (e.g. multi-junction concentrating PV) to novel concepts still in need of basic R&D (e.g. quantum-structured PV cells). Some third-generation PV technologies are beginning to be commercialised, but it remains to be seen how successful they will be in taking market share from existing technologies. There are four types of third-generation PV technologies:

- Concentrating PV (CPV);
- Dye-sensitized solar cells (DSSC);
- Organic solar cells; and
- Novel and emerging solar cell concepts.

Concentrating photovoltaic technology

Concentrating PV (CPV) systems utilise optical devices, such as lenses or mirrors, to concentrate direct solar radiation onto very small, highly efficient multi-junction solar cells made of a semiconductor material. The sunlight concentration factor ranges from 2 to 100 suns (low- to medium-concentration) up to 1 000 suns (high concentration). To be effective, the lenses need to be permanently oriented towards the sun, using a single- or double-axis tracking system for low and high concentrations, respectively. Cooling systems (active or passive) are needed for some concentrating PV designs, while other novel approaches can get round this need.

Low- to medium-concentration systems (up to 100 suns) can be combined with silicon solar cells, but higher temperatures will reduce their efficiency, while high concentration systems (beyond 500 suns) are usually associated with multi-junction solar cells made by semiconductor compounds from groups III and V of the periodic table (e.g. gallium arsenide), which offer the highest PV conversion efficiency. Multi-junction (either 'tandem' or 'triple' junction) solar cells consist of a stack of layered p–n junctions, each made from a distinct set of semiconductors, with different band gap and spectral absorption to absorb as much of the solar spectrum as possible. Most commonly employed materials are

[8] These are sometimes also referred to as micromorphous silicon cells.

Ge (0.67 eV), GaAs or InGaAs (1.4 eV), and InGaP (1.85 eV). A triple-junction cell with band gaps of 0.74, 1.2 and 1.8 eV would reach a theoretical efficiency of 59%. Given their complexity and costs, multi-junctions are used for small-area solar cells with high sunlight concentration or in space applications (Nature Photonics, 2010).

Commercial CPV modules with silicon-based cells offer efficiency in the range of 20% to 25%. CPV based on multi-junction solar cells using III-V semiconductors have achieved laboratory efficiency of more than 40% (IEA, 2010).[9] Commercial multi-junction devices manufactured by Sharp, Emcore, Spectrolab and Azur have efficiencies of around 35% - significantly higher than conventional single-junction c-SI solar cells. Continued R&D holds the promise of increasing CPV efficiencies up to 45% or even 50% (Cotal, 2009).

To maximise the electricity generation, CPV modules need to be permanently oriented towards the sun, using a single- or double-axis sun-tracking system. Multi-junction solar cells, along with sun-tracking systems, result in expensive CPV modules in comparison with conventional PV. On the other hand, their higher efficiency and the smaller surface area of active material required may eventually compensate for the higher costs, depending on the evolution of costs and efficiency. Because CPV modules rely on direct sunlight, they need to be used in regions with clear skies and high direct solar irradiation to maximise performance.

Dye-sensitized solar cells

Dye-sensitized solar cells use photo-electrochemical solar cells, which are based on semiconductor structures formed between a photo-sensitised anode and an electrolyte. In a typical DSSC, the semiconductor nanocrystals serve as antennae that harvest the sunlight (photons) and the dye molecule is responsible for the charge separation (photocurrent)[10]. It is unique in that it mimics natural photosynthesis (Grätzel, 1991). These cells are attractive because they use low-cost materials and are simple to manufacture. They release electrons from, for example, titanium dioxide covered by a light-absorbing pigment. However, their performance can degrade over time with exposure to UV light and the use of a liquid electrolyte can be problematic when there is a risk of freezing.

Laboratory efficiencies of around 12% have been achieved due to the development of new broadband dyes and electrolytes (Grätzel, 2009), however, commercial efficiencies are low - typically under 4% to 5%. The main reason why efficiencies of DSSC are low is because there are very few dyes that can absorb a broad spectral range. An interesting area of research is the use of nanocrystalline semiconductors that can allow DSSCs to have a broad spectral coverage. Thousands of organic dyes have been studied and tested in order to design, synthesise and assemble nanostructured materials that will allow higher power conversion efficiencies for DSSCs.

Organic solar cells

Organic solar cells are composed of organic or polymer materials (such as organic polymers or small organic molecules). They are inexpensive, but not very efficient. They are emerging as a niche technology, but their future development is not clear. Their success in recent years has been due to many significant improvements that have led to higher efficiencies. Organic PV module efficiencies are now in the range 4% to 5% for commercial systems and 6% to 8% in the laboratory (OrgaPVnet, 2009).

In addition to the low efficiency, a major challenge for organic solar cells is their instability over time. Suppliers of organic solar cells are moving towards full commercialisation and have announced plans to increase production to more than 1 GW by 2012 (EPIA, 2011a). Organic cell production uses high-speed and low-temperature roll-to-roll manufacturing processes and standard printing technologies. As a result, organic solar cells may be able to compete with other PV technologies in some applications, because manufacturing costs are continuing to decline and are expected to reach USD 0.50/W by 2020 (EPIA, 2011a).

Organic cells can be applied to plastic sheets in a manner similar to the printing and coating industries, meaning that organic solar cells are lightweight and flexible, making them ideal for mobile applications and for fitting to a variety of uneven surfaces. This makes them particularly useful for portable applications, a first target market for this technology. Potential uses include battery chargers for mobile phones, laptops, radios, flashlights, toys and almost any hand-held device that uses a battery. The

[9] Solar Junctions (U.S.) reported that USDOE NREL has confirmed that the III-V multi-junction CPV cell developed by Solar Junctions has achieved a record 43.5% efficiency at greater than 400 suns and preserved an efficiency as high as 43% out to 1000 suns (Solar Junction, 2011).
[10] This type solar cell is also known as the Grätzel cell, after its inventor Michael Grätzel.

modules can be fixed almost anywhere to anything, or they can be incorporated into the housing of a device. They can also be rolled up or folded for storage when not in use. These properties will make organic PV modules attractive for building-integrated applications as it will expand the range of shapes and forms where PV systems can be applied. Another advantage is that the technology uses abundant, non-toxic materials and is based on a very scalable production process with high productivity.

Novel and emerging solar cell concepts

In addition to the above mentioned third-generation technologies, there are a number of novel solar cell technologies under development that rely on using quantum dots/wires, quantum wells, or super lattice technologies (Nozik, 2011 and Raffaelle, 2011). These technologies are likely to be used in concentrating PV technologies where they could achieve very high efficiencies by overcoming the thermodynamic limitations of conventional (crystalline) cells. However, these high-efficiency approaches are in the fundamental materials research phase. Furthest from the market are the novel concepts, often incorporating enabling technologies such as nanotechnology, which aim to modify the active layer to better match the solar spectrum (Leung, 2011).

2.4 THE SOLAR PV RESOURCE

Solar PV systems operate in the presence of direct or diffuse solar irradiation. The higher the level of solar resource, the lower the LCOE will be. Siting solar PV systems in areas with high solar resources, usually expressed as annual mean figures in kWh/m^2/year or as kWh/m^2/day, will therefore minimise the cost of electricity from solar PV.

The global solar resource is massive. Around 885 million TWh worth of solar radiation reaches the Earth's surface each year (IEA, 2011). The solar resource varies

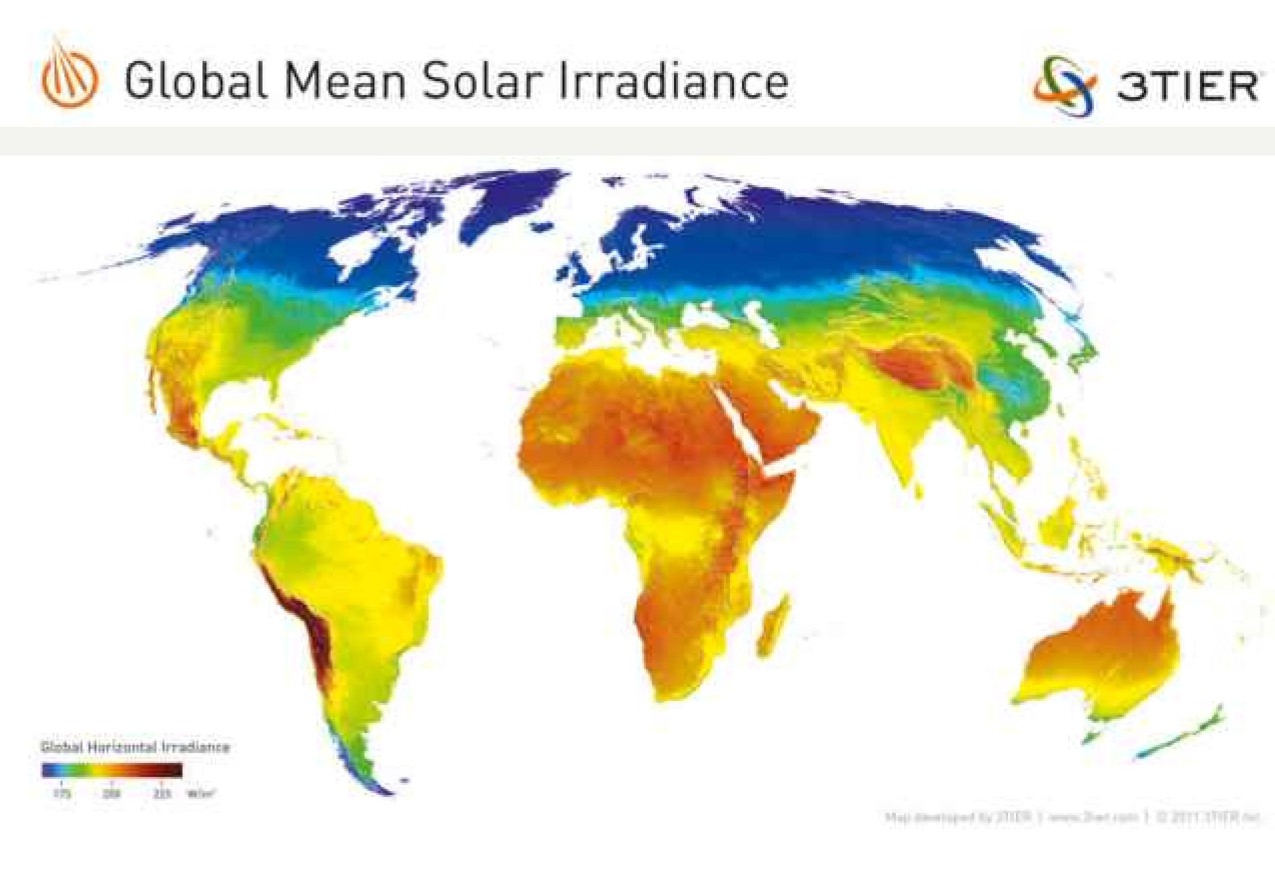

Figure 2.1: Global mean horizontal irradiance

Source: 3Tier, 2012.

significantly over the day, week and month depending on local meteorological conditions. However, most of the annual variation is related to the Earth's geography.

Figure 2.1 presents the global solar resource, expressed as the global horizontal irradiation (GHI). GHI is the total amount of shortwave radiation received from above by a horizontal surface. This is expressed as W/m^2 and includes both direct normal irradiance (DNI) and diffuse horizontal irradiance (DIF). In Europe, the average solar resource is a round 1 200 $kWh/m^2/year$, while in the Middle East it typically varies between 1 800 and 2 300 kWh/m /year.

The global horizontal irradiance as presented in Figure 2.1 is an overall measure of the solar resource. However, using tilting collectors can increase the irradiance (per unit of surface area) by up to 35% (500 kWh $m^2/year$), especially for latitudes lower than 30°S and higher than 30°N. Tracking can also increase the yield, but with considerable additional expense.

Figure 2.2 presents the solar resource for the United States for PV systems tilted at an angle equal to the latitude in which they are situated and facing due South. If the PV modules are not orientated due South, the electricity production would be correspondingly less.

The yield of a solar PV system in the United States can vary by a factor of two or more, depending on where it is sited. The United States has one of the best solar resources of developed countries, with particularly good resources in the South-West.

2.5 SUMMARY OF PV TECHNOLOGIES

Below are the key characteristics, strengths and weaknesses of the different PV technologies:

- First-generation solar cells dominate the market with their low costs and the best

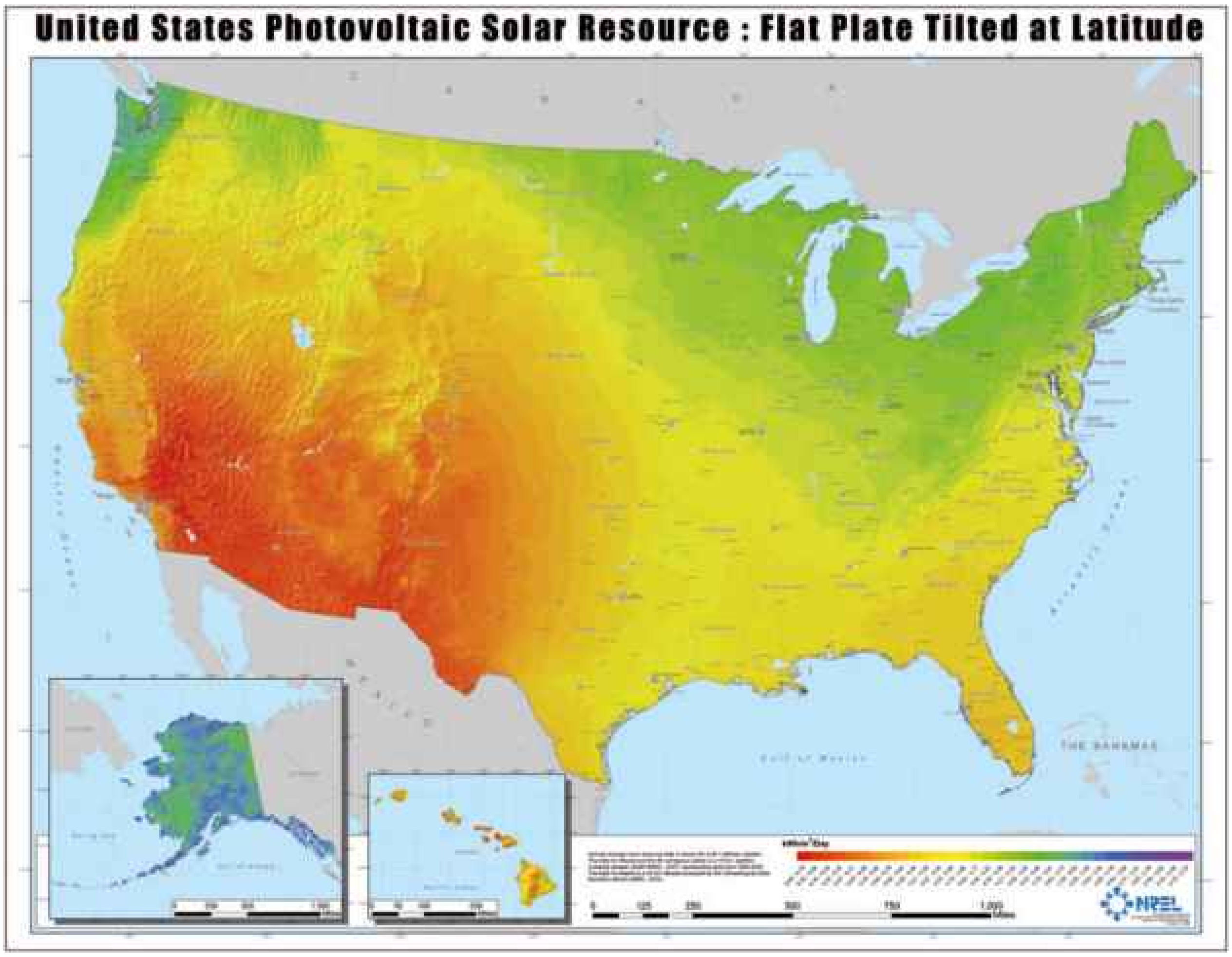

Figure 2.2: The solar PV resource in the United States

Source: NREL.[11]

[11] *See http://www.nrel.gov/gis/solar.html*

TABLE 2.1: AN OVERVIEW AND COMPARISON OF MAJOR PV TECHNOLOGIES

		1st Generation PV		2nd Generation PV			3rd Generation PV		
Technology	Units	Single crystalline silicon (sc-Si)	Polycrystalline silicon (pc-Si)	Amorphous silicon (a-Si)	Copper Indium Gallium Diselenide (CIS/ CIGS)	Cadmium Telluride solar cells (CdTe)	III-V compound Multijunction, Concentrated PV (CPV)	Dye-sensitized (DSSC)	Organic or Polymer (OPV)
Best research solar cell efficiency at AM1.5*	%	24.7		10.4 Single junction 13.2 Tandem	20.3	16.5	43.5	11.1	11.1
Confirmed solar cell efficiency at AM1.5	%	20-24	14-18	6-8	10-12	8-10	36-41	8.8	8.3
Commercial PV Module efficiency at AM1.5	%	15-19	13-15	5-8	7-11	8-11	25-30	1-5	1
Confirmed maximum PV Module efficiency	%	23	16	7.1/ 10.0	12.1	11.2	25	-	-
Current PV module cost	USD/W	< 1.4	< 1.4	~ 0.8	~ 0.9	~ 0.9	-	-	-
Market share in 2009	%	83	3	1	13		-	-	-
Market share in 2010	%	87	2	2	9		-	-	-
Maximum PV module output power	W		320	300	120	120	120	-	-
PV module size	m^2	2.0	1.4-2.5	1.4	0.6-1.0	0.72	-	-	-
Area needed per kW	m^2	7	8	15	10	11	-	-	-
State of commercialisation		Mature with large-scale production	Mature with large-scale production	Early deployment phase, medium-scale production	Early deployment phase, medium-scale production	Early deployment phase, small-scale production	Just commercialised, small-scale production	R&D phase	R&D phase

Note: Standard Testing Conditions, temperature 25°C, light intensity 1000W/m², air mass 1.5.

commercially available efficiency. They are a relatively mature PV technology, with a wide range of well-established manufacturers. Although very significant cost reductions occurred in recent years, the costs of the basic materials are relatively high and it is not clear whether further cost reductions will be sufficient to achieve full economic competitiveness in the wholesale power generation market in areas with modest solar resources.

» Second-generation thin-film PV technologies are attractive because of their low material and manufacturing costs, but this has to be balanced by lower efficiencies than those obtained from first-generation technologies. Thin-film technologies are less mature than first-generation PV and still have a modest market share, except for utility-scale systems. They are struggling to compete with very low c-Si module prices and also face issues of durability, materials availability and materials toxicity (in the case of Cadmium).

» Third-generation technologies are yet to be commercialised at any scale. Concentrating PV has the potential to have the highest efficiency of any PV module, although it is not clear at what cost premium. Other organic or hybrid organic/conventional (DSSC) PV technologies are at the R&D stage. They offer low efficiency, but also low cost and weight, and free-form shaping. Therefore, they could fill niche markets (e.g. mobile applications) where these features are required.

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3. Current global PV market trends

3.1 TOTAL INSTALLED PV CAPACITY

PV is one of the fastest growing renewable energy technologies today and is projected to play a major role in global electricity production in the future. Driven by attractive policy incentives (e.g. feed-in tariffs and tax breaks), the global installed PV capacity has multiplied by a factor of 37 in ten years from 1.8 GW in 2000 to 67.4 GW at the end of 2011, a growth rate of 44% per year (Figure 3.1) (EPIA, 2012). New capacity installed in 2011 was 27.7 GW, two-thirds more than the new capacity added in 2010. Assuming an average capacity factor of 0.2 would imply that solar PV in 2011 produced 118 TWh of electrical power.

This rapid expansion in capacity has led to significant cost reductions. The learning rate for the price of PV modules is estimated to be around 20% to 22%% (23% to 24% for thin films and 19% to 20% for c-Si), so that each time the cumulative installed capacity has doubled, PV module costs have declined by 20% to 22% (EPIA, 2011a and Kersten, 2011).

3.2 ANNUAL PV CAPACITY ADDITIONS

Up until the mid-1990s, most PV systems were stand-alone off-grid applications, such as telecommunications units, remote houses and rural electricity supply. Since

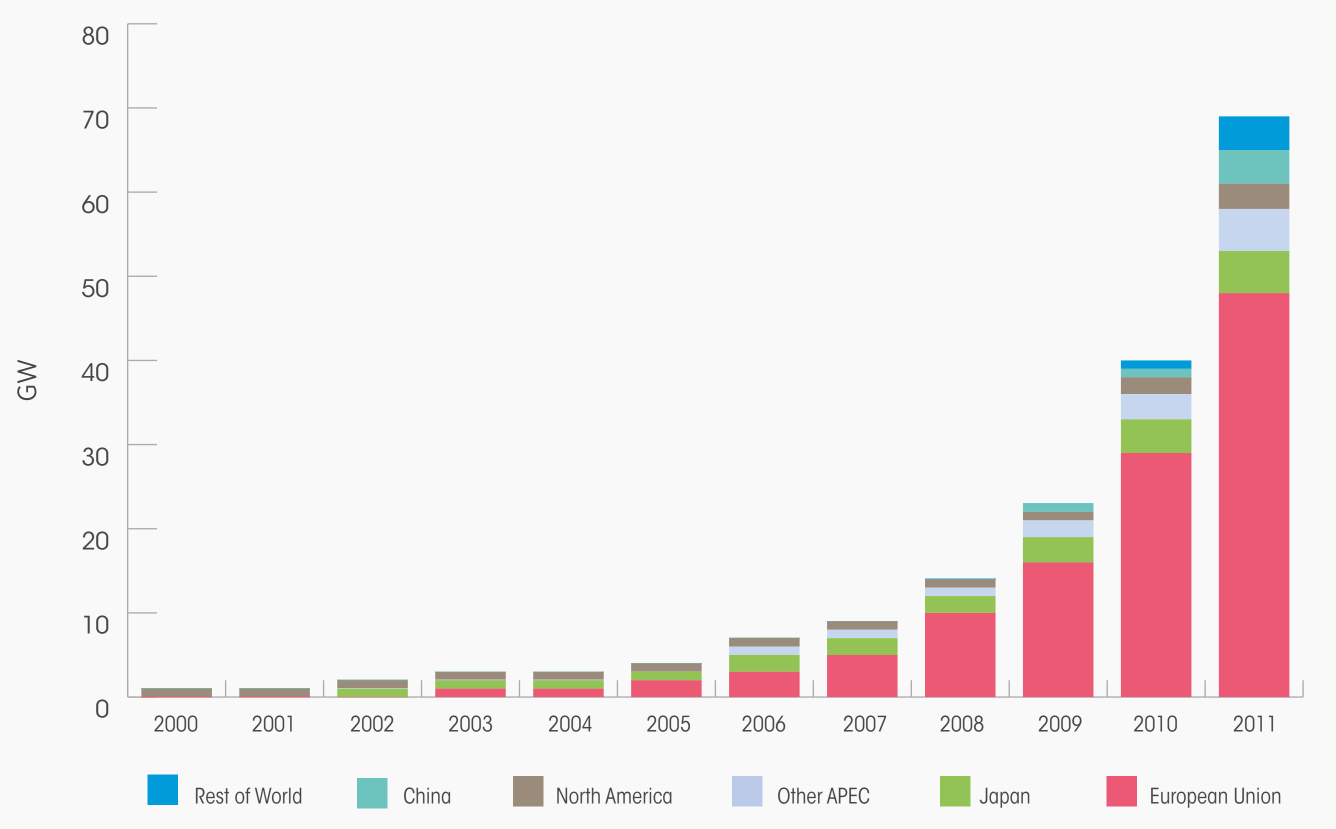

FIGURE 3.1: EVOLUTION OF GLOBAL CUMULATIVE INSTALLED CAPACITY, 2000-2011.

Source: EPIA, 2011b and EPIA, 2012.

then, the number of grid-connected systems has increased rapidly due to the impact of various support and incentive schemes introduced in many countries. In the last decade—and this trend has accelerated in recent years—grid-connected installations have become the largest sector for new PV installations. The growth in utility-scale systems has also accelerated in recent years and is now an important market.

In 2010, new installed capacity PV capacity was 16.6 GW. Most of this growth was driven by the rapid expansion of the German and Italian markets. With 7.4 GW installed in Germany in just one year, the country continues to dominate the global PV market. Italy installed 2.3 GW, starting to exploit some of the potential of its huge solar resources. Other countries also saw significant growth (EPIA, 2011a).

In 2011, 27.7 GW of new PV capacity was installed, two-thirds more than was installed in 2010. Europe accounted for around three-quarters (20.9 GW) of all new capacity added in 2011. Italy built on its growth in 2010, adding an impressive 9 GW of new capacity, increasing total installed capacity by 260%. Germany added 7.5 GW in 2011. Six countries added more than one GW in 2011 (i.e. Italy, Germany, China, United States, Japan and France).

Despite the rapid growth of the PV market, less than 0.2% of global electricity production is generated by PV. The market outlook is entering an uncertain phase with the problems facing the global economy. It remains to be seen what the long-term impact of the economic challenges facing the world economy and government budgets will have on the PV market. Given that the European market has accounted for 80% of global demand in recent years, any reduction in annual demand in Europe as a result of the depressed economic situation will have a large impact on supply and demand in the global PV industry. However, any slowing in the European market could conceivably be offset by policy measures that boost other PV markets, such as Australia, Canada, China, India, Japan, the United States and other countries that are experiencing strong growth. The biggest emerging markets are China, the Middle East, South Korea, India and other Southeast-Asian countries. Although emerging PV markets will probably not grow by as much in absolute terms as Europe has done in recent years, growth in these markets looks set to be sustained.

3.3 FUTURE PROJECTIONS OF PV CAPACITY GROWTH

The global PV market growth in 2011 was well below manufacturers' capabilities, as global PV silicon wafer capacity may have reached 50.9 GW/year by the end of 2011 (a 62% increase on 2010) and the total c-Si solar cell capacity may have reached 60.6 GW/year in 2011 (a 91% increase on 2010) (EPIA, 2011b). Most of this expansion took place in mainland China and Taiwan.

Most of the PV growth in recent years has been driven by promotion policies, including effective feed-in tariffs (FiT) and other incentives that have helped develop markets in key countries, reduce prices (through deployment), improve the economics of PV investments and raise investors' interest. There are already over 120 PV power plants with a capacity of 10 MW or more (Komoto, 2010). The largest operational solar PV plant is an 100 MW ground-mounted plant in California. The largest building-integrated/roof-mounted system (11.8 MW) is located in Spain (Komoto, 2010).

Projections to 2015 are particularly challenging, given that new installed capacity has been growing so rapidly. Projections from 2010 to 2015, made in 2011, already risk being out of date, given the rapid growth in installed capacity in 2011. Analysing trends in 2011 resulted in projections of total installed PV capacity in 2015 of between 131 GW and 196 GW (EPIA, 2011b). Although the upper range of this projection still looks reasonable, the lower end looks unduly pessimistic as even if new capacity growth stabilised at 2011 levels, this figure would already be reached by around the end of 2013 or early 2014.

Although it remains to be seen what impact, if any, the continued economic weakness in Europe might eventually have on capacity additions.

The International Energy Agency's (IEA) PV roadmap is based on scenarios that yield an average annual market growth rate of 17% in the next decade, leading to a global cumulative installed PV power capacity of 200 GW by 2020 (IEA, 2010). Given the pace of developments in the PV sector, even small differences in start years or assumptions can lead to very divergent results for future installed PV capacity and the IEA roadmap is likely to have underestimated installed capacity by 2020.

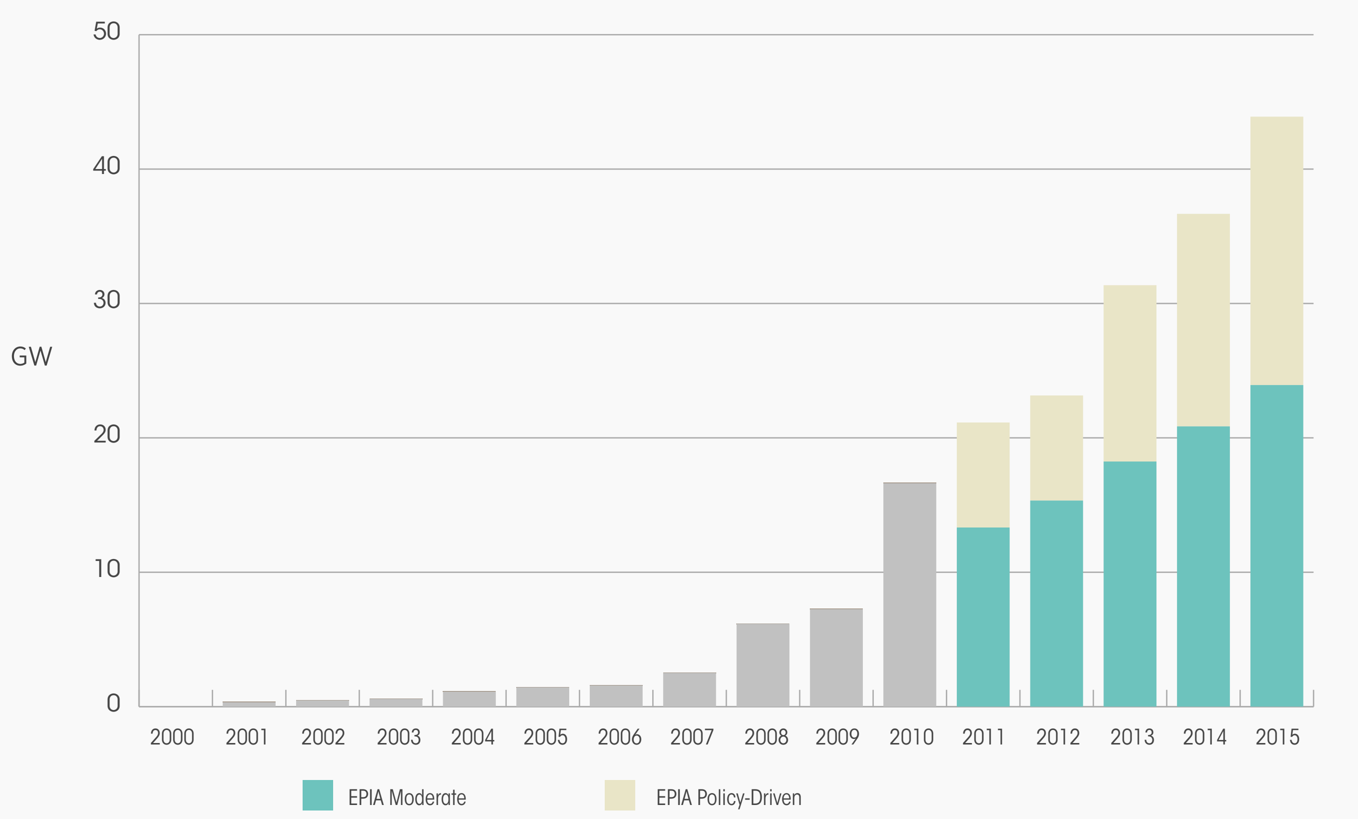

Figure 3.2: EPIA scenarios for global annual new installed PV capacity, 2000 to 2015

Source: EPIA, 2011b.

4. Cost and performance

PV is a mature, proven technology that is rapidly approaching grid parity.[12] It is a renewable, secure energy source with very high plant reliability and is not exposed to any fuel price volatility. PV has made remarkable progress in reducing costs, as until recently grid parity still seemed very far away. It was only a few years ago that PV electricity was four to five times more expensive than fossil fuels. However, with increases in fossil fuel prices and continuing cost reductions in PV modules, grid parity could occur as early as 2012 to 2013 in sunny regions of USA, Japan and Southern Europe. Other regions with lower electricity production costs and/or more moderate solar resources may achieve grid parity as early as 2020 (Breyer and Gerlach, 2011). That is without taking into account that PV is often already competitive for peak power production, for generation in grid-constrained areas, and for many off-grid applications.

The cost of the electricity generated by a PV system is determined by the capital cost (CAPEX), the discount rate, the variable costs (OPEX), the level of solar irradiation and the efficiency of the solar cells. Of these parameters, the capital cost, the cost of finance and efficiency are the most critical and improvements in these parameters provide the largest opportunity for cost reductions.

The capital cost of a PV system is composed of the *PV module* cost and the *Balance of system (BOS)* cost. The PV module is the interconnected array of PV cells and its cost is determined by raw material costs, notably silicon prices, cell processing/manufacturing and module assembly costs. The BOS cost includes items, such as the cost of the structural system (e.g. structural installation, racks, site preparation and other attachments), the electrical system costs (e.g. the inverter, transformer, wiring and other electrical installation costs) and the battery or other storage system cost in the case of off-grid applications.

4.1 SOLAR PV MODULE PRICE/COST

The PV module cost is typically between a third and a half of the total capital cost of a PV system, depending on the size of the project and the type of PV module.[13] Projecting PV module costs into the future is complicated by the high learning rate of 22% that has been experienced historically (see Figure 4.1).[14] With the PV market growing so rapidly compared to the installed base, projections of cost reductions can quickly become out of date.

The absolute cost and structure of PV modules varies by technology. Conventional c-Si PV modules are the most expensive PV technology, with the exception of CPV modules, but they also have the highest commercial efficiency. However, CIGS modules are approaching the efficiency levels of c-Si modules and are cheaper. Figure 4.2 illustrates average worldwide PV module cost structures by technology.

Accurate data on global average PV module prices are difficult to obtain and in reality there is a wide range of prices, depending on the cost structure of the manufacturer, market features and module efficiency. However, an estimate for the global price of c-Si PV modules in 2008 was USD 4.05/W and this had declined to USD 2.21/W in 2010 (Solarbuzz, 2011), a decline of 45% in just two years.

The rate of decline in costs has not slowed and by January 2012 spot market and factory gate prices in Europe for low-cost Chinese and other emerging market manufacturers of c-Si modules had dropped to around USD 1.05/W (Photovoltaik, 2012). Spot and factory gate prices for c-Si modules from European, Japanese and other manufacturers had declined to between USD 1.22 and USD 1.4/W (Table 4.1).

By the fourth quarter of 2010, the cost of monocrystalline silicon PV modules in Europe was between USD 1.43/W

[12] The term "grid parity" is often used loosely and inconsistently. In this paper, it is meant to represent the point where the LCOE of PV, without subsidies, is the same or lower than the residential electricity price, excluding taxes. Other definitions include a price equal to or lower than the price of peak, shoulder or base-load electricity generation. In some cases, it will include or exclude taxes and subsidies.

[13] PV module prices are usually quoted per "DC Watt peak" (Wp), based on the rated PV module output power (at the maximum power point) under Standard test condition AM1.5 (solar insolation 1000W/m², temperature 25°C). All prices in this paper are "DC Watt peak".

[14] After deviating from the historical trend between 2003 and 2008 due to supply bottlenecks, learning rates have returned towards the historic rate in recent years (Hearps, 2011).

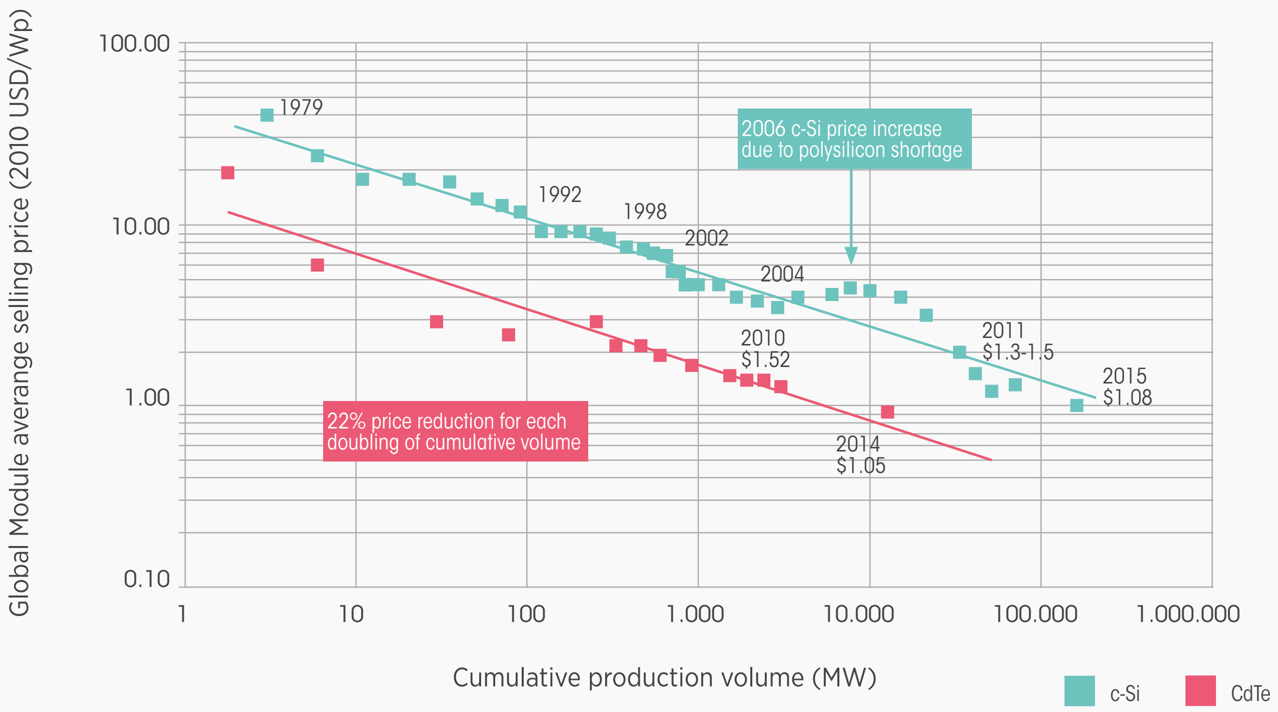

FIGURE 4.1 THE GLOBAL PV MODULE PRICE LEARNING CURVE FOR C-SI WAFER-BASED AND CDTE MODULES, 1979 TO 2015

Sources: based on data from EPIA and Photovoltaic Technology Platform, 2010 and Liebreich, 2011.

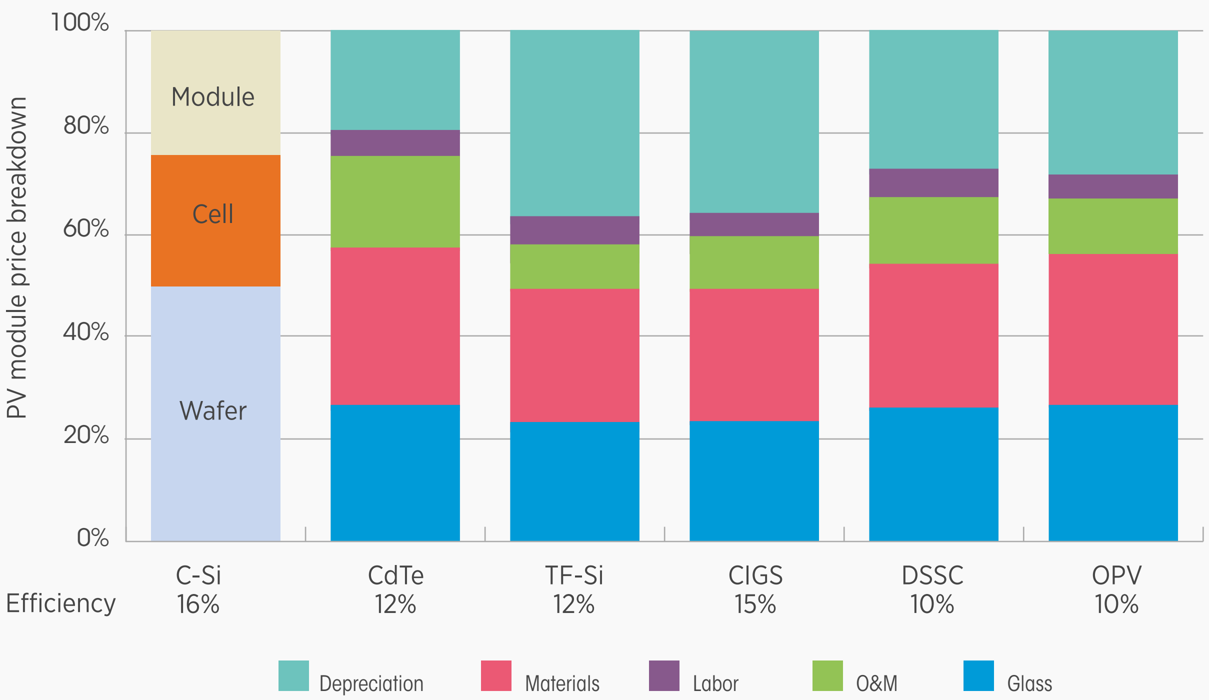

FIGURE 4.2 AVERAGE WORLDWIDE PV MODULE PRICE LEVEL AND THEIR COST STRUCTURE BY TECHNOLOGY (2010).

Sources: IRENA and data from Japan's National Institute for Advanced Industrial Science and Technology (AIST)

Table 4.1 Summary of the worldwide market price of PV modules , Q4 2009 to Q1 2012

Factory-gate price in Europe (USD/Watt)										
	2009	2010				2011				2012
PV module suppliers	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1
High efficiency c-Si	2.45	2.22	2.25	2.29	2.21	2.20	2.15	2.10	2.00	1.94
Japanese/Western c-Si **	1.98	1.81	1.83	1.74	1.66	1.40	1.27	1.08	1.22	1.22
Chinese major c-Si ***	1.51	1.42	1.52	1.51	1.45	1.39	1.39	1.39	1.39	1.24
Emerging economies c-Si ****	1.45	1.35	1.42	1.43	1.43	1.36	1.31	1.03	1,02	1.02
High efficiency thin-film (via distribution, First Solar)	1.26	1.30	1.39	1.37	1.27	1.16	1.05	0.98	0.93	0.93
Factory-gate price in the United States (USD/Watt)										
High efficiency c-Si	2.86	2.20	2.55	2.55	2.53	2.30	2.30	2.30	2.30	2.20
Japanese/Western c-Si	2.10	2.05	1.95	1.95	1.93	1.91	1.91	1.91	1.91	1.82
Chinese major c-Si	1.91	1.87	1.83	1.87	1.80	1.43	1.43	1.47	1.43	1.34
Emerging economies- c-Si	1.89	1.75	1.70	1.78	1.74	1.50	1.50	1.50	1.50	1.41
High efficiency thin-film (via distribution, First Solar)	1.21	1.20	1.22	1.25	1.19	1.20	1.22	1.25	0.93	0.93

*Notes: Based on short-term contract prices for quantities of 0.5 MW or more. Spot market prices are typically more volatile. * Sunpower and Sanyo ** Sharp, Kyocera, Solarworld and Schoth *** Suntech, Yungli, Trina Solar and Green Energy, etc. **** Chinese, Taiwanese, Korean and Indian manufacturers.*

Sources: Solarbuzz, 2011; Photovoltaik, 2012 and Luo, 2011.

(emerging economy manufacturers) and USD 2.21/W (high efficiency c-Si modules), while thin-film PV modules cost USD 1.27/W. In the United States, the price range for monocrystalline silicon PV modules was between USD 1.74/W and USD 2.53/W, with thin-film PV modules costing USD 1.19/W. In general, factory-gate prices appear to be slightly higher in the United States than in Europe (Figure 4.3). This is perhaps due to the higher support offered by United States' policies in 2010. Also, Chinese modules tend to be cheaper than modules from OECD manufacturers. In the past this could be attributed to their lower quality, but this is not always the case as today many Chinese makers meet international and OECD national quality standards.

PV module prices have continued to decline in 2011 and the lowest prices in the market were USD 1.59/W for monocrystalline PV modules, USD 1.63/W for multicrystalline PV modules, USD 1.52/W for CdTe thin-film PV modules and USD 1.22/W for amorphous silicon PV modules (Bolman, 2011). However, average prices are significantly higher. In Germany, market prices for PV modules made in Europe and the United States (excluding those from First Solar and Sunpower), averaged USD 2.15/W in the second quarter of 2011, slightly higher than those of Japanese PV modules at USD 2.13/W. In contrast, the price of PV modules from Asian countries was USD 1.87/W.

The PV module prices presented so far are factory gate prices. Accurate data on retail prices for PV modules are difficult to obtain, but are estimated to be between 35% and 45% higher than factory gate prices (Figure 4.4). The purchase of multiple PV modules can reduce

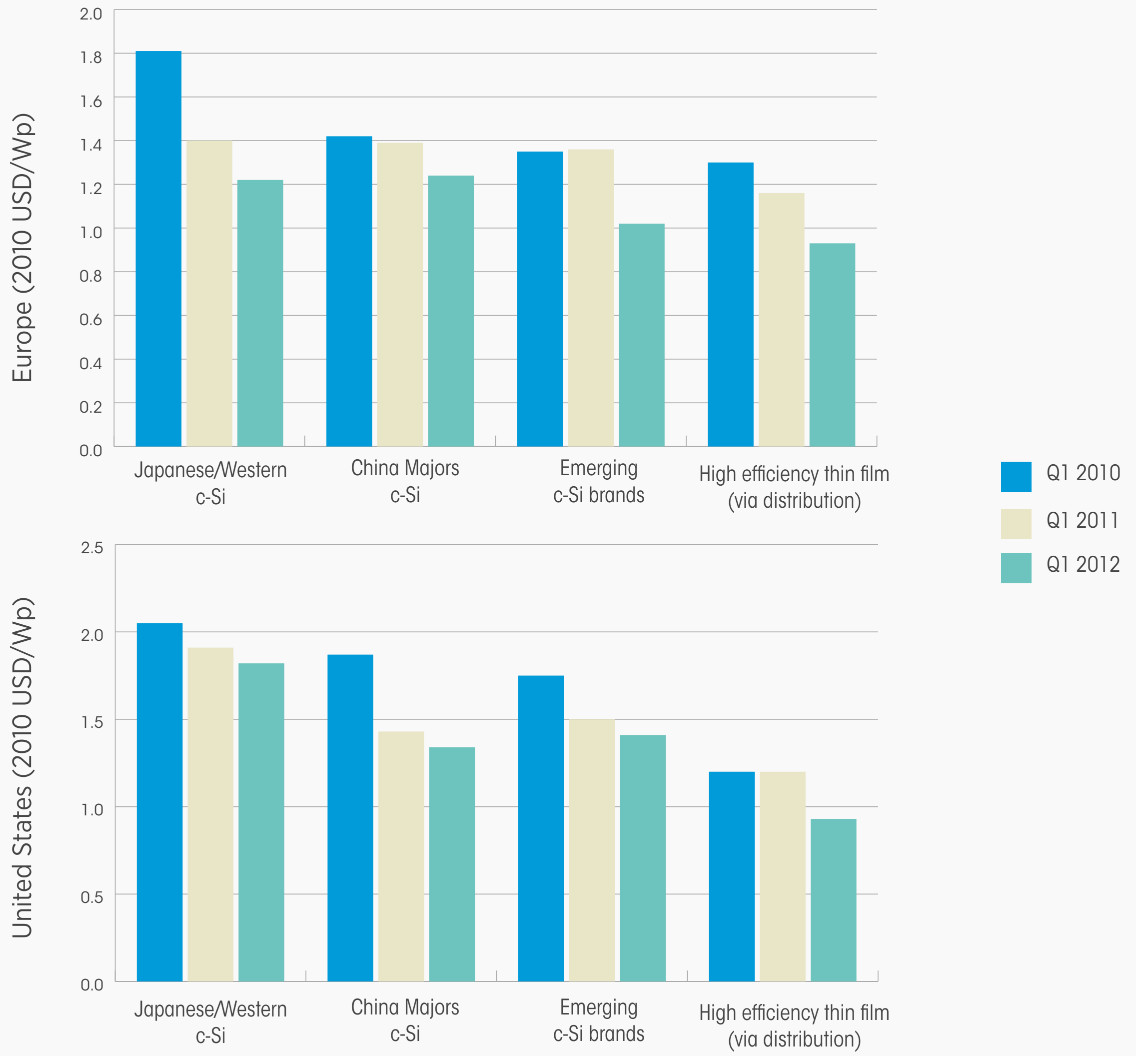

Figure 4.3: European and United States PV module factory-gate prices, Q1 2010 to Q1 2012.

Sources: Solarbuzz, 2011; Photovoltaik, 2012 and Luo, 2011.

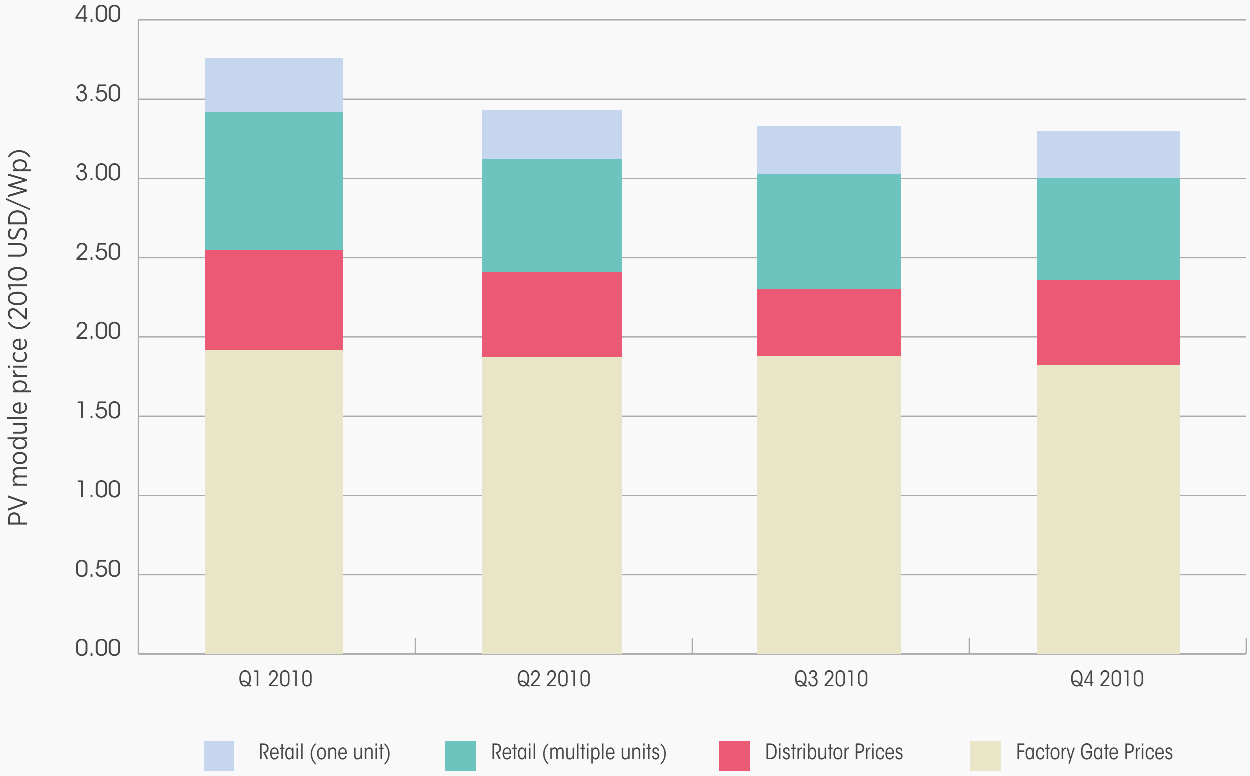

FIGURE 4.4: WEIGHTED AVERAGE RETAIL C-SI PV MODULE PRICE LEVELS AND STRUCTURE IN 2010.

Source: Solarbuzz, 2011.

prices by almost one-tenth for retail customers. The retail prices of c-Si PV modules in Europe, the United States and China are estimated to average around USD 3.00/W to USD 3.50/W (Solarbuzz, 2011). The margins charged by distributors and retailers appear to have declined by around 10% (USD 0.36/W) between the first quarter and the last quarter of 2010.

4.2 BALANCE OF SYSTEM COST

The BOS costs and installation comprise the remaining capital costs for a PV system. The BOS costs largely depend on the nature of the installation. For utility-scale PV plants, it can be as low as 20% (for a simple grid-connected system) or as high as 70% (for an off-grid system), with 40% being representative of a standard utility-scale ground-mounted system (IEA PVPS, 2009). For residential and small-scale systems, the BOS and installation costs comprise 55% to 60% of total PV system costs. The average cost of BOS and installation for PV systems is in the range of USD 1.6 to USD 1.85/W, depending on whether the PV system is ground-mounted or rooftop, and whether it has a tracking system (Bony, 2010 and Photon, 2011). The LCOE of PV systems is therefore highly dependent on BOS and installation costs, which include:

- The inverter, which converts the direct current (DC) PV output into alternating current (AC);
- The components required for mounting and racking the PV system;
- The combiner box and miscellaneous electrical components;
- Site preparation and installation (i.e. roof preparation for residential systems, or site preparation for utility-scale plants), labour costs for installation and grid connection;
- Battery storage for off-grid systems; and

- System design, management, installer overhead, permit fees and any up-front financing costs.

Rooftop-mounted systems have BOS costs around USD 0.25/W higher than ground-mounted systems, primarily due to the additional cost of preparing the roof to receive the PV modules and slightly more costly installation. In absolute terms, the electric system costs are roughly the same in both systems and account for around one-third of the BOS costs in ground-mounted systems and somewhat less in residential rooftop systems due to their higher BOS costs (Figure 4.5).

The inverter is one of the key components of a PV system. It converts the DC electricity from the PV modules into AC electricity. Inverter sizes range from small textbook-sized devices for residential use to large container-sized solutions for utility-scale systems. The size and numbers of inverters required depend on the installed PV capacity and system design options. Inverters are the primary power electronics components of a PV system and typically account for 5% of total installed system costs. Currently, inverter cost ranges from USD 0.27/W to USD 1.08/W, depending on the system size (Photon, 2011b). Larger systems tend to have lower inverter costs per unit of capacity, with systems in the 10 to 100 kW range having costs of between USD 0.23 to USD 0.57/W. However, some of the most competitive inverters for small-scale applications (<5 kW) can rival those costs, as the range in 2010 was USD 0.31 to USD 1.03/W (Photon, 2011b).

Mounting structures and racking hardware components for PV modules are typically pre-engineered systems of aluminium or steel racks. They account for approximately 6% of the total capital cost of PV systems (Mehta and Maycock, 2011). Mounting structures vary depending on where the PV systems are sited, with different solutions for residential and commercial systems, for roof types

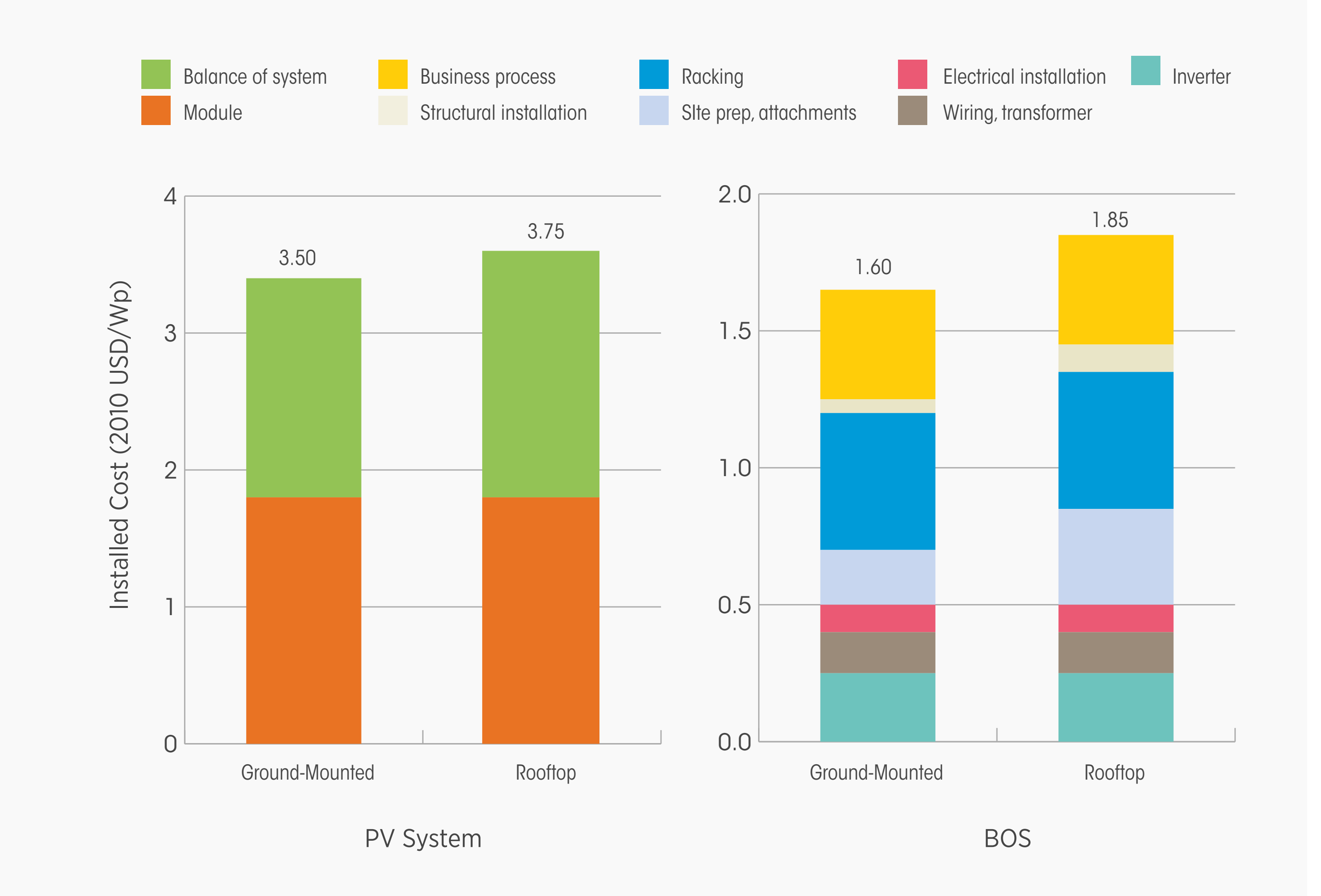

Figure 4.5: Cost breakdown of current conventional PV systems in the United States , 2010

Source: Bony, 2010

(e.g. flat membrane, sloped metal) and ground-mounted systems. Because of their low value and substantial weight, mounting and racking structures are generally produced and/or assembled locally, as shipping would be prohibitively expensive, except from countries where labour costs are so low that they can offset transportation costs.

Combiner box and miscellaneous electrical components include all remaining installation components, including combiner boxes, wires/conductors, conduits, data monitoring systems, and other miscellaneous hardware. Combiner boxes are the only PV system-specific product included in this category and they are sourced from dedicated manufacturers who supply pre-engineered systems. Other miscellaneous electrical hardware (e.g. wires, electrical conduits, overcurrent protection) are commodity products and can be sourced virtually anywhere.

Site preparation and system installation are major components of the BOS and installation costs. They include site preparation (roof or ground-based), any physical construction works (e.g. electrical infrastructure), installation and connection of the system. Labour costs make up the majority of the installation costs, and vary by project and country.

System design, management and administrative costs include system design, legal, permitting, financing and project management costs. For residential and small-scale PV systems, these costs are typically included in the total PV installed prices quoted by companies. For large-scale installations these costs might be managed directly by the promoter or sub-contracted to a service provider. When PV system costs are quoted in literature, these costs are typically included in overhead costs and profit margins. These soft costs depend significantly on local conditions. In the United States (2010), they accounted for an average 37% of total system costs (GTM Research, 2011).

Electricity storage systems for off-grid PV systems enable electricity use at night or during cloudy periods. A variety of electricity storage systems exist, or are under development, but they are expensive and tend to be more suited to large-scale applications. For small-scale systems, standard lead-acid batteries are the technology of choice. Redox flow batteries represent an emerging option, but these are not yet commercially available. Capacitors are another emerging technology, but are more suited to very short-term electricity storage.

Batteries increase the cost of the PV system, but much less than grid connection in remote areas. They are needed not only for remote residential and commercial applications, but also for off-grid repeater stations for mobile phones, radio beacons, etc.

Lead-acid batteries are the oldest, most widely applied electricity storage technology and are a proven option. Car or truck batteries are sometimes used because they are the cheapest option, but they are not designed for use with power generation technologies and have a short lifespan (as low as 50 cycles). Deep-cycle, lead-acid batteries are a proven option, with much longer lifespans than car batteries. However, even deep-cycle batteries will last longer if the discharge rate is kept low. For instance, limiting the discharge to 20% or less can allow the battery to last for ten years. The trade-off is higher initial costs, as 5 kWh of battery storage is needed for every 1 kWh of electricity used from storage.

In sunny African conditions a 1 kW PV system may supply 1 500 kWh per year (4 kWh/day). Assuming half of this energy is needed in the evenings, this means 2 kWh of useful storage is needed, requiring 10 kWh of battery storage if battery life is to be optimised. This represents an investment of USD 1 500 (USD 150/kWh), to which a battery charge controller must be added if this is not included in the PV system. The addition of storage, assuming the PV system costs around USD 3 000/kW, therefore adds 50% to the PV system cost (total USD 4 500/kW).

Other battery options include lithium-ion (Li-ion) or sodium-sulphur (NAS) batteries. Their cost, at USD 550 to USD 600/kWh, is higher than for deep-cycle, lead-acid batteries. However, NAS is a new battery technology and global production capacity is less than 150 MW per year, so cost reductions are likely. NAS batteries are currently large-scale storage solutions, with a single NAS battery being in the several MW capacity range (the battery will weigh ten tonnes, or more). Production of smaller scale NAS batteries is just starting. NAS batteries could therefore be used for a mini-grid, village or small city size storage solutions. In the longer-term, NAS battery costs could come down significantly, as they have been designed to use cheap and abundant materials. Li-ion batteries are small-scale, often powering laptop computers, and may therefore be better suited to highly modular small-scale off-grid solutions if costs come down. Other options such as redox flow batteries are still at a development stage and their practical feasibility is not yet proven.

Batteries are connected to the PV array via a charge controller to protect against overcharging or discharging, and this controller can provide information about the state of the system. Off-grid PV systems can be hybrids (e.g. in conjunction with wind and electricity storage) and / or be combined with a back-up power system (e.g. a biomass or diesel generator) to ensure a more reliable supply of electricity or to allow higher loads.

4.3 TOTAL PV SYSTEM COSTS

The total cost of a PV system is made up of the costs of the PV modules, BOS and installation. While different PV technologies have different PV module costs, the overall PV system cost also depends on the size of the system (due to the economies of scale with large utility-scale projects), and on whether the system is ground- or roof-mounted. To analyse costs, PV systems can be grouped into four main end-use markets:

- **Residential PV systems** typically do not exceed 20 kW and are usually roof-mounted;
- **Large-scale building** PV systems typically do not exceed 1 MW and are placed on large buildings or complexes, e.g. commercial buildings, schools, hospitals, universities;
- **Utility-scale** PV systems are larger than 1 MW and are generally ground-mounted; and
- **Off-grid applications**[15] vary in size from small systems for remote beacons or relay stations to mid-size systems for homes or businesses not connected to the grid, all the way up to large-scale PV systems that provide electricity to off-grid communities.

The total installed cost of a PV system also depends on the project location, scale and funding conditions in individual countries, and the maturity and size of the market. For instance, Germany has one of the more competitive PV markets, given the large domestic PV market and its history of stable long-term incentives.

Costs of Residential PV Systems

In Germany in 2011, the price of a residential PV system with a capacity of between 2 kW and 5 kW averaged USD 3 777/kW, including installation (Figure 4.6). In Italy, Portugal and Spain, the price of the equivalent PV system is USD 5 787/kW on average, which is about the same as the average in the United States of USD 5 657/kW (Photon, 2011a and 2011b).

Larger PV systems with a capacity of between 5 kW and 10 kW in Germany cost USD 3 600/kW on average, including installation in 2011 (Photon, 2011a and 2011b). In the other countries, such as Italy and Portugal, the average price is USD 5 314/kW. In the United States, the average price for these systems is USD 5 433/kW (Photon, 2011b).

The differences in the prices of PV systems in different countries can also depend on incentive schemes that are not sufficiently reactive to PV cost reductions. If incentives are not regularly realigned with declining PV manufacturing costs, installers and promoters can maintain high prices and achieve higher margins. Thus, PV system prices can be higher in countries with higher solar subsidies.

Costs of Large-scale Utility PV Systems

Large-scale utility PV systems are generally at least 1 MW in size. They operate as any other centralised power plant, providing power to the grid. Thousands of such PV plants are currently in operation worldwide. In addition to the choice of the basic PV technology, their cost depends on whether the system is roof- or ground-mounted, and whether it is equipped with a sun-tracking mechanism.

[15] Off-grid applications dominated the PV market until the mid-1990s. Since then, grid-connected systems have increased rapidly due to the impact of incentive policies introduced in many countries. The majority of today's installations are grid-connected, building systems, as incentives are usually the most generous for these applications. However, large-scale ground-mounted systems have gained a considerable market share in recent years as a result of changing incentive schemes and the rapid cost reductions of PV systems. Off-grid systems are still an important market in regions with poor grid access, but their share of new PV installations has dropped to less than 10%.

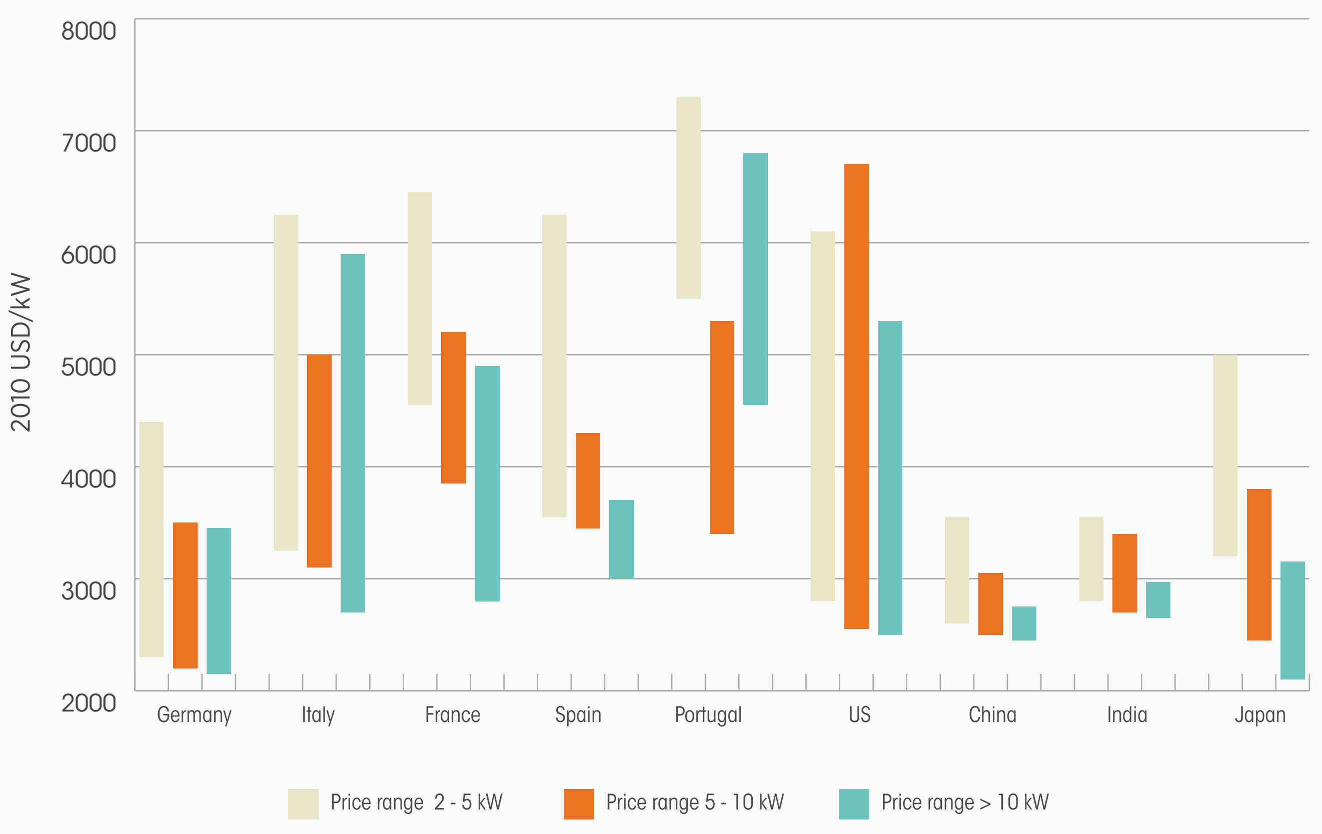

Figure 4.6: Installed PV system prices for residential applications in different countries, 2011

Source: IRENA and Photon, 2011a.

Average system prices and a cost breakdown for typical utility-scale c-Si PV systems installed in Europe and the United States in 2010 are shown in Figure 4.7.

Looking at different utility-scale PV technologies in 2010, fixed, ground-mounted systems were the cheapest option for c-Si-based utility-scale systems with an average cost of USD 4.19/W. Adding a tracking system increases the costs to an average of USD 6.39/W, only slightly cheaper than mounting the PV system on roofs (USD 6.45/W). Thin-film PV systems are cheaper than c-Si systems and have a higher market share for utility-scale application. In 2010, ground-mounted fixed systems using thin-film PV modules cost an average of USD 3.87/W (Solarbuzz, 2011).

Figure 4.8 highlights the cost hierarchy and breakdown for PV systems of different scales and characteristics. Most of the economy of scale achieved by utility-scale PV systems comes from BOS cost reductions and saving in the installation, permitting and commissioning costs. Lower financing costs can also be achieved, depending on the project specifics. One-axis tracking, although it increases capital costs by 10% to 20%, can be economically attractive because of the increase in energy-production (25% to 30% more kWh/kW/year in areas with a good solar resource) (Campbell, 2011).

Data from 92 utility-scale PV projects averaging 10 MW (either installed or proposed) in 2010 in Canada, Australia, China, Thailand, India, Japan, the Czech Republic, Belgium, Greece, Spain, France, Germany, Italy and the United States (Figure 4.9) resulted in an average installed price in 2010 of USD 4.71/W, about 16% lower than the average price in 2009 (USD 5.61/W for 117 projects). The average 2010 price for c-Si PV plants was USD 5.03/W, while the average price for thin-film plants was USD 4.16/W (Solarbuzz, 2011). PV plants with capacity above 2 MW do not appear to offer significant economies of scale (e.g. the cost of a 20 MW is not significantly lower than a 2 MW plant).

In 2010, the lowest price (USD 3.38/W) was recorded in Thailand (Figure 4.10), although this result was dominated

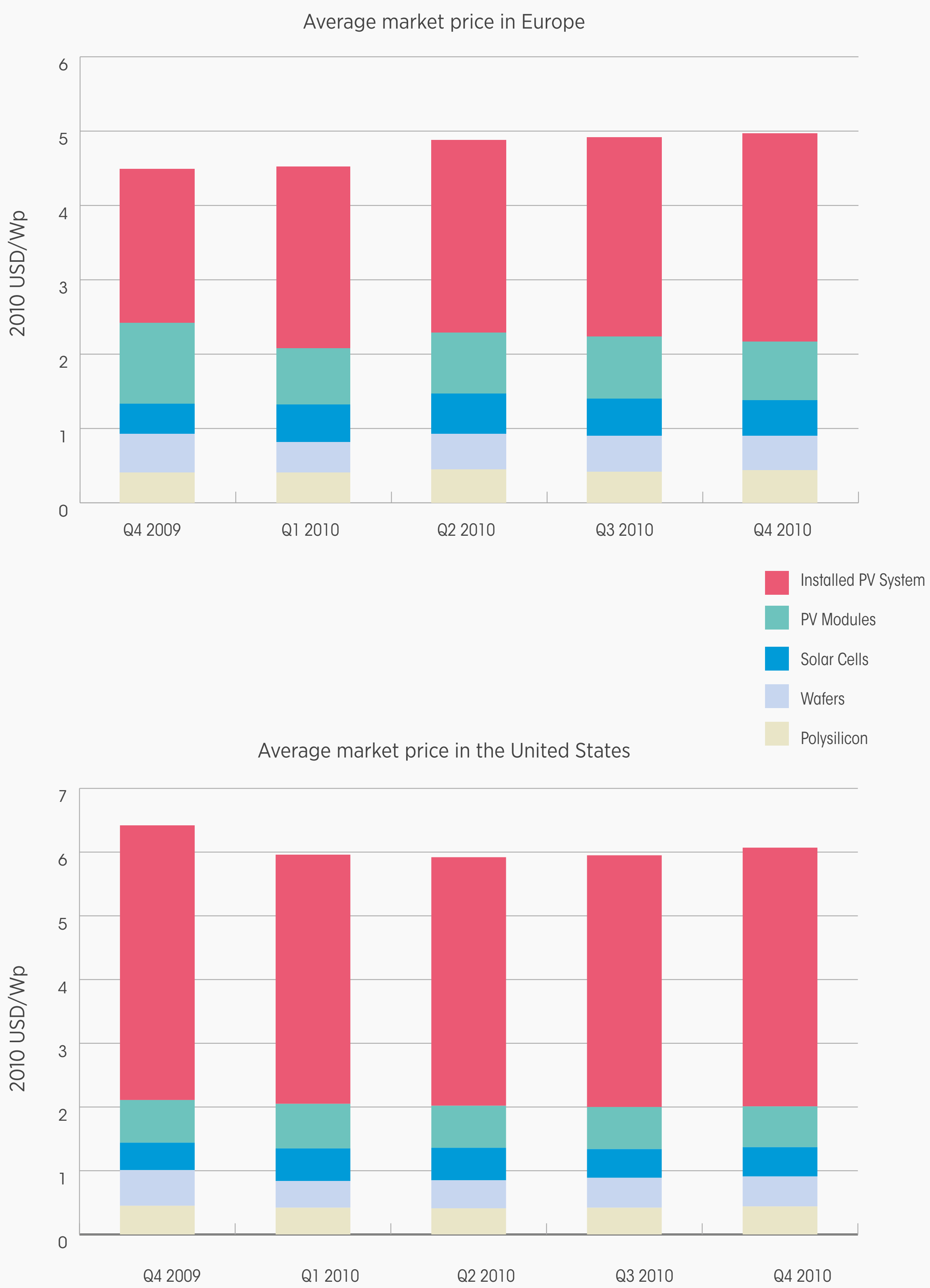

Figure 4.7 Cost breakdowns of typical utility-scale c-Si PV systems installed in Europe and the United States, Q1 2009 to Q4 2010.

Source: IRENA and Solarbuzz, 2011.

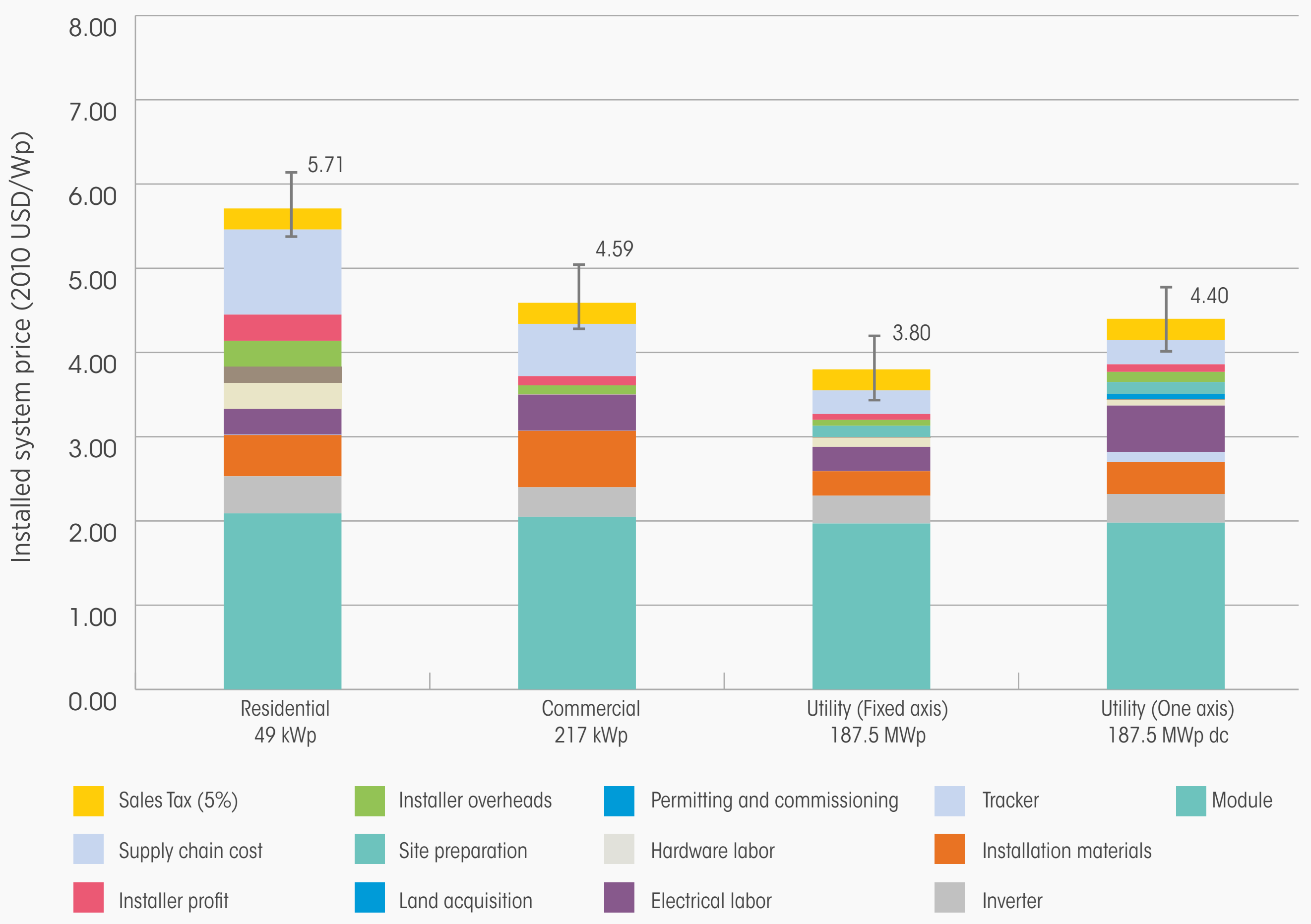

Figure 4.8: System cost breakdown for residential, commercial and utility-scale c-Si PV systems in the United States, 2010.

Source: Goodrich, 2012.

by an 84 MW thin-film PV plant installed in Thailand. The highest for utility-scale PV plants was recorded in Japan (USD 6.50/W), albeit the average project size is lower than in Europe and China. Among the major PV markets, Germany showed the lowest average price at USD 3.64/W for c-Si-based PV plants. It was noted that prices of c-Si systems (USD 3.65/W) were surprisingly close to those of thin-film systems (USD 3.61/W). The widest price variation occurred in Italy with lowest and highest figures of USD 2.89/W and USD 6.67/W. In the United States, the average price was USD 4.83/W, with an average capacity of 4.8MW.

Falling PV system prices, the high cost of fossil fuels in many markets in recent times and effective and broader incentive schemes have driven the growth in utility-scale PV plants. Since 2005, more than 1 200 PV plants with a capacity of 1 MW or more have been commissioned, with over 120 of these PV plants having an output of 10 MW or more (Philibert, 2011). Since 2007, the number and size of MW-scale PV systems has risen, especially in Germany and Spain (Komoto, 2010). Today's leading markets for utility-scale PV systems are Germany, Spain, Canada and the United States[16], but utility-scale PV systems are also being commissioned in India, China and the Middle East. An important emerging issue for utility-scale systems is that BOS and installation costs have, in some cases, not been declining as fast as the cost of PV modules. Therefore, their share of the overall PV cost, currently around half of utility-scale c-Si PV system costs, could increase over time.

[16] Some of the largest plants are located in Spain (60 MW Olmedilla, 50 MW Puertollano) and Germany (54 MW Strabkirchen and 53 MW Turnow Perilack).

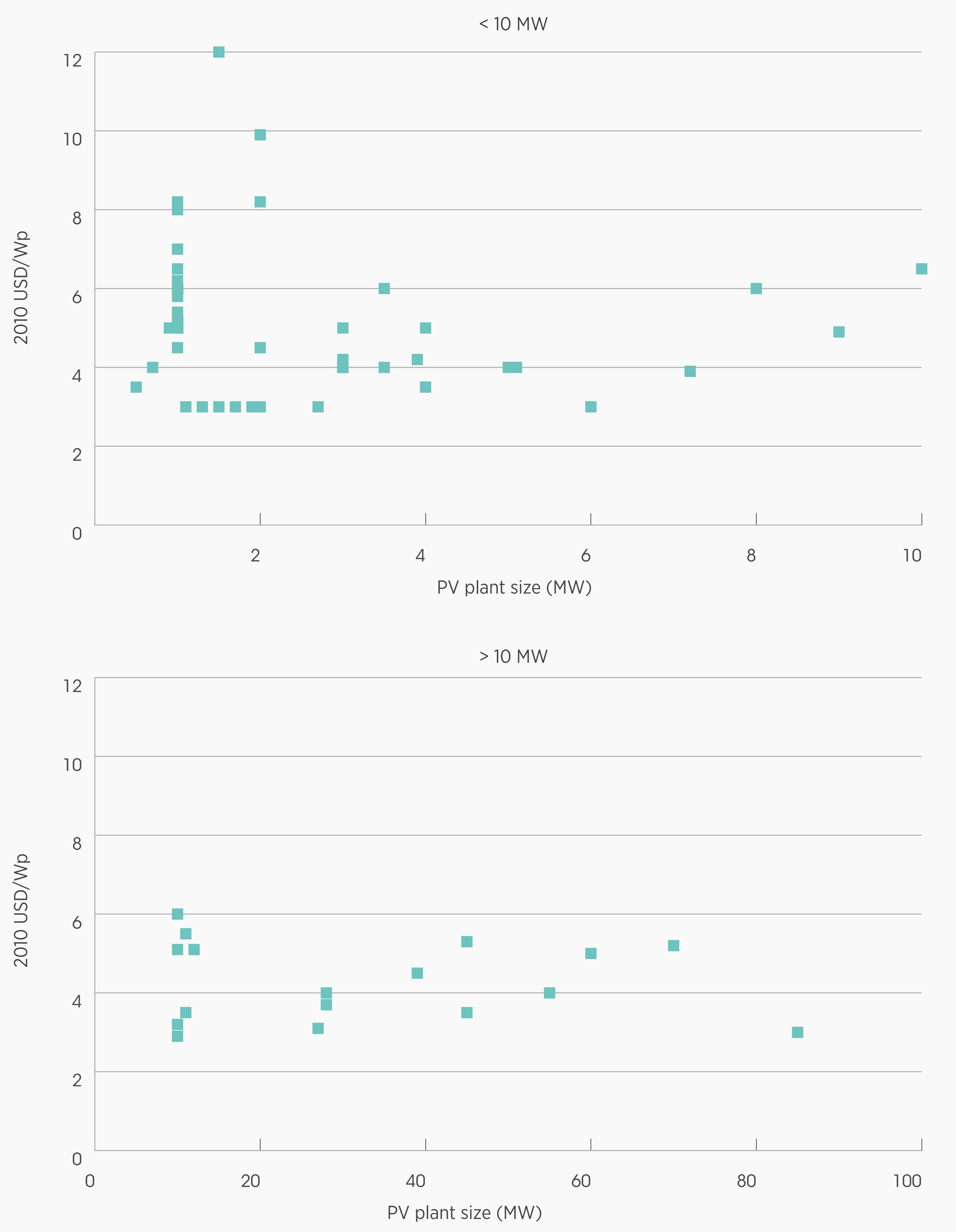

FIGURE 4.9: INSTALLED COSTS OF UTILITY-SCALE PV PLANTS IN 2010 (<10 MW AND >10 MW)

Source: Solarbuzz, 2011

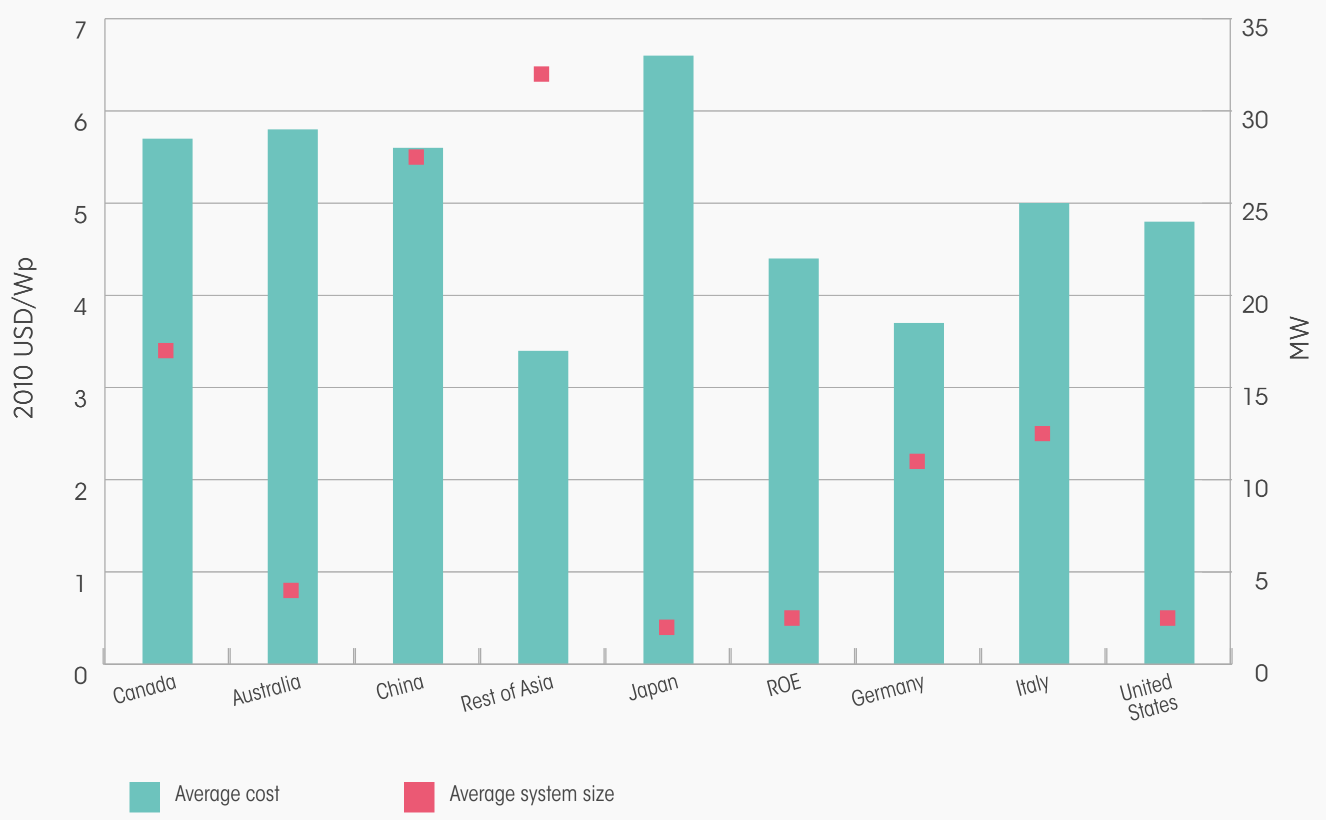

Figure 4.10: Average prices and sizes of large utility-scale PV plants by country, 2010.

Source: Solarbuzz, 2011

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5. PV system cost reduction potential

PV costs will continue to decline with increased deployment due to the high PV learning rate. However, significant uncertainty exists on how fast costs will come down in the short-term. On one hand, incentives are now in place in a number of countries, thus unlocking new markets and a new wave of PV deployment that will help reduce costs through the learning effect. On the other hand, the uncertain global economic outlook could result in many investment decisions being delayed or postponed indefinitely, slowing the rate of deployment growth.

5.1 COST REDUCTION POTENTIAL FOR c-Si PV MODULES

The PV module itself accounts for around half of total PV system costs. The continued reduction in PV modules costs is therefore a key component of improving the competitiveness of PV.

While c-Si PV is the most mature PV technology, there still exists significant room for reducing manufacturing costs through technology innovation and economies of scale. According to one study (Mehta and Maycock, 2010), both low- and high-cost manufacturers could halve their production costs by 2015. Figure 5.1 shows c-Si PV module cost projections for period 2010 to 2015 and the assumed increase in average PV manufacturing plant size required to achieve the cost reductions. Table 5.1 and 5.2 provide more detailed projections, including the cost breakdown for c-Si PV modules. The costs of polysilicon and wafer production could decline dramatically by 2015 driven by the increasing scale of production and ongoing manufacturing innovations.

Table 5.1: Crystalline Silicon PV module prices projections for European, North American and Japanese manufacturers, 2010 to 2015

High-cost producers	2010	2011	2012	2013	2014	2015
Production scale (MW)	150	400	650	900	1 150	1 400
Polysilicon production (USD/W)	0.43	0.33	0.23	0.18	0.15	0.13
Silicon wafer production (USD/W)	0.46	0.37	0.33	0.29	0.27	0.25
Solar cell production (USD/W)	0.36	0.29	0.25	0.23	0.20	0.19
PV module production (USD/W)	0.50	0.42	0.37	0.33	0.31	0.29
Total PV module cost (USD/W)	**1.75**	**1.41**	**1.18**	**1.03**	**0.93**	**0.85**

Note: Production scale refers to the annual production capacity of a single manufacturing plant required to achieve the cost presented.

Source: Mehta and Maycock, 2010.

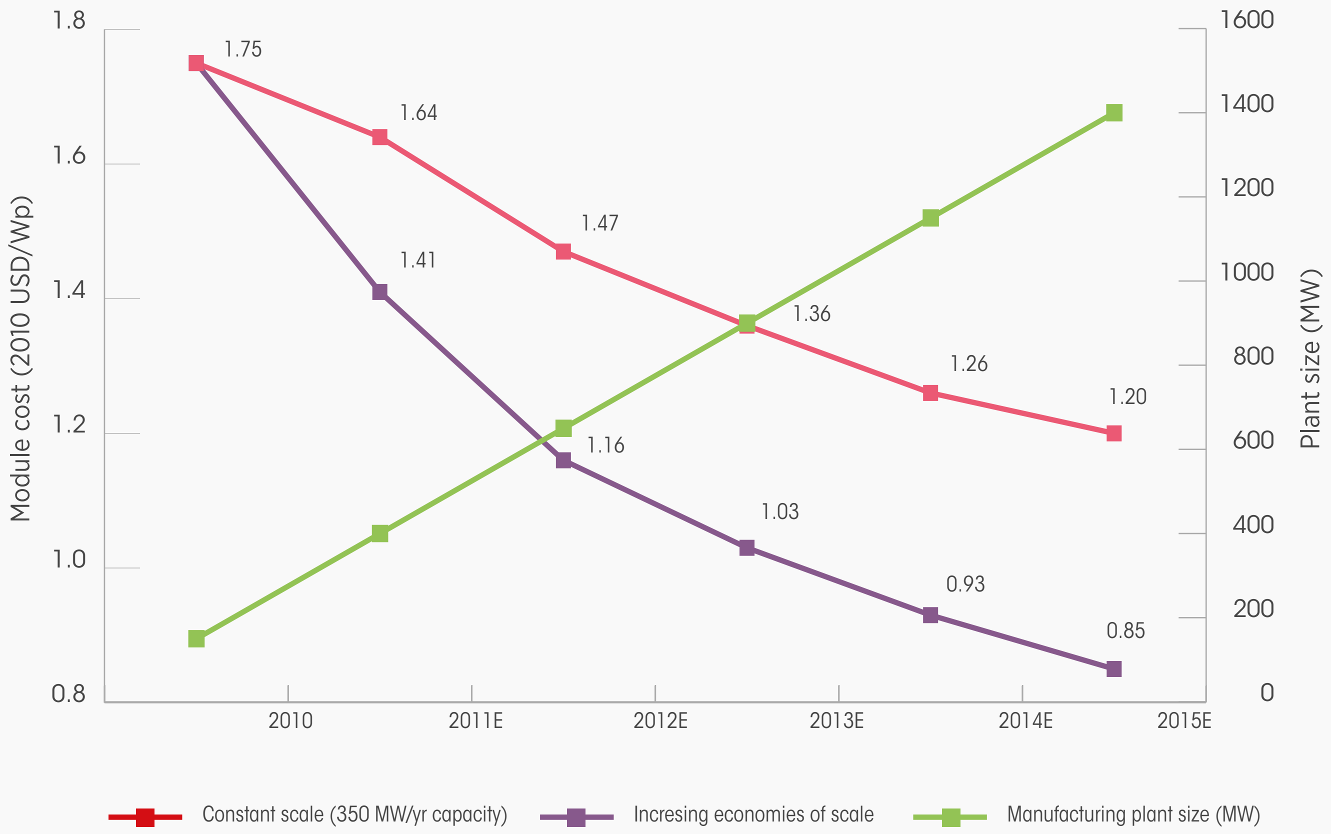


Figure 5.1: Crystalline silicon PV module cost projections, 2010 to 2015

Source: Mehta and Maycock, 2010.

Table 5.2: Crystalline Silicon PV module prices projections for low-cost manufacturers; 2010 to 2015

Low-cost producers – China, etc.	2010	2011	2012	2013	20 14	2015
Production scale (MW)	350	600	850	1 100	1 350	1 600
Polysilicon production (USD/W)	0.47	0.39	0.25	0.20	0.16	0.14
Silicon wafer production (USD/W)	0.34	0.28	0.26	0.24	0.22	0.20
Solar cell production (USD/W)	0.24	0.21	0.19	0.18	0.16	0.15
PV module production (USD/W)	0.36	0.31	0.29	0.27	0.25	0.23
Total PV module cost (USD/W)	**1.41**	**1.20**	**0.99**	**0.87**	**0.73**	**0.73**

Note: Production scale refers to the annual production capacity of a single manufacturing plant required to achieve the cost presented.

Source: Mehta and Maycock, 2010.

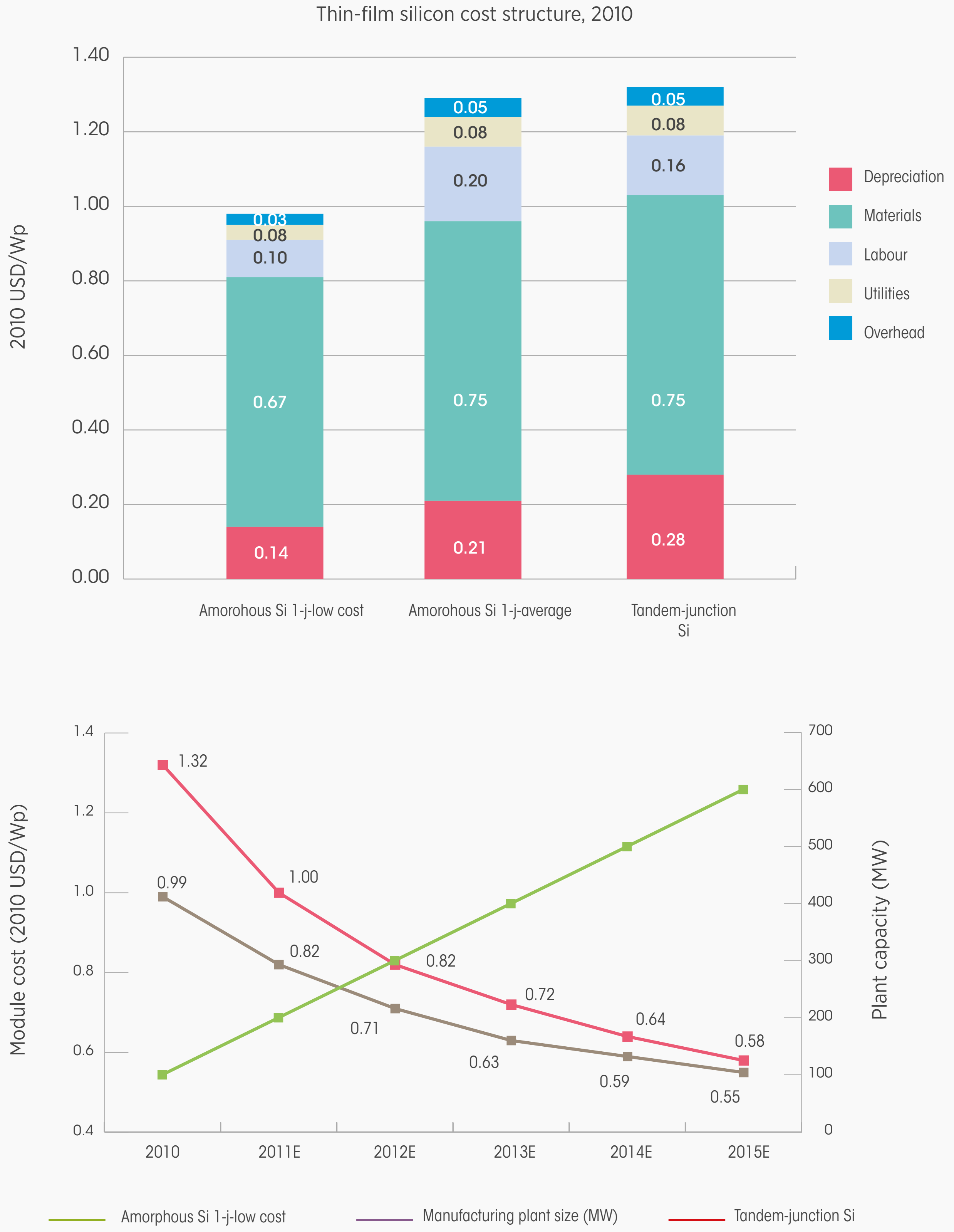


Figure 5.2: Single junction and tandem structures of amorphous silicon thin-film PV module cost breakdown and projections, 2010 to 2015

Source: Mehta and Maycock, 2010.

Alternative studies project a similar decline in PV module prices by 2015. Solarbuzz projects that c-Si PV module prices will decline from USD 2.17/W in 2010 to as low as USD 1.07/W in 2015; Lux Research projects a slightly less aggressive decline to around USD 1.2/W in 2015 (Lux Research, 2010). Given the rapid cost reductions in 2011, these projections for average c-Si module prices are likely to be bettered.

5.2 COST REDUCTION POTENTIAL FOR THIN-FILM PV MODULES

Thin film PV modules are cheaper than c-Si modules, but further cost reductions are expected by 2015. Single-junction amorphous PV modules are projected to decline from USD 0.99/W in 2010 to just USD 0.55/W, while tandem-junction silicon PV modules could decline from USD 1.32/W in 2010 to USD 0.58/W by 2015 (Figure 5.2).

For co-evaporation CIGS PV modules, costs could reduce from around USD 1.31/W in 2010 to USD 0.63/W by 2015 while the reduction for sputtering-based CIGS systems is more modest (USD 0.69/W by 2015, Figure 5.3) (Mehta and Maycock, 2010). CdTe modules' manufacturing costs could drop from around USD 0.73/Wp in 2010 to just USD 0.49/Wp in 2015 (Figure 5.4).

5.3. BOS COST REDUCTION POTENTIALS

The BOS and installation costs will become proportionately more important over time as PV module costs continue to decline. Therefore, BOS cost reductions will become vital to continuing the rapid LCOE cost reductions of PV systems. Among BOS components, the cost of the inverter is generally well-known while this is often not the case for remaining electrical, structural and installation costs, which vary widely depending on local conditions and labour costs.

Achieving cost reductions is more challenging for BOS than for PV modules because BOS involves a number of different components[17] and suppliers, more mature technologies, and is, and will probably always be due to its nature, a less integrated industry. However, technological developments to optimise physical design and reduce BOS costs are still possible. There are many possible design strategies, but further work will be required to identify what combination of approaches is optimal in different circumstances and markets. This is an area of debate in the industry (Bony, 2010 and Newman, 2011). The most important factors to reduce BOS and installation costs are outlined below. These factors together could result in BOS and installation cost reductions similar to those for PV modules.

Electrical system improvements start with efforts to improve the design of the inverter. Historically, inverter costs have trended down with PV module costs. Continued investment in R&D and improvements in manufacturing processes should allow this trend to continue. One interesting area of development and cost reduction is the use of micro-inverters directly integrated into the PV modules, which also reduce the installation cost[18]. Also important for both inverters and micro-inverters are efforts to increase the lifetime from today's 5-10 years which is significantly shorter than the lifetime of the PV system life[19]. All of these efforts are projected to halve inverter costs by 2020 (Mott MacDonald, 2011).

Structural system improvements include downsizing of the structural components. This could yield up to 40% of the BOS cost reductions. Efficient designs to minimise the impact of wind loads could result in significant reduction in the structural costs by allowing lighter, cheaper structures (Bony, 2010).

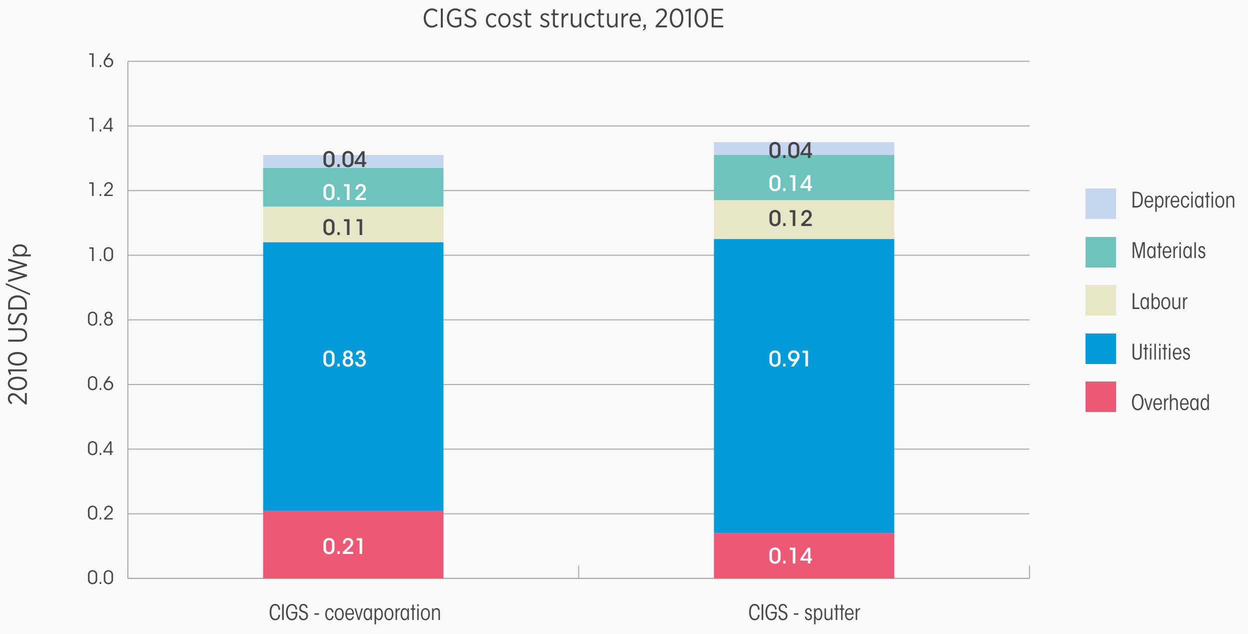
Installation costs can be reduced with continued experience, increased market scale and competition. Process automation and high-level pre-assembly and standardisation could reduce labour costs for installation by up to 30% (Bony, 2010).

Standardisation and economies of scale will help reduce component costs by high volume manufacturing of BOS components. The potential cost reduction is large, as most BOS component manufacturers today are small companies. Large companies are pursuing important economies of scale strategies to remain competitive. (Bony, 2010).

[17] An idea of the number of components involved can be taken from the example of a utility-scale PV system (>20 MW plant) currently under construction. At this plant, 45 of 63 cost items for the BOS cost less than USD 0.02/W and these 45 components contributed only about USD 0.25/Wp to the total BOS cost (US DOE, 2010).

[18] The introduction these more intelligent PV modules with integrated micro-inverters and DC optimising devices has already begun and these so called "smart AC modules" are expected to take a significant share of the residential market.

[19] In the short-term, this could lead to higher inverter prices, but a lower LCOE for PV systems. However, it is likely that the incremental gains in inverter life should be able to be achieved at modest cost and the overall downward trend in inverter costs will continue.



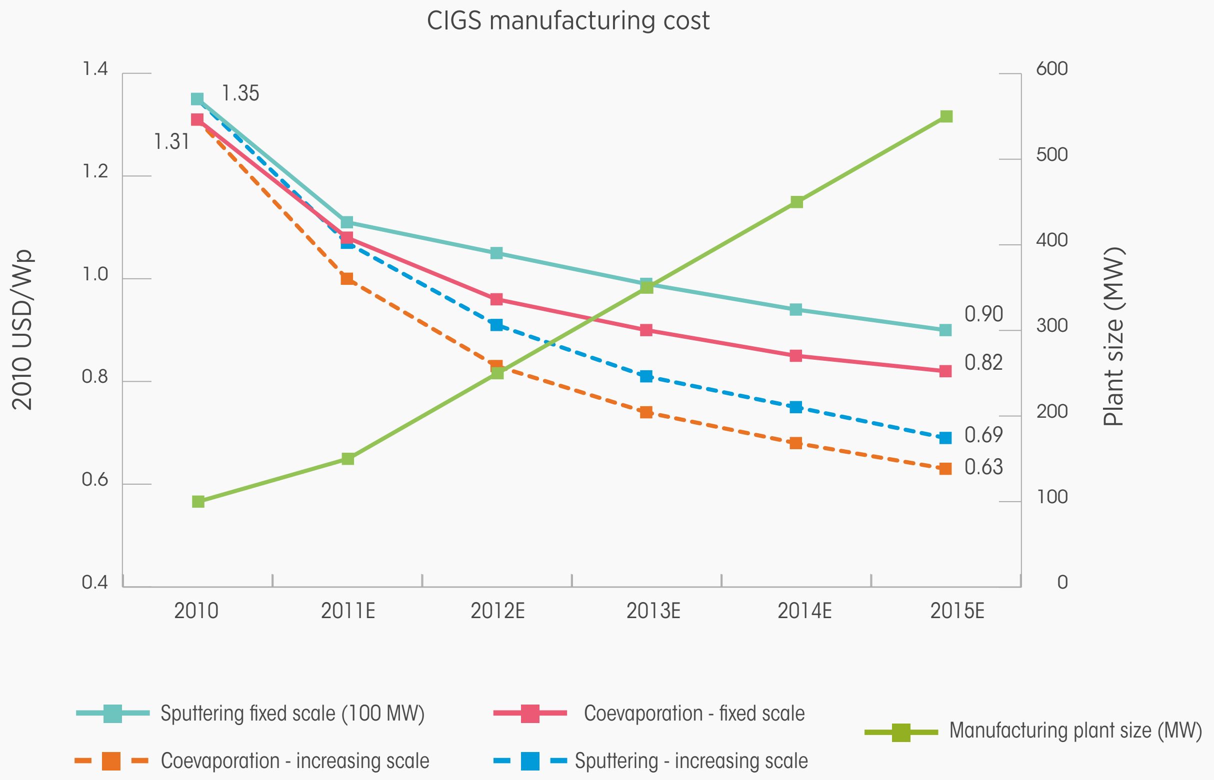
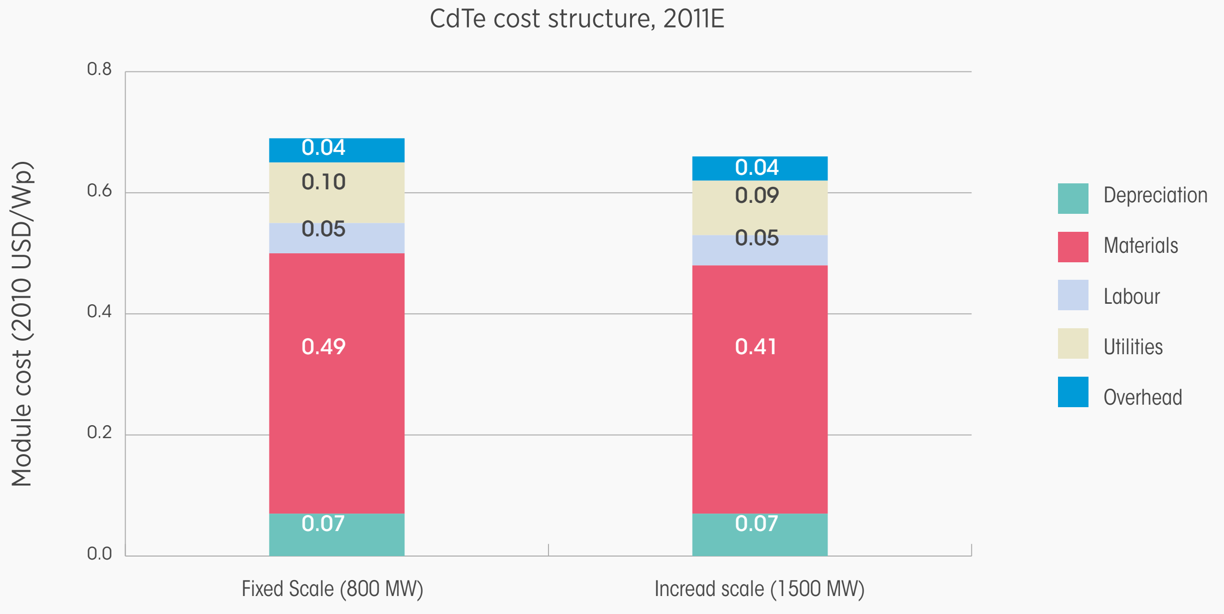


Figure 5.3: CIGS thin film PV module cost breakdown and projections, 2010 to 2015

Source: Mehta and Maycock, 2010.



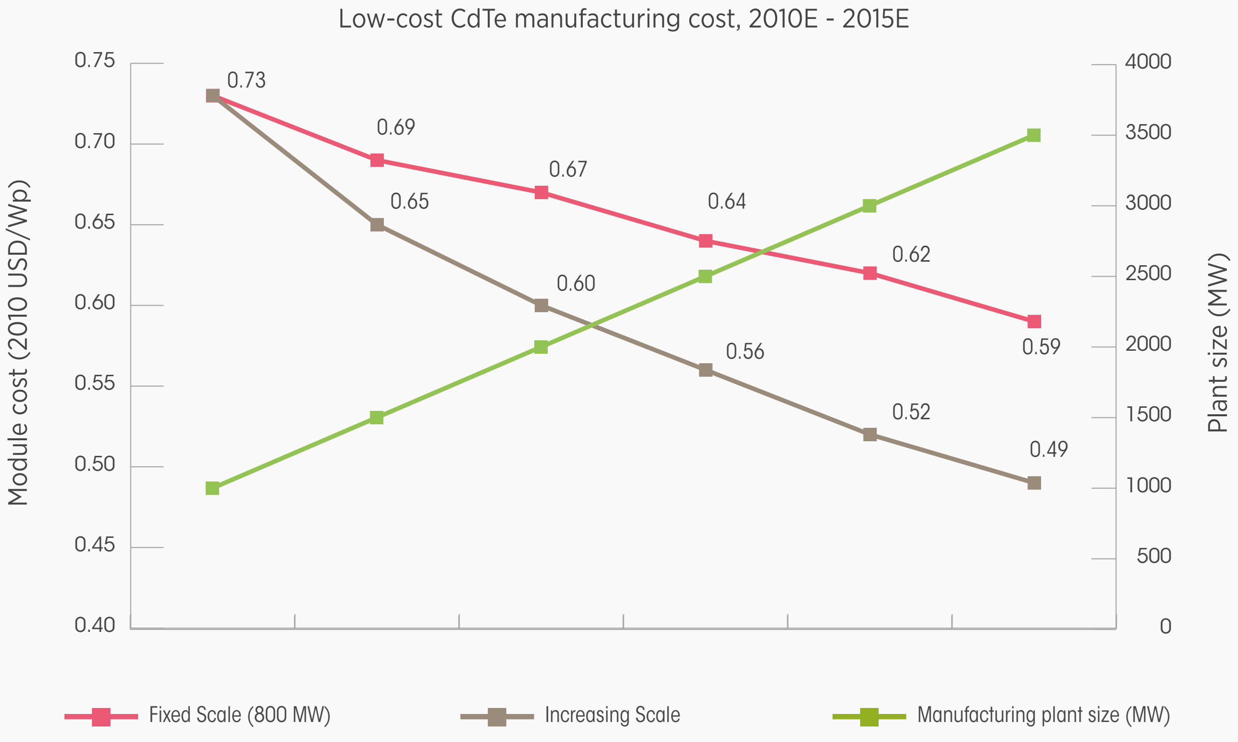


Figure 5.4: CdTe thin film PV module cost breakdown and projections, 2010 to 2015

Source: Mehta and Maycock, 2010.

5.4. OVERALL COST REDUCTION POTENTIALS FOR PV SYSTEMS

Overall PV system costs are projected to continue to decline rapidly, although uncertainties exist at the moment regarding the markets growth in the short term. Short-term projections for the PV market are rapidly out of date given the rapid pace of developments. Longer term projections are likely to experience less volatility.

PV system costs for residential systems are projected to decline from USD 4 200 to USD 6 000/kW in 2010 to between USD 1 800 to USD 2 700/kW by 2020 and to USD 1 500 to USD 1 800/kW by 2030 (Table 5.2). Utility-scale systems can expect to achieve similar reductions from between USD 3 600 to USD 4 000/kW in 2010 to USD 1 800/kW in 2020 and as low as USD 1 060 to USD 1 380/kW by 2030. These projections might be too conservative in the medium- to long-term given that they are based on a learning rate of 18%, which is less than the historical rate of 22%. However, this uncertainty is balanced by the possibility that the learning rate will reduce slowly over time as the technology becomes more mature.

Taking into account the near-term market growth, a more nuanced cost reduction scenario is projected for residential systems by 2015 (Figure 5.5). Large-scale PV plants are projected to reduce system costs from between USD 3 730 to USD 3 900/kW in 2011 to USD 2 200 to USD 2 640/kW by 2015 (Solarbuzz, 2011). For c-Si PV systems, the total installed costs could decline to between USD 2 270/kW and USD 2 770/kW by 2015, while thin-film PV systems could decline to between USD 1 860/kW and USD 2 240/kW.

In addition to projections based on deployment and learning rates, more aspirational goals (backed by significant R&D and market transformation policies), such as the Sunshot initiative in the United States, exist. The Sunshot initiative aims to achieve a "$1/W PV system" for utility-scale applications in 2020 and USD 1.5/W for residential systems (US DOE, 2012). This would mean that PV systems could produce electricity at USD 0.05 to USD 0.07/kWh, making PV systems competitive not only with the residential and commercial tariffs for electricity, but also with the wholesale rate of electricity without subsidies in virtually all regional electricity markets in the United States (US DOE, 2012 and US DOE, 2010). However, this does not take into account transmission line development / strengthening and electricity storage needs to meet demand when the sun is not shining. The view of US DOE experts is that, at the current rate of progress, the PV system cost by 2016 is likely to reach USD 2.20/W for utility-sized systems, USD 2.50/W for commercial building-scale, and USD 3.50/W and residential systems (US DOE, 2010). By 2020, utility-scale systems could decline in an "evolutionary" scenario to between USD 1.71 and USD 1.91/W (Goodrich, 2012). Residential systems might decline in this same scenario to USD 2.29/W in 2020.

TABLE 5.3 INSTALLED PV SYSTEM COST PROJECTIONS FOR RESIDENTIAL AND UTILITY-SCALE SYSTEMS, 2010 TO 2030

	2010	2015	2020	2030
Utility-scale				
EPIA (c-Si)	3 600		1 800	1 060 - 1 380
IEA (c-Si)	4 000*		1 800	1 200
Resdiential/Commercial				
IEA	5 000 - 6 000*		2 250 - 2 700	1 500 - 1 800
Solarbuzz (c-Si)	4 560	2 280 - 2 770		
Solarbuzz (thin film)	4 160	1 860 - 2 240		

*Note: * data is for 2008.*

Sources: EPIA, 2011a; Solarbuzz, 2011 and IEA, 2010.

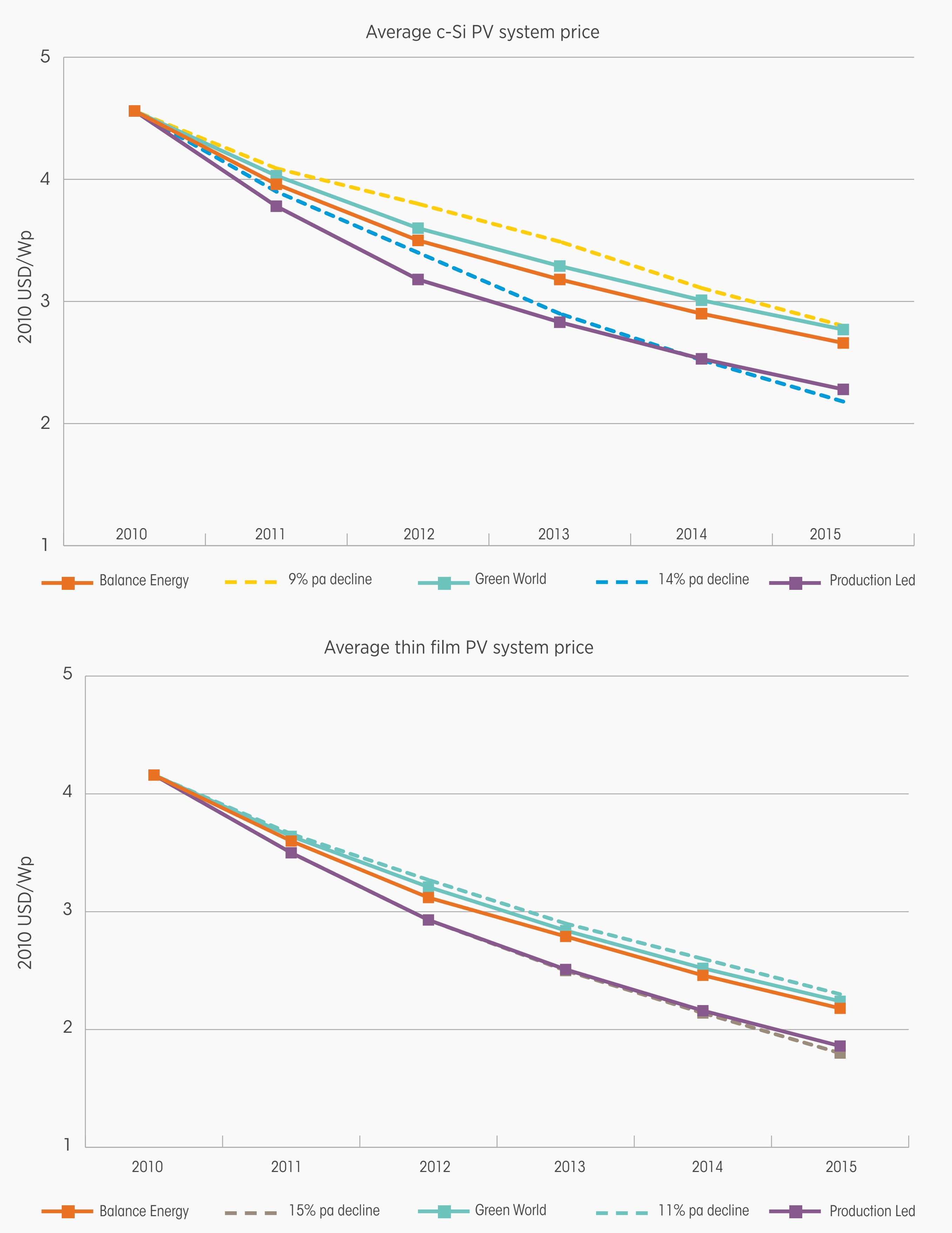


Figure 5.5: Average crystalline silicon and thin-film PV system price forecasts for 2010 to 2015

Source: Solarbuzz, 2011.

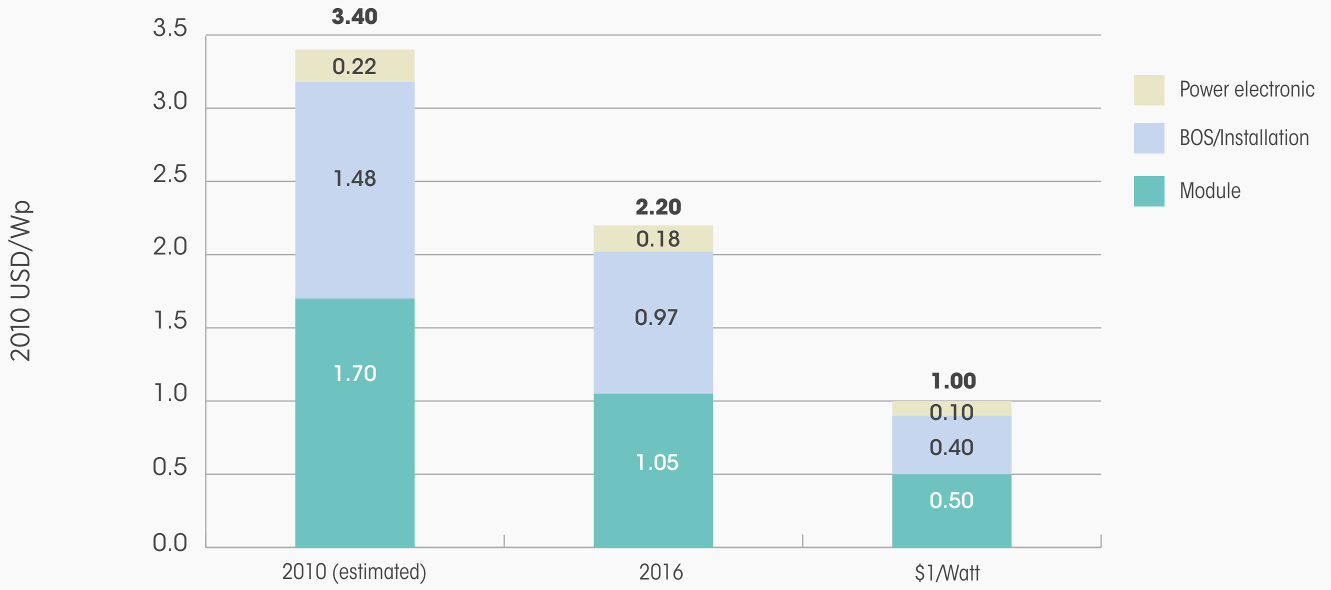


FIGURE 5.6: US DOE COST REDUCTION GOALS TO ACHIEVE USD 1/W

Source: Lushetsky, 2010.

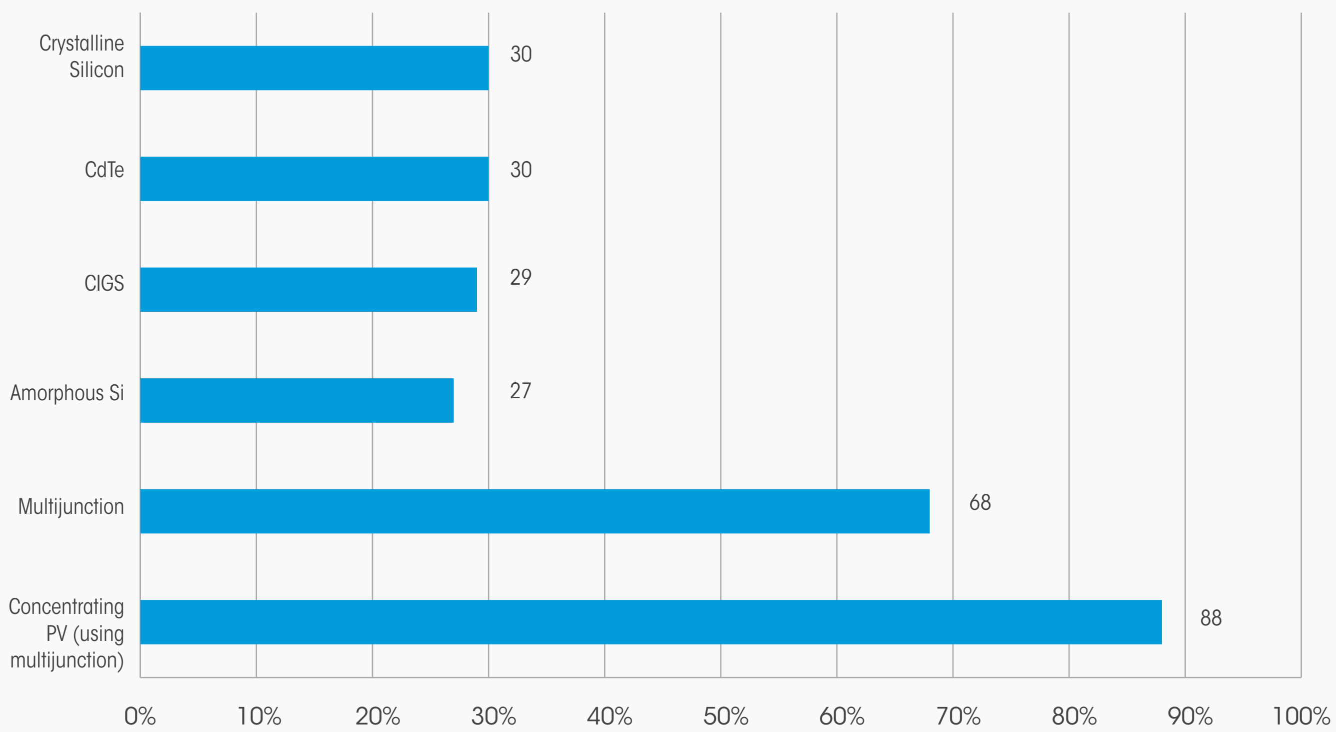


FIGURE 5.7: THEORETICAL SOLAR CELL MAXIMUM EFFICIENCY BY PV TECHNOLOGY

Source: Mehta and Maycock, 2010.

Preliminary analysis shows that achieving the "$1/watt" target for PV systems will require module costs of USD 0.50/W, BOS and installation cost of USD 0.40/W, and USD 0.10/W for the power electronics (Figure 5.6) (US DOE, 2012). The industry view is that these figures are ambitious, but potentially achievable. Ideas on how to achieve these targets are already being explored (US DOE, 2010). Important improvements could be obtained for PV modules, BOS and electronics if the PV efficiency improves and the area required for a given generation capacity decreases. As a rule of thumb, every 1% increase in PV module efficiency reduces the BOS cost by between USD 0.07 and USD 0.10/W (Surek, 2010).

5.5 PV MODULE EFFICIENCY IMPROVEMENTS

The LCOE of PV systems can also be reduced by improving the PV efficiency. While for physical reasons PV modules will never reach the maximum theoretical cell efficiency (Figure 5.7) nor the highest cell efficiency obtained at laboratory level (often referred to as the "champion" efficiency), the efficiency of the current commercial modules still has significant room for improvement. Analysis suggests that efficiency improvements may occur for all PV commercial modules (Lux Research, 2010). By 2015, the efficiency of the best commercial monocrystalline Silicon modules could be well above the current 20%, while the average efficiency of multicrystalline c-Si modules could approach 17% and commercial CIGS thin-film modules (with a current efficiency of 10%-13%) could rival today's c-Si module efficiency (Figure 5.8)

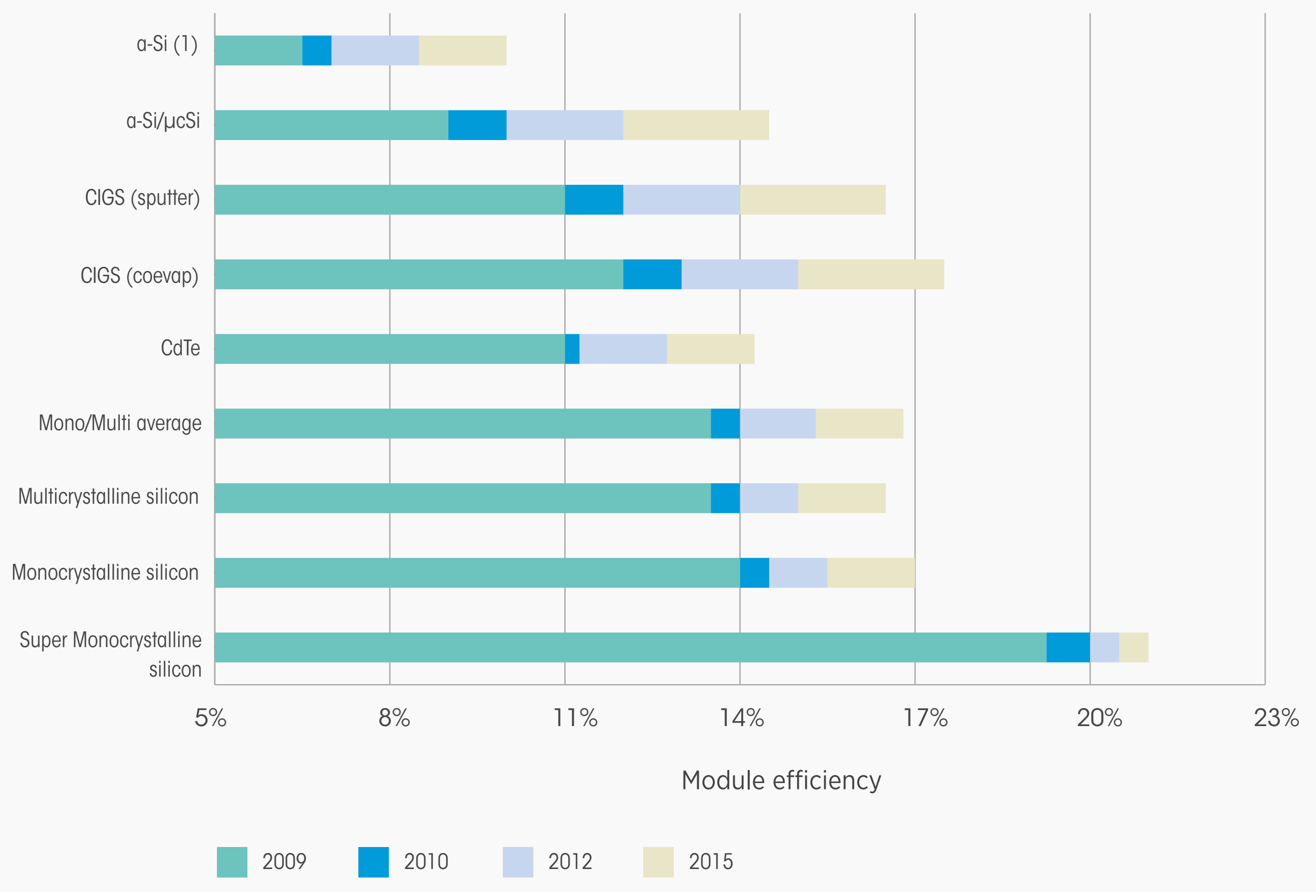


FIGURE 5.8: CURRENT AND PROJECTED PV MODULE EFFICIENCY IMPROVEMENTS TO 2015.

Sources: Mehta and Maycock, 2010.

6. Levelised cost of electricity from solar PV

PV systems, like most renewable power generation technologies, are capital intensive, but have no fuel costs. The three key drivers of the LCOE of PV systems are:

- The capital and the installation costs of PV modules and BOS (USD/W);
- The average annual electricity yield (kWh per kW), a function of the local solar radiation and the solar cells' technical performance; and
- The cost of finance for the PV system.

The solar resource is the key determinant of the output yield of a PV system per kW, in that it is the key determinant of the average capacity factor achieved. The tilt and orientation of the panels, as well as the presence of any tracking system, also impacts on the yield. Avoiding shading of the systems wherever possible is vital.

When the LCOE of a PV system is the same or less than residential electricity tariff, then the PV electricity is economically competitive for residential users. Competitiveness has been already achieved in some countries where the electricity retail price is particularly high and solar irradiation and climate are particularly favourable to the PV electricity generation (e.g. some Southern European countries). With PV system costs continuously declining, PV will become economically attractive for residential and many commercial sector consumers in many countries. Some projections suggest that PV systems will be economic without support for residential consumers in most countries by 2020 and that the cost of PV electricity will continue declining steadily toward a full competitiveness with conventional electricity generation options.

However, much depends on whether the current rate at which PV system costs decline continues and the rate of deployment. Critically, in many countries which experience afternoon demand peaks, the value of PV electricity can substantially exceed the average grid-based generation cost. Similarly, many of these projections are based on continued increases in the cost of electricity from conventional power generation technologies.

The International Energy Agency (IEA) in its PV Technology Roadmap (IEA, 2010) projects that:

» Over the current decade, continued government support will enable the LCOE of PV to decline sufficiently to compete with retail electricity prices in a growing number of countries.

» In 2020, the LCOE of PV systems will range between USD 0.105 and USD 0.21/kWh for large, utility-scale plants, and between USD 0.16 and USD 0.315/kWh for residential PV systems.

Under the IEA scenario, the LCOE of PV systems will not reach grid parity in most countries until after 2020. However, given how fast PV costs have been declining and how rapid PV markets are growing in many countries, a more favourable PV scenario might be possible. The European Photovoltaic Industry Association (EPIA) estimates that the LCOE of PV could drop from USD 0.22 to USD 0.27/kWh in 2010 to USD 0.06 to USD 0.10/kWh by 2020 (Figure 6.1) (EPIA and A.T. Kearney, 2011c), while analysis of the US market projects that the LCOE of residential c-Si PV systems could decline to between USD 0.10 and USD 0.18/kWh by 2015, and to between USD 0.07 and USD 0.12/kWh by 2020. The LCOE of utility-scale systems for both thin film and c-Si could decline to between USD 0.06 and USD 0.10/kWh by 2020 (Table 6.1). This would enable PV systems to compete with residential tariffs in a wide range of regions in the United States and to reach grid parity in high-cost regions by 2015 (Figure 6.2).

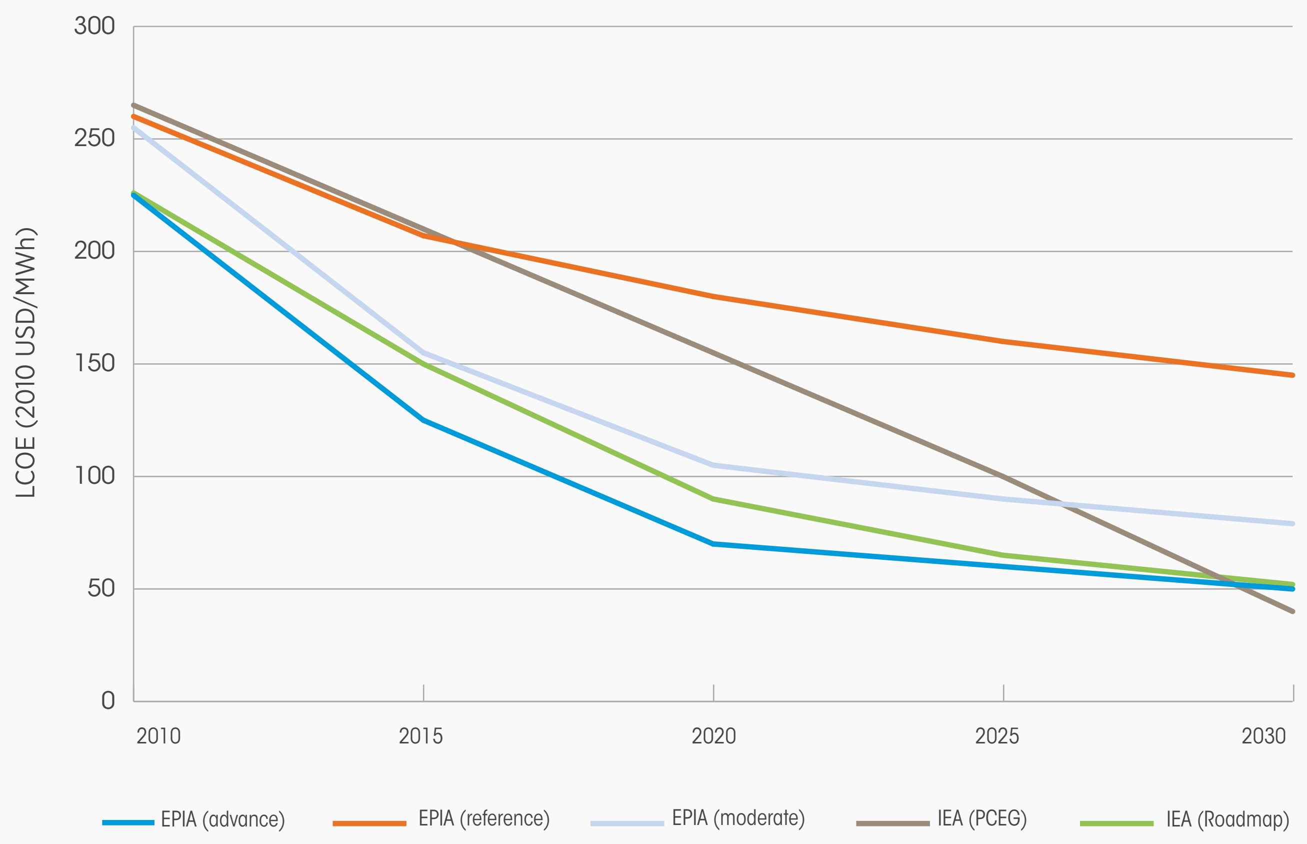


Figure 6.1: LCOE scenarios for PV systems, 2010 to 2030.

Sources: IEA, 2010; and EPIA and A.T. Kearney, 2011.

Table 6.1: C-Si and thin-film PV system costs and LCOE, 2010 to 2020

Year	Crystalline Silicon PV Average Price (USD/Wp)	Crystalline Silicon PV (US cents/kWh)	Thin-Film and Low-Price Crystalline PV - Average Price (USD/Wp)	Thin-Film and Low-Price Crystalline (US cents/ kWh)
2010	5.59	15 — 26	4.39	12 — 20
2015	3.85	10 — 18	3.02	8 — 14
2020	2.65	7 — 12	2.08	6 — 10

Source: Pernick and Wilder, 2008

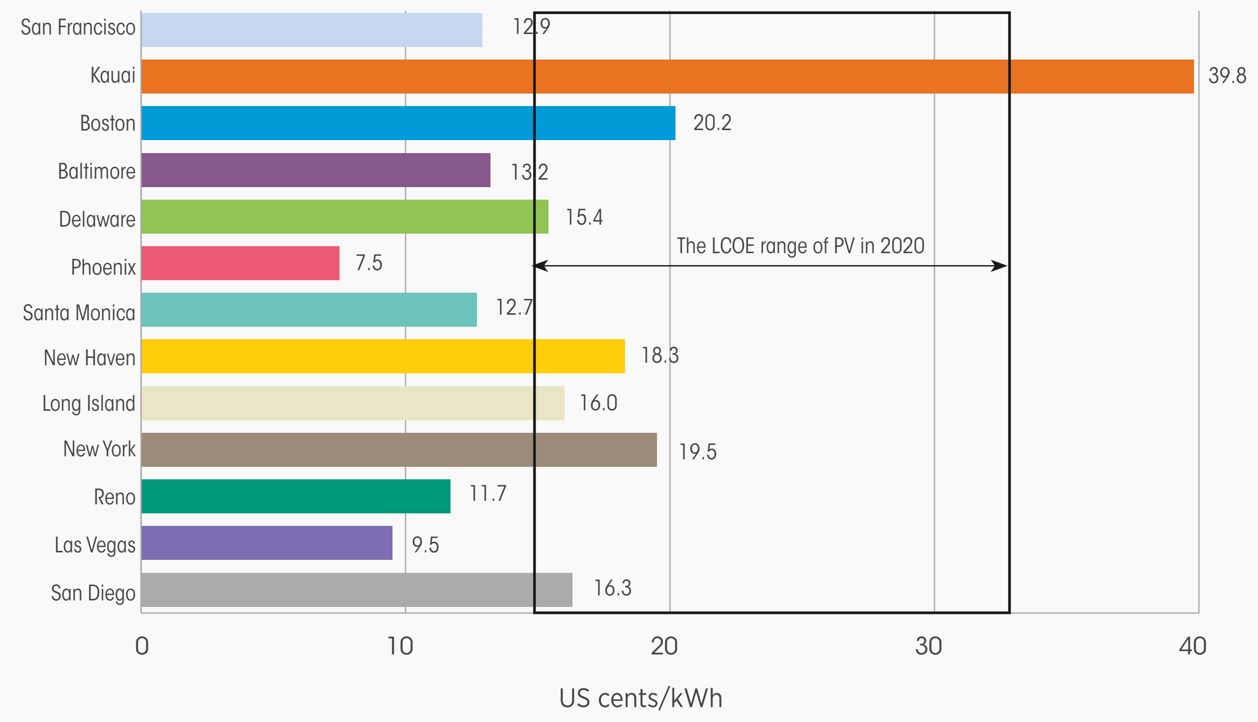


Figure 6.2: Retail electricity prices (2007) and the projected LCOE of PV systems (2020)

Source: Pernick and Wilder, 2008.

6.1 LCOE ESTIMATES FOR 2011 TO 2015

This section analyses the current estimates of the LCOE of utility-scale and residential PV systems for different technologies and looks at the outlook for cost reductions to 2015. The analysis is based on the data presented in the earlier sections, and the main assumptions are summarised in Tables 6.2 and 6.3.

The LCOE of current c-Si residential PV systems without battery storage was estimated to be between USD 0.28 and USD 0.70/kWh in 2010. This is estimated to have declined to between USD 0.25 and USD 0.65/kWh in 2011 with the reduction in c-Si module prices to as low as USD 1.04 to USD 1.34/Wp by the end of 2011. By 2015 it is estimated that the LCOE of these systems could decline to between USD 0.21 and USD 0.49/kWh. This

Table 6.2: Installed cost and efficiency assumptions for residential PV systems, 2010 to 2015

	2010	2011	2015
c-Si PV system			
Installed cost (2010 USD/kW)	3 800 to 5 800	3 070 to 5 000	2 850 to 4 100
Efficiency (%)	14	14	17
C-Si PV system with battery storage			
Installed cost (2010 USD/kW)	5 000 to 6 000	4 000 to 5 000	3 800 to 4 300
Efficiency (%)	14	14	17

Table 6.3: Installed cost and efficiency assumptions for utility-scale PV systems, 2011 to 2015

	2010	2011	2015
Amorphous Si thin film			
Installed cost (2010 USD/kW)	3 600 to 5 000	3 600 to 5 000	2 500 to 3 400
Efficiency (%)	8 to 9		11 to 12
CdTe and CIGS			
Installed cost (2010 USD/kW)	3 600 to 5 000	2 640 to 4 500	2 500 to 3 500
Efficiency (%)	11 to 12	11 to 12	13 to 17

would make the LCOE of PV systems in areas with good solar resource competitive for the residential end-user compared to grid prices in many countries.[20]

When storage is included, the LCOE range of residential PV systems is estimated to be between USD 0.36 and USD 0.71/kWh, although this does not take into account the additional value of the flexibility to supply PV electricity when the sun is not shining. By 2015, the LCOE of these systems could decline to between USD 0.31 and USD 0.52/kWh (Figure 6.3).

Utility-scale systems have lower average costs than residential systems, but the lowest LCOE of utility-scale systems is not significantly lower than the most competitive residential markets. The LCOE of current utility-scale thin-film PV systems was estimated to be between USD 0.26 and USD 0.59/kWh in 2010. The significant drop in PV module prices in 2011 resulted in this range declining to between USD 0.20 and USD 0.52/kWh. By 2015 the LCOE of utility-scale systems could reduce to between USD 0.19 and USD 0.42/kWh.

Figure 6.3: Illustrative LCOE of residential and utility-scale PV systems, 2010 and 2015

Note: Capital costs and efficiency are from Tables 6.2 and 6.3. DC to AC efficiency is assumed to be 77%. Load factors are assumed to be between 15% and 25%, and O&M costs are fixed at USD 6.5/kW/year.

[20] *For instance, average residential prices in Europe are in the region of USD 0.23/kWh.*

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Acronyms

APEC	Asia-Pacific Economic Cooperation
a-Si	Amorphous silicon
BOS	Balance of system
CAPEX	Capital expenditure
CdTe	Cadmium-Telluride
CIF	Cost, insurance and freight
CIGS	Copper-Indium-Gallium-Diselenide
CIS	Copper-Indium-Selenide
CPV	Concentrating PV
c-Si	Crystalline silicon
DCF	Discounted cash flow
DNI	Direct normal irradiance
DSSC	Dye-sensitized solar cells
EU-27	The 27 European Union member countries
FOB	Free-on-board
GHG	Greenhouse gas
GW	Gigawatt
kW	Kilowatt
kWh	kilowatt hour
mc-Si	multi-crystalline silicon
MENA	Middle East and North Africa
MW	Megawatt
MWh	Megawatt hour
LCOE	Levelised cost of energy
O&M	Operating and maintenance
OPEX	Operation and maintenance expenditure
PV	Photovoltaics
R&D	Research and Development
sc-Si	Single crystalline silicon
USD	United States dollar
Wp	Watt peak
WACC	Weighted average cost of capital

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