2012 · VOLUME 2 · NUMBER 4

# GREEN



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ISSN 1869-876X · e-ISSN 1869-8778

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**TYPESETTING** Asco Typesetters, Hong Kong

**PRINTING** Franz X. Stückle Druck und Verlag e.K., Ettenheim

Printed in Germany

**COVER ILLUSTRATION** iStockphoto/Thinkstock

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## Special Issue: Photovoltaics
Edited by Joachim Luther

DOI 10.1515/green-2012-0010 —— Green 2012; 2(4): 127–134

Wim C. Sinke*

# Prepare(d) for Impact: PV Cost Reduction and Beyond

**Abstract:** Photovoltaic solar energy technology (PV) may reach the terawatt deployment scale within a decade. This is enabled by rapid cost reduction through which PV is able to compete with conventional power in an increasing fraction of electricity markets globally. Although further cost reduction is essential for very large scale deployment and requires dedicated research and development efforts, it is not sufficient. Availability of fully sustainable technology and (electrical & physical) integration are other necessary ingredients for multi-terawatt-scale use. This paper quantifies and discusses the development challenges of PV and reviews some of the recent publications addressing the future of PV.

**Keywords:** solar energy, photovoltaics, PV, cost reduction, sustainability, integration, deployment

**PACS® (2010).** 88.05.Hj, 88.05.Lg, 88.05.Np, 88.05.Ec, 88.40.hj, 88.40.hm, 88.40.mp, 88.40

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## 1 Introduction

Photovoltaic solar energy (PV) has demonstrated impressive progress in terms of cost reduction over the past decades and in particular over the past few years. As a result PV can now compete with conventional electricity at retail price levels in an increasing number of countries throughout the world, enabling the establishment of the first major self-sustained markets. Although this is generally considered a very important milestone in the development of PV, it is not yet sufficient for deployment at the multi-terawatt level, which is necessary to have impact on a global scale in terms of $CO_2$ emission reduction, security of supply, air quality, rural access to energy or other important aspects. Therefore further cost reduction is necessary, to enable PV to compete at the levels of wholesale electricity prices or even fuel costs. Such cost reduction will rely on a combination of economies of scale and technology development in all parts of the PV value chain from materials to complete systems. As the global market grows and the technology matures it becomes increasingly clear, however, that cost reduction needs to be considered in the broader context of sustainability and applicability of PV. In other words: very large scale use at low cost will only be possible if materials and components are available in sufficient quantities and at sufficiently low prices and if PV technology is able to serve a wide variety of markets in a competitive and attractive way, to mention just a few aspects. This papers discusses the drivers and enablers for very large scale deployment of PV.

## 2 PV technology: state of the art

### 2.1 Cells and modules

The heart of any PV system is formed by the solar modules, also called panels. They are generally divided into flat-plate and concentrator. In the former, the solar cells in the modules are exposed to natural sunlight, in the latter the cells are exposed to sunlight that is concentrated through lenses and/or mirrors. Flat-plate modules are commercially available in a variety of forms: wafer-based crystalline silicon (c-Si), thin-film silicon (tf-Si), thin-film cadmium telluride (CdTe) and thin-film copper-indium/gallium-diselenide/sulphide and related compounds (CIS, CIGS, CIGSS). Concentrator modules are generally based on multi-junction cells built from gallium-arsenide and related (III-V) compounds, although c-Si cells are also used. The efficiencies of c-Si modules are typically in the range of 12–20%, those of thin-film modules 5–14% [1], while concentrator modules reach values up to ≈30% [2]. More specifically, efficiencies per thin-film PV technology family are: 5–10% for tf-Si, 9–12% for CdTe and 8–14% for CIGS [1]. Note that these ranges correspond to a wide variety of modules, including a few flexible types. The production shares of the different commercial technologies in 2011 were: c-Si 87.9%, tf-Si 3.4%, CdTe 5.5%, CIGS 2.4% and others (including concentrators) 0.8% [3].

In research and in pilot production a wide range of novel and emerging technologies are under development. They can be roughly categorized as options aimed primarily at very low cost, options aimed primarily at very high efficiency and options for new applications or enhanced sustainability. Of course low-cost options also need to be as efficient as possible and high-efficiency options need to become cheap, but early in the development it is often difficult or even impossible to address both aspects with the same weight.

Well-known examples of options aiming at very low cost are 'organic' (dye-sensitized, small-molecule or polymer) solar cells and printed (non-vacuum) versions of commercial thin-film technologies. On a laboratory level device efficiencies of 10 to 11% have been demonstrated for organic cells [4].

Options for very high efficiency – apart from the commercial III–V multi-junction cells – include devices based on intermediate band semiconductors, hot carriers and multi-carrier generation. These options are still in an early stage of development and have not yet demonstrated high device efficiencies [5, 6, 7].

A separate category is formed by spectrum converters [8, 9, 10, 11] ('external efficiency boosters'), aimed at improving the match between the spectral composition of the light and the spectral sensitivity of the solar cell. Rather than optimizing the cell for the light, the light is optimized for the cell in this approach. Converters can shift wavelengths, generate two or more low energy photons from one high energy photon (downconversion) [10, 12] or generate a high energy photon from two or more low energy photons (upconversion) [11], sometimes popularly called 'slicing and dicing' or 'cutting and pasting' of photons [13].

An example of a development aimed at improved sustainability is the replacement of indium by zinc-tin in thin-film solar cells, as in CZTSS (copper-zinc-tin-selenide/sulphide) [14].

A recent development that may potentially be used in all commercial, emerging and novel technologies is that of advanced structures for light management. This concerns nanostructures for very low reflection and light trapping in ultra-thin absorber layers [15]. It has been argued that by applying appropriate structures, the theoretical efficiency limit for single-junction devices operating under 1 sun (direct) illumination intensity may be boosted to the limit so far associated only with concentrator devices (i.e. around 40%) [16].

## 2.2 Systems and applications

PV is a highly modular technology. This is reflected in the range of applications: from consumer and rural applications in the (sub)watt- to kilowatt-range through residential and commercial applications in the kilowatt- to megawatt-range to utility-scale applications in the multi-megawatt- and soon gigawatt-range. Moreover, PV can be used in stand-alone systems and grid-connected systems. Early PV markets were dominated by stand-alone applications but recent markets largely rely on grid-connected applications [17]. While cell- and module performance is usually measured in terms of light-to-electricity conversion efficiency under standard test conditions (STC) to enable comparison between different technologies, system performance is expressed through the so-called system performance ratio (PR). In the case of a grid-connected system the PR is defined as the ratio between (e.g. year-)average system efficiency on the AC-side and the STC module efficiency, thus linking nameplate module efficiency (or rated system power: DC power at STC in watt-peak; Wp) with the annual electricity production of the installed system for a given insolation. Typical PR values range from 75% up to 90%, depending on module type, system design and size, location and some other factors [18].

## 2.3 Economy

Because of their dominance in the market and for the sake of simplicity, here we focus on grid-connected systems. Although the economic strength of PV is determined by many factors, the Levelized Cost of Electricity generation (LCoE) [19, 20, 21] is a useful indicator allowing a first-order assessment of the competitive position. The LCoE ($/kWh) is determined by, among other factors, the initial investment for the turn-key system ($/Wp), the annual cost of capital ($/Wp or $/kWh), the specific annual electricity yield (kWh/Wp) and the operation and maintenance (O&M) costs ($/Wp or $/kWh). For a given turn-key system price and specific electricity yield the LCoE may vary strongly because of differences in cost of capital and O&M costs. Therefore a discussion of different business cases on the basis of LCoE is only useful when explicit information on the underlying calculation parameters is given.

In its simplest form, the often used concept of "grid parity" refers to the situation where the LCoE of PV equals the price of the alternative; usually the retail electricity price. This is called "static grid parity". It is basically a snapshot of the competitive position of PV at a certain moment in time. The usefulness of this simple concept in practical situations relies on the possibility to apply net metering, so that PV generation costs can be compared directly and completely with prices of electricity from the grid. It has been argued that static grid parity is not a useful measure of the competitive position of PV in more realistic and complex situations and therefore not a useful indicator for investment decisions [22]. Therefore the concept of "dynamic grid parity" or "investment parity" has been introduced. In this definition the life-cycle costs of operating a PV system are compared with the revenues generated by the system over the same period. In this way anticipated changes over time of electricity prices can be incorporated in the comparison, but also differences between the value of "self-consumed" solar electricity (directly avoided purchase) and solar electricity sold to the grid can be taken into account.

Turn-key PV system prices until mid 2012 were typically in the range of 2–6 \$/Wp [23, 24], with tails towards (slightly) lower and (significantly) higher prices for very large systems in mature markets and building-integrated systems. System prices in Germany, the biggest market in the world, were in the low end of the indicated range. A price level of 2 \$/Wp translates into an LCoE of less than 0.10 \$/kWh for sunny regions and favorable calculation parameters to more than 0.20 \$/kWh for regions with moderate sunshine and less favorable parameters. This illustrates the statement in the Introduction that PV has now entered the regime where it can compete with retail electricity prices.

## 2.4 Sustainability

PV is *inherently* renewable but *not automatically* sustainable. In other words: very large scale sustainable deployment of PV is associated with several boundary conditions and development challenges related to materials consumption and closing materials cycles (cradle to cradle), environmental impact, and even public acceptance.

The main commercial PV technology of today is based on crystalline silicon. Silicon is an earth-abundant element and therefore there are no fundamental limitations on the supply side. This does not automatically mean that the practical availability of silicon of adequate purity and quality is unlimited, as has been demonstrated clearly in the period 2006–2008, when silicon feedstock supply was short and prices were extremely high due to insufficient production capacity. This became apparent in increased PV module prices [22]. The main materials-related issue in c-Si PV is currently the use of silver for contacts. The direct urgency of the issue is determined by the increase of silver prices by a factor 5 in less than a decade [25], but in the longer term also the absolute availability may become an issue [26]. This has led to a strong trend towards copper-based metallization [27].

For thin-film PV technologies, the issues related to sustainability discussed most frequently are the use of non-earth-abundant elements like indium and tellurium (and germanium) and of toxic elements like cadmium. These issues need to be considered and discussed with great care since the (potential) problems and hazards are strongly dependent on the assumptions made concerning resources, future materials requirements, manufacturing practices, take-back and recycling methods, etc. In fact, thin-film technologies making use of those elements show a very high efficiency (CIGS) or a very low cost (CdTe), which are not easily reproduced using earth-abundant and non-toxic elements only. Moreover, by moving towards ultra-thin devices and by fully closing materials cycles the actual environmental and sustainability profile may be significantly improved. Only a full life-cycle analysis of technologies is able to provide the information needed for a fair assessment of different technology options. Several studies on "critical materials" for energy technologies have been published recently, for instance by the US Department of Energy, the European Commission and the American Physical Society/Materials Research Society [28, 29, 30]. These studies do not yet provide a fully coherent picture and show the importance of "informed action and cooperation between governments, industries and researchers" [31].

Another sustainability aspect of PV systems is the so-called energy pay-back time (EPBT, not to be confused with the economic pay-back time) and the related carbon footprint. As long as PV modules and systems are produced using, at least partially, conventional energy they result in indirect $CO_2$ emissions. For state-of-the-art systems the EPBT under 1700 kWh/($m^2 \cdot a$) insolation conditions is 0.5 to 2 years, which is to be compared with the anticipated lifetime of ≈30 years. The corresponding carbon footprint is then 10 to 50 g $CO_2$-eq/kWh. This is typically an order of magnitude lower than coal-fired power plants equipped with carbon capture and storage [32]. As the contribution of solar energy to the total energy mix increases, the carbon footprint of PV will decrease further and eventually vanish [33]. When solar cells, modules and systems are produced using solar electricity especially generated for that purpose, the carbon footprint of newly built PV systems may be extremely small even when the total energy supply still largely relies on fossil fuels. This is the 'solar breeder' concept [34].

# 3 PV technology: what is needed for impact?

If PV technology is to make a significant contribution to the global energy supply in the longer term and hence, to solving energy-related problems such as climate change, security of supply, air quality and access to energy, very large-scale deployment is necessary. Although the interpretation of "significant contribution" may vary, a typical range could be from 10% of global *electricity* to 25% or more of global primary *energy* (the latter would require storage of electricity on a large scale and possibly conversion of electricity into other energy carriers). Assuming a 5-fold increase of global electricity consumption in the long term, a 10% contribution corresponds to some 6000 GWp (6 TWp) of installed PV capacity [35]. Depending on the assumption of the total global primary energy consumption (e.g. 1.5× to 2× current use), a 25% contribution would roughly correspond to 30 to 50 TWp. The total installed capacity today is ≈0.1 TWp, therefore a growth by two orders of magnitude or even significantly more is required for impact of PV on a global scale. This demonstrates the importance of further development of PV towards a technology that is not only renewable and economically competitive, but also sustainable in the broadest sense of the word.

# 4 Development of PV technology

## 4.1 Cost reduction: 2020 and long term targets

Cost reduction of PV electricity primarily requires reduction of the specific investment for turn-key systems (in $/Wp). In addition, increase of the system lifetime and performance stability, increase of the specific electricity yield (in kWh/(Wp · a)), reduction of O&M costs and costs of repair or replacement of system components and several other factors contribute to reduction of the LCoE. At yet another level, the *value* of generated electricity, which determines the actual competitive position of PV in electricity markets, is influenced by timing and predictability of supply to the grid, sustainability (PV as a low carbon technology) and other factors. This leads to the development of grid-connected systems including storage [36, 37], and methods for forecasting [38]. Storage systems also facilitate a high penetration of PV in electricity grids [39, 40].

Turn-key system costs (or: prices) are composed of module costs and Balance-of-Systems (BoS) costs. The BoS mainly comprises electronic components, cabling, support structures, and, if applicable, electricity storage, optics and sun trackers, and/or site preparation. BoS costs also include labor costs for turn-key installation. BoS costs can be roughly divided into area-related costs, power-related costs and fixed costs. BoS costs represent 50% or more of turn-key system costs for current PV systems [41].

Targets and projections for future PV system prices vary between different studies and tend to become lower with time due to the unexpectedly rapid price reduction in the recent past. For example, the 2007 Strategic Research Agenda (SRA) of the European Photovoltaic Technology Platform [42] mentions a typical (building applied) system price level of 2 €/Wp excluding sales tax for 2020. This level has actually already been reached in 2012, although with very small profit margins along the value chain. In the 2011 update of the SRA [2] the 2020 target value has therefore been decreased to 1.5 €/Wp for a 100 kWp commercial roof system. Utility-scale systems would be available at significantly lower prices (in the range of 1–1.3 €/Wp). These numbers are roughly in correspondence with the targets in the 2011 IEA Solar Energy Perspectives [35]. The SunShot Vision Study of the US Department of Energy published in 2012 sets an even more ambitious 2020 target of 1 $/Wp for utility-scale systems [20], leading to generation costs of 0.05–0.06 $/kWh in sunny regions. This will enable PV to compete with conventional electricity at all price levels in such regions.

The long-term cost potential of PV system prices (including a reasonable margin) is estimated to be well below 1 $/Wp (0.5 €/Wp~0.85 $/Wp) [2, 35]. Reaching such low values will only be possible if there are no serious supply constraints (and related price increases) for essential materials, i.e. active and passive materials in modules and BoS components. On the other hand, if materials prices would go up, this would affect many energy technologies and therefore not necessarily weaken the competitive position of PV.

## 4.2 Challenges for research and technology development

To reduce PV system prices or rather the underlying costs to the indicated levels, cost reductions have to be achieved all along the value chain and for all hardware components [20]. As mentioned in the Introduction, such cost reductions are generally the result of a combination of econo-

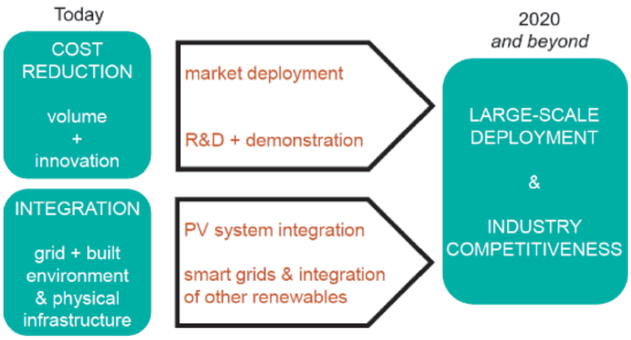


**Fig. 1:** Overall development challenges for very large scale deployment of PV and industry competitiveness (Solar Europe Industry Initiative) [44].

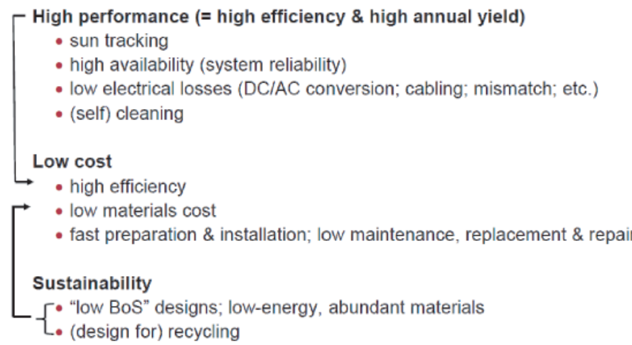


**Fig. 3:** Selected scientific and technological challenges for PV systems.

mies of scale and improvements of technology, in other words: of volume and innovation [43, 44]. This is illustrated in Figure 1, which shows the development challenges for very large scale PV deployment and industry competitiveness, as addressed in the Solar Europe Industry Initiative [44]. In practice, however, these two elements are interlinked. For instance, efficient very large scale manufacturing and installation requires the development of suitable processes and equipment. Simply multiplying solutions for small-scale manufacturing and installation does not give an optimum solution for the large scale. Achieving economies of scale therefore often involves dedicated technology development. In turn, many topics in research and development are not related to improvement of technology in the strict sense (e.g. to higher energy conversion efficiencies), but rather to improvements enabling, or at least compatible with, very high throughput manufacturing and/or installation.

Figure 2 summarizes some important challenges for scientific research and technology development on the level of solar cells and modules, in relation to very large scale deployment. The figure shows the strong relation

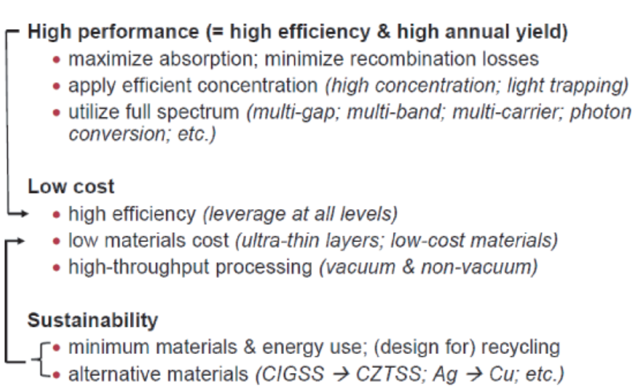


**Fig. 2:** Selected scientific and technological challenges for PV cells & modules.

between performance, cost and sustainability aspects. Assuming all other parameters to be constant, increasing the efficiency or energy yield on cell and module level (more $Wp/m^2$ or $kWh/(m^2 \cdot a)$ is an effective way to reduce costs since it reduces the materials requirements per Wp and increases the throughput of manufacturing equipment in Wp. This is the efficiency leverage effect. Secondly, while minimizing materials consumption and using earth-abundant materials enhances sustainability, it generally also leads to lower cost. As a last example, the efficiency of very thin devices may be higher than that of thick devices, provided they are designed well. This way of minimizing materials consumption may therefore coincide with maximizing performance.

On the system level similar effects of performance and materials consumption can be seen as on the cells and modules level, see Figure 3. It should be noted that the importance of low costs also relates to materials that are used in construction, such as steel, aluminum, plastic, wood and concrete. The high relevance of materials costs follows from the fact that as the cost of PV systems decreases, it becomes increasingly dominated by materials.

Very large scale deployment of PV not only relies on the availability of low cost, sustainable systems, but also on the possibilities for electrical and physical integration: into the electricity grids and into buildings, infrastructures and landscapes. Deployment at the multi-terawatt level, as required for impact on a global scale, implies that the degree of penetration in grids and into the physical environment will be very high. Figure 4 shows some of the related challenges for research and development. These include technical solutions for high grid penetration (such as demand-side management and storage) and application in complex environments (e.g. performance optimization under partial shading conditions) as well as aspects related to public support (aesthetics of PV in the built

**High performance**
- electrical integration: avoid having to switch down or off
- physical integration: optimize system lay-out; select optimum sites

**Low cost**
- electrical integration: concepts & technologies for high penetration
- physical integration: standardisation; prefab; integrated fixtures; click-on/click-off; etc.

**Sustainability**
- electrical integration: optimize energy technology portfolio
- physical integration: low-impact & durable materials; (design for) recycling; low intrusion; good aesthetics

**Fig. 4:** Selected scientific and technological challenges for PV system integration.

environment [45], PV landscape architecture, etc.). As is well known from other energy technologies such as wind energy, carbon capture and storage and shale gas, public support is not to be taken for granted. This demonstrates the importance of PV development "beyond cost reduction".

Table I gives a "looking through the eyelashes" summary of the potential (and related challenges) for performance enhancement, cost reduction and improved sustainability of PV technology. Data compiled and adapted from the references in this paper.

## 5 Towards the ultimate PV technology

Research and technology development worldwide are aimed at reduced cost, enhanced performance, improved sustainability, high grid penetration, and other aspects. A question often asked is whether we need a "breakthrough" to enable terawatt-scale deployment of PV without extensive financial or other incentives. On the one hand, the current commercial technologies still have substantial potential for further cost reduction and performance enhancement. It is expected that advanced versions of those technologies will bring the 2020 targets within reach [2]. On the other hand it is uncertain whether, or even unlikely that they will enable cost reduction to the lowest levels mentioned in paragraph 4.1. This is partly related to the fact that they are not expected to give commercial module efficiencies well beyond 25% (with the exception of concentrator technologies) [35], see Figure 5. Moreover, as discussed, current technologies still have some sustainability-related challenges that may not be addressed by incremental improvements. Therefore, it is important to develop new technologies, sometimes called "disruptive" options. These options, discussed in paragraph 2.1, are mostly high-risk, high-potential and their development may be considered an insurance policy for large-scale deployment of PV. The fact that PV has such a broad portfolio of options is an important strength of the technology. If some options fail, there are always other options left, making the overall development very robust. It is not so much the question *whether* PV will be successful, but rather *in which form(s)*. It is tempting to speculate about the "ultimate" PV technology. Although the definition of "ultimate" is rather straightforward (very low cost, fully sustainable and applicable in all major markets) it is very difficult to translate this definition into an imaginable technology option. Moreover, when that technology appears we will probably not be able to recognize it since it will not be perfect from the start. This shows the importance and logic of continuing the development of a portfolio of options. Research and development are very cheap to society compared to large-scale deployment of a sub-optimal technology.

| | Current | 2020 | Long-term potential (≈ 2050) |
|---|---|---|---|
| Commercial module efficiency flat plate/concentrator (%) | 5~20 / 25~30 | 10~25 / 30~35 | 20~40+ |
| Turn-key system price (flat plate) ($/Wp) | 2~6 | 1~2 | 0.6~1.2 |
| Cost of electricity (LCoE, $/kWh) | 0.10~0.40 | 0.05~0.20 | 0.03~0.12 |
| Energy pay-back time (yrs) | 0.5~2 | 0.5~1 | 0.25~0.5 |
| Installed capacity (TWp) [46, 40] | 0.1 | 0.5~1.5 | 10~50+ |

**Table I:** Simplified overview (typical, rounded numbers) of state the art, mid-term future (2020) and long-term potential of PV technology. Note that ranges correspond to different applications (e.g. buildings and power plants), insolation conditions (high and moderate), country-to-country differences, and other factors.

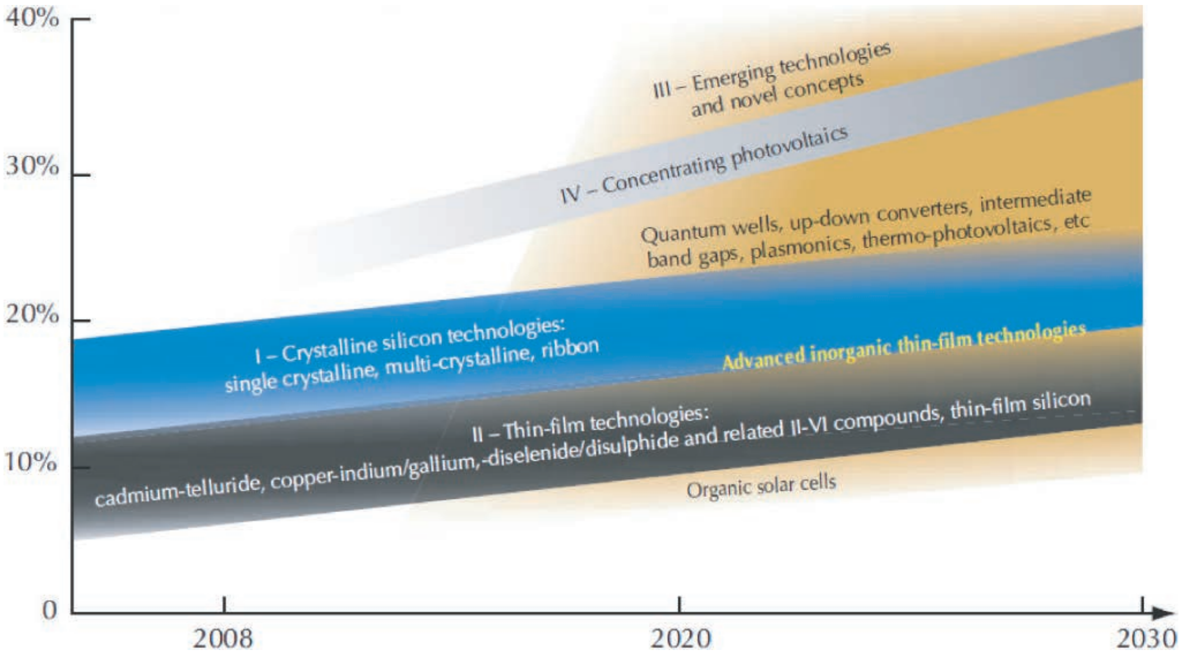


**Fig. 5:** Possible evolution of commercial PV module efficiencies. Figure from: IEA Solar Energy Perspectives [35].

## 6 Conclusions

PV is very well positioned to take a role as mainstream sustainable energy technology. System prices and generation costs have been reduced drastically over the past decades and especially over the past years, enabling competition in retail electricity markets today or in the near future and competition in wholesale electricity markets from 2020 on. The PV technology portfolio in “lab and fab” is well filled, which guarantees a robust development in the short and longer term. Although current technologies may not yet fully qualify for sustainable multi-terawatt-scale use in all aspects, advanced versions of those technologies and new technology options currently under development most likely will. This is assuming that research and technology development are continued or even intensified globally, since the justified statement that “technology is not expected to be the limiting factor in large-scale deployment” is not to be confused with the false statement that “the technology is already available today”.

## Acknowledgements

The author would like to thank members of the European Photovoltaic Technology Platform and the European Photovoltaic Industry Association EPIA for fruitful discussions.

Received: June 23, 2012. Accepted: August 7, 2012.

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