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The multi-terawatt challenge
Preparing photovoltaics for global impact

Photovoltaic solar energy will soon enter the era of self-sustained growth, limited by integration rather than by solar-panel cost. We need to prepare now for truly large-scale deployment.

Wim Sinke

GROUND BASED

ROOFTOPS

GIGAWATT

INCENTIVE

IMPACT

As photovoltaic solar energy technology matures, it gradually moves away from incentivised markets and becomes a competitive option with enormous potential for major commercial markets worldwide. This creates business opportunities beyond imagination, but also brings along new challenges. Realising this potential requires continued cost reduction but not, as is often stated, a technological breakthrough. The technology is already available in a variety of forms that, by further improvements and combination, could yield the necessary cost reduction already. However, the many new options that are under development hold out the promise of a still broader or accelerated deployment of photovoltaics. For photovoltaics to truly flourish, however, more emphasis should be placed on its electrical, physical and societal integration. This would pave the way for photovoltaics to have a large impact on a global scale, making it an important building block for a future sustainable energy system.

In fact, a combination of factors has determined the course of photovoltaic technology from its earliest days. John Perlin, in his book *From Space to Earth*,[1] describes how the modern solar cell became a success in space shortly after its invention. Large-scale terrestrial applications of photovoltaics were also already envisaged in those early days in the 1950s. Terrestrial success failed to materialise, however, because of high prices and a lack of urgency. Without a mass market for the product, prices would remain high – a stalemate that lasted a number of decades. Yet through dedicated stand-alone products, photovoltaics served small, high-value markets such as rural electrification, telecom and recreation. On top of that, there were many demonstration projects, with photovoltaics on rooftops, ground-based power plants and other grid-connected and stand-alone applications. This allowed the sector to grow steadily, build a track record and gain experience. A robust, predictable, but rather slow process.

The development of photovoltaics gained impetus with Germany's '1,000 roofs' programme in 1991, followed by the '100,000 roofs' programme in 1999 and an optimised feed-in tariff system in 2004. This moved the market away from complex stand-alone applications selling only small units in relatively small numbers and with wildly varying support schemes, if any. The German incentive model for grid-connected photovoltaics applications was simple and extremely effective. It created a gigawatt-scale market for a range of system sizes and types. In modified forms it was adapted by several other countries. This helped photovoltaics grow rapidly (see Figure 1).

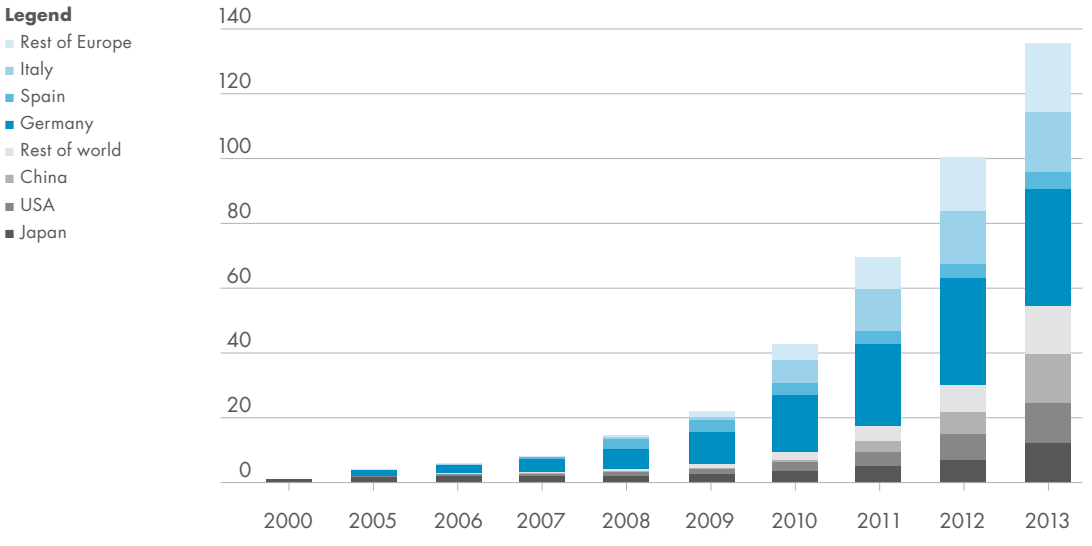


Figure 1: Cumulative photovoltaic installations in GWp (source: Arnulf Jäger-Waldau, EC JRC (2013). *PV Status Report 2013*, Report EUR 26118 EN, EU: Luxembourg).

Today the global market is dominated by residential rooftop systems (typically 1-10 kilowatt-peak[2] (kWp)), larger building-added systems (10 kWp to 1 megawatt-peak (MWp)) and ground-mounted power plants (100 kWp to 1 gigawatt-peak (GWp)).

The success of this large-scale deployment may in turn finally spur the development of stand-alone applications, particularly in cases where this is hampered by high prices. At current and future low price levels, reliable photovoltaic products holding the potential to change rural life are feasible, especially in the many regions of the world where electricity is rare or completely absent.

The development of photovoltaics in the past decade has been driven by incentives that create immediate business opportunities. The incentive schemes themselves, on the other hand, are usually motivated by the promise of real impact in the longer term. Yet there are very different ideas about what is meant by 'impact' and what 'longer term' it will take to have its full effect.

The term 'impact' can be related to total global electricity consumption. If it is loosely defined as a 25% or more share of future consumption, it requires 10 terawatt-peak (TWp) of photovoltaic systems,[3] approximately two orders of magnitude more than the current installed capacity.[4] If 'impact' is measured against total *energy* consumption, an even higher installed capacity would be needed. Such a definition becomes particularly relevant when electricity from photovoltaics is also expected to replace other forms of energy (fuels and heat), for example through power-to-gas, electric vehicles and electric heat pumps. The level of 25% is not meant to suggest that the contribution of photovoltaics should in any way be limited to that. On the contrary, the global potential of photovoltaics is practically unlimited and its role could become much bigger.

And what would the 'long term' be, over which this impact might be realised? Over the past few years photovoltaic solar energy has become increasingly popular, due to cost reductions and price erosion. Although this made margins shrink or even disappear and slowed down global photovoltaics innovation, it has boosted the photovoltaics market, reaching a share of almost 1% of global electricity consumption in 2014. In Germany and Italy, the contribution of photovoltaics now exceeds 5%, double the average of the European Union. The cost of photovoltaic electricity has decreased to a level that competes with retail electricity prices in many countries. In the well-developed market of Germany, generating costs in 2013 averaged between €0.10 and €0.14 ($0.14 and $0.19) per kWh for residential systems and between €0.08 and €0.12 ($0.11 and $0.17) per kWh for large systems, in spite of Germany's modest insolation levels.[5]

This has brought self-sustaining markets closer, a long-cherished dream of the photovoltaic sector and its customers. Sustainably priced turnkey photovoltaic systems with generation costs as low as €0.04 to €0.08 ($0.06 to $0.24) per kWh are projected for 2020,[6] which overlaps with the range of today's commercial electricity prices. Photovoltaics may therefore enter commercial electricity markets sooner than many people have expected. After that, system prices and, consequently, generation costs are expected to further fall to €0.02 ($0.03) per kWh in sunny regions.[7] Solar electricity will then become competitive in a major part of the total global electricity markets, even without carbon pricing. Photovoltaics thus gradually leaves the era of incentive-driven markets and enters the era of self-sustained growth, starting to make significant contributions to the energy system.

Diversifying technology

The development of photovoltaics builds on a broad and still-growing range of technologies. The commercial modules available today are based on silicon wafers, similar to those used in the micro-electronics industry, and on several types of thin film, with efficiencies from 7% to 22% (see Figure 2).

A wide range of new photovoltaics technologies is under development. One category aims at ultra-high efficiencies by using a larger fraction of the solar spectrum and reducing losses as much as possible. The usual approach is to adapt the cell to the solar spectrum. This can be done by combining materials (sub-cells) with different absorption characteristics in tandem or 'multi-junction' designs, but there are several other possibilities. An alternative approach is to adapt the spectrum to the cell, using 'spectrum shapers': materials that convert high-energy photons into two or more low-energy photons or vice versa, to create a better match between the light spectrum and the sensitivity of the solar cell. These are 'efficiency boosters' that could be added to existing solar cells and modules. Nanotechnologies have recently brought new options for design of (synthetic) materials and devices to reach the old goal of full spectrum utilisation with low losses, for example by using quantum dots and nanowires.

MIRRORS

MULTI-JUNCTION

CONCENTRATOR

DIFFUSE

LENSES

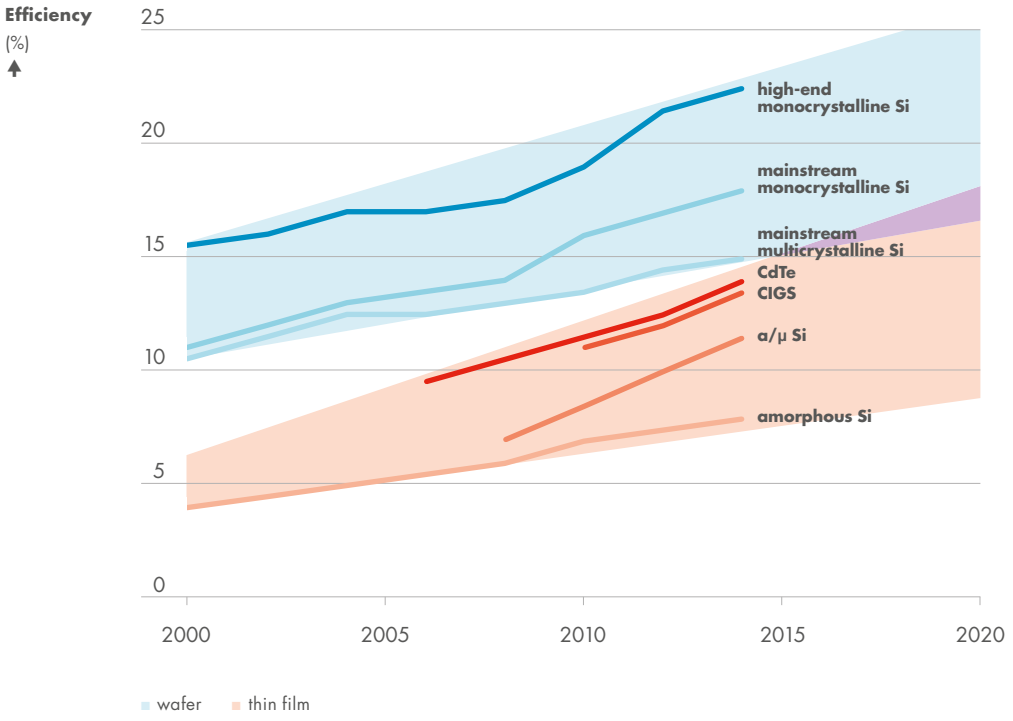


Figure 2: Typical commercial module efficiencies.

Concentration of light by lenses or mirrors is another way to increase efficiency, although not as drastically as by using multi-junction designs. Concentration only works on direct sunlight, not on the diffuse light that is scattered in the atmosphere. This implies that concentrator modules have to track the sun on its daily path. The fraction of diffuse light in the total amount of sunlight ranges from less than 20% in sunny regions to more than 50% in moderate climate regions. In concentrator modules, the active cell area is much smaller than the light-receiving area (which now consists of lenses or mirrors). This allows for the use of more complex and costly cells, such as high-efficiency multi-junction devices. It is therefore not surprising that record-high efficiencies are achieved for concentrator modules, since they combine the benefits of multi-junction cells and light concentration. Current laboratory concentrator cells have efficiencies up to 45% (the world record for photovoltaic conversion), while commercial concentrator modules reach 25-33%.

By applying nanoscale 'photonic' patterns for advanced light management to solar cells, it may be possible to achieve efficiency gains similar to those for light concentration with lenses and mirrors, although probably again at the cost of not being able to utilise diffuse light. Another advantage of light management could be that all sunlight can be absorbed in extremely thin layers of material, using light trapping. This would drastically reduce consumption of expensive active cell materials.

Eventually, conversion efficiencies of 60 to 70% for laboratory cells should be possible, enabling commercial module efficiencies of 40 to 50% or even higher. Today, however, only multi-junction devices operating under concentrated light have demonstrated very high efficiencies (> 40%) in practice. Nevertheless some other approaches will probably reach maturity too, further broadening the range of photovoltaic options. Wafer-based silicon/thin-film hybrid modules, which combine the best of two (commercial) worlds, are now under development as medium-high efficiency candidates for '1 sun' operation.

The second category of technologies under development aims at ultra-low costs or new

applications. Obviously, high efficiency is still desirable, but it is often not yet possible or even not desirable to address both aspects to the same extent at the same time. Cost reduction is primarily a matter of materials and processing. This involves reduction of materials consumption and the use of low-cost materials, as well as the development of very high throughput, preferably non-vacuum processes. Examples include organic solar cells (using polymers or small molecules), printed versions of existing thin-film technologies, and several quantum dot based devices. Recently so-called perovskite-based solar cells have also attracted great interest. These promise to be low-cost, and in laboratories a rapid advance in efficiency has been obtained – to as high as 16% by the end of 2013. Yet the long-term stability of perovskite-based solar cells and modules still needs to be demonstrated. Moreover, current best-performing perovskites are not yet fully sustainable since they contain hazardous elements. These issues need to be addressed when perovskites are considered for very-large-scale use.

Ultra-low-cost technologies need a sufficiently high efficiency to become attractive, as well as large-scale production to demonstrate their cost potential. This represents a serious barrier to market introduction, which may be overcome with speciality markets as stepping stones towards large-scale deployment. Examples include devices with low weight and flexibility, semi-transparency, tuneable colour or freedom of form. If these markets are big enough they may even be the final target market for the technologies involved.

The value of efficiency

Higher efficiencies allow for more photovoltaic power to be installed if the available area is limited. This is the case in densely populated regions and in constructed environments in general. Reaching ambitious targets for the contribution of photovoltaics to the total electricity consumption (for instance 25%) typically requires areas comparable to the total net area available on roofs and façades at current efficiency levels.[8] The potential of photovoltaics in such cases is therefore dependent on the efficiency of commercially available modules and systems.

Building a 'turnkey' photovoltaic system out of modules has costs associated with it. Some of these costs are related to the area needed for a given system power and hence to the efficiency of the modules. This is the case for costs of land or roof preparation, system installation labour, support structures, cabling, etc. Moreover, the costs of operation and maintenance such as land use and module cleaning in dusty regions also are area dependent. Hence the statement dating back to the early days of photovoltaics that very-low-cost modules are only useful if they have a certain minimum efficiency. Even if low-efficiency modules were available for free they would not give low-cost electricity in a system, it was argued. Although this is far too simplistic in view of the wide variety of system types and cost structures, high efficiency is clearly advantageous, as it enables more compact and thus cheaper systems and lower-cost electricity generation, all other parameters assumed constant. This argument can also be reversed: high-efficiency modules may be somewhat more expensive than lower-efficiency modules, since this will be compensated by lower costs to build the complete system.

A similar argument holds at the level of solar cells. More efficient cells allow construction of modules with a higher output power for the same area. In this way the costs associated with module materials can be reduced. Finally, at the deepest level, a higher cell efficiency helps to reduce the amount of cell materials needed and to increase manufacturing throughput, again all other factors assumed constant. Efficiency is therefore the universal lever for cost reduction of photovoltaic: it works at the levels of cells, modules and systems.

Although the cost of (that is, the initial investment in) a photovoltaics system is clearly a very important parameter in the cost of photovoltaic electricity generation, it is not the only one. Cost of capital and the depreciation period chosen, insurance, system lifetime, reliability and stability, cost of operation and maintenance and of replacement of parts and specific output[9] (expressed in kilowatt-hours per year produced per watt-peak system power installed), are all important as well. Differences in cost of capital can lead to the surprising fact that electricity from photovoltaics may be cheaper in cloudy Germany than in sunny Spain.

Photovoltaics is the breakthrough

The broadening range of technologies in research and commercial production makes photovoltaics a robust option for the future. If several technologies fail or have to be rejected for some reason, there are sufficient others left to carry the development further. All the more reassuring is that current technologies



BREAKTHROUGH

LANDSCAPES

HAZARDOUS

FEED-IN TARIFF

CITIES

could already advance photovoltaics to multi-terawatt scale. Halving the cost of today can be reached with ambitious further development and deployment of technologies that are already commercially available. In addition, combinations of such technologies are expected to come into play. Photovoltaics therefore does not need a technological breakthrough to become really big, contrary to what is often believed. Photovoltaics *is* the breakthrough. Yet new technologies can help bring the costs down even further, increasing the efficiency to higher values, broadening the range of applications and thus accelerating photovoltaics deployment. All of this is very welcome in view of the need to fight climate change, secure energy supplies, provide access to energy in rural areas, and more. Novel photovoltaic technologies, even if their development risk is high, are therefore essential. The world can and should afford this modest investment in its energy future.

If a breakthrough is needed, it is in integrating photovoltaics into the energy system. The 5% share in countries like Germany and Italy has been reached without major modifications to the grid system and electricity market (apart from the feed-in tariff). A 5% share of photovoltaics in the total consumption of electricity implies that at noon on a sunny day as much as half of the power produced may come from photovoltaics. The reason is that photovoltaics systems do not operate at peak power continuously. Their average power production is 10-25% of peak power, dependent on the annual amount of sunlight available. There is little reason to doubt that this share can and will be repeated on a global scale, where 5% (requiring 1 TWp) would correspond to 5-10 times the current installed capacity. This level may be reached in the early 2020s.[10] It is expected that beyond this level of penetration new challenges will appear. Several studies show that substantial further growth will first require adaptations of the electricity grid (for example, adding intelligence and storage) and ultimately a transition of the energy system as a whole, including market transformations.[11] Photovoltaics then enters a new phase. Electrical and physical integration as well as societal acceptance will largely determine further growth, as will sustainability and total quality. This will change photovoltaics from a technology-driven development with mostly 'one size fits all' products to an application-driven market, with differentiated products. If growth will be limited by integration rather than cost, it becomes essential to consider the complete set of requirements for large-scale use of photovoltaics and to prepare for the multi-terawatt-scale application expected after 2020.

Triple integration

There is no consensus yet on the strategies and policies needed for further integration of photovoltaics in the energy system to achieve growth into the terawatt regime. The world seems involved in a big experiment in large-scale deployment of photovoltaics, with some countries providing valuable experience and results to many others. Issues related to electrical integration and market integration have received broad attention, especially where the limits of the current system are felt most prominently. We can only be thankful for the lessons learnt from Germany, a leading global laboratory in this respect.

Physical integration into cities, infrastructures and landscapes has so far received much less attention. Yet if photovoltaic technology is going to provide terawatts of electricity, it will be literally everywhere and we have to make sure that people like it. The biggest mistake is to take public and political support for granted. The 'not on my roof' or 'not in my backyard' syndromes need to be and *can* be prevented. A unique property and valuable asset of photovoltaics is that it can be applied in an aesthetically pleasing way as building-integrated photovoltaic (BIPV) systems and infrastructure-integrated (I^2PV) systems, or as ground-mounted power plants using landscape architecture. Well-integrated systems should not be considered a costly niche, but a necessary building block for very-large-scale use and a requirement for societal acceptance. It is not rocket science to develop the products and approaches needed, but it is not trivial either, especially since flexibility and versatility of use have to be combined with standardisation and sufficiently low cost. Possibly some of the new technology options discussed before fit well here.

In summary, a key notion is that a very-large-scale deployment of photovoltaics will rely on more than low cost alone. Such a deployment is only possible if systems can be integrated into the energy system, into the physical environment and into markets and society. This is the 'triple integration challenge'.

Follow the sun?

Large-scale deployment of photovoltaics on a global scale should perhaps start with the question where all

these systems can best be placed. The German success is remarkable, considering the country's moderate levels of insolation. Shouldn't photovoltaics be installed in sunnier regions, as some argue? Indeed, a photovoltaic unit can deliver two to three times more energy in sunny countries. The centre of gravity of photovoltaics deployment will therefore no doubt move gradually from the moderate regions where markets kick-started its development in the past decade to more sun-blessed regions, although not necessarily only the 'sunbelt'. In these regions, economic growth and increasing electricity consumption will necessitate new generating capacity, which can be partly filled in with photovoltaics. Photovoltaics is attractive for these regions due to its relatively low and still decreasing costs and sustainable nature. Moreover, large-scale roll-out can build a new economic sector, creating jobs and generating welfare and wellbeing. In a somewhat different form, these are also drivers of the recent ambitious photovoltaic deployment in the USA and China.

It is unlikely, however, that all photovoltaic installations will be constructed in the world's sunbelt. Large-scale deployment in arid regions has its technical and economic challenges. Operation and maintenance costs of photovoltaics may become very significant when frequent cleaning and other forms of maintenance are needed. High levels of insolation are therefore not enough to ensure low generation costs.

For that matter, relying on sunny regions is in fact undesirable. Such a concentration would leave the attractive photovoltaic potential of moderate regions unused. Moreover, with generating costs between €0.02 ($0.03) and €0.05 ($0.07) per kWh, the cost of long-distance transport becomes significant, apart from the fact that a whole new transnational infrastructure would be needed. Generation close to the consumer therefore has big advantages.[12] On top of that, distant generation would lead to a new form of energy dependence.

'Desert photovoltaics' may well become an important part of the global market, but global photovoltaic deployment will be diverse, with regional use and export from countries with high insolation. Export will not always necessitate cables. In the longer term, solar energy may be used for fuel production, with power-to-gas, power-to-liquid and perhaps even direct solar fuels.

Sustainability

Integration of photovoltaics into society requires a vision that is expansive both in space and time. A view on spatial planning is required, as discussed above, but also a vision about the production and replacement of photovoltaic panels once they are deployed at scale. Photovoltaics are inherently renewable, but this does not make them automatically fully sustainable. Although the amount of energy used in production was a major issue in the early days of photovoltaics, this is no longer the case. The energy consumption expressed as the system's energy payback time has come down as a natural consequence of technological improvements and cost reductions. It now typically stands at 1-2 years of a system lifetime of 25 to 30 years,[13] and this continues to be reduced. The payback time of future systems may be as low as 0.5 years or less. If photovoltaic systems are produced using solar energy in a so-called solar breeder,[14] the energy payback time will no longer be a sustainability issue.

A more pressing sustainability issue is therefore the use of materials. Major studies over the past few years[15] have emphasised the importance of choice of materials in the development of improved and new energy technologies, including photovoltaics. Strategic considerations related to long-term availability, but also prices on the actual market may steer developments, as is the case for the use of silver as a contact material in silicon photovoltaic cells. The combination of increased silver prices and reduced overall module production costs has turned silver usage into a significant cost component, driving the development of alternatives, mainly in the form of copper-based metallisation techniques. Since availability and price of critical materials present a risk factor, the photovoltaic sector also embraces hedging strategies. A prominent example is the development of zinc-tin as an alternative to indium in specific thin-film solar modules. This alternative is still technically immature and has much lower levels of efficiency, but that is why development has started early. Commercial technologies are not created overnight.

Taking sustainability a step further, it is important to start considering 'design for recycling' as another aspect of 'design for sustainability'. Photovoltaic modules are currently designed to 'last forever' and are therefore difficult to take apart and recycle. It is still an open question whether it is possible to ease recycling without sacrificing quality and lifetime. It



DURABLE

COST REDUCTION

DESERTS

also remains to be seen whether it is preferable – from a sustainability point of view – to aim to reclaim valuable and toxic materials or to avoid their use entirely. The establishment of the PV CYCLE organisation[16] was an important initiative in the context of recycling of commercial photovoltaic modules. Since sustainability is a necessary requirement for very-large-scale use, it may be considered the third major driver photovoltaic technology development, next to cost reduction and performance enhancement.

Quality

Eventually, private and professional users will determine the future of photovoltaics. Newspaper headlines about quality issues, such as those we saw in 2013 when global overproduction was at its peak and module prices reached a minimum, do the photovoltaic sector no good, even if these problems are far from representative of the photovoltaic product portfolio as a whole. They also demonstrate that it is not trivial to make a product that operates reliably for decades and is very cheap at the same time. Users and potential users are uncertain about quality and confused by the different certificates, labels and warranties they find. The crucial difference between high technical quality, high efficiency, and high energy yield is usually only clear to insiders. For instance, high-efficiency modules can be poorly manufactured and hence rapidly degrade or fail, while low-efficiency modules can be highly reliable and durable. The photovoltaic sector works hard to improve transparency, independence and coherence, but there is still much to be done. Further explicit product differentiation and corresponding labelling may also help users to make the best choice for their application. Deserts are very different from roofs in north-western Europe. Terawatt-scale use of photovoltaics requires quality control and assurance at all levels.

Continued cost reduction and sustainable pricing will help the global photovoltaic sector enter the terawatt age within a decade. This brings the inspiring and challenging perspective of a self-propelling market, no longer limited in growth by prices. Yet to sustain this dynamic, it is crucial to address *all* challenges in a timely manner. The next potentially limiting factors should by then already have been addressed in a joint effort of industry, research and other stakeholders.

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1. J. Perlin (1999). *From space to earth: The story of solar electricity*, Earthscan: London. See also Perlin (2013). *Let it shine: The 6,000-year story of solar energy*, New World Library: Novato, CA.
2. The power of photovoltaic cells, modules and systems is expressed in terms of watt-peak (Wp), i.e. the power produced at full sun (1,000 watt/m^2 intensity). Note that the total amount of sunlight received per year varies significantly per region of the world, whereas the maximum intensity of sunlight does not: it is approximately 1,000 watt/m^2 ('1 sun') everywhere.
3. Assuming an average capacity factor of photovoltaic systems of 15-20%, 1 gigawatt-peak (GWp) of photovoltaic systems will produce ≈1.5 terawatt-hours per year and it takes 12 terawatt-peak (TWp) of installed photovoltaic capacity to generate an amount of electricity equal to current demand (18,400 terawatt-hours in 2011: IEA 2013). Assuming a growth in electricity consumption by a factor of 2 to 4 or even more in the long term we would thus typically need 10 TWp to cover 25% of (future) demand. This back-of-the-envelope calculation does not consider losses related to transport and storage.
4. In 2013 cumulated capacity reached 135 GWp. IEA PVPS Report T1-22:2013 (2013). *A snapshot of global PV 1992-2012*, IEA-PVPS: Paris.
5. See, for instance, C. Kost et al. (November 2013). *Levelized cost of electricity renewable energy technologies*, Fraunhofer Institute for Solar Energy Systems: Freiburg.
6. This is based on a price of €0.8 ($1) per Wp with costs of capital in a reasonable range; the upper and lower limits are determined by insolation. See, for instance, European Commission, *Solar Europe Industry Initiative,* see www.eupvplatform.org and setis.ec.europa.eu and US Department of Energy, *SunShot Initiative,* www1.eere.energy.gov/solar/sunshot. System prices at or below €1 per Wp have been reached in selected cases in 2012 and 2013 already, but not at sustainable margins and not on average.
7. This corresponds to €0.40 ($0.60) per Wp. See IIASA, Vienna (2012). *Global Energy Assessment – Towards a Sustainable Future*, Chapter 11: Renewables, www.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/Home-GEA.en.html and recent cost studies.
8. Taking the example of the Netherlands and estimating the area available on roofs at 300 km^2, there is room for 40-60 GWp of PV systems at current efficiency levels, if *all* the area can be used effectively (which is probably a theoretical case). These systems would generate 30-50 TWh, i.e. 25-40% of 2012 electricity consumption (and a smaller fraction of total energy).
9. The specific output (kWh/Wp/year) is primarily determined by the amount of sunlight available (the insolation), but also, to a lesser extent, to the photovoltaic module technology used, the system design and other factors.
10. A. Gerlach and Ch. Breyer (2012). *Global grid parity dynamics on a national and regional level*, 27th European Photovoltaic Solar Energy Conference, 4467-4492.
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13. See M.J. de Wild-Scholten, various publications on www.smartgreenscans.nl/publications.html.
14. See, for instance, www.nytimes.com/1982/02/28/business/other-business-a-solar-factory-to-make-solar-cells.html.
15. US Department of Energy (2011). *Critical materials strategy,* Nova Science Publishers, Inc.: New York; R.L. Moss, E. Tzimas, H. Kara, P. Willis & J. Kooroshy, Joint Research Centre of the European Commission (2011). *Critical metals in strategic energy technologies*, Report EUR 24884 EN, EU: Luxembourg; American Physical Society and Materials Research Society (2011). *Energy critical elements: Securing materials for emerging technologies,* APS: Washington, DC.
16. PV CYCLE (www.pvcycle.org) "as the leading take-back and recycling scheme in Europe, offers waste treatment and WEEE compliance solutions for all commercially available photovoltaic (PV) technologies" (text taken from the website).

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