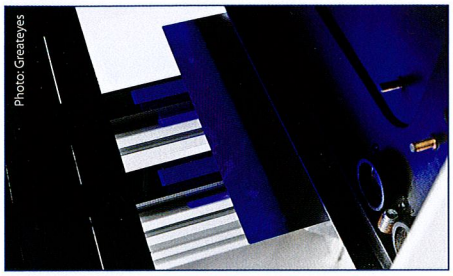
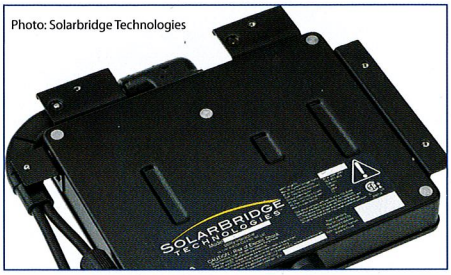
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Photo: Solarize


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pv magazine

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29 GW - New power plant capacity needed by 2021

Turkey aims to generate **30%** of its energy from **renewable** energy sources by 2023

9 GW PV pipeline

Electricity prices *on average have* **increased**

75 *million* inhabitants

6.7% Yearly economic **growth**

Turkey is identified as the country with the ***highest solar potential*** in Europe

See page 44

Graphic: Stefan Lochmann



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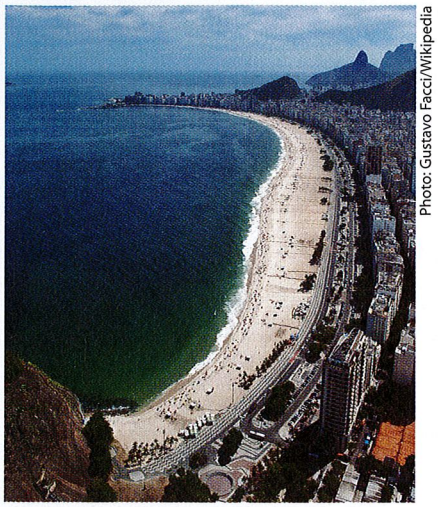


Photo: Gustavo Facci/Wikipedia

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Photo: Berger Lichttechnik

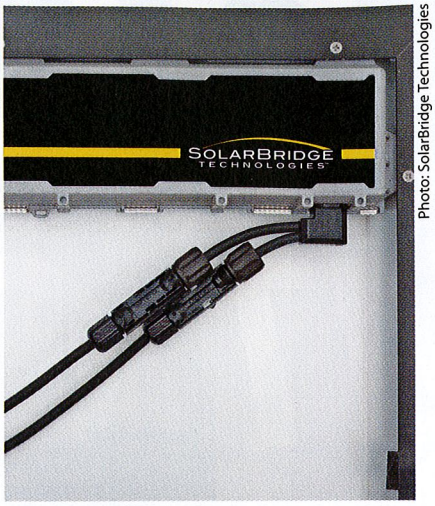


Photo: SolarBridge Technologies

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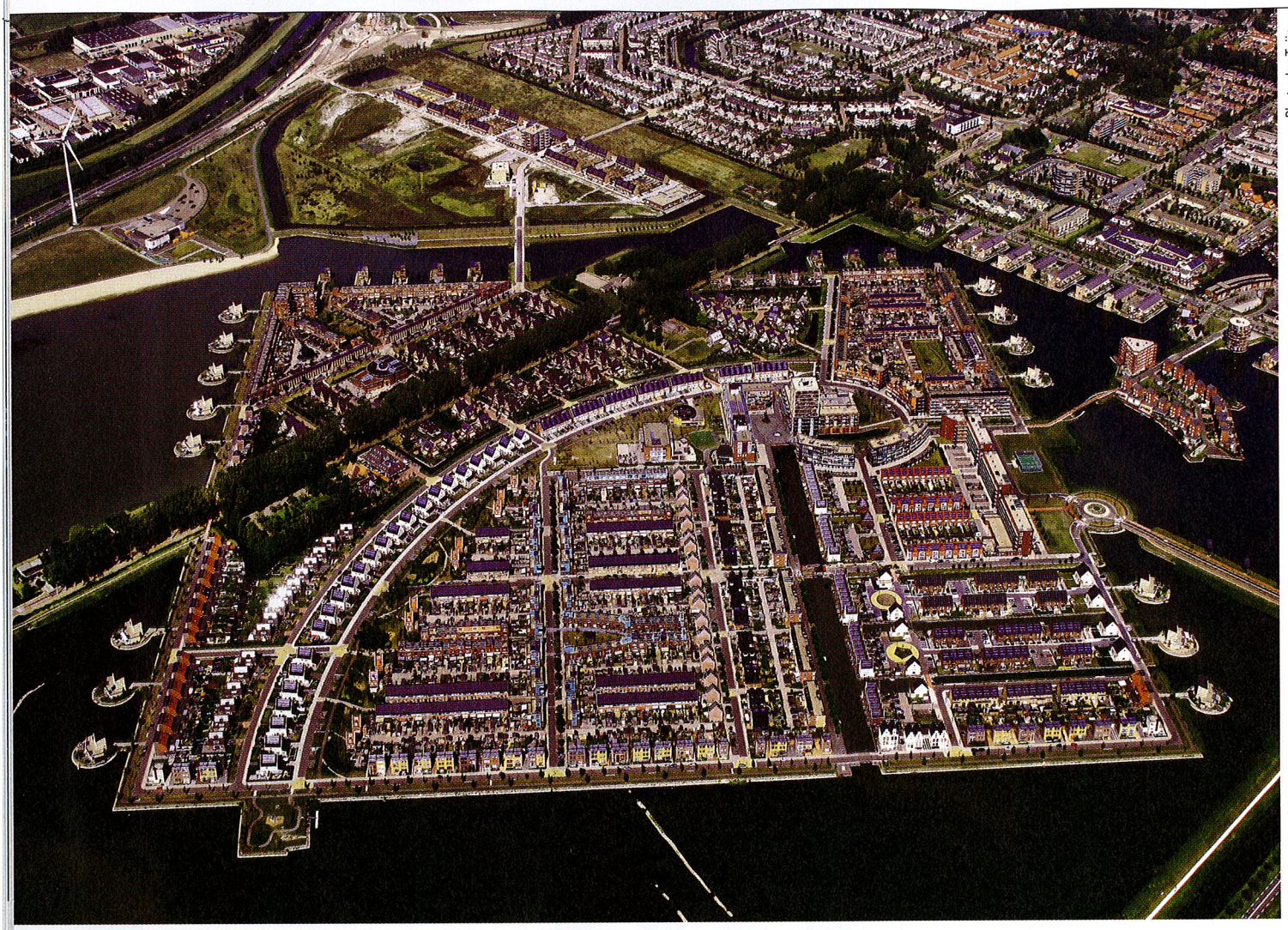


Photo: Jan Tuijp

Urban area with a high penetration of PV: City of the Sun, Municipality of Heerhugowaard, The Netherlands.

Photovoltaics: beyond cost reduction

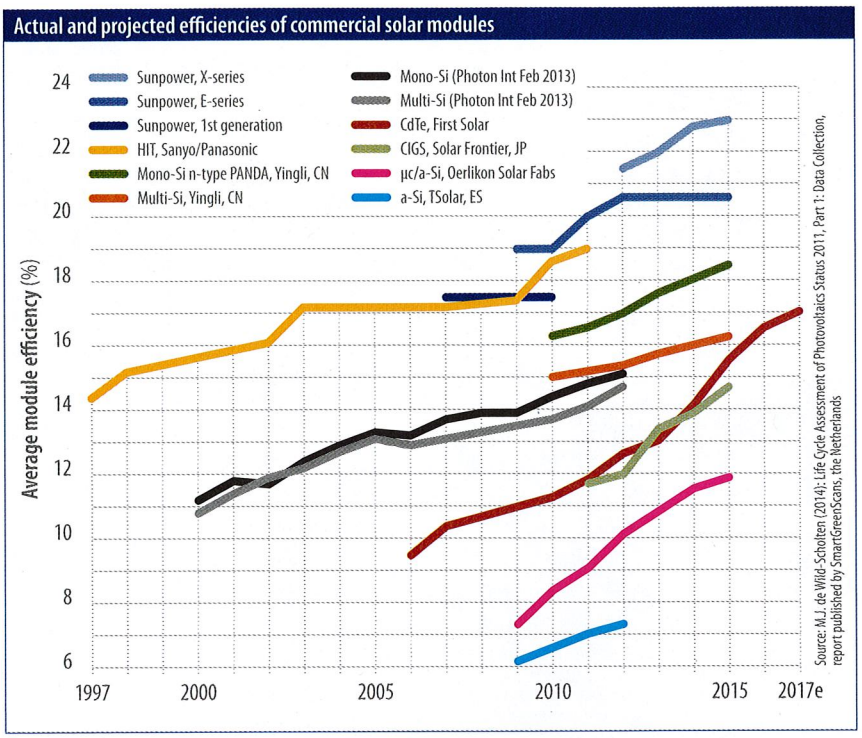
Cost reduction: Photovoltaics may become a terawatt-scale renewable energy technology within a decade. To get to that level and be able to grow further, low cost alone is not sufficient. It is necessary to address other growth factors in time, argues Wim Sinke.

Over the past few years PV solar energy has attracted broad international attention because of drastic cost reduction and price erosion across the board. Although the latter has caused margins to shrink (or even disappear altogether) and slowed down global PV innovation, it has also had the positive effect of bringing self-sustained markets closer. This is something the PV sector and its customers have worked on and looked forward to for decades. PV system prices and, related to that, generation costs have decreased to values that allow competition with retail electricity prices in many different countries.

Moreover, the wider perspectives for further cost and price reductions are such that PV may enter commercial electricity markets sooner than many people have anticipated, even taking into account the pressing need for restored profit margins. As PV gradually leaves the era roughly characterized by technology-driven developments, mostly "one size fits all" products; incentive-driven markets; small contributions to the energy system, and growth limited by cost, it enters the era where developments are largely application-driven; products are more differentiated; markets are increasingly self-sustained within a suitable framework; contributions to the energy system are

KEY POINTS

- Terawatt-scale photovoltaics is a distinct possibility within a decade, provided high efficiency and low cost work hand in hand.
- Achieving the required high efficiency in a truly commercial sense is an important initial hurdle to overcome, with numerous technologies in the running.
- Lower material and processing costs are equally important, with advanced cell technology driving cost reduction.
- Other important aspects, such as the value of efficiency, the importance of sustainability, and the consistence of quality will play their part too in the shift towards terawatt-scale.



Actual and projected efficiencies of commercial solar modules. Source: M.J. de Wild-Scholten (2014): Life Cycle Assessment of Photovoltaics Status 2011, Part 1: Data Collection, report published by SmartGreenScans, the Netherlands.

significant or even huge, and growth is limited by integration rather than merely cost.

Therefore, it becomes essential to consider the complete set of requirements for very large-scale use of PV and to prepare for the terawatt-scale application expected after 2020: not just low cost, but also electrical, physical and societal integration, the question of sustainability, overall quality, and more.

Well stocked tech toolbox

Large-scale application of PV is only possible if suitable PV conversion technologies are available. The PV module, or more generally the PV electricity generating unit, remains the beating heart of any system, even if other aspects of deployment become increasingly important as the sector progresses. Hence, it is useful to look at what we have and what may still be to come.

Commercial technologies

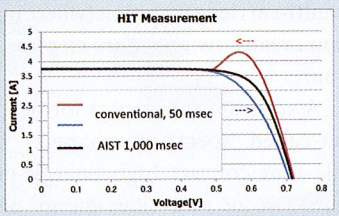
The development of PV is robust because it is based on a broad evolving portfolio of technologies and application options. This diversification of technologies means that if several options fail, there are always sufficient others left to carry overall development further.

Commercial modules are available as a variety of wafer-based silicon and thin film technologies. For the sake of clarity they may be categorized as technology families, for instance: multicrystalline silicon, monocrystalline silicon (p-type and n-type, front & rear contact and rear contact, homojunction and heterojunction), thin film silicon,

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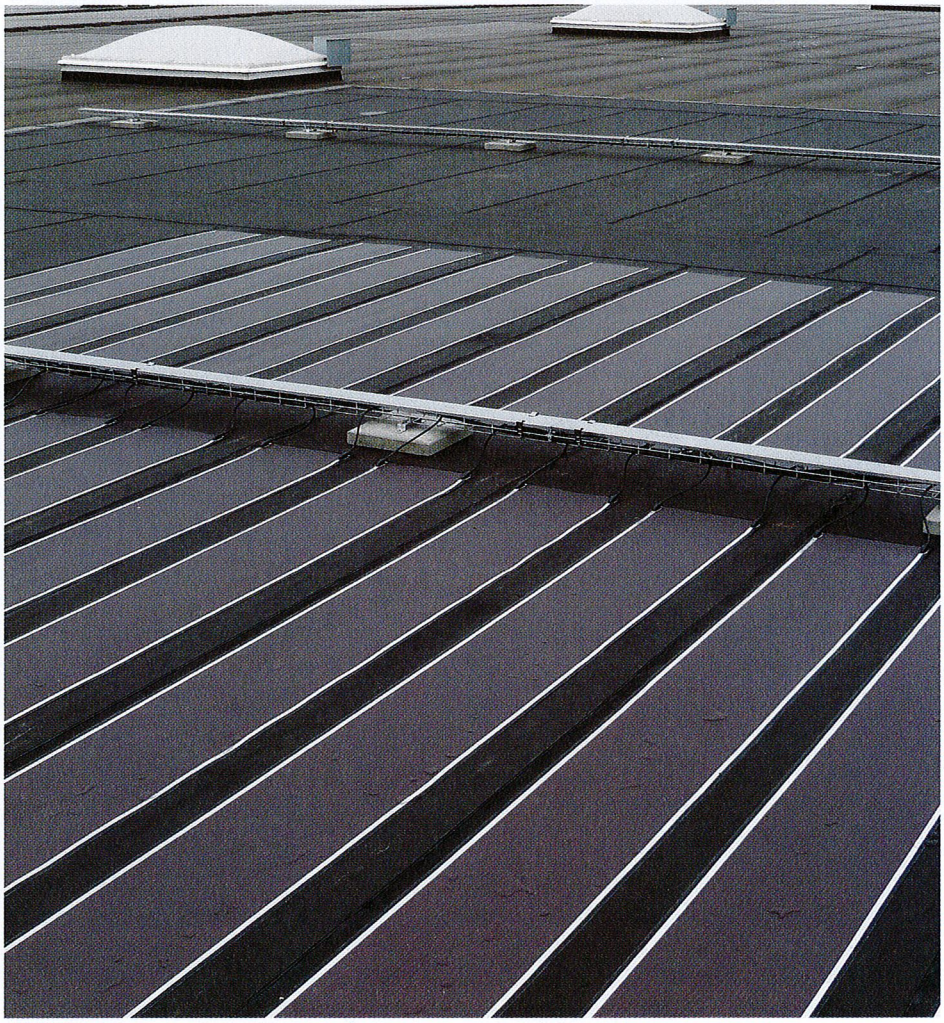


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Photo: HyET Solar



Application of flexible thin film silicon solar foils in use on a rooftop installation.

thin film cadmium telluride (CdTe), and thin film copper indium gallium (di)selenide (CIGS). Flat-plate (i.e. non-concentrating) module efficiencies range from approximately 7 to 22%, as can be seen in the graph (see p. 27). In addition to flat-plate module technologies, several concentrator technologies have also begun to enter the market.

Novel and emerging technologies

In laboratories worldwide and in pilot production, a wide range of new options are under development. Although this represents a severe simplification, it is useful to distinguish options primarily (or at least initially) aimed at ultra-high efficiencies, and options aimed at establishing an ultra-low cost solution. Obviously, the ideal scenario is to combine high efficiency with low cost, but at an early stage of development it is often not yet possible or even desirable to address both aspects to the same extent.

High efficiency: Obtaining very high efficiencies requires using a large fraction of solar spectrum and reducing losses as close to their fundamental limits as possible. High efficiency options include multi-junction devices (using two or more materials with different spectral sensitivities) as already used in concentrator modules, intermediate band semiconductors (comprising single materials with light absorption properties that "mimic" a combination of materials with different absorption properties), hot carrier devices (enabling the use of the excess energy of energetic photons, which in most circumstances is normally lost), multi-carrier generation (where one photon creates two or more electrons), and more.

A separate category is formed by the so-called spectrum shapers: materials that convert high energy photons into two or more low energy photons, and vice versa, to create a better match between the light spectrum and the sensitivity of the solar cell. They are "external efficiency boosters" that could – in principle at least – be added to existing solar cells and modules. Nanotechnologies have brought a wide range of new options to reach the old goals of full spectrum utilization and low losses. Many of the new high efficiency concepts, therefore, rely on the use of nanostructures, including quantum dots and nanowires. A related recent development concerns advanced light management. Concentration of light by lenses or mirrors is a well-known and effective way to increase efficiency, although this process occurs at the expense of not being able to make use of the diffuse part of sunlight. By using nanopatterns for light management, however, it may be possible to achieve similar efficiency gains.

Although none of the options mentioned have demonstrated a very high or even improved efficiency yet (with the notable exception of multi-junction devices), it is likely that one or more will develop into high efficiency technologies in the longer term, further broadening the portfolio of PV options. Perhaps the first market-ready option in this category will be the wafer-based silicon/thin film hybrid, combining the best of the two (currently commercial) worlds.

A further category is low cost and new application possibilities: To drastically reduce the cost of PV cells and modules, it is essential to reduce both materials costs and processing costs. This can be done at a given efficiency, but also by increasing efficiency (linking this category with the high efficiency category previously mentioned). In focusing on the former, reducing materials costs implies reducing materials consumption or using lower cost materials. Reducing processing costs often involves the use of very high throughput and non-vacuum processes. A typical example is the development of organic solar cells, such as polymer and small molecule-based devices.

However, printed versions of existing thin film technologies also fall into this category, as do several quantum dot-based device concepts. Moreover, recently so-called Perovskite-based solar cells have attracted great interest. These types of cells combine low cost potential with an exceptionally rapid laboratory efficiency increase to 16%, as witnessed in lab tests at the end of 2013. It is important to note that for the technologies mentioned in this category to actually demonstrate low cost, they need to be produced at a sufficiently large scale

and with a sufficiently high efficiency. This represents a serious barrier to market introduction of novel technologies because initially neither large scale nor mature efficiency is generally available. One way to overcome this problem may be to use niche applications as stepping stones towards large-scale deployment. Such applications should rely on unique properties of the novel technologies concerned, and have sufficient market size to facilitate up-scaling of production and fine-tuning of the technology. Examples are market segments where low weight and flexibility – exemplified by flexible thin film silicon solar foils (see image, p. 28), semi-transparency, color, or freedom of form is essential. If these segments are big enough they may even be the final market target for the technologies involved.

Considering cost and performance projections, advanced versions of PV technologies basically available today could, in theory, serve PV applications at terawatt-scale. This is to contradict the oft-heard statement that we need a breakthrough in technology for PV in order for the sector to become really big. PV does not need a breakthrough – PV itself is the breakthrough.

Novel technologies, however, can help in broadening PV application possibilities, accelerate PV deployment and make it even more competitive in the longer term. Since the world should reduce CO_2 emissions as soon as possible and at an affordable cost, any option that can support this process should be warmly welcomed. Novel PV technologies, therefore, even if their development is high risk, are considered especially important in this regard.

The value of efficiency

A well-known statement dating back to the early days of PV is that very low cost modules (in terms of $/watt peak) are only useful if they have a certain minimum efficiency. This is because otherwise the area-related (balance of) system costs become too high to allow low-cost electricity generation. This statement can be reworded thus: "Even if low efficiency modules were available for free they would not give low cost electricity." Although this statement is overly simple and does not do justice to the wide variety of system types and cost structures available, one can nonetheless tweak it slightly and turn it into a more positive statement: Module efficiency generally has clear added value at the system level, and efficient modules yield compact, and thus cheaper, systems (in $/Wp).

This also implies that more efficient modules can compete at a higher price if the comparison is done at the system level. A comparison in terms of generation costs instead of initial investment requires additional knowledge of the specific electricity production under practical operating conditions (e.g. kWh/Wp per year), stability and the lifetime of the technology considered. These numbers are not available as readily as efficiency under standard test conditions (used in module power rating) and warranty time frames, but there is a clear trend to move away from just module nameplate rating to compare technologies and products.

A value of efficiency not related to the economy of PV systems is that higher efficiencies allow for more PV power to be installed if area is limited. This is the case in densely populated countries and regions and in the built environment in general.

For instance, reaching ambitious targets for the contribution of PV to the total electricity system (i.e., well above 10%) typically requires areas comparable to the total net area readily available on roofs and facades at current efficiency levels (as displayed at the City of the Sun in the Netherlands, see image p. 26). The application potential of PV in such cases is, therefore, dependent on the efficiency of commercially available modules and systems.

Triple integration

Large-scale deployment of PV is only possible if systems can be integrated into the energy system, into the physical environment, and into markets and society – the so-called "triple integration challenge." Electrical integration and market integration already receive the broad attention of stakeholders, mostly driven by the challenges faced in countries exploring the frontiers (and facing up to the limits) of the current system. There is no consensus yet on the strategies and policies needed to accelerate or merely to enable a transition to a sustainable energy system. The world appears to be involved in a grand experiment, with some countries providing valuable experiences and results to many others. For example, in PV, we can only be thankful to the contributions from Germany, who are a globally leading laboratory in this respect.

An aspect of integration that does not yet receive the attention it may deserve is physical integration into our cities, our infrastructures and our landscapes. If PV is going to play a major role in the future energy system, it will be literally everywhere and we have to make sure that peo-

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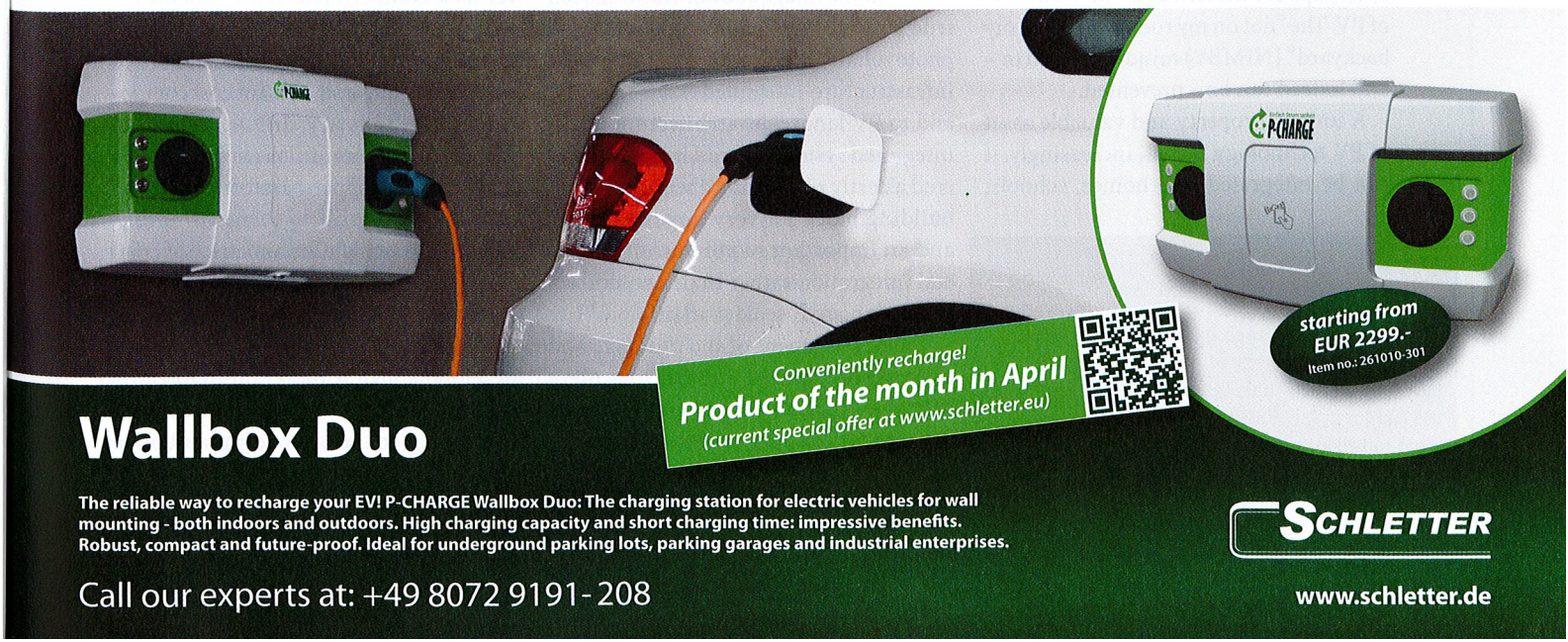


Photo: ECN Solar Energy



Combining high efficiency with aesthetic quality: ECN's "Black Beauty" module is based on rear-contact (metal wrap through) silicon cells.

ple like it. The biggest mistake that can be made in this respect is to take public and political support for granted. Without such support there will be no terawatts of PV. The "not on my roof" or "not in my backyard" (NIMBY) mind-sets need to – and indeed can be – prevented.

A unique property and valuable asset of PV technology is that, increasingly, it can be integrated into homes, schools, offices, hospitals and the general landscape in aesthetically pleasing ways (as ECN's "Black Beauty" module demonstrates in the image above). This is indeed true for well-known building-integrated photovoltaic (BIPV) systems, but also for infrastructure-integrated (I2PV) systems and to PV landscape architecture. Well-integrated systems should not be considered a costly niche but rather a necessary building block for very large-scale use, and an important requirement for societal integration rather than a secondary add-on or small-scale market.

The development of the products and approaches required in order to achieve this is not rocket science, but then again it is also far from trivial, especially since flexibility and versatility have to be combined with standardization and the growing need to be sufficiently low cost. Possibly some of the novel and emerging technology options discussed earlier in this article also fit well here. It all starts, however, with the notion that very large-scale deployment of PV systems relies on more than low cost alone.

ACKNOWLEDGEMENTS

The author would like to thank his colleagues at ECN, AMOLF, University of Amsterdam and the European Photovoltaic Technology Platform for the fruitful discussions that helped shape the ideas raised in this article.

Sustainability

The world of PV is inherently renewable, but not automatically fully sustainable. Since today's environmentally aware populace deems sustainability to be a necessary requirement for very large-scale use, it may be considered the third major driver for technology development, just after cost reduction and performance enhancement. Therefore, PV systems should most certainly be "designed for sustainability."

The entire spectrum of sustainability covers many aspects, ranging from attitudes and behaviors to technologies and political will, but so far – for PV at least – the majority of attention is given to materials and energy use.

Several major studies on the impact of certain materials have been published over the past few years (e.g. US Department of Energy, Joint Research Centre of the EC, and American Physical Society / Materials Research Society). They do not all agree in their detailed conclusions, but each emphasizes the importance of choice of materials in the development of improved and new energy technologies, including PV.

Apart from strategic considerations related to long-term availability and prices, actual market factors may also steer developments within the realm of sustainability.

An example concerns the use of silver as a contact material in silicon PV cells. The combination of increased silver prices and reduced cell costs has turned silver usage into a significant cost component for the industry, driving the necessary developments of alternatives, mainly in the form of copper-based metallization schemes.

Since the availability and price of critical materials presents a risk factor, the PV sector has also embraced hedging strategies. A prominent example of this is the development of a more affordable and sustainable alternative to indium in CIGS technology, in the form of zinc and tin in CZTS technology. This replacement cur-

rently represents a major step back in terms of efficiency and technology maturity, but it is important to develop an alternative in time. Commercial technologies are not made overnight.

Taking the concept of sustainability a step further, it is important to start considering "design for recycling" as another aspect of "design for sustainability."

Whether recycling would have to be aimed at reclaiming valuable materials or simply avoiding a large and growing amount of end-of-life waste remains to be seen. The establishment and continued growth of the PV CYCLE organization (a pan-European PV recycling and take-back organization with representation in many countries across Europe) has been an important initiative in this context, but inherent difficulties arise from having to work with technologies that are not designed, for the most part at least, to be recycled.

PV modules by their very nature are designed to "last forever" and hence are rather difficult to take apart in preparation for the recycling process. The challenge facing the industry, therefore, is to maintain the quality, performance and lifetime of the products, while easing and simplifying the recycling process. It remains to be seen whether that will prove possible and useful from a life cycle analysis point of view.

Quality

Terawatt-scale use of PV requires quality control and assurance at all levels. Negative newspaper reports about quality issues (such as those published in numerous countries in 2013) do the PV sector no good. Even if these problems are far from representative for the PV product portfolio as a whole, bad PR is damaging and can take years to overcome. Moreover, many users and potential users of PV products and equipment can often be confused by the different certificates, labels and warranties that exist in the industry.

Furthermore, the crucial difference between high technical quality and high efficiency or high energy yield is usually only clear to experts and insiders. In other words, there could be ill-manufactured high efficiency modules that rapidly degrade or fail, and excellent, durable low efficiency modules (both "high" and "low" being relative terms here) that firmly stand the test of time.

The PV sector works hard to improve transparency, independence and coherence throughout the industry, but there is still a world of gains to be made. Some further explicit product differentiation and corresponding labeling may also help users to make the best choice for their application. Deserts, for example, are very different from Northwest European rooftops, and users need to know that there are different technologies available that are better suited for certain environments.

Outlook

The global PV sector is faced with the inspiring and challenging goal of entering the terawatt level (cumulative capacity) within the space of a decade. Clearly, continued cost reduction and sustainable pricing are necessary conditions for success. But to serve the world well on this scale, it is crucial to address all the challenges facing the PV industry in time. Ideally, by the time we reach a point where prices are no longer the limiting factor for growth, the next potentially limiting factors will have already been addressed by anticipating joint efforts of industry, research and other stakeholders. ◆

Wim Sinke

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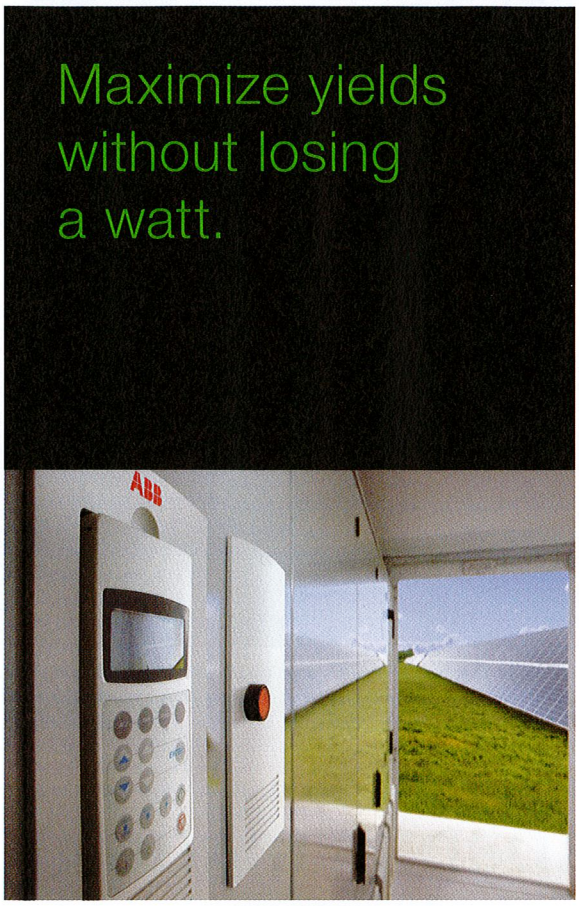


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