Renewable Energy 138 (2019) 911–914

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Development of photovoltaic technologies for global impact

Wim C. Sinke [a], [b], [c]

[a] University of Amsterdam, Science Park 904, 1098 XH, Amsterdam, the Netherlands
[b] AMOLF, Science Park 104, NL-1098 XG, Amsterdam, the Netherlands
[c] ECN Part of TNO, POB 15, NL-1755 ZG, Petten, the Netherlands

ARTICLE INFO

Article history:
Received 17 December 2018
Accepted 6 February 2019
Available online 7 February 2019

Keywords:
Photovoltaics
Solar energy
PV technology
Silicon
Thin film
Tandem

ABSTRACT

Photovoltaic solar energy (PV) is expected to play a key role in the future global sustainable energy system. It has demonstrated impressive developments in terms of the scale of deployment, cost reduction and performance enhancement, most visibly over the past decade. PV conversion is and can be done with a wide range of materials, device architectures and technologies, at very different levels of technical and economic maturity. In this context it is customary to distinguish between first, second, third, and sometimes even fourth generation PV. This has initially been very useful to clarify the complex and, for many, confusing landscape of PV. In this paper it is argued, however, that in view of actual developments in PV over the past few decades there are good reasons to adopt another approach, that does more justice to the role and potential of existing and new PV concepts and technologies.

1. Introduction

An important strength of photovoltaic solar energy (PV) is that PV conversion can be realised with a multitude of materials and device designs and can be used for many different applications and markets. This makes PV development and deployment very robust: if some approaches are not yet, no longer or not at all successful, there are always other options left. In fact, this is an important reason why the PV sector has been able to grow ever since its early days, more than half a century ago. At the same time, this multitude of options leads to confusion among stakeholders; some often-heard questions are: what is the best technology, should I wait until something better/cheaper/more efficient becomes available, will this product be obsolete soon? Although there are no easy answers to some of these questions, it is useful to put PV technology developments into perspective.

2. PV technologies and applications

In this paper, the term “PV technologies” refers to a combination of an absorber material, a cell architecture in the form a wafer or a stack of thin layers, a module, and (where relevant) a system application. This is more specific than, for instance, simply “crystalline silicon” or “thin film”. Such a more detailed differentiation fits with the development stage of the PV sector, where different market segments require dedicated solutions for optimum technological, economic or societal PV performance. Examples are Building Integrated PV (BIPV), Infrastructure-Integrated PV (I^2PV), floating PV systems, ground-based PV power plants, vehicle-integrated PV, and more.

Whereas the PV industry has been able to reduce manufacturing costs and selling prices spectacularly [1] by, primarily, producing a huge quantity of cells and modules that are very similar, thus achieving optimum economies of scale, this now also starts limiting the application possibilities of PV. One could say that one size no longer fits all. The challenge is to broaden the product portfolio without increasing cost to unacceptable levels: additional manufacturing cost should not outweigh enhanced application value. Since the niche market of yesterday may develop into the multi-gigawatt market of tomorrow, this should in principle be possible if the initial hurdle of small volumes and high prices can be overcome. The PV sector as a whole has demonstrated this to be possible, critically aided by market incentives in Germany and some other countries [2]. Broadening the product portfolio may be enabled further through the implementation of smart manufacturing concepts [3] that combine the benefits of mass production with product customisation. An intermediate approach is to produce semi-manufactures in very large numbers and turning them into final products flexibly and on demand.

E-mail address: w.c.sinke@uva.nl.

https://doi.org/10.1016/j.renene.2019.02.030

3. Technology development

3.1. Generations

The diversity of photovoltaic materials used or studied is large and still growing, as illustrated by the widely known and frequently used NREL chart showing the record efficiencies of laboratory devices (usually small-area cells) versus time [4] and the more recently introduced interactive IEEE chart [5] which gives background information on the individual efficiency points. Further, comprehensive efficiency tables for cells and (sub)modules are published periodically since 1993 in Progress in Photovoltaics [6,7]. This technology diversity has obvious advantages, such as robustness of the overall PV development and choice for different types of applications, but also disadvantages: uncertainty and confusion among potential investors, policy makers and even researchers, dilution of public funds for research and development and a tendency to wait until something better becomes available, to mention a few. To bring structure into this complex landscape, the concept of "PV generations" was introduced by professor Martin Green of the University of New South Wales [8], see Fig. 1.

In this concept, first generation PV (GenI) refers to wafer-based devices, normally crystalline silicon. Second generation devices (GenII) are "conventional" thin films, such as cadmium-telluride (CdTe), copper-indium/gallium-diselenide/sulphide (CIGSS) and amorphous or microcrystalline silicon (aSi or μcSi). First and second generation cells have in common that their performance does not (cannot) exceed the Shockley-Queisser (SQ) limit for single-bandgap devices [9]. As is clear from Fig. 1, GenI technologies typically have a higher efficiency than GenII technologies, but they also have substantially higher cost per m^2, implying that they are usually more costly than GenII per *watt-peak* (Wp) of module power as well. The term "third generation PV" (GenIII) is then used for advanced thin films, or, more accurately, for devices with a potential efficiency above the SQ limit. Exceeding this limit can potentially be achieved in a number of different ways [Green, 2003], of which stacked multi-junction devices are by far the most advanced: they have topped the efficiency charts ever since their first publication [7]. The categorisation in three generations has been used frequently by researchers, students, analysts and others over the past 25 years.

3.2. The need for a new view

Although "generations" thinking has initially served an important purpose, namely to give structure to the complex landscape of PV technologies, it needs revision because of the actual developments in PV. First of all, the majority of users of the PV generations concept have interpreted it as describing the order of commercial success: at some point in time GenII will take over the position of GenI because it is cheaper per Wp. GenIII will then eventually make GenII obsolete because it is not only cheaper per Wp, but also more efficient. This has often led to the conclusion that wafer-based crystalline silicon technology is something of the past, not innovative and not worthy of R&D efforts anymore. After all, who wants to work on, or invest in first generation technology? The fact is, however, that wafer-silicon technologies had a global market share of around 95% in 2017 and even strengthened their position in the past decade [10]. Another conclusion that many people have falsely drawn is that thin-film PV modules are *by nature* cheaper (or more accurately: lower cost) than wafer-based modules. Thin-film modules, however, are *not automatically* cheap and wafer-based silicon modules are *not inherently* expensive, as the spectacular price (and to a somewhat lesser extent, cost) reduction of the latter has demonstrated [1]. The massive scale at which silicon feedstock, silicon ingots and wafers, silicon cells and silicon modules are produced (equivalent to ≈100 GWp in 2017 [1]), combined with an efficient supply chain, standardisation and strongly reduced profit margins and some other factors, have caused a price reduction beyond projections and even beyond what was considered possible. Even more surprising may be that there appears to be significant room for even further reduction [11]. The strong position of wafer-based silicon technologies has made it increasingly difficult for thin-film technologies to compete in the mainstream PV market, where the decisive parameter is cost, be it per Wp module or system power or per kWh electricity produced. Presently, CdTe thin-film technology explicitly aims to address the highly competitive utility-scale PV market [12], but other thin-film technologies mainly focus on higher-value applications such as in buildings. Market entry of new technologies (such as organic PV and quantum-dot PV) based on cost competitiveness has practically become impossible in recent years, which may lead to a technology lock-in: in spite of the many new options under development, the existing market leader is very difficult to beat and even strengthens its position and track record further. New technologies are initially usually not yet cheap and not yet efficient and obviously lack a track record. Bankability in relation to standard use is therefore often problematic. For those reasons, research and development efforts in the fields of thin-film PV and new technologies are increasingly aimed at addressing new (niche) markets that require, or at least value, specific properties like ultra-light weight and flexibility, freedom of shape and size, excellent aesthetics or even partial transparency. An often mentioned market example is BIPV, but there are several others. The properties mentioned cannot, or not easily be realised by standard wafer-based silicon technologies. Using these new markets as stepping stones, some technologies may then eventually enter more cost-competitive markets. An alternative approach may perhaps be to use bold action or even brute force: helping a promising new technology through the commercial valley of death by scaling up rapidly to the volume needed for competitiveness, enabled by launching customers with a sufficiently long commitment who are willing to take the residual risk inherent to a new technology.

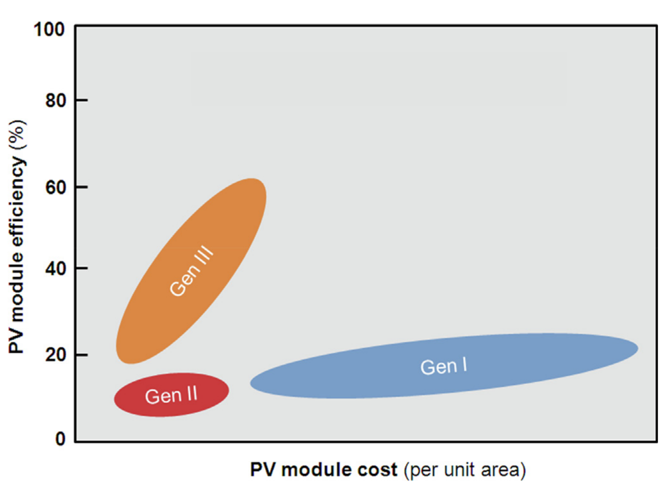

Fig. 1. PV technology generations, redrawn after [8]. See 3.1 for details.

3.3. Technologies teaming up for success

Looking at the development of wafer-based silicon technologies in the past decades and at what may still come, it is possible to distinguish different phases. It is suggested here to use the term "generations" for these phases (see Fig. 2). Gen1 devices are then

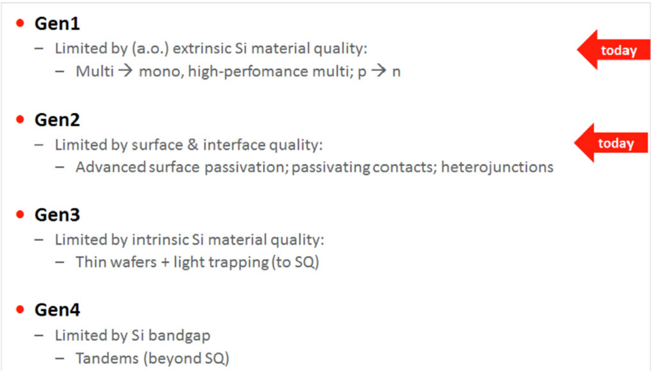

Fig. 2. Crystalline silicon PV technology generations.

characterized by the fact that their efficiency is limited by the extrinsic (i.e. determined by defect and impurities) quality of the absorber material: the crystalline silicon quality (expressed as the minority carrier lifetime and diffusion length). Strategies to enhance the efficiency therefore have a strong focus on improving material quality. Key examples are the replacement of multicrystalline silicon by high-performance multicrystalline silicon or monocrystalline silicon, but also moving from p-type silicon to n-type silicon falls in this category. If material quality is no longer the main limiting factor, the quality of surfaces and interfaces comes in as key limitation. This is then tackled by the introduction of thin films for advanced surface passivation such as hydrogenated silicon nitride (SiN_x:H) [13] or aluminium oxide (Al_2O_3) [14,15], by passivating contact structures, for instance including an ultrathin silicon oxide (SiO_2) film [16]), or by using a heterojunction instead of a homojunction [17]. Of course, Gen1 and Gen2 cannot be separated as strictly as done here for the purpose of clarity. In many cases, strategies for performance enhancement address(ed) aspects of bulk material quality and surface and interface quality in parallel, or even in one process step. An example of the latter is the application of a hydrogenated silicon nitride anti-reflection coating to provide surface passivation but also passivation of bulk defects by in-diffusion of hydrogen [13]. Most current R&D efforts in crystalline silicon fall within these Gen1 and Gen2 categories.

When extrinsic material quality and surface and interface quality are no longer limiting, the next step is to minimise the effect of the intrinsic material quality. This is the essence of the challenges in Gen3 silicon technology. In simple terms, it implies using as little material as possible, while still ensuring (almost) full absorption of all photons that can be absorbed by silicon given its bandgap of 1.12 eV, using an effective light trapping scheme. Standard commercial devices are typically 180 μm thick [1], which is, at least partially, determined by the fact that thinner silicon wafers are more difficult to make and therefore more expensive than thicker wafers and that some cell and module process steps need modification to ensure a high yield. The ultimate silicon solar cell, which reaches the fundamental efficiency limit of 29.4% [18], however, has a thickness of only 110 μm. Therefore there is room for improvement compared to the commercial state-of-the-art by reducing absorber material thickness and enhancing light trapping.

At 29.4% efficiency, a crystalline silicon solar cell is perfect, and cannot be improved further without adding external functionality to the device. For large-area commercial silicon modules it is very unlikely that this 29.4% will ever be reached and 26–27% may be a more realistic limit. The limiting factor for Gen3 is the silicon bandgap, or rather the fact that silicon cells use a single bandgap to convert a broad spectrum of (sun)light. Therefore the most straightforward approach to reach higher efficiencies, although far from easy and not the only [19], is to add a second absorber material to the silicon and to build a hybrid (wafer-silicon/thin-film) tandem [20]. Because the silicon bandgap of 1.12 eV corresponds to infrared light while the solar spectrum peaks in the visible, the biggest gain in efficiency can be achieved when silicon is combined with a wider-bandgap absorber, typically 1.4–1.8 eV. The tandem then consists of a –preferably thin-film- wide-gap top cell and a silicon bottom cell. Unfortunately, a significant gain above the already high efficiency of the silicon cell can only be achieved if the top cell has a very high efficiency itself also. Wide bandgap materials and cells that fulfil this requirement ánd offer the potential of very low cost are not readily available and this has severely hampered Gen4 work until a few years ago. It was the discovery of a new class of (organic-inorganic) perovskites [20] that has kick-started a huge global research effort in the field of silicon-based tandems. Perovskite cells have demonstrated surprisingly high efficiencies given their short history and can potentially be produced at low cost. Recently, the highest tandem cell efficiency achieved with perovskites [21] has passed the highest efficiency of any silicon cell (26.6%) [6], demonstrating the potential of this approach. Tandems using a III-V semiconductor top cell and a silicon bottom cell have already demonstrated an efficiency of 32.8% [6], but there the big challenge is to produce the tandems at such low cost that they can also become cost-competitive.

In view of the huge global efforts on silicon-based tandems and the practical barriers towards to use of very thin wafers, it remains a question whether Gen3 silicon PV will be realised commercially in “pure form”. It is expected that wafer thickness will decrease over time, but recent projections are less ambitious than older projections [1] and rather driven by potential cost reduction than by efficiency gain as such.

Looking at two main steps in the development of silicon PV technologies, from Gen1 to Gen2 and from Gen2 to Gen4, it is clear that the introduction of thin-film technology in various forms is decisive for success. High-quality passivation, heterojunction technologies and efficient tandems cannot be achieved without using thin-film processes. Hence, it is the merger of Gen1 and Gen2 that brings both of them further and that makes them enter GenIII together.

3.4. An alternative view on PV technology development

Considering that within the class of wafer-based silicon PV technologies, several generations can be distinguished and that wafer-based silicon PV technologies increasingly make use of thin-film technologies, or even merge, it is proposed to redraw the “generations” picture (Fig. 3, top) into a new, “families” picture (Fig. 3, bottom) [21]. Technology families develop because new generations within the families come and older ones go. Moreover, families overlap and even merge. This new view does more justice to the actual PV technology development in the past decade and explains why technologies do not simply become obsolete and disappear, but follow a more complex and evolutionary path. Although this may be interpreted as bad news for “disruptive” innovations and for new PV technologies, it actually only shows that they should choose the right battle to be successful and enter the market.

4. Conclusions

The development of PV technologies and their market position in the past decade has followed a very different path than the one that might have been expected on the basis of the categorisation in

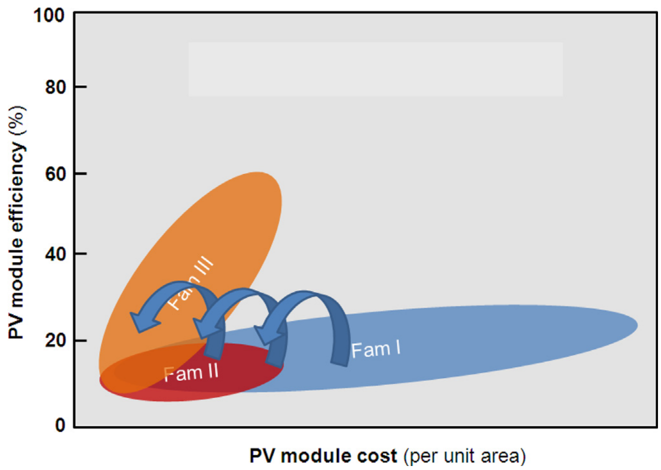

Fig. 3. Reconstruction of the visualisation of PV technology development in Fig. 1 into a proposed new one. In this approach, several generations can be found with one family of technologies. See 3.3 and 3.4 for details.

"generations". It is therefore proposed to introduce a new view, that does more justice to the actual evolutionary development of PV technologies and that puts current innovation efforts in a clear context and perspective.

References

[1] International Technology Roadmap for Photovoltaic (ITRPV), http://www.itrpv.net/Reports/Downloads/.
[2] Joern Hoppmann, Joern Huenteler, Bastien Girod, Compulsive policy-making—the evolution of the German feed-in tariff system for solar photovoltaic power, Res. Policy 43 (2014) 1422–1441, https://doi.org/10.1016/j.respol.2014.01.014.
[3] T. Stock, G. Seliger, Opportunities of sustainable manufacturing in industry 4.0, Procedia CIRP 40 (2016) 536–541, https://doi.org/10.1016/j.procir.2016.01.129.
[4] For the latest version, see: https://en.wikipedia.org/wiki/Solar_cell_efficiency.
[5] For the latest version, see https://spectrum.ieee.org/static/interactive-record-breaking-pv-cells.
[6] Martin A. Green, Yoshihiro Hishikawa, Ewan D. Dunlop, Dean H. Levi, Jochen Hohl-Ebinger, W. Anita, Y. Ho-Baillie, Solar cell efficiency tables (version 52), Prog. Photovoltaics Res. Appl. 26 (2018) 427–436, https://doi.org/10.1002/pip.3040.
[7] A. Martin, Green, Keith Emery, Solar cell efficiency tables (version 1), Prog. Photovoltaics Res. Appl. 1 (1993) 25–29.
[8] A. Martin, Green, Third generation photovoltaics: ultra-high conversion efficiency at low cost, Prog. Photovoltaics Res. Appl. 9 (2001) 123–135, https://doi.org/10.1002/pip.360.
[9] A. Polman, M. Knight, E.C. Garnett, B. Ehrler, W.C. Sinke, Photovoltaic materials: present efficiencies and future challenges, Science 352 (2016) 6283 (Updates of the graphs are available at: http://www.lmpv.nl/sq/), 10.1126/science.aad4424.
[10] S. Philipps, W. Warmuth, Photovoltaics Report, Fraunhofer Institute for Solar Energy Systems, 2018 for the latest version, see: https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html.
[11] Pietro P. Altermatt, Yang Yang, Yifeng Chen, Daming Chen, Xueling Zhang, Guanchao Xu, Zhiqiang Feng, Learning from the past to look beyond the roadmap of PERC Si solar cell mass production, in: Proc. 35th EU Photovoltaic Solar Energy Conference and Exhibition, 2018, pp. 215–221, https://doi.org/10.4229/35thEUPVSEC20182018-2BP.1.1.
[12] See, for instance: http://www.firstsolar.com/en-EMEA/PV-Plants/Utility-Scale.
[13] Machteld W.P.E. Lamers, reportApplication and analysis of silicon nitride films for surface passivation of high efficiency silicon solar cells (2015), PhD-thesis University of Amsterdam, available from: https://dare.uva.nl/search?identifier=a3780c46-bb27-41ea-acd8-6227598b0872.
[14] B. Hoex, S.B.S. Heil, E. Langereis, M.C.M. van de Sanden, W.M.M. Kessels, Ultralow surface recombination of c-Si substrates passivated by plasma-assisted atomic layer deposited Al_2O_3, Appl. Phys. Lett. 89 (2006), https://doi.org/10.1063/1.2240736, 042112/1-3.
[15] J. Schmidt, A. Merkle, R. Brendel, B. Hoex, M.C.M. van de Sanden, W.M.M. Kessels, Surface passivation of high-efficiency silicon solar cells by atomic-layer-deposited Al_2O_3, Prog. Photovoltaics Res. Appl. 16 (2008) 461–466, https://doi.org/10.1002/pip.823.
[16] Frank Feldmann, Martin Bivour, Christian Reichel, Martin Hermle, Stefan W. Glunz, Passivated rear contacts for high-efficiency n-type Si solar cells providing high interface passivation quality and excellent transport characteristics, Sol. Energy Mater. Sol. Cells 120 (2014) 270–274, https://doi.org/10.1016/j.solmat.2013.09.017.
[17] Takahiro Mishima, Mikio Taguchi, Hitoshi Sakata, Eiji Maruyama, Development status of high-efficiency HIT solar cells, Sol. Energy Mater. Sol. Cells 95 (2011) 18–21, https://doi.org/10.1016/j.solmat.2010.04.030.
[18] A. Richter, M. Hermle, S.W. Glunz, Reassessment of the limiting efficiency for silicon solar cells, IEEE J. Photovoltaics 3 (4) (2013) 1184–1191, https://doi.org/10.1109/JPHOTOV.2013.2270351.
[19] Other, very elegant but also very challenging, ways to enhance the efficiency of silicon cells are for instance to use a spectrum shaper (photon cutting and pasting) or a multi-electron generator. In the first case, the solar spectrum is tuned to better match the absorption characteristics of the cell rather than the other way around. In the second case, energetic photons are used to generate two or more electrons (instead of only one) that can be collected in the cell.
[20] Jérémie Werner, Bjoern Niesen, Christophe Ballif, Perovskite/silicon tandem solar cells: marriage of convenience or true love story? – an overview, Adv. Mater. Interfaces 5 (2018) 1700731, https://doi.org/10.1002/admi.201700731 (19 pages).
[21] W.C. Sinke, Technology Diversity: Blessing or Curse? Future Photovoltaics, Sept. 2010 (available from: the author), www.futurepv.com.