Present trends in crystalline silicon photovoltaic cells and modules

V. Benda
Department of Electrotechnology
Czech Technical University in Prague, faculty of Electrical Engineering
Prague 6, Czech Republic

Abstract

Photovoltaics (PV) is expected to play an important role in the future global energy system. Advances in technology have led to an impressive reduction in the price of photovoltaic modules and other parts of photovoltaic systems, so that the cost of electricity produced by photovoltaic systems has fallen close to the long-term cost of electricity in the grid. The key components are PV modules, which are basic devices that are capable of long-term operation in outdoor conditions. PV modules can be implemented from different materials with different production technologies. Innovative driving forces are module cost, module efficiency and module life. At present, wafer-based crystalline silicon technologies best meet the criteria due to their high efficiency, low costs, and long service life, and in the current production of photovoltaic energy they represent almost 95% of the total module production. The article discusses trends in crystalline silicon technologies.

Keywords: PV modules technology; PV module efficiency; LCOE; PV module service life

INTRODUCTION

Photovoltaics (PV) is expected to play a key role in the future global energy system. Advances in technology have led to a significant reduction in the price of PV systems, so that the cost of electricity produced by PV systems has fallen almost to the level of the long-term cost of electricity in the grid.

The impressive development in photovoltaics during last ten years can be characterised by very fast increase of both annual installed power and cumulative installed power [1; 2], as demonstrated in Fig.1.

PV cells and modules can be made of different materials by different production technologies. The conditions that any technology for a wide range of applications should meet are: low production cost, high efficiency, high operational reliability, and availability of input materials.

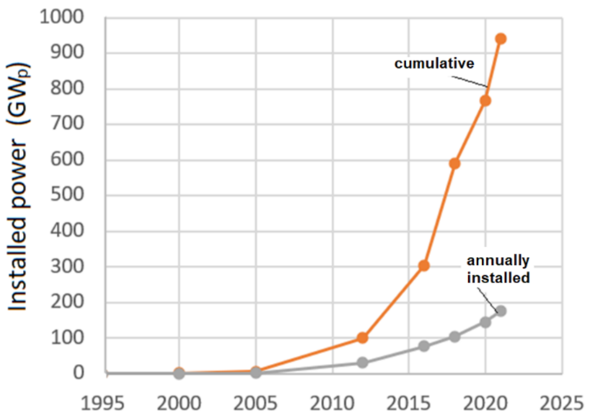

Fig.1. The developments of the PV cumulative installed capacity and annual production

During the 50 years of development of photovoltaic technologies, many materials and technologies have been studied (3 generations [3] are listed in Table 1). Regarding technological and economic aspects (high efficiency requirements, low prices, long life, wide availability of materials), crystalline silicon cells and modules predominated [4], accounting for 95% of total production [5], as demonstrated in Fig. 2. Although some thin film technologies (CdTe, CICS) can compete both in terms of efficiency and price, resources (Te, In) are limited and their annual production could hardly exceed 20 GW$_p$ [6]. Other technologies have not yet reached the

1st generation *– wafer-based technology (mostly crystalline silicon solar cells)*

2nd generation *- thin film solar cells amorphous silicon (a-Si) and microcrystalline silicon (μc-Si), cadmium telluride/cadmium sulfide (CdTe/CdS) and copper indium gallium diselenide (CIGS) solar cells, kerstenits*

3rd generation *- technologies based on newer compounds including nanocrystalline films, active quantum dots, tandem or stacked multi-layers of inorganic based on III-V materials, organic (polymer)-based solar cells, dyed-sensitized solar cells, perovskites, etc.*

Table 1. PV cell generations [3]

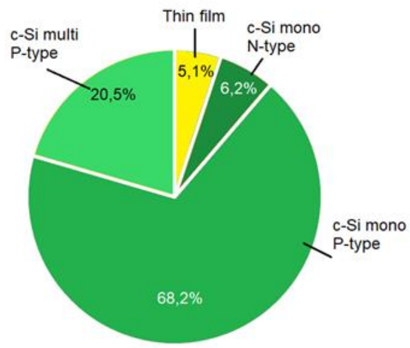

Fig.2. PV module technology share in 2020

level of series production. The current development of photovoltaic cells and modules is therefore connected mainly with wafer-based crystalline silicon technologies.

PROGRESS IN CRYSTALLINE SILICON TECHNOLOGIES

The impressive development of crystalline silicon module technology in the last decade can be demonstrated by the development of annual production (see Fig.1), price, and efficiency, as shown in Fig. 3.

The most important drivers of the technology developments [7] are:

- The module cost
- The module efficiency
- The module service life

The expansion of technology on a gigawatt production scale also requires:

- No material constrains
- Environment friendly fabrication processes

Wafer-based crystalline silicon technologies best meet the criteria of high efficiency, low cost and high service life, and currently account for about 95% of total module production.

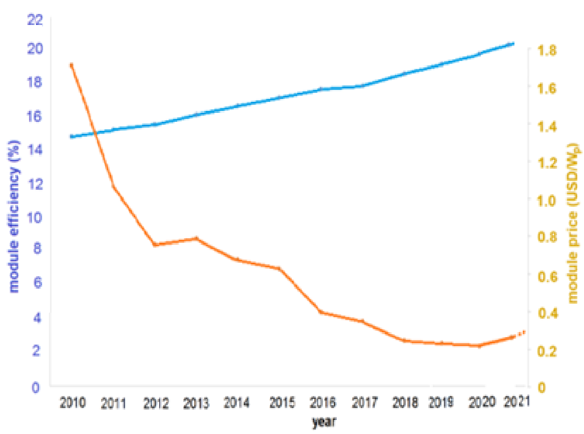

Fig.3. Development of average price and average efficiency of c-Si modules

The main technological changes in mass production technology can be observed in the last 5 years. These changes, which lead to an increase in the efficiency and service life of the modules, can be observed in the field of the starting crystalline material, in the field of the structure and technology of PV cells, in the field of the construction and technology of the modules. New technologies, new materials, and highly productive manufacturing equipment are required to reduce production costs.

Changes in starting material. In the period 2008-2016, the main trend was to improve the starting multicrystalline material as to reduce the cost of the starting material. However, the introduction of the continuous Czochralski pulling method in 2016 has reduced the cost of mono-crystalline silicon rods and due to lower losses in wafering by diamond-plated wire also the cost of wafers.

The changes in mono/multi c-Si cells ratio are shown in Fig.4. Replacing boron doping with gallium doping in monocrystalline silicon [8] results also in an efficiency improvement. Currently mono-crystalline gallium doped wafers of thickness of 0.17 mm predominate as the starting material for cell production [9]. The transition to the initial N-type material may further increase the efficiency of PV cells.

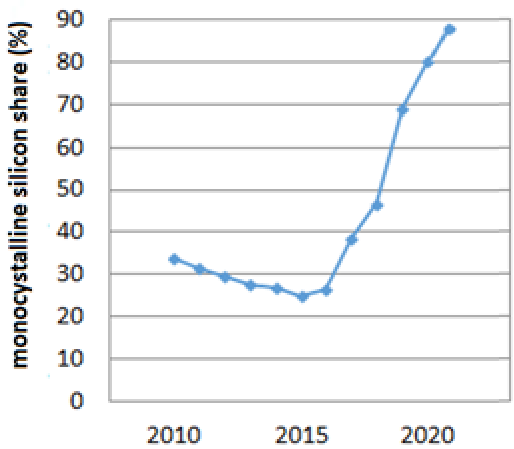

Fig.4 . Development of the share of monocrystalline silicon in the total production of c-Si cells

Module cost reduction

Cost reduction is associated with the steps of techno-logical breakthroughs, the expansion of production plants and increasing the level of automation, and the costs of materials and components (silicon, glass, polymer films, etc.) and energy in the production chain. Efficiency improvements in PERC technology and the deployment of larger wafers in larger module resulted in higher average module efficiencies. Development in average module efficiency and average module price in the last decade is demonstrated in Fig.3. The rise in module prices started in 2020 is related to the lack of polycrystalline silicon resources, which is likely to last throughout 2022 [10].

One of the tools for reducing the cost of PV cells and modules was also to increase the wafer area (from 164x164 mm^2 in 2016 to 210x210 mm^2 in 2020). This increase in cell area was followed by an increase in module power [11]. The maximum module power development is shown in Fig.5. Increasing module power can also help reduce BOS [12] costs and reduce costs for other components, including racks, foundations, and cabling.

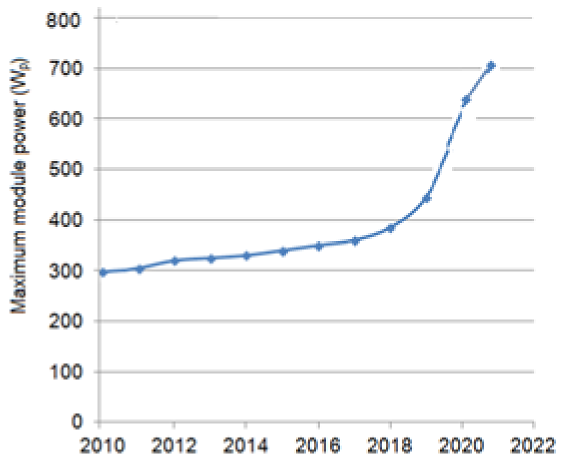

Fig.5. Maximum module power development

The module efficiency increase

The increase in the efficiency of the module is usually associated with an increase in the efficiency of the cells from which it is composed. The efficiency improvements are reached by decreasing all types of losses – both optical loses, recombination losses and electrical losses. Individual loss components are minimized by using new physical design principles, optimizing technological tools and materials. After reducing the volume recombination losses to an acceptably low level, the surface recombination on the rear contact was reduced by switching from all-area contact used in Al BSF cells to the local contacts on the passivated rear surface used in PERC cells. The next step is a fully passivated surface realizing the all-area contact by tunneling the carriers through a very thin passivation oxide layer - TOPCon cells. This technology development is indicated in Fig.6.

At the module assembly level, there are used construction improvements to decrease inner resistive losses (half cut cell configuration, shingled construction improvements to decrease inner resistive losses (half cut cell configuration, shingled cell configuration), optical losses (using AR coated glass, white EVA, wire cell connection).

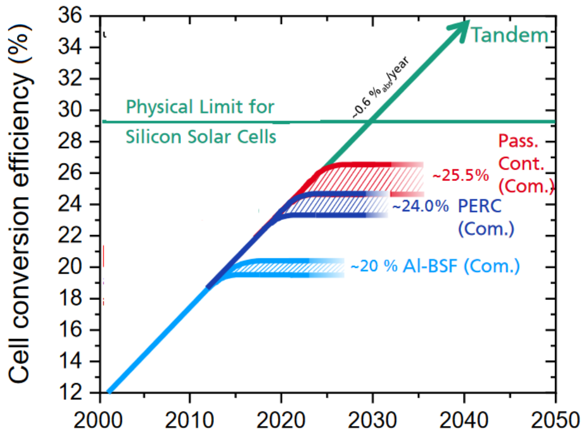

Fig.6. Development of the efficiency of c-Si cells depending on the technology [5]

The possibility of making better use of solar radiation has led to the development of bifacial cells and modules, which currently account for about 30% of total production and their market share is expected to grow.

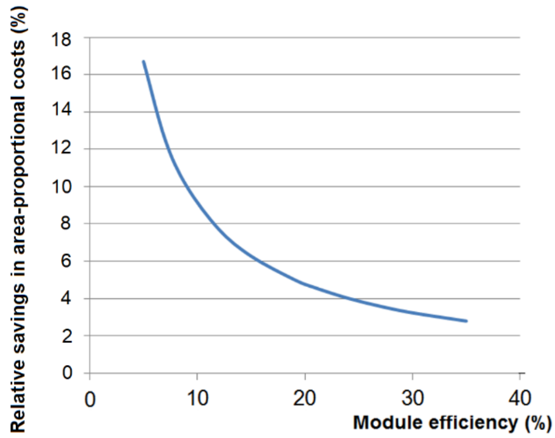

Fig.7. The relative savings of area-related costs caused by a 1% increase in module efficiency

Improving module costs and module efficiency are very important for reducing the investment costs of a PV system, which consist of module costs, BOS costs and soft costs. Part of the non-modular costs is proportional to the area and is therefore inversely proportional to the efficiency of the module. In this way, increasing the efficiency of the module leads to a reduction in the area-dependent part of the investment [7, 12]. However, the relative changes in these parts of the investment costs decrease with the increasing efficiency of the module. Fig. 7 shows the relative savings in area-proportional costs due to a 1% increase in module efficiency. In order to maintain the module efficiency as an effective innovative driver, the savings from efficiency gains should be greater than the increase in module technology costs associated with this efficiency gains.

The module service life extension

Due to the environment, the efficiency of the module decreases over time. The service life n is often taken as the number of years until the efficiency of the modules is reduced to 80% of the initial value and in this form is often used as the warranty period of the PV modules specified by the manufacturer.

The encapsulation material and the back cover materials are key module components to ensure long time stability. Intensive development efforts have been (and are) being made to optimize these components in terms of performance and cost.

Foils will stay mainstream as back cover material, but glass is expected to gain a significant higher market share as backside cover material especially for bifacial c-Si module applications. Polyolefins are a forthcoming alternative to EVA especially for bifacial products in glass-glass combination and for SHJ [13].

The module service life influences resulting cost of electrical energy generated (the LCOE of photovoltaic systems). For constant investment cost and the energy output, the module service life prolongation results in a decrease of the LCOE. Some results can be obtained using a simplified model [7]. In Figure 7, the relative decrease of LCOE caused by an increase in the module service life of 1 year (from n to n+1, e.g., from 20 to 21 years) are plotted as a function of module service life n.

In addition to the effect of module degradation, described by the expected decrease in module efficiency, faults can also occur on both modules and other parts of the installation causing accidental malfunctions of the PV system. The repair of these faults increases the operating costs of the system, which results in an increase in the ratio ε between the annual operating costs of the PV system and the investment costs with a consequent decrease in the relative LCOE reduction, as shown in Fig. 8.

Present service life of c-Si modules is usually declared 25 years (or more). For example, bifacial modules with double-sided glass with polyolefin (POE) encapsulation have a service life of well over 30 years [13]. However, it is also important to increase the service life of the other components of the PV system to a similar level in order to take advantage of the savings resulting from extending the service life of the modules [14].

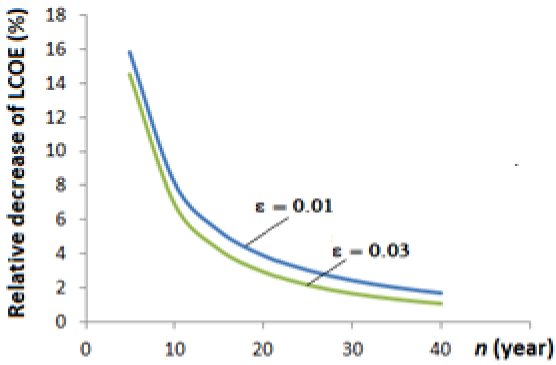

Fig.8. The relative decrease of LCOE caused by an increase in the module service life of 1 year for different ε - ratio between average annual operating cost and the investment cost

THE TECHNOLOGY ROADMAP

Global demand for photovoltaics as a source of electricity is growing and certain scenarios assume that annual production will approach 1 TW_p over the next decade. In principle, silicon technology has the potential to handle this volume of production.

Further development of photovoltaics requires

- Improve module efficiency without significantly increasing processing costs.
- Further optimize unit costs throughout the value chain by increasing the overall efficiency of the installed production capacity equipment, implementing upgrades and new production capacities, more efficient use of Si and non-Si materials and ensuring high efficiency of newly installed capacities.
- Prepare specialized product modules for various market applications (e.g. specialized for hot and wet environment)

Large-scale production of some structures may have problems in terms of the availability of some materials [15] (e.g., lack of indium can significantly reduce the production of cells using ITO), which needs to be taken into account at the development stage.

High hopes are associated with the development of perovskite PV cells and modules which, due to their high efficiency and expected low cost, could replace crystalline silicon modules in the future. Perovskite modules have undergone rapid development, but there are still some stability and longevity issues that prevent the rapid introduction of mass production.

REFERENCES

[1] 2022 Snapshot of Global PV Markets, Report IEA-PVPS T1-42:2022 April 2022

[2] Global Market Outlook For Solar Power 2022 – 2026, Solar Power Europe 2022

[3] M. A. Green, Third generation photovoltaics: Ultra-high conversion efficiency at low cost, Progress in Photovoltaics, vol. **9**, no. 2, pp. 123-135 (2001)

[4] Wim C. Sinke, Development of photovoltaic technologies for global impact, Renewable Energy **138**, p. 911-914 (2019).

[5] Photovoltaics report , February 2022, https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/ studies/Photovoltaics-Report.pdf

A. Feltrin, A. Freundlich, Material considerations for terawatt level deployment of photovoltaics. Renewable Energy **33**, p. 180–185 (2008)

[6] Benda V. and Cerna L., A Note on Limits and Trends in PV Cells and Modules, Applied Sciences, 2022

[7] S.W. Glunz, S. Rein, J. Knobloch, W. Wettling and T. Abe, *Comparison of boron and gallium doped p-type Czochralski silicon for photovoltaic application, Progress in Photovoltaics: Research and Applications* 7(6), 463-469 (1999)

[8] International Technology Roadmap for Photovoltaic

[9] (ITRPV) Results 2021 Thirteenth Edition, March 2022

[10] Shashinger, M.: Module prices set to rocket back to 2019 levels, PV magazine, 11, 2021, p.10-11

[11] S. K. Chunduri, M. Schmela:,Very High-Power Solar Modules, TaiyangNews Report 2021

[12] Wang, X.; Barnett, A. The Evolving Value of Photovoltaic Module Efficiency. *Appl. Sci.* **2019**, *9*, 1227

[13] S. K. Chunduri, M. Schmela, Advanced Module Technologies, TaiyangNews Report 2021

[14] Review of Failures of Photovoltaic Modules, Report IEA-PVPS T13-01:2014

[15] Y. Zhang, M. Kim, L. Wang, P. Verlinden and B. Hallam, Design considerations for multi-terawatt scale manufacturing of existing and future photovoltaic technologies: challenges and opportunities related to silver, indium and bismuth consumption, (Analysis) *Energy Environ. Sci.*, 2021, 14, 5587-5610

[16] Urbina A., The balance between efficiency, stability and environmental impacts in perovskite solar cells: a review, *Journal of Physics: Energy* 2, Number 2 (2020)

Address of the author:
Czech Technical University in Prague,
Dept. Electrotechnology, Technicka 2, 166 27 Praha 6,
Czech Republic
E-mail: benda@fel.cvut.cz