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EVOLUTION OF THE MANUFACTURING TECHNOLOGY OF PHOTOVOLTAIC PANELS AND FACTORS AFFECTING THEIR PERFORMANCE

BY

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Abstract. The efficiency of the production of electricity from solar energy depends on technological developments and the performance of the photovoltaic panels. A positive trend depends on diversifying the materials used to manufacture plates and adapting them to the climatic conditions. The article presents several technological aspects to give an idea about the evolution of the yields of photovoltaic panels, especially about the photovoltaic technology in the first, the second, and third generations. After the statement of the main characteristics of the photovoltaic panels, an analysis of the factors that can affect their performances and can create difficulties in implementing projects is made. This approach aims to choose the most advantageous combination of concepts and techniques when making photovoltaic parks.

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1. Introduction

In the years to come, importance will be given to energy production as there is an increasing increase in energy needs; since we are more and more numerous and we consume more and more (Arras, 2018; Khadraoui, 2017). Photovoltaic conversion is of great importance. It can be achieved with several materials and devices with different applications and is available on the market (Green *et al*., 2018). There are three main families of renewable energies, energy in the form of heat (solar thermal, geothermal energy, etc.), energy of mechanical origin (wind power, swell), or electrical energy (photovoltaic panels (Kendouli, 2017). To meet this challenge, researchers are making significant efforts to increase energy production from a variety of renewable energy sources, without posing environmental risks or depleting natural resources.

The scientific community has attached more importance to solar photovoltaic panels in recent decades among other sources of renewable energy (Kanoun, 2019). The coupling between several naturally different sources such as the hybrid system is a solution not to be neglected for remote or isolated regions. The inclination of a photovoltaic module so the sun's rays are perpendicular is a condition to produce high amount of electricity. However, due to the variation in the sun's position with the seasons and the time of day, this makes this impossible. Searching the optimal value of the tilt angle of photovoltaic modules is one of the good optimizing methods for the photovoltaic generator (Mechlouch *et al*., 2009; Adouane *et al*. 2014). Some frequently asked questions include: what is the best technology, the most efficient, why is it not easily adaptable?

Despite the difficulty of answering to these questions, it is important to put into perspective the evolution of photovoltaic panel manufacturing technology and problems in their application. Thus, in this work we will talk about photovoltaic cells, comparative analysis of the performance of different types of photovoltaic cells and the influence of environmental factors on performance.

2. Photovoltaic Cells: Types and Technologies of Manufacture

Instead of “crystalline silicon” or “thin film”, the photovoltaic technology is better described by a combination of an absorbent material with a cell architecture in the form of a wafer or a stack of thin layers (Sinke, 2019). More differentiation responds to the different market segments that require dedicated solutions as Building Integrated PV (BIPV), Infrastructure-Integrated PV (I2PV), ground-based PV power plants, etc.

As a whole, the photovoltaic sector has shown the possibility of market incentive in some countries as well as in Germany (Hoppmann *et al*., 2014). Policy makers have stimulated the development and implementation of PV technologies within large geographical areas (Lacerda, 2016).

- 1st Generation

In the part of conventional solar cells, it emerges from solid silicon (c-Si) from a substrate with a thickness greater than 100 μm. The technology of this generation is mature and well mastered, for its two types, multicrystalline and monocrystalline. Indeed, starting with 2010 almost 84% of the PV market is occupied by silicium wafers (2% ribbon, 37% monocrystalline and 45% multicrystalline). The yield ranges between 15-26% as it is shown in Table 1 (Mekemeche, 2017).

Table 1
1st generation solar cells (Green 2017)

Solar cell	Area (cm^2)	Efficiency (%)	Test Center (date)
Silicium monocristallin	180.43	26.3 ± 0.5	FhG-ISE[a] (07/2016)
Silicium multicristallin	242.74	21.3 ± 0.4	FhG-ISE (11/2015)

[a]FhG-ISE : Fraunhofer –Institut für Solare Energiesysteme

- 2nd Generation

Titanium dioxide (TiO2), copper indium diselenide (CuInSe2), cadmium telluride (CdTe) and gallium arsenide (GaAs) constituting the materials of compounds II-VI or amorphous silicon are used by thin film solar cells with a thickness below 50 μm. Unlike the first generation, the possibility of reducing the production costs of these solar cells exists. Their use is more variable and therefore, they are flexible. Also, because high temperature treatments and vacuum processes are used, the production steps require more energy. Thus, Table 2 gives examples of 2nd generation solar cells (Mekemeche, 2017).

Table 2
Examples of 2nd generation solar cells (Green 2017)

Solar cell	Area (cm^2)	Efficiency (%)	Test Center (date)
GaAs	0.9927	28.8 ± 0.9	AIST(05/2012)[b]
CIGS	0.9927	21.0 ± 0.6	AIST(04/2014)[a]
CdTe	1.0623	21.0 ± 0.4	Newport(08/2014)
Silicium amorphe	1.001	10.2 ± 0.3	AIST(07/2014)[c]

[b]NREL: National Renewable Energy Laboratory
[c]AIST: Japanese National Institute of Advanced Industrial Science and Technology

- 3rd Generation

The 3rd generation solar cells are those currently being researched in photovoltaics for types of cells whose efficiency is above 20%. Conventional printing press technologies, polymers and organic dyes use solar inks. Apart from nanotubes, silicon wires, concentrating cells, this generation is based on the variety of new materials apart from silicon. Table 3 gives examples of 3rd generation solar cells (Mekemeche, 2017).

Table 3

Examples of 3rd generation sollar cells (Green 2017)

Solar Cell	Area (cm^2)	Efficiency (%)	Test Center (date)
Coloring (Dye-sensitised)	1.005	11.9 ± 0.4	AIST(09/2012)
Organic	0.992	11.2 ± 0.3	AIST(10/2015)
InGaP/GaAs/InGaAs (multijonction)	1.047	37.9 ± 1.2	AIST(02/2013)
Perovskite/Si (monolithic)	0.990	23.6 ± 0.6	NREL(08/2016)
GaInP/GaAs;GaInAsP/GaInAs (concentrated)	0.0520	46.0 ± 2.2	AIST(10/2014)

The crystalline silicon solar cell with 29.4% laboratory efficiency cannot be improved further without adding external functionality to the device. In practical applications an efficiency of 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 (Sinke, 2019). To reach higher efficiencies, the next step is to add a second absorber material to the silicon and to build a hybrid (wafer-silicon/thin-film) tandem (Werner, 2018), preferably with a thin-film-wide-gap top cell and a silicon bottom cell.

The development of Gen4 cells was delayed by the high costs of wide bandgap materials and cells. The discovery of a new class of (organic-inorganic) perovskites has relaunched efforts to realize efficient and cheap tandems. High efficiency as 32.8% (Green, 2018) was reached by Tandems using a III-V semiconductor top cell and a silicon bottom cell, but despite the yield, they are not yet cost-competitive.

3. Advantages and Drawbacks of Different Types of PV Cells

Significant improvements have been made in materials used and the production processes to reduce the costs, and to avoid possible issues induced by some hazardous materials (Nkuissi, 2020).

The choice of the different types of application and the robustness of the photovoltaic development are some of the advantages of the various technologies. But it has drawbacks namely confusion and uncertainty among potential investors, researchers and policy makers and the development and dilution of public funds for research are also trends to be expected. The first generation photovoltaic refers to devices based on normally crystalline silicon and a wafer. Those of the second generation are conventional thin films, namely cadmium telluride (CdTe), amorphous or microcrystalline silicon (aSi or mcSi) and copper-indium / gallium diselenide / sulphide (CIGSS). Indeed, the second- and first-generation cells have in common the performance not exceeding the Shockley-Queisser (SQ) limit only for bandgap devices (Stock, 2016). In addition, the technologies of the first generations have a very high cost unlike those of the second generation. Third-generation photovoltaics are suitable for devices whose efficiency is above the SQ limit (Polman, 2016). Over the past 25 years, researchers, analysts, students, and others specialists have frequently categorized these four generations. This evolution demonstrates that the combination of diverse technologies can stimulate innovation. It is broadly accepted that that diversity contributes to technological development (Lacerda, 2016). Diversification of materials and innovative combinations assures the dynamics of the solar PV field.

4. Characteristics of Panels

A system is more efficient in cold weather (wind or cooling system, low ambient temperature) than in hot weather, with equal sunshine. For increasing energy production from 3% to 7%, is needed a decrease in temperature of 10°C. The performance of an installation therefore varies depending on the inclination with respect to the ground and the technical characteristics of the photovoltaic panels for given atmospheric and environmental conditions (Adouane *et al*., 2014).

- *The lifespan of a photovoltaic panel*

It can be defined as a point in time from which the module is no longer acceptable for any reason, whether in terms of safety, appearance, catastrophic event, or when the power supplied falls into line below an acceptable value. The period during which its performance is guaranteed in a given interval is the useful life of a module. The current consensus is that a PV module is guaranteed for 25 years at 80% of its initial power (and 90% after 10 years) (Grätzel, 2014).

- *Maintenance of the photovoltaic installation*

Solar panels operate on their own after installation and maintenance is usually limited to an annual cleaning after fall. Rain and wind keep the facility clean.

- *Recycling of solar panels*

Solar panels are recyclable. The transport of photovoltaic waste and collection is organized by the PV Cycle Association, which has implemented a process allowing solar panels to be recycled at 95%.

- *Manufacturer warranty*

Solar panel manufacturers offered 10-year warranties in the early 1990s. These warranties are typically 25 years today. Ultimately, the lifespan of solar panels is much longer than expected. Solar professionals estimate that a well-installed and maintained photovoltaic solar panel will produce electricity for around 40 years.

5. Factors Influencing the Performance of Photovoltaic Panels

• *Form factor*

We call form factor FF or fill factor, the ratio between the maximum power supplied by the cell P_{max} (I_{opt}, V_{opt}) and the product of the short-circuit current I_{cc} by the open-circuit voltage V_{co} (that is, the maximum power of an ideal cell). The form factor indicates the quality of the cell. In practice, the closer it gets to the unit, the more efficient the cell is. Normally, the form factor is around 0.7 for efficient cells and decreases with temperature. It is defined by:

$$FF = \frac{P_{max}}{I_{cc}V_{co}} = \frac{I_{opt}V_{opt}}{I_{cc}V_{co}} \quad (1)$$

with, I_{opt} the optimal current et V_{opt} the optimal tension.

• *The yield*

The efficiency represents the ratio between the maximum electric power supplied by the cell and the incident solar power. It is important here to emphasize that the incident solar power is equal to the product of the illumination with the surface of the solar cell. Efficiency gives us the quality of converting solar energy into electrical energy. It is given by (Kaidi and Kaal, 2020):

$$\eta = \frac{P_{max}}{P_{inc}} = \frac{I_{opt}V_{opt}}{E_S S_{cellule}} \quad (2)$$

• *Lighting influence*

The illuminance of the sun has a considerable impact on the performance of a photovoltaic cell. Since the photo-current and the irradiance (illuminance) are proportional, because the illuminance varies during the day, the characteristic of a photovoltaic cell changes. At constant temperature, we notice that the short-circuit current increases with illumination while the circuit voltage varies a little. The increase in illuminance therefore increases the yield (Kaidi and Kaal, 2020).

• *Influence of temperature*

The temperature has an influence on the efficiency and, consequently, on the power output, due to increased internal carrier recombination rates, caused by increased carrier concentrations. Indeed, efficiency decreases when the temperature increases. So, the PV cells yield depends linearly on the operating temperature and regions with high altitude have higher performance ratios due to low temperature (Dubey, 2013).

The PV cell temperature depends on weather variables (as ambient temperature, local wind speed or solar radiation), material and system dependent properties (glazing-cover transmittance, plate absorbtance etc.).

It is necessary to clarify that the temperature in consideration is the temperature of the cell. The increase in temperature causes an almost constant current, while the open circuit voltage decreases (Kaidi and Kaal, 2020).

• *Positioning influence*

The energy supplied by the photovoltaic panel strongly depends on the amount of solar illumination absorbed by it. This amount depends on the orientation of the panel in relation to the sun. In order to have the maximum energy, the photovoltaic panel must be constantly perpendicular to the sun's rays. Each time the angle increases or decreases, the area of the panel exposed to the rays decreases and therefore the yield decreases since this depends on the area of the panel exposed to the sun.

• *Inclination influence*

One factor that influences performance is tilt, which is the angle formed by the plane of the solar panel from the horizontal (the ground plane). The evolution of the sun's trajectory varies with the seasons and with the angle of inclination being smaller in the summer and greater in the winter.

• *Influence of wavelength*

The visible spectrum occupies most of the optical window, a range of wavelengths that are easily transmitted through the Earth's atmosphere. This region of the electromagnetic spectrum intersects with that where solar irradiance is maximum at the surface of the Earth.

6. Conclusions and Recommendations

This work consists of carrying out bibliographical research on the evolution of the manufacturing technology of photovoltaic panels and application difficulties. This study deals with the different types of constraints that can influence the production of photovoltaic system. Taking into account climatic factors is important for decision making in the manufacture of photovoltaic cells. The position of photovoltaic technologies and the development over the past decade in the market seems to differ from generation to generation. Therefore, the vision to think about the current evolution of photovoltaic panel manufacturing and application difficulties in a context is a clear prospect. Increasing or dosing the amount of materials for the manufacture of panels will increase the efficiency and performance of photovoltaic systems under different conditions beyond 20% and may be suitable for desert climates. It would be better for the population to buy solar panels made from third or even fourth generation cells that could be adapted to different climates.

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EVOLUȚIA TEHNOLOGIEI DE FABRICAȚIE A PANOURILOR FOTOVOLTAICE ȘI FACTORI CARE AFECTEAZĂ PERFORMANȚELE ACESTORA

(Rezumat)

Eficiența producerii de electricitate din energie solară depinde de evoluțiile tehnologice și de performanța panourilor fotovoltaice. Un trend pozitiv depinde de diversificarea materialelor utilizate în fabricarea plăcilor și de adaptarea acestora la condițiile climatice. În articol se prezintă mai multe aspecte tehnologice pentru a da o idee despre evoluția randamentelor panourilor fotovoltaice, în special despre tehnologia fotovoltaică din prima, a doua și a treia generație. După enunțarea principalelor caracteristici ale panourilor fotovoltaice, se face o analiză a factorilor care pot afecta performanțele acestora și crea dificultăți la implementarea proiectelor. Acest demers are scopul de a alege cea mai avantajoasă combinație de concepte și tehnici la realizarea parcurilor fotovoltaice.