Brussels, 13.06.2024

# EUROPEAN SOLAR PV INDUSTRY ALLIANCE
# PV PASSPORT JOURNEY I: Paving the way

## Understanding Solar PV as a Preliminary Step Toward Implementing a PV Module Passport

## Background

A digital product passport is a comprehensive digital record that tracks the entire lifecycle of a product, from raw materials to disposal. It includes information on materials, manufacturing processes, and environmental impact, providing transparency and accountability. For solar modules, which have a complex supply chain involving critical raw materials, such as silicon and rare earth elements, a passport would streamline traceability, ensuring sustainability and ethical sourcing. By digitizing and centralizing data, stakeholders can make informed decisions, enhance efficiency, and promote circular economy principles, ultimately advancing the sustainability of solar energy.

The aim of this paper is to provide a comprehensive overview of solar photovoltaic (PV) technologies as a preliminary step toward proposing the implementation of a solar PV Passport, or material passport, into regulation within the European Union. Solar PV technologies represent a critical component of renewable energy systems and in line with the REPowerEU plan and the EU Solar Energy Strategy, their deployment in EU is accelerating, aiming to reach over 320 GW of solar PV capacity by 2025 and nearly 600 GW by 2030. This impressive deployment demands an understanding of the diverse array of solar PV technologies and their underlying principles, so that stakeholders can make informed decisions regarding their adoption and integration into regulatory frameworks.

Although inverters are a critical component of solar PV systems, converting the direct current (DC) generated by solar panels into alternating current (AC) for use in electrical grids and homes, they are out of the scope of the PV module passport paper. The complexity of listing the numerous and varied components within inverters, such as semiconductors, capacitors, and other electronic parts, presents significant challenges. Consequently, this paper focuses exclusively on the solar PV modules themselves, ensuring a more manageable and focused approach to establishing the PV passport framework. In the future, there should be a workstream that tackles inverters directly within the European Solar Industry Alliance (ESIA), to propose policies pertaining material passports and more.

Solar photovoltaic modules, also known as PV modules, are devices designed to harness sunlight and convert it into electricity. When sunlight hits the solar cell, it creates electron-hole pairs. The positively charged holes move to one surface, while electrons move to the opposite, depending on the direction to which the charges move, the solar cells can be described as p- or n-type. Metal contacts on both surfaces collect the electricity. . This phenomenon, known as the photovoltaic effect, generates direct current (DC) electricity.

PV modules are widely used to generate electricity for residential, commercial, and industrial applications, powering everything from homes and businesses to remote off-grid installations. The production of solar modules involves various manufacturing steps, ranging from the processing of semiconductor materials to fabricate the solar cells, to the assembly of the cells into modules. Various technologies, including wafer-based crystalline silicon, thin-film, tandem, and emerging materials like perovskites or organics, contribute to the diverse landscape of solar module production. As the demand for clean energy continues to rise, innovative deployment routes are required and advancements in solar module technology and manufacturing processes play a crucial role in achieving a sustainable energy future.

Applications of solar PV vary widely but typically these resources are used as:

- **Residential:** PV modules are commonly used on residential rooftops to generate electricity for household consumption. They can help homeowners reduce their reliance on grid-supplied electricity and lower their energy bills.
- **Commercial:** Many commercial buildings utilize PV modules to offset their energy consumption and reduce operational costs. They can be installed on rooftops or as part of ground-mounted solar arrays.
- **Utility-scale:** Large-scale solar farms deploy PV modules to generate electricity for the grid. These utility-scale installations contribute to renewable energy generation and help meet the increasing demand for clean energy.

We will now delve into detailed descriptions of current and upcoming solar technologies. This exploration aims to articulate their characteristics and enumerate fundamental components. Our focus encompasses existing market offerings and emerging innovations poised to shape the future of solar energy generation.

## 1. Wafer-based crystalline silicon technology

Silicon-based solar modules are photovoltaic devices that convert sunlight into electricity using silicon as the primary semiconductor material. There are two main types of silicon cells, mono and multicrystalline.

- **Monocrystalline** silicon-based solar modules are renowned for their high efficiency, uniformity and sleek aesthetics. They are crafted from single-crystal silicon ingots. Due to their single-crystal structure, monocrystalline modules achieve higher efficiency in converting sunlight into electricity compared to other types of solar modules. The efficiency advantage makes them particularly suitable for installations where space is limited, or maximum energy production is desired. Additionally, the uniform appearance of monocrystalline panels adds to module appeal, making them a popular choice for residential and commercial applications seeking both performance and visual harmony. The nature of the required manufacturing processes to manufacture single-crystal ingots requires high energy input, hence making the location and management of these processes a key component on the value chain.
- **Multi-crystalline** silicon modules offer cost-effective alternatives, utilizing silicon ingots with varied crystal structures for widespread adoption in solar applications. These modules are manufactured by melting raw silicon and then casting it into molds, resulting in multiple crystal structures within each silicon wafer. While muti-crystalline modules typically have a slightly lower efficiency compared to monocrystalline panels, they make it up with lower production costs, making them a popular choice for large-scale solar installations where cost-effectiveness is a priority. Their versatility and affordability contribute to their widespread use in both residential and commercial projects.

Current common technologies for silicon-based modules:

- **Passivated Emitter and Rear X** (PERC, PERT, PERL…) technologies enhance silicon solar cells' efficiency through various methods like passivation, improving light absorption and reducing electron recombination.
- **Tunnel Oxide Passivated Contact** (TopCon) solar cells feature high-efficiency designs with contacts placed strategically on both front and rear sides, maximizing energy output.
- **Heterojunction Technology** (HTJ) merge different semiconductor layers, achieving high efficiency and stability with low temperature coefficients and higher bifaciality.

- **Interdigitated Back Contact** (IBC) cells minimize shading losses with contacts on both cell sides, offering improved efficiency.

## 2. Thin Film technologies

Solar thin film technology is a type of photovoltaic technology that utilizes thin layers of semiconductor materials to convert sunlight into electricity. Unlike traditional silicon-based solar modules, which use thick silicon wafers, thin film solar cells are composed of much thinner layers of semiconductor materials deposited onto a substrate. This approach offers several advantages, including flexibility, lightweight construction, and potentially lower manufacturing costs.

- **Composition:** Thin film solar cells are typically composed of one or more layers of semiconductor materials deposited onto a substrate. Compared to the c-Si PV batch process, thin-film PV modules are produced in a single continuous process by depositing semiconductor material on cost-effective substrates like glass or plastic. These materials are deposited using various techniques such as chemical vapor deposition (CVD), sputtering, or printing onto substrates such as glass, plastic, or metal foils.
- **Types:** There are several types of thin film solar cells, each based on different semiconductor materials.
    - **Cadmium telluride:** CdTe thin film cells offer high efficiency and stability with a semiconductor made from cadmium and tellurium.
    - **Copper Indium Gallium Selenide** (CIGS) thin film cells feature a semiconductor blend of these materials, providing versatility and efficiency.
    - **Amorphous Silicon** (a-Si) thin film technology utilizes non-crystalline silicon deposited on substrates like glass or flexible materials. It offers flexibility, lightweight construction, and potential cost advantages in solar applications.
    - **Perovskite** thin film cells offer high efficiency and potential for low-cost manufacturing with promising materials. Research focuses on optimizing materials and designs to achieve greater performance and commercial viability in renewable energy applications.
    - **Organic** thin film cells utilize carbon-based materials for flexibility and potential large-scale production.

## 3. Next generation PV

Multijunction technologies are considered the next generation of PV applications. These technologies combine 2 or more cells (junctions) in a single device, each of the cells generating energy at complementary wavelengths of the solar spectrum, increasing the total efficiency of the final device. Multijunction devices can be made combining wafer-based silicon cells with thin film technologies, or thin film technologies only. Tandem technologies are a class of multijunction systems where only 2 cells (junctions) are processed together. The tandem technology that is expected to reach the market soon is the one combining perovskite with silicon cells. Typically, tandem cells consist of a top solar cell that absorbs high-energy photons (perovskite) and a bottom solar cell that captures lower-energy photons (silicon), covering a broader spectrum of sunlight. Tandem technology offers potential for significantly higher efficiencies, making it promising for improving solar energy generation.

## 4. Other technologies

Concentrated Photovoltaics (sometimes silicon-based): CPV systems use optical concentrators to focus sunlight onto high-efficiency solar cells, increasing energy output.[1]

## 5. Other applications

Aside from the applications listed throughout the introduction of the paper, we believe that it is important to mention certain specialty applications that do require changes in the composition on the solar module.

- **Building Integrated PV** (BIPV): BIPV systems integrate solar modules into building materials, providing energy generation and architectural benefits. These modules are integrated directly into building materials, such as roofs, windows, or facades, during the construction or renovation process. This integration differs from traditional solar modules that are mounted on top of existing structures. BIPV systems may have different components tailored to their specific integration points. For instance, solar roof tiles or shingles replace conventional roofing materials, while solar windows incorporate transparent solar cells into glass panels.

---

[1] See more on Concentrated Photovoltaics (CPV) in the references.

- **Vehicle Integrated PV** (VIPV): involves integrating solar modules directly into vehicles, such as cars, buses, or boats, to supplement onboard power and extend range. Unlike traditional solar modules mounted rooftops or ground-based structures, VIPV systems are specifically designed to withstand the unique conditions and constraints of vehicle integration. VIPV systems may include components for seamless integration with the vehicle's electrical system, such as inverters, charge controllers, and wiring harnesses. These components ensure efficient energy transfer from the solar modules to the vehicle's battery or auxiliary power systems.
- **Agro-photovoltaics** (APV): combines agriculture with solar energy production by installing solar modules above or alongside crops. Unlike traditional solar modules, APV systems are designed to coexist with agricultural activities and provide additional benefits beyond electricity generation. These modules must be carefully spaced and laid out to minimize shading of crops and optimize sunlight exposure. The spacing between solar modules and the of support structures are critical factors that must be considered to ensure adequate sunlight reaches the crops for photosynthesis.
- **Floating PV:** require buoyant structures to support solar modules on water bodies. Components must be waterproof and corrosion-resistant, using marine-grade materials. Mooring systems anchor structures, preventing drifting, while access platforms facilitate maintenance. Anti-fouling measures prevent debris accumulation, ensuring module efficiency. Electrical safety measures, including insulated wiring and ground fault protection, are crucial. FPV designs prioritize environmental considerations to minimize ecological impact, such as avoiding sensitive habitats. These systems offer efficient land use, reduced water evaporation, and renewable energy generation.

As solar PV technology advances, new innovations will emerge, necessitating regulation under a PV passport. While current technologies are crucial, future advancements, such as next-generation solar cells or integrated systems, will also benefit from standardized tracking and regulation. It is possible that this paper has overlooked certain technologies, but comprehensive regulation ensures that all advancements are accounted for, fostering sustainability, transparency, and responsible innovation in the solar energy sector.

This paper aims to lay the groundwork for subsequent discussions on implementing a solar PV Module Passport within EU regulation. By understanding the fundamentals of solar PV technologies, policymakers can develop informed policies to promote the adoption and sustainability of solar energy within the European Union.

## REFERENCES

European Commission (2022). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: EU REPowerEU Plan, COM/2022/220 final

European Commission (2022). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: EU Solar Energy Strategy, COM/2022/221 final

Study: Current Status of Concentrator Photovoltaic (CPV) Technology Maike Wiesenfarth, Dr. Simon P. Philipps, Dr. Andreas W. Bett, Fraunhofer ISE / Kelsey Horowitz, Dr. Sarah Kurtz, National Renewable Energy Laboratory NREL, USA | Version 1.3, (2017, April). https://www.ise.fraunhofer.de/en/publications/studies/studie-current-status-of-concentrator-photovoltaic-cpv-technology.html

“Strategic Research and Innovation Agenda on Photovoltaics”, ETIP-PV, 2022

What is thin-film PV?. PVthin. (2024, April 2). https://www.pvthin.org/what-is-thin-film-pv/

Wilson, G. M., Al-Jassim, M., Metzger, W. K., Glunz, S. W., Verlinden, P., Xiong, G., Mansfield, L. M., Stanbery, B. J., Zhu, K., & Yan, Y. (2020, September 9). The 2020 photovoltaic technologies roadmap. Journal of Physics D: Applied Physics. https://iopscience.iop.org/article/10.1088/1361-6463/ab9c6a/meta