Life Cycle Analysis & Sustainable Technological Roadmap for Photovoltaic Panels: Case Study with the Silicon Heterojunction Technology

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The Earth is a planet which possesses finite physical boundaries (known as planetary boundaries) and host a great diversity of living organisms. Among them, the Human being is strongly influencing the Earth ecosystems with its activities since the past century, leading to a **Climate crisis** with consequent detrimental impacts on human health, earth's environment and the economic system. In this context, **Life Cycle Assessment** (**LCA**) methodology was developed to quantify the **impact** of a **product** or activity on the different **planetary boundaries** (represented by impact categories).

Over the **past decade** (2009-2019), energy consumption showed 2% (**3.75%** for **electricity**) of **increase per year** with still an intense use of non-renewable energy sources (such as coal, oil and gases) [1]. In addition, **resources supply** represents a **challenge** with the current and future resources rarefaction (water, raw materials, energy). Therefore, a **clean energy** production technology based on **accessible resources** is required to ensure the worldwide energy supply while limiting its impact on the planetary boundaries.

In this context, **Photovoltaic (PV),** which produces electricity thanks to the energy of the Sun, is poised to be the key pillar of the future **low carbon** energy mix [2], with crystalline silicon (c-Si)-based technologies called to take the lion's share of it [3]. The **heterojunction technology (HJT)** has been under development for three decades and is now identified as one of the PV technologies to succeed to **PERC** (which was the successor of **Al-BSF**). In **Europe** alone, **8.8 TW** of installed PV capacity is required by **2035** to fulfil the **net-zero carbon** emission objectives [4]. Nevertheless, widely acknowledged technological **roadmaps** for PV [5] mostly focus on the race to **higher efficiency** and **lower cost**, while **environmental** aspect **should be considered** for a successful TW-scale deployment.

Therefore, this work mainly gravitates around a crucial question: **"How to reduce the environmental impact of PV systems, especially for Heterojunction Technology?"** and is treated in **3 steps: (i) upgrade LCA data, (ii) calculate environmental impact** & **evaluate scenarios** and finally **(iii) provide recommendations** for European PV manufacturers.

1. Upgrade LCA data for c-Si technologies (Al-BSF, PERC, HJT)

As a first step, I constructed a **PV system model**. A PV system grid-connected is composed of a PV module (in our case a Glass-Backsheet (GBs) as depicted in Figure 2) and the Balance of System (BOS) (inverter, structure for PV). The PV module is itself composed of solar cells based on sc-Si wafer, that convert solar energy into electricity. Finally, the end-of-life (disposal/recycling) of PV system is modelled separately (see Figure 1).

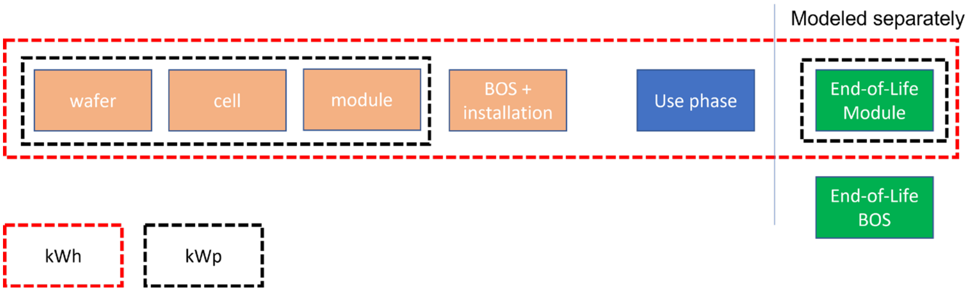

Figure 1. Simplified representation of the PV system for **FU (kWh)** and **FU1 (kWp)**

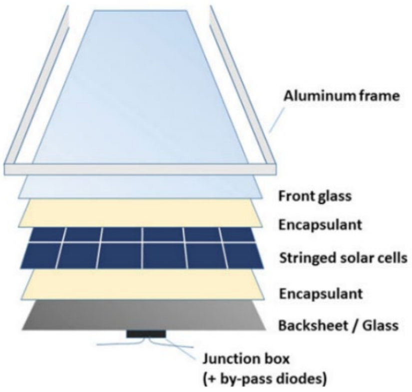

Figure 2. Composition of a PV module

The **functional units (FU)** considered in our investigation are twofold and are represented in Figure 1:

- **FU**: "*ensure the production of* ***1 kWh*** *of AC* ***electricity*** *in Europe over 30 years with a 3 kWp grid-connected PV-system*" which is directly linked to final purpose of PV systems (electricity production) [6].
- **FU 1**: "*ensure the production and end-of-life of* ***1 kWp*** *PV* ***panels*** *in Europe*", which is mainly used by PV manufacturers, as it focuses on PV panel production (wafer, cell, module) and excludes use phase and BOS.

The Ecoinvent 3.7.1 database was used for the life cycle inventory. The main **challenge** of this project was to acquire state-of-the-art **technological data** and convert it into usable data (Ecoinvent compatible) for environmental impact calculations (on Simapro software). For each building block of the PV system (**wafer, cell, module, BOS + Installation, use phase, End-of-Life**), a back-up Excel sheet records all Ecoinvent compatible processes and key parameters used in Simapro software.

The Environmental Footprint 3.0 method was used for the life cycle impact assessment and all 16 impact categories were calculated. We focus here on the **5** of **major relevance** for PV system of the current disruption to the planetary boundaries, namely **climate change (CC)** linked to global warming potential, **particulate matters (PM)** linked to air pollution**, water use (WU), resource use, fossil (RUF)** and **resource use, minerals & metals (RUM**) linked to resource depletion.

2. Calculated environmental footprint for c-Si technologies, and evaluation of scenarios for HJT

As a second step, I performed the LCA for three sc-Si-based PV technologies, namely **Al-BSF** (using a first set of data dating back **2010**, and a more recent one dating back **2020**), **PERC** (**2020** data set), and **HJT** (using CSEM's most recent knowledge for the data collection).

Figure 3 plots the **CC impact** category for the three above-mentioned PV technologies. Remarkably, between 2010 and 2020, the CC impact of Al-BSF has been divided by 5. This mainly owes to the massive reduction in the **wafer thickness** (270 µm vs. 170 µm) in this period, as well as to the **increased efficiency** of the Al-BSF modules (14 % vs. 19.5 %). Compared to this dramatic reduction, the PERC and the HJT technologies offer only a marginal CC impact mitigation, **HJT** having eventually the **lowest CC impact** (88% reduction of EU energy mix impact). Noteworthy, the 2020 CC impact for the three c-Si technologies under consideration is dominated in equal shares by the wafer manufacturing and the BOS.

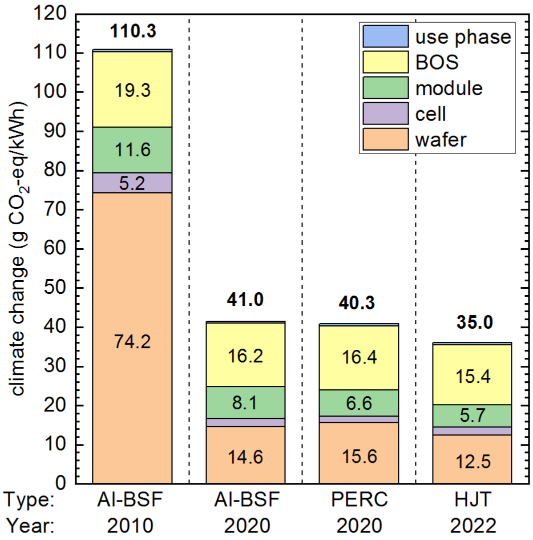

Figure 3. Climate change impact for the 3 PV technologies (Al-BSF, PERC, HJT) for kWh FU

Figure 4 plots the CC, PM, WU, RUF, and RUM impacts for the specific case of **HJT** broken down by contributions (wafer, cell, module, BOS and use phase). For **CC**, **PM**, and **RUF**, the impact is dominated in similar shares by the **wafer** and the **BOS**. For **WU**, it is interesting to note that the **cell processing** presents an important impact, calling for potential adaptation and optimization of this process step. For **RUM**, **80 %** of the impact owes to the sole **BOS**.

To clearly identify which process or materials were responsible of the environmental footprint of HJT PV system, I carried out a more **in-depth analysis** for **each building block** of the PV system (wafer, cell, module, BOS, use phase and end-of-life). Thanks to this analysis, **alternative scenarios** were evaluated for each building block to **reduce** the environmental **footprint** of HJT technology.

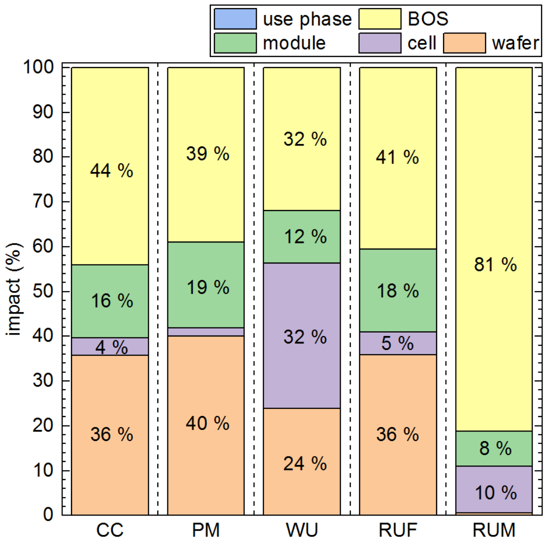

Figure 4. HJT 2022 PV system repartition of impact (for CC, PM, WU, RUF and RUM) for kWh FU

3. Recommendations for European PV manufacturers

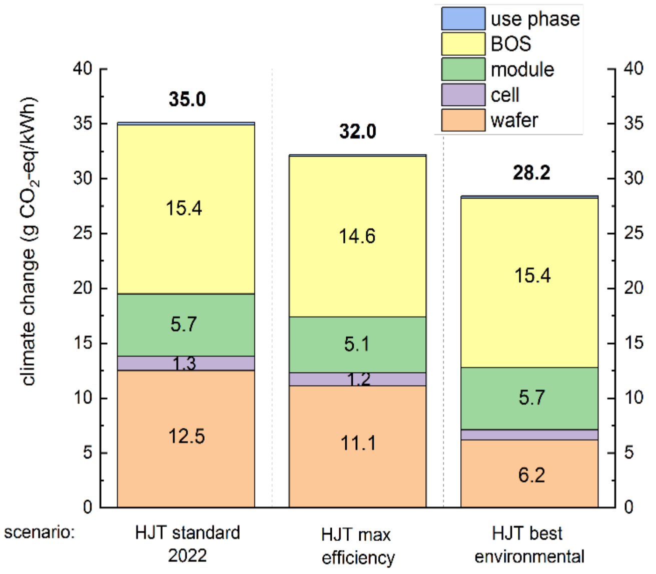

Figure 5. HJT carbon footprint for kWh FU for 3 different scenarios (standard 2022, max efficiency and best environmental)

Finally, I compared the alternative scenarios with the current development tendency for HJT technology. Figure 5 shows the carbon footprint of three different cases for HJT technology:

- HJT **standard** 2022
- HJT max efficiency: Future HJT developments thanks to PV roadmaps (module **efficiency increase** from 21.75% to 24.5%)
- HJT best environmental: Implementation of 2 major changes for HJT PV manufacturers: (i) **European wafer** supplier instead of Asian suppliers (partial recycle of c-Si and low carbon electricity mix), (ii) optimized cell processes by **suppressing the use** of indium and silver (**Critical Raw Materials (CRMs)**).

Figure 5 shows the impact of these different scenarios than can be implemented by PV manufacturers (concerning wafer, cell and module). I observe that **choosing European wafer** and **removing CRMs (indium and silver free)** for cell processes leads to a **larger carbon footprint reduction** than the race to **module efficiency** and **cost reduction** (PV roadmaps).

To further **reduce** the overall **environmental footprint** of HJT technology I identified the following points:

- **Extend PV system lifetime** (standard lifetime being 30 years, an increase of 10% of lifetime leads to a 9% reduction of environmental impacts)
- Choose sunny **location** (for example a PV system installed in South of Spain will produce 2.7 times the energy produced by the same PV system installed in the north of Norway over the same period)
- **Recycle PV module** & **BOS** (recycling PV module instead of a standard disposal will lead to a reduction of 7% of the carbon footprint for HJT module)
- Reduce **BOS** impact (by developing eco-designed inverters and reducing the weight of aluminum structure)

To overcome the current global energy crisis and climate change, renewable energies, and in particular **solar photovoltaic** energy, will have to play a **major role** in the future **low-carbon energy mix**. However, the large-scale deployment of photovoltaic energy is not without its many **environmental** and **societal challenges**.

Over this work, I used **life cycle assessment** tools to guide photovoltaic technologies towards greater **environmental sobriety** and **social equity**. First, I gathered **recent** and first-hand data from current solar panel manufacturers which allow us to get a comprehensive and **up-to-date** mapping of the **environmental impacts** of photovoltaic systems. Then, by highlighting the **major contributors** for each impact category (e.g., climate change, resource use, particulate emissions), I identified the most **promising technology** solutions to **reduce** these **impacts**. Finally, a I proposed a **sustainable roadmap** for integrating these technological innovations with materials produced locally and under ethical conditions, e.g., using European silicon wafer. The results obtained for this project have aroused strong interest at the European level as well as for the CSEM where I currently work on PV module reliability (to extend their lifetime) and continue LCA activities. As a conclusion, **this project** and its implications **participate** actively in the **sustainable development** of **current** and **future European solar technologies**.

Bibliography

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