

Life Cycle Analysis of Heterojunction Solar Cells - From Raw Materials to Final Devices



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Abstract

Photovoltaic (PV) is poised to be the key pillar of the future low carbon energy mix [1], with crystalline silicon (c-Si) based technologies called to take the lion's share of it [2]. In Europe alone, 8.8 TW of installed PV capacity is required by 2035 to fulfil the net-zero carbon emission objectives [3]. On the one hand, pitfalls in achieving such TW-scale deployment in an environmentally sustainable manner are well known [4][5]: scarce materials (silver, indium), imported wafers with high carbon footprint, etc. On the other hand, the widely acknowledged technological roadmaps for PV [6] mostly dismiss these caveats, as the key driver for the PV industry remains the race to higher efficiency and lower cost.

Life Cycle Assessment (LCA) is the method of choice to compute the short- and long-term impacts of PV technologies [7], but the data it uses are often obsolete, and its outcomes are too rarely taken into consideration in the PV devices process flows and materials. Along these lines, this study aims at bridging the gap between the LCA dataset and the current PV technologies by providing the latest figures, starting with the case study of the Heterojunction Technology (HJT). Comparing the results to other updated single-crystalline silicon (sc-Si) technologies (Aluminum-back Surface Field (Al-BSF), Passivated Emitter and Rear Contacts (PERC)), this thesis identifies the areas of major environmental impact and technological pathways to address these challenges.

This thesis shows that the HJT technology has a lower environmental impact than Al-BSF and PERC, with a carbon footprint of 35 gCO₂-eq/kWh. Assuming European-made wafers, optimized metallization and Physical Vapor Deposition (PVD) cell process, HJT has the headroom to further reduce its environmental impact to 28.8 gCO₂-eq/kWh considering the current module efficiency (21.75%). Wafer production and Balance of System (BOS) & Installation are shown to dominate, with similar shares, most of the impact categories for HJT, except for the (Resource Use, Minerals and Metals (RUM)) for which the BOS alone accounts for 80% of the impact per kWh. The wafer carbon footprint of HJT and its use of minerals & metals resources can be reduced by 90 % if the sc-Si wafers are produced in European countries with a low carbon electricity mix and if the wafer thickness is reduced by 20% compared to nowadays baseline (170 μ m). Furthermore, this work shows that the use of copper electroplating instead of screen-printed silver pastes only marginally mitigates the carbon footprint of HJT, but in contrast potentially reduces the RUM resources by more than 50% considering the kWp Functional Unit (FU). Finally, a sum-up of results and their implications in terms of PV processes and materials is delivered to PV manufacturers as a take-home message.

Keywords

Life Cycle Assessment (LCA), Heterojunction Technology (HJT), sustainability, Photovoltaic (PV), Environmental Footprint (EF), Carbon Footprint, Critical Raw Material (CRM),

Acknowledgments

This project, called Master Thesis, is the latest step of the master cycle for EPFL students. It was realized in the frame of an internship at CSEM between September 2021 and March 2022. I would like to thank all the people who helped me during this project and more generally through EPFL time.

I would like to thank Matthieu Despeisse I met at Monaco for the Swiss Solar Boat project and introduced me to the CSEM world. Many thanks to Christophe Ballif who supervised this master thesis and showed a strong interest and provided good advices for my research in PV sustainability. I would like to also thank Jérôme Payet who supported me for many projects at EPFL and provided me a very useful support for LCA aspects. Furthermore, I would like to express my gratitude to Bertrand Paviet-Salomon and Laurie-Lou Senaud who provided me support and advice of very high quality all along this project, while keeping a very friendly work atmosphere.

Many thanks to my other colleagues at the CSEM, Business Unit V, from the 568 group (Nicolas, Patrick, Christophe, Jun, Jonas, Agata) as well as 564 group (Jonathan, Antonin, Sukanya, Jacques) for nice moments, data and support. I would like to thank Jonathan from VOLTEC, Damien from MBR, Rolf Frischknecht from TREEZE, Mariska Wild-Scholten from SmartGreenScans and speakers of the EU-PVSEC for their data and exchanges that helped me to have a more impacting thesis. Furthermore, I would like to thank the team of interns (Lison, Kléber, Hugo, Loïc, Ziad, Pascaline) for their support and good times shared around a well deserved beer.

I would also like to thank all associative comrades who help me through EPFL and conducted me to CSEM (TREE members, PolySports members, Swiss Solar Boat members) and to the people I met more recently in Neuchâtel: rugby team members, Abby and my roommates (Alain, Léa, David and Emma). Many thanks to my Strasbourg friends (Eliott and Robin) for the great time shared together. More than anything else, thanks to my EPFL friends team (Raphael, Nouha, Edouard, Blanche, Hugo, JA, Aurélien, Aurélie, Julie, Mélodie, Gaël, Lorenzo and Marisa) who contributed to make the EPFL time a great and memorable time [8].

Finally I would like to thank my parents Franck and Géraldine for their trust, listening and support all along my studies: they always helped me to make the right choice. Thanks to my brother (Quentin) and sisters (Claire-Sophie and Philippine) for the always good family time shared together.

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Abbreviations

EPFL	Ecole Polytechnique Fédérale de Lausanne
CSEM	Swiss Center for Electronic and Microtechnology
IEA	International Energy Agency
PV	Photovoltaic
HJT	Heterojunction Technology
PERC	Passivated Emitter and Rear Contacts
Al-BSF	Aluminum-back Surface Field
c-Si	crystalline silicon
sc-Si	single-crystalline silicon
mc-Si	multi-crystalline silicon
AZO	Aluminium-doped Zinc Oxide
BF	Bifacial
IBC	Interdigitated Back Contact
TCO	Transparent Conductive Oxide
ITO	Indium-Tin Oxide
PVD	Physical Vapor Deposition
PECVD	Plasma Enhanced Chemical Vapor Deposition
GHG	Greenhouse Gas
PEF	Product Environmental Footprint
LCOE	Levelized Cost of Electricity
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
FU	Functional Unit
CRM	Critical Raw Material
EF	Environmental Footprint
RF	Reference Flow
BOS	Balance of System
EoL	End of Life
CC	Climate Change
PM	Particulate Matter
RUF	Resource Use, Fossils
RUM	Resource Use, Minerals and Metals
WU	Water Use
EPBT	Energy Payback Time
CED	Cumulative Energy Demand

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Chapter 1

Introduction

1.1 General Context

The scientific consensus is unequivocal: Global warming is mainly caused by Greenhouse Gas (GHG) emissions from anthropological activities [9]. Industry, transport, residential and other sectors are all consuming energy, whose production and consumption impact the Earth ecosystems. GHG emitted in the atmosphere leads to changes in the climate system yielding many detrimental effects, such as the loss of biodiversity, more severe droughts, and more powerful storms. Consequently, human, environmental and financial costs are drastically increasing [10]. Despite this situation, the total final energy consumption was increasing by 2% per year in average during the past decade (2009-2019) according to the International Energy Agency (IEA) [11]. This trend is most pronounced for final electricity consumption, 3.75% of increase per year in the same period (2009-2019) [12] with an electricity demand expected to grow of 17.4% between 2019 and 2030, to represent 21% of the world total energy demand in 2030 according to IEA New Policies Scenario [13].

In 2020, electricity was mainly produced from non-renewable technologies (coal, oil, gas) that are harmful for the environment. In parallel, the sun provides us with a large amount of energy. In just over an hour, the equivalent to the world's annual energy consumption is radiated to the earth's surface [14]. Two major types of technology exist to convert this free and available solar energy to usable energy. Solar Photovoltaics (PV) panels, which generate electricity, and solar thermal systems which provide domestic hot water. Different from conventional sources of energy, PV system are available all over the globe and can be adapted to various configurations (grid-connected, stand alone, hybrid), various uses (utility plant, captive plant), and installation types (rooftop, ground-mounted, floating).¹

The development of renewable energy sources urgently needs to be encourage to limit CC. Renewable energy sources are expected to meet 99% of the global electricity demand increase during 2020-25 mainly thanks to the development of solar PV and wind technologies. Nevertheless, a rise of 110% of renewable energy production between 2019 and 2030 is needed to achieve 15000 TWh production and thus to be aligned with the Sustainable Development Scenario (SDS) [13].

¹For non-PV-initiate readers, please check videos with detailed explanations on how PV works [15] and what are the different types of PV systems [16]

1.2 State of the art

1.2.1 PV market & technologies

The PV production market has been mainly dominated by Asia for the last decade, as depicted in Figure 1.1. The Asian production is nowadays leading the world market (95%), mainly related to Chinese production of PV (67% of world production)[2].

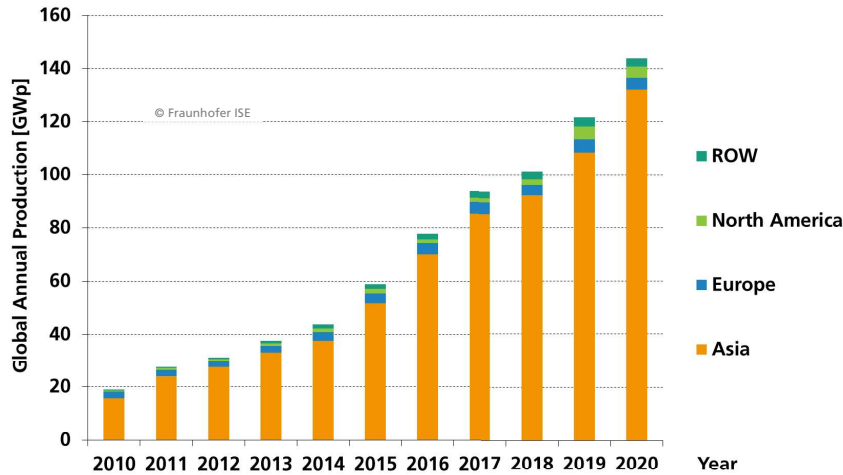


Figure 1.1: World PV production market, Fraunhofer ISE [2]

According to IEA [17] solar PV production increased by 22% (+131 TWh) in 2019 and is still on track to reach the levels envisioned in the SDS which will require average annual growth of 15% between 2019 and 2030. This growth is expected to be fostered thanks to a reduction of the LCOE, that represents in this study the cost to produce 1 kWh of electricity with a PV system. The yellow line in Figure 1.2 shows the PV LCOE reduction of 90% during the period 2009-2020, making solar PV the new cheapest technology to produce electricity in 2020.

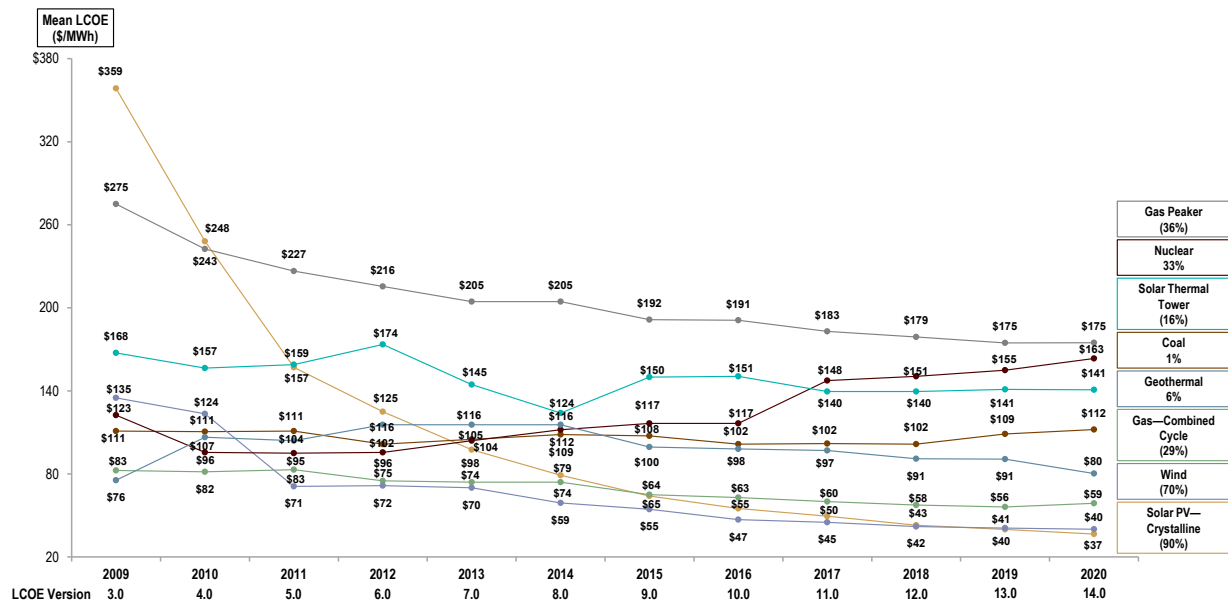


Figure 1.2: LCOE of diverse energy production technologies between 2009 and 2020. Figure from Lazard [18]

Nevertheless, PV gathers various types of technology to produce electricity and their cost of ownership and performance may differ, leading to different LCOE.

A solar PV system is composed of a solar module (also named solar panel) and a BOS (usually mounting structure, inverter (converting DC electricity in AC electricity) and cables, sometimes also a battery). The modules and BOS are dependent of the type of PV technology and system used. The active devices that convert light into electricity in solar modules are the solar cells. They are mostly based on positively (p-type) and negatively (n-type) doped semiconductors that allows the extraction of the carriers. The most widely used semiconductor is silicon [19]. The major technologies using silicon wafers for cell production are the Aluminum-back Surface Field (Al-BSF), the silicon Heterojunction (HJT) as well as the Passivated Emitter and Rear Contact (PERC). In addition to silicon, other materials can be used such as, CdTe, CIGS, perovskites and III-V semiconductors to built other PV solar cells. Four classes of PV technologies are usually defined according to the semiconductor used for the cell production:

- **III-V single- and multi-junction cells** (Single-junction GaAs, multijunction (2 to 4+, concentrated or not))
- **Crystalline-Si** (based on mc-Si or sc-Si wafers, using technologies such as Al-BSF, PERC (and its variations), HJT, etc.)
- **Thin film technologies** (CdTe, CIGS, a-Si:H)
- **Emerging PV** (Perovskite, dye-sensitized, exciton, intermediate band)

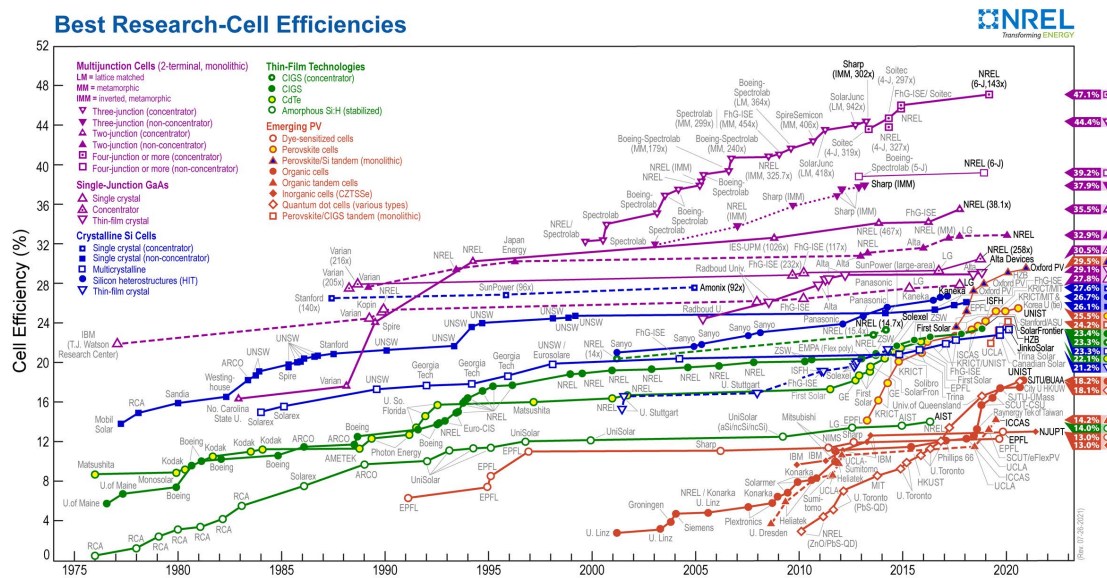


Figure 1.3: Evolution of the solar cell efficiencies for various technologies reported in 2021 by NREL [20]

Figure 1.3 shows the progress of the solar cell efficiency for the different PV technologies. Each technology presents a maximum efficiency limit which is defined by the physical properties of the semiconductors and of the other materials used to built the solar cells. For single-junction, sc-Si-based technologies, this cell efficiency limit is slightly above 29% [2]. Despite the fact that multijunction solar cells are showing impressive efficiency (up to 47.1%), their production costs are still nowadays expensive as those cells use high quality III-V semiconductors. Emerging PV technologies are still under development and not yet commercialized in large volumes.

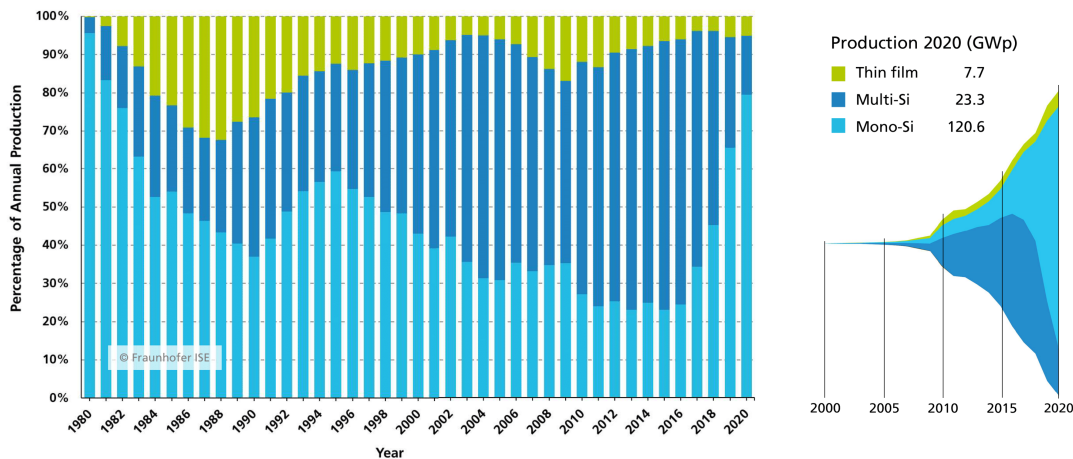


Figure 1.4: Evolution of the PV annual production of electricity for three solar cell categories namely thin-film, mc-Si and sc-Si reported by Fraunhofer ISE [2]

Figure 1.4 shows the evolution of the PV annual production of electricity, which is dominated (95% in 2020) by c-Si cell technologies, with an important growth of sc-Si technologies, representing 80% of the market in 2020. Figure 1.5 depicts the prospective distribution of cell technologies of the world market. A clear trend shows the progressive phasing-out of Al-BSF by 2028, the important share (>80%) of PERC (and equivalent technologies) until 2025, diminishing after 2025. Another interesting trend shown by Figure 1.5 is the progressive spread of the HJT technology from now to the last year of the plot (2031).

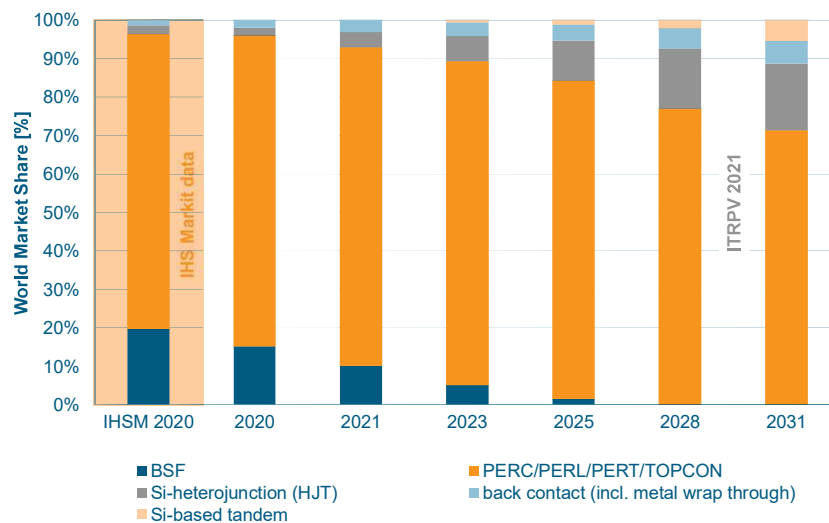


Figure 1.5: Expected distribution of solar cell PV technologies world market, ITRPV 2021 [6]

1.2.1.1 HJT technology

The heterojunction (HJT) technology has been under development for three decades and is now identified as one of the PV technologies to succeed to PERC. HJT solar cells now hold the efficiency record (26.3% for Longi Solar [21]) for c-Si single junctions on industrial wafer sizes. In this context, CSEM is at the forefront of the HJT technology development, and is now focusing on conversion efficiency improvement and diminution of the use of Critical Raw Materials (CRM) such as indium or silver in cell production processes, to reach lower environmental impact and cheaper costs.

1.2.2 Life Cycle Analysis

Life cycle analysis (LCA) is a method employed to analyze the environmental impact of an action, a product, a service or a system over its complete or partial life cycle based on a specific function. Simapro [22], OpenLCA [23] and GaBi [24] are the three major professional tools used to perform LCA [25]. A complete life cycle includes the following stages: Raw material extraction, Manufacturing, Distribution, Use phase, End-of-Life (disposal or recycling). LCA makes it possible to identify the aspects and different stages of a product that are harmful to the environment or, in contrast, those that are less harmful. According to the ISO 14040 and 14044 standards [26], as depicted in Figure 4.3, the LCA is carried out in four phases: definition of targets (Goal and Scope), inventory of emissions and extractions (Life Cycle Inventory (LCI)), impact assessment (LCIA) and interpretation. The LCA is an iterative process, each phase is upgraded based on other phases upgrade. LCA applications are numerous and could be for product development, marketing or public policy. This methodology is also useful to compare different products or processes while considering the same functional unit, orienting decision-making from an environmental point of view.

International standard ISO14040

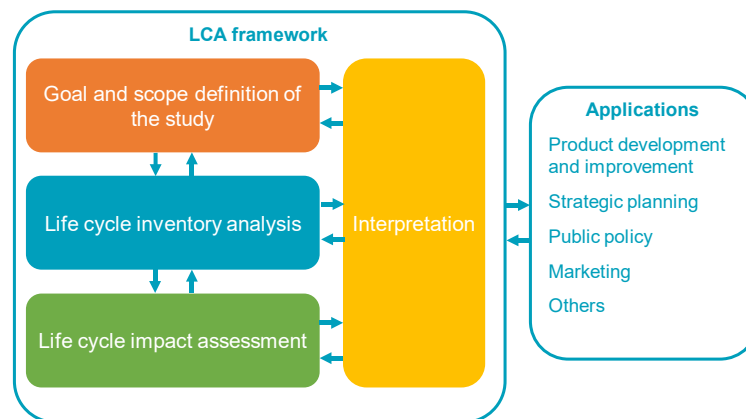


Figure 1.6: LCA methodology

1.2.3 LCA of PV systems: recommendations and overview

In addition to ISO standards, the European Union defines a methodology to establish the Product Environmental Footprint (Product Environmental Footprint (PEF)) through LCA methodology [27]. PEF methodology is reviewed regularly and provides guidelines to be applied at each stage of the life cycle (raw materials, manufacturing, transport, use, end-of-life) and recommendations for each domain such as agriculture, transport or energy [27]. The use of LCA methodology for PV systems is not recent but still very diverse. As mentioned previously, the PV domain evolves very rapidly and LCI datasets are often outdated by 5 to 10 years. In this context, the task 12 of the IEA PV Power Systems Programme [28] aims to set the main recommendations to perform a meaningful LCA of PV system. This working task released a recent report on LCA recommendations for PV systems [7] and a recent LCI dataset [29]. To complete these recommendations, insightful state-of-the-arts of Solar PV LCA were performed in the past decade. All those studies shown that there are rapidly evolving life-cycle performances of PV technologies [30, 31], underlying the importance of timely updating and reporting the changes [30]. A more detailed review of relevant studies has been performed in our work to justify the assumptions set for this study. Major information linked to literature review of PV LCA shows that:

- The carbon footprint (kgCO₂-eq) is the most frequently used environmental indicator to assess environmental impact of solar PV [32]. Other indicators used for grid-connected PV system are

energy indices like Energy Payback Time (EPBT), Cumulative Energy Demand (CED), and primary energy demand (PED)[32].

- For grid-connected PV system, the three major FU used are kWh (13 studies), m² (11 studies) and kWp (8 studies) over 39 LCA studies on PV systems [32]. This observation is aligned with the recommendations of the IEA PVPS Task 12 [7] which establishes AC electricity delivered to the grid quantified in kWh for comparison of different PV technologies.
- Results per kWh are directly linked with electricity produced by the PV system, that is strongly dependent of irradiance [32][7].

Additionally, a recent study [33] focused in more details on the environmental impact of a PERC PV system and evaluated diverse scenarios for PV manufacturers, using a double FU: kWp and kWh. RUM and PM were considered in addition to CC impact category. A detailed distribution of PV system impact per kWp allows PV manufacturers to identify key stages to limit the environmental impact of PV system [33]. Furthermore, a key identified parameter was the energy mix used for different scenario (Chinese, German, European) being sometimes outdated in the Ecoinvent database.

1.3 Motivations

The major motivation of this work is to fill the gap between state-of-the-art HJT devices and LCA studies as well as to provide relevant results exploitable to improve the HJT technology at CSEM, its partners and beyond in Europe. By performing a state-of-the-art analysis, the following outcomes were pinpointed:

- There is no existing full LCA of PV technology detailed with a very fine scale, and this trend is more marked for the HJT technology (due to its recent development and current confidentiality considerations). For instance, the AMPERE report [34] provides a detailed LCA work on PERC (non-confidential) and HJT (confidential) technologies. Only Louwen [35] shows good detail for LCA but only for the cell building block and already dating back 2016.
- PV is now challenged on its carbon footprint, which is not very flattering because LCI database (as Ecoinvent) are often outdated by 5 to 10 years, which is problematic in the very rapidly evolving PV domain. The upgrade of LCA study with recent data from PV manufacturer is thus a motivation to show an up-to-date carbon footprint of PV systems.
- An important number of LCA studies focus on the CC impact category only (also known as carbon footprint), but do not treat other impact categories such as PM RUM that needs to be considered as they represent two other major threats (resource depletion and human health) in addition to CC in the current disruption of the planetary boundaries [33].
- Advice for PV manufacturers based on LCA are not common. More and more, LCA is used by PV manufacturers to show the low carbon footprint of their products to be able to bid to public tenders (e.g. in France) and attract consumers sensitive to environmental considerations. However, development of PV technologies is still mainly driven by economics, the goal being to produce a profitable product. Therefore LCA is very rarely used to test and justify technological improvements, this must change.
- The challenges for a PV technology are mainly linked with the materials used to produce it. For instance, an important challenge for HJT technology is to limit the use of CRM such as indium and silver in the cell production processes, eventually leading to both a reduction of costs and environmental impact.

Therefore, the motivations for this thesis are to provide a recent and filled database for major sc-Si technologies (Al-BSF, PERC, HJT), with particular emphasis on the HJT technology. Another motivation is to observe more closely the environmental impact of PV system on diverse impact categories and to not only limit the evaluation to the carbon footprint. Finally, an important motivation is to use LCA as a driver for PV technology development at CSEM (especially for HJT technology).

1.4 Project objectives and structure

This thesis aims to compare the environmental impact of grid-connected PV systems of the three major types of state-of-the-art sc-Si technologies (Al-BSF, PERC, HJT) and observe the evolution of solar PV impact between 2010 and 2020 (using the Al-BSF technology as a reference). The goal of this project is also to provide a detailed environmental impact of the state-of-the-art HJT technology as well as evaluating different improvement scenario for the HJT technology and to challenge their pertinence from an environmental point of view. Additionally, obtaining recent and relevant data from PV manufacturers and datasets represent a challenging task of this project, as well as providing recommendations to European PV manufacturers and LCA studies on PV.

Methodology chapter: First, this thesis aims to define and develop a clear methodology to evaluate the environmental impact of sc-Si technologies. The methodology developed for this research project focus on the three first phases of the LCA methodology, i.e. definition of targets (Goal and Scope), LCI analysis and LCIA. The methodology chapter thus describes the model of PV systems developed for all sc-Si technologies evaluated (Al-BSF, PERC, HJT). The methodology also presents the different key parameters, sources and assumptions of each building blocks of the PV system (wafer, cell, module, etc.) for each technology, with a more detailed description for HJT technology scenarios evaluated. Furthermore, the treatment of data (from raw data to final results) is presented to ensure a better understanding of the results. A short and specific literature review will be presented for each topic in the methodology to justify the different choices made for this study as numerous LCA researches on PV systems were carried out based on various goals, using different assumptions, scopes and data sources.

Results & discussion chapter: Secondly, this thesis evaluates the environmental impact of the four PV system types studied (namely the Al-BSF 2010, Al-BSF 2020, PERC 2020 and HJT 2020) with a specific focus on the HJT technology. In each section, the results are presented considering both FU with the environmental impact per kWh and per kWp. The data for kWp are more detailed as they concern more directly PV manufacturers. The results chapter is divided in four sections:

- **Environmental impacts:** presents the major results along the 16 impact categories for four PV systems and for both FU: kWp and kWh;
- **Carbon footprint:** evaluates the impact on the CC impact category for the four PV systems studied. Results are shown per kWp and per kWh;
- **Sensitivity analysis:** shows the response of PV system to multiple variations of key parameters such as module efficiency, wafer thickness;
- **Upgrade of HJT PV technology towards reduced environmental impacts:** looks into detail at each building block impact (wafer, cell, module, BOS & Installation, Use, End-of-Life) specifically for the HJT technology and evaluates alternative scenarios to mitigate the environmental impacts of some of those building blocks.

Recommendations & Conclusion chapter In a third time, a summary of major results, advice and recommendations is provided to PV manufacturers to produce the lowest carbon footprint PV-system with current market trends. Importantly, advice are provided to perform relevant LCA studies on PV system and area for improvement of this study are tackled. Finally the conclusion shows the major outcomes of this work and possible future developments.

Chapter 2

Methodology

2.1 Concept and summary

The methodology developed for this research project focus on the three first phases of the LCA methodology, i.e. definition of targets (Goal and Scope), LCI analysis and LCIA (see introduction chapter). Numerous LCA researches on PV systems were carried out based on various goals, using different assumptions, scopes and data sources. Therefore, a short and specific literature review is presented for each topic to justify the different choices made for this study.

Modeling of the PV systems is performed on the software Simapro (version 9.2.0.2 with an academic license). The Ecoinvent 3.7.1 database available on Simapro as well as peer-reviewed and CSEM internal data are used to obtain relevant results and ensure a high quality of the work. Environmental Footprint (EF 3.0) [36] is used as unique impact assessment methodology. Detailed data and assumptions are recorded in an Excel file to ensure transparency of results as well as an easier actualization of the project's data.

2.2 Life Cycle Assessment Methodology

2.2.1 Scope and goal of this work

The first stage of the LCA defines the objectives and field of study. The goals of this LCA are:

- to compare the environmental impact of PV system grid-connected of the 3 major types of state-of-the-art single-Si technologies (Al-BSF, PERC, HJT) and observe the evolution of solar PV impact between 2010 and 2020 (for Al-BSF technology).
- to provide a detailed environmental impact of the state-of-the-art HJT technology as well as evaluating different scenario for HJT technology and compute their pertinence from an environmental point of view
- to offer an LCA based approach to European PV manufacturers for the upgrade of HJT processes and materials used

LCA specific concept are applied to fulfill LCA goal and scope:

- the *Function* of the system under study
- the *Functional Unit (FU)* which defines the amount of material required to carry out the action
- the *Boundaries* of the system

All scenarios are compared on this common basis and all the Reference Flow (RF) of the system are related to the quantity of product needed to fulfil the function. The function, FU and boundaries of the system are interdependent and must be compatible to perform a relevant LCA study.

2.2.1.1 Function and Functional Unit

A PV system represents an energy production technology, its function is therefore to produce a given amount of energy, in our case alternative current (AC) electricity. ISO14004 defines the FU as the “quantified performance of a product system for use as a reference unit”, in other words, the FU is useful as it allows to compare every flow or process through a common unit, representing an amount over a certain period. A very recent review [32] of 39 LCA PV studies shows that the three major FU used are kWh (13 studies), m² (11 studies) and kWp (8 studies). This observation is aligned with the recommendations of the IEA PVPS Task 12 [7] which establishes AC electricity delivered to the grid quantified in kWh for comparison of PV technologies. Alternatively, the RF “m²” or “kWp (rated power)” may be used. However, these RF are not suitable for comparisons of other technologies to PV. Nevertheless, “m²” reference flow can be used to compare the same technology integrating different materials or architectures [7]. The kWh allows the quantification of the environmental impacts of PV technologies devices in relation to their final purpose: the production of electricity. On the other hand, the kWp is mainly used by PV manufacturers as it does not take into account the use phase and BOS of the PV system, that are mainly not dependent (especially for the use phase conditions) of the production of PV wafer, cell and module (performed by PV manufacturers).

This LCA study has twofolds FU :

- FU: "to ensure the production of 1 kWh of AC electricity in Europe over 30 years with a 3 kWp grid-connected PV-system"
- FU1: "to ensure the production and end-of-life of a 1 kWp PV panel in Europe"

2.2.1.2 Product System Description and Boundaries

LCA product system description and boundaries The lifecycle of a product (here PV-system) is split into 5 major stages :

- **Raw material extraction** refers to the extraction (mainly mining) of all raw materials needed in the different processes performed to obtain the final product. For example, sand is extracted to produce wafer and solar glass, coal is mined to produce electricity.
- **Processing/Manufacturing** represents all processes needed to produce the final product. Each process is defined by all its inputs (energy, materials, factory) and outputs (product, waste, emissions). Major processes of this study are wafer production, cell production and module production.
- **Transportation** refers to the transportation process of the final product from its production site to the use phase site. It can also include previous transportation stages, depending on the boundary choice.
- **Use phase** refers to the phase where the final product is used. For our study, it will represent the period of time when the PV system is active and can produce electricity during (sunny) daytime.
- **End-of-Life** phase is the last one and occurs after the use of the final product. It usually includes the dismantling of the product as well as a scenario of waste management (recycling and/or disposal). Transportation process also occur in this stage to ensure the displacement between use site, dismantling site and waste site.

Furthermore, the stages of the life cycle considered (cradle to gate, cradle to grave, cradle to cradle, single step) as depicted in figure 2.1 influences and are dependent of the FU of the system.

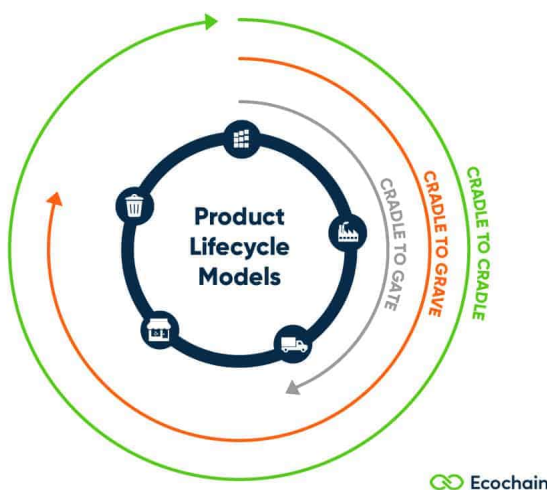


Figure 2.1: Life cycle stages

The general boundary of the system under study here is cradle to grave, i.e. it includes all stages of the PV-system, from raw material extraction to its end-of-life. The major PV system building blocks are detailed in the following table.

Table 2.1: PV model building blocks description and main products

Process/stage	Process/stage description	Main product
0.Wafer production	A wafer is a thin slice of sc-Si semi-conductors and represents the absorber bulk of solar cells, i.e. the solar cell bulk where the light is absorbed and converted into electricity. Silicon wafers are obtained from quartz sand through multiple transformation subprocesses. All processes from mining of quartz sand to obtaining the sc-Si wafer at cell production location are included. The wafer production consumes a lot of energy and is an important contributor to the PV-system environmental impact.	1 m ² of sc-Si Wafer
1.Cell production	Solar cells are produced from sc-Si wafers through multiple subprocesses. Activity starts with sc-Si wafers at cell production location and ends with the production of sc-Si solar cells at production site. Those processes diverge between technologies, nevertheless the common basis is applied to a wafer: cleaning and texturing with chemicals in wet benches, deposition of layers by high-temperature diffusion, Plasma Enhanced Chemical Vapor Deposition (PECVD), or PVD, screen-printing of metallic contacts, and solar cells measuring and sorting.	1m ² of sc-Si Cell
2.Module production	A PV module is produced from multiple sc-Si solar cells. Activity starts with sc-Si solar cells at module production location and ends with the production of module at production site. PV cells are electrically connected into a string, and a series of strings are packaged into a module composed of multiple layers of glass and polymers. An aluminum frame and a junction box are added and the PV module is characterized and sorted.	1m ² of PV module OR 1 kWp of PV module
3.Balance of System & Installation	The Balance of System (BOS) includes all materials needed to obtain an operational PV-System from a PV module. Activity starts with the extraction of raw materials required for BOS production and ends with the production of the PV system at production site. Therefore, the BOS includes the inverter production needed to transform the direct current (DC) into AC current. It also includes the mounting structure (usually in aluminium) as well as cables to wire the PV system. Battery are not included as the PV-system is assumed to be grid-connected. The electrical grid to which the PV-system is connected is excluded but its connection (through cables) is included. The transportation of PV system from PV production site to use site is carried out by trucks (for European PV used in Europe). Activity includes the use of the trucks and are dependent of the weight of PV system and distance from production site to use site.	1 unit of 3 kWp PV system at use site
4.Use phase	The use phase is the longer of the PV system. It represents the production of AC current from incoming solar radiations according to the characteristics of the PV system. Activities included are the maintenance of the PV system (washing) as well as the replacement of some components/panels.	1 kWh of AC electricity
5.End-of-Life	The end-of-life of the PV system is the last stage and occurs after the use of the final product. It includes the dismantling of the product as well as a scenario of waste management (recycling of glass, aluminum and copper and disposal of other materials). The transportation processes to ensure the displacement between the use site, dismantling site and waste site are also included. Nevertheless, the benefits linked to the reuse of recycled materials are excluded of the system. (except for recycling with benefits scenario)	1 kg of waste/recycled materials

The process-tree presented in figure 2.2 applies to all sc-Si PV technologies.

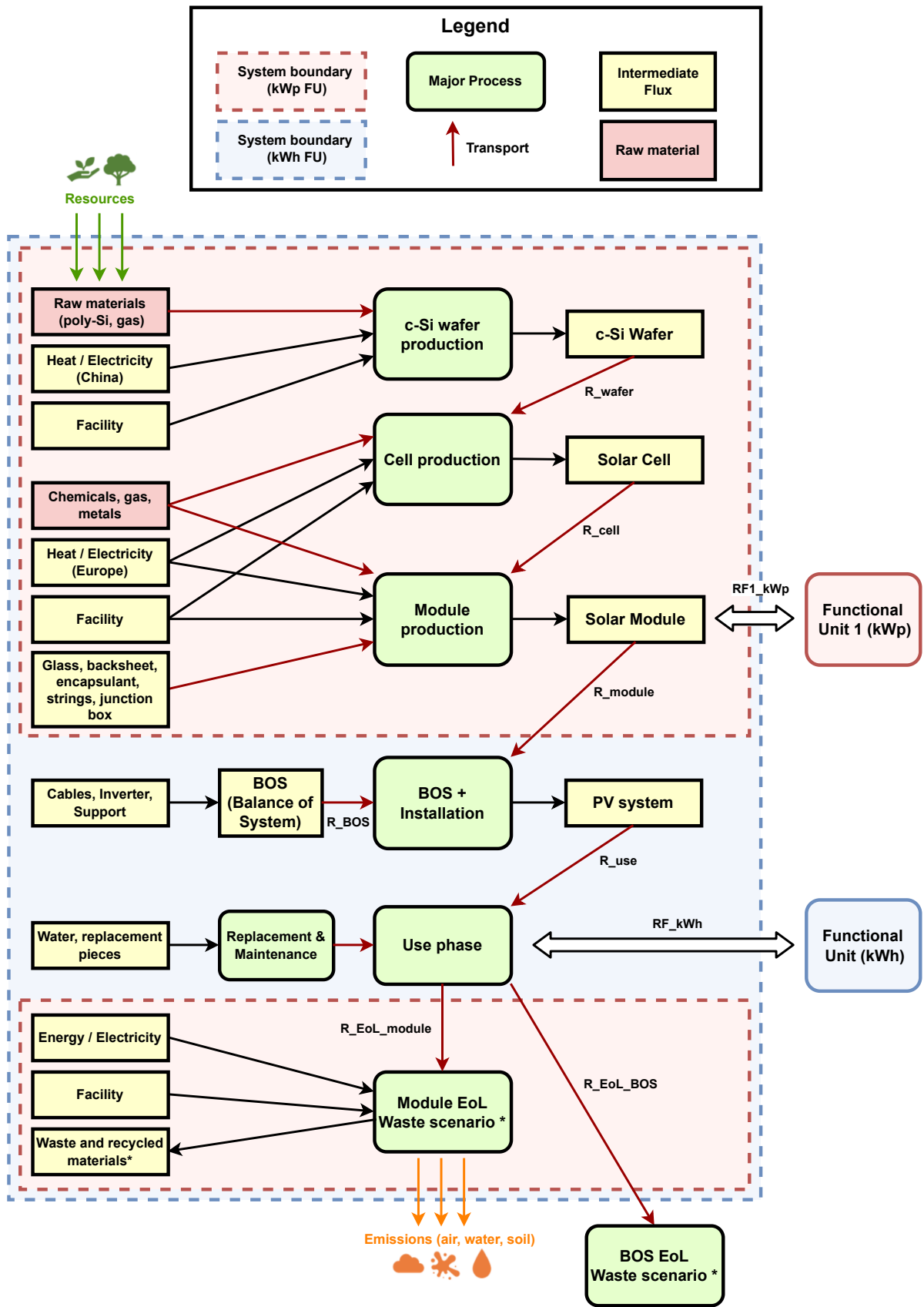


Figure 2.2: PV system process tree

Figure 2.2 represents the complete system process tree. The productions of all materials required to build the complete PV-system (fulfill the FUs) are included. The blue dashed line illustrates the boundary of the system for the FU (kWh) and the red dashed line illustrates the boundary of the system for FU1 (kWp). Major processes (referred as building blocks) are depicted by green boxes. Transport are represented by red arrows and intermediate fluxes are related to building blocks by a factor R.

In summary, this study considers the cradle to grave model for kWh FU and cradle to gate model for FU1 kWp¹ of a grid-connected 3 kWp PV system using sc-Si based solar cell technology. The process tree represented in figure 2.2 applies to all sc-Si based solar technologies analyzed (Al-BSF, PERC, HJT) to ensure a meaningful comparison.

2.2.2 Life Cycle Inventory

The Life Cycle Inventory (LCI) is the Inventory of emissions and extractions necessary to achieve the function of the system i.e emissions to air, water and soil (outputs) as well as raw material extraction and land use (inputs). An inventory of all elemental flows (all material, energy and pollutant flows crossing the system boundary) is carried out. This inventory includes all quantities of pollutants and resources extracted during the product's life cycle.

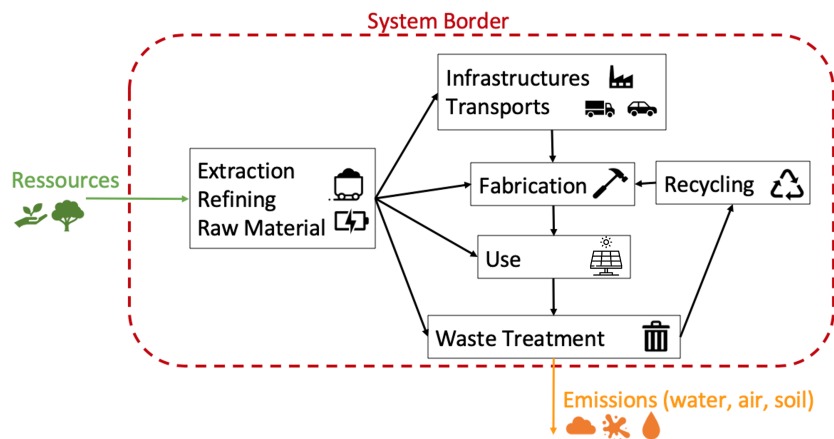


Figure 2.3: General System Boundary in the Life Cycle Analysis

The LCI strongly influences the LCA results as the LCI deals with data acquisition and treatment directly used by the LCA. Therefore the LCI represents a critical point of the LCA and should be studied in detail. The challenge here is to transform technology data into elemental flows which can then be treated. The Simapro software with Ecoinvent database is used for this purpose.

2.2.3 Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) assesses the environmental impact of the emissions and extractions listed in the LCI. The Impact Assessment is used to assess emissions in the air, water and soil into impacts on the environment. Different methodologies with diverse weighting exist, leading to very different results. Following European Commission recommendations for LCA of products, **the impact assessment methodology EF 3.0** published in 2019 [36] was used for this project. The more recent adaptation (June 2021) of this methodology on Simapro 9.2 was preferred to ensure consistent and exploitable results for the LCIA thanks to the database. EF 3.0 classifies elemental flows from LCI in 16 (midpoint) Impact categories [36]. Impact categories (and their acronyms) are described in the figure 4.6 (see appendix for figure and additional knowledge).

Different impact assessment methodologies and impact categories are investigated and applied for different research works presented in the literature of PV solar systems. Furthermore, environmental impact categories are oftenly coupled with energy indicators for PV LCAs.

¹End-of-Life building block is treated separately from the other building blocks for both kWp and kWh FUs. Furthermore, some end-of-life scenario may consider a cradle to cradle model

For environmental impact categories, Climate Change (CC) (also known as Global Warming Potential) appears as the most used indicator for PV panels [32][7] but other environmental indicators like Acidification potential (AP), Eutrophication potential (EF, EM, ET), Ozone depletion (OD), and Photochemical Ozone Formation (POF), etc can be calculated [32]. The major challenges faced by Energy production systems are: to limit the climate change, use less resources and pollute less. Those three major challenges are tackled in the Müller study [33] by showing the result of a sensitivity analysis among CC, RUM and PM impact categories.

Therefore, the relevant impact categories analyzed for this study are:

- Climate Change (CC) for quantifying PV influence on the global warming potential;
- Particulate Matter (PM) to quantify the influence of PV system on the incidence of disease due to PM, the most frequent pollution.
- Water use (WU), RUF and Resource Use, Minerals and Metals (RUM) to quantify the influence of the PV system on resource depletion;

On the other hand, some studies focused only on energy assessment through indices such as Energy Payback Time (EPBT) and Cumulative Energy Demand (CED), Overall, **CED, EPBT, and GWP are the most used indices for PV studies** [32]. The study carried by Louwen [35] uses these three indicators to quantify the environmental impact of a PV system and confirms the interest for CED as an indicator that can be used for other environmental impacts.

EPBT and CED concept are detailed in the appendix section but are not used in this work due to the priority set on environmental impacts rather than energy indices.

2.2.4 Interpretation

The interpretation is the last step of the LCA methodology and is used to test and validate the assumptions made, to analyze the results obtained and to assess uncertainties. Moreover, positive points and areas for improvement at the product level are highlighted. According to ISO 14040, it means that one should test whether the conclusions are valid and supported by data that was used throughout the procedure. This topic is tackled in the Results & Discussion chapter as well as in Recommendation & conclusion chapter.

The two major LCA tools are Ecoinvent database [37] and Simapro software [22]. They are detailed in the appendix appendix.

2.3 Data Acquisition & Treatment

The main challenge of this project is to acquire state-of-the-art technological data and convert it into usable data (Ecoinvent compatible) for environmental impact calculations (on Simapro software). Figure 2.4 represents a schematic view of the work carried out to obtain environmental impact results. For each building block of the PV system, a back-up Excel sheet records all Ecoinvent compatible processes and key parameters used in Simapro software. Results are obtain through two processes: (i) applying EF 3.0 LCIA method to PV system model in the Simapro software and (ii) treating Simapro data tables in an Excel file to obtain specific data and plots.

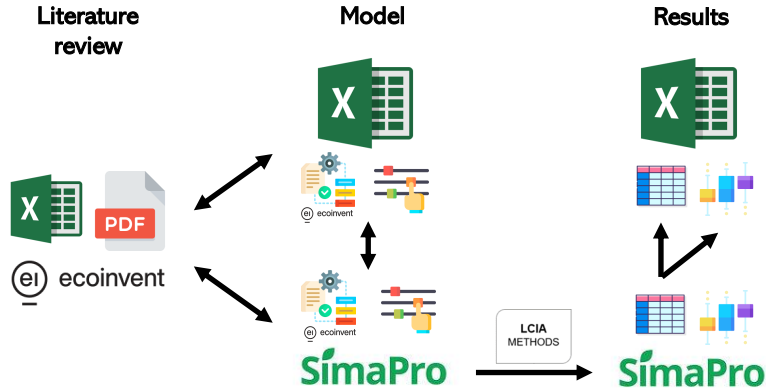


Figure 2.4: Schematic of Data Acquisition and Treatment

2.3.1 PV system model

The building blocks of PV system model are detailed in the Goal and Scope section.

The RF is a quantified amount of the product(s), including product parts, necessary for a specific product system to fulfill the FU. The factor (R) of a building block of the system defines the quantity of a building block which is required for another building block, for example R_{wafer} represent the factor to obtain 1 m² of Cell from 1m² of sc-Si wafer. The main factors (R) and RF of the PV system are presented in the figure 2.5. RF refers to FU (kWh) while RF1 refers to FU1 (kWp). Therefore, as a exemple, RF_{wafer} and $RF1_{wafer}$ represent the factor to fulfill FU kWh, respectively FU1 kWp from 1m² of sc-Si wafer.

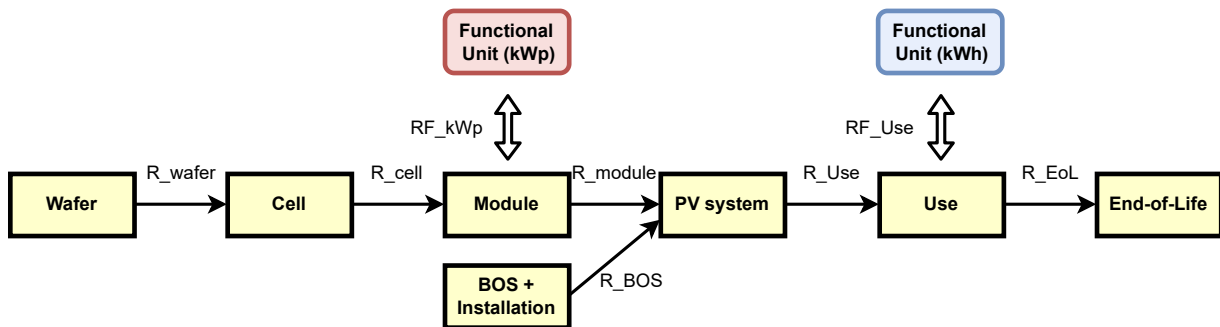


Figure 2.5: Reference Flows Process Tree

Relations between R, RF and RF1 are detailed below.

$$RF_{use} = 1/E_{total} = 1.07 * 10^{-5}$$

$$RF_{wafer} = R_{wafer} * RF_{cell}$$

$$RF_{cell} = R_{cell} * RF_{module}$$

$$RF_{module} = R_{module} * RF_{BOS}$$

$$RF_{BOS} = R_{BOS} * RF_{use}$$

$$RF_{EoL} = R_{EoL} * RF_{use}$$

$$RF1_{kWp} = 1/PV_{systemoutput} = 0.333$$

$$RF1_{wafer} = R_{wafer} * RF1_{cell}$$

$$RF1_{cell} = R_{cell} * RF1_{module}$$

$$RF1_{module} = R_{module} * RF1_{kWp}$$

$$RF1_{EoL} = R_{EoL} * RF1_{kWp}$$

Each R, RF and RF1 are specific to each PV system analysed (Al-BSF 2010, Al-BSF 2020, PERC 2020, HJT 2020).

The PV model is made of several building blocks with embedded processes and subprocesses as depicted in Table 2.2. For each building block, an excel file records all processes and subprocesses as well as key parameters.

Table 2.2: Major PV system processes and subprocesses nomenclature

0.Wafer	1.Cell	2.Module	3.Balance of System	4.Use phase	5.End-of-Life
0.1.MG-Si	1.1.Sorting	2.1.Cells cutting	3.1.Cable	4.1.Electricity production	5.1.Dismantling
0.2.SoG-Si	1.2.Chemical Baths	2.2.Soldering process	3.2.Inverter	4.2.Maintenance	5.2.Disposal
0.3.CZ-Si	1.3.PECVD or eq.	2.3.Lay-up	3.3.Support	4.3.Replacement	5.3.Recycling
0.4.Wafering	1.4.Sputtering	2.4.Lamination			
	1.5.Screen-Printing	2.5.Post lamination			
	1.6.Cell-measuring	2.6.Testing			
0.7.Energy	1.7.Energy	2.7.Energy	3.7.Energy		
0.8.Facility	1.8.Facility	2.8.Facility	3.8.Facility		
0.9.Intermediate flux	1.9.Intermediate flux	2.9.Intermediate flux	3.9.Intermediate flux	3.9.Intermediate flux	5.9.Intermediate flux
0.10.Transport	1.10.Transport	2.10.Transport	3.10.Transport	3.10.Transport	5.10.Transport

Inputs and outputs of a process are identified by a name, a location, if they are an infrastructure or not and their unit. The two last columns shows the matching of a input or output with Ecoinvent (or our own) dataset. Quantities of input/output are defined in the blue columns. Those numbers are obtained from literature data, and/or calculations. Extra columns not shown in Table 4.3 shows data source, hypothesis and data validity (if available).

In addition to inputs and outputs of a process, extra information are added (if available):

- specific process parameters
- process description and schematic
- detailed calculations

Other data such as key parameters are also recorded on a separate sheet of the Excel file for each of the PV building blocks.

2.3.2 Implementation in Simapro

Simapro software working principle and basic functions are described in the appendix Simapro.

2.3.2.1 Process vs Assembly

Each process described in the Excel files can be created for the project with Ecoinvent data in the Simapro > Process.

Thus, all the processes and subprocesses of the building blocks of the PV system are created (or adapted from existing Ecoinvent processes) on the Simapro Software. Building blocks of the PV system are embedded. As an exemple, Module depends on Cell, itself depending on Wafer building block. Therefore the **main challenge of impact assessment is to avoid double impact accounting of building blocks that are embedded in other ones.**

Simapro software offers two manners to deal with the PV system:

- Process structure
- Assembly structure (Process without the main input)

Those two structures are defined in Figure 2.6

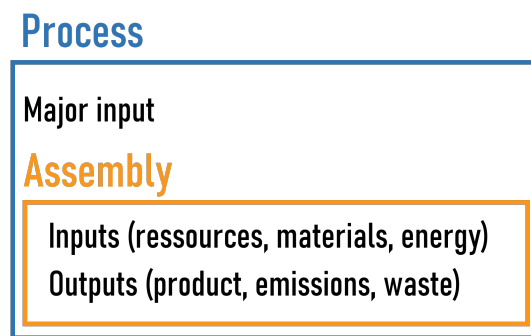


Figure 2.6: Process versus Assembly structure

Process structure is very similar to the process described for the back-up Excel file (see Table ??). Importantly, the processes are interdependent. This means that some data of a process may refer to another process and are directly updated in case of a modification of this second process. Impact assessment performed on the Simapro software with process structure shows only results of the last or upper process of the final product, which is limiting the global overview of the system.

In contrast, assemblies are independent. This structure avoids double accounting by removing the major input of a process. That means that a modification of an assembly may not be automatically reported on another assembly. Therefore, attention needs to be paid on factors between assemblies. The advantage of this model is for impact assessment visualization: an assembly can be made of sub-assemblies, allowing a representation of choosen blocks and their weight in the PV system.

Process and Assembly structures were adopted in this work to ensure the quality of the PV system dataset. An assembly is compared with an equivalent process to evaluate the good set up of the assembly factors. Assembly structure is used for data visualization, giving a better overview of the PV system than the process structure.

2.3.2.2 Parameters implementation and sensitivity analysis

Simapro offers the possibility to set parameters for a specific process or assembly. Nevertheless, some parameters influence different processes or building blocks and need to be copied from one process and pasted to another one to be used. A modification of the same parameter in a process will therefore not automatically be reported on the other process using the previously copied parameter. The implementation of parameters valid for the whole project is the best way to tackle the subject and centralize information on parameters at one specific place. This option is available on the Simapro software under the Parameters section. Those project parameters can be used in all the processes or assemblies created or used by the project.

Parameters can also be used to perform a sensitivity analysis of the PV system model. The goal of this analysis is to observe the resilience or dependence of the PV system to specific key parameters such as wafer thickness, PV module lifetime, irradiance and so on. For a given parameter, a variation of -10% respectively + 10% is set and the response of the system is analyzed. If the variation of the PV system impact is close to -10%, respectively +10% , the system will be considered as strongly dependent of the parameter studied which will be defined as a key parameter. If the variation of the PV system impact is close to 0% with the modification of a key parameter, the PV system will be considered as not influenced or resilient to this parameter variation, which will not be considered as a key parameter.

An illustrative sensitivity analysis is represented in Figure 4.10 taken from the report of Müller et al. [33] and allows to define which materials, process or assemblies should be studied in detail (or not), as they strongly influence (or not) the impact of the PV system for given impact categories.

2.3.3 From Simapro to Excel results

Impact assessment gives the impact of an assembly (or process) among 16 impact categories. Results obtained on the Simapro software are in a table shape. Rows refers to impact categories and columns to the components and total of an assembly. A plot of data is also available. In case of comparison between two or more PV system, the results shown are global values of each PV system in columns and Impact Categories in Rows. No detail of PV system is available on the plots, only showing the relative impact of PV systems to the higher PV system, which is problematic to understand what are the weight of each building blocks among the 16 impact categories for each PV system.

A solution is to export the impact data table of each PV system in a CSV format. The file is then processed in an Excel file with macros. The goal is to perform:

- Analysis of the PV system
- Comparison with other PV system

For the analysis of the PV system, the data table is reversed to have in columns the impact categories, and in rows the building blocks of the PV system. Data are visualized in a 100% stacked column plot as for exemple the Figure 3.27. Furthermore, data tables have different units (kg CO₂-eq, CTUh, etc). Therefore, the impact of each building block (α), for a given impact category is normalized (Norm) thanks to the total impact of the PV system for the same impact category. The normalization is performed for all impact categories (β).

$$Norm(\alpha, \beta)[\%] = Impact(\alpha, \beta) / Total(\beta) * 100$$

For the comparison with other PV system :

- A list of PV systems to be compared is chosen and a PV system is chosen as the reference one. Total Raw data for each of the 16 impact categories are imported for each PV system.
- As a first comparison, a spider plot shows the relative impact of each PV system (γ) to the reference one.

$$Total_{relative}(\beta, \gamma)[\%] = Total(\beta, \gamma) / Total(ref, \beta) * 100$$

- For a more detailed comparison, data are processed to find the higher total for each PV system and impact category :

$$Total_{real}(\beta, \gamma)[\%] = Total(\beta, \gamma) / \max(Total(\beta, \gamma)) * 100$$

The data are then compiled by taking into account the building block (α), impact category (β) and PV system (γ):

$$Result(\alpha, \beta, \gamma)[\%] = Norm(\alpha, \beta)[\%] * Total_{real}(\beta, \gamma)[\%]$$

A stacked column chart is obtained through this data treatment and shows the relative impact of each PV system to another, while detailing the weight of the building blocks for each PV system. The Figure 4.12 is a good illustration of the results that are obtained through this methodology.

The different charts described above can be found in the Results & Discussion chapter.

To conclude methodological part:

- For each building block of the PV system, an Excel file exists and contains sheets with the processes and Subprocesses as well as an additional sheet containing the assembly structure and key parameters.
- FU1 kWp include Wafer, Cell, Module and EoL Module building blocks
- FU kWh includes all building blocks (Wafer, Cell, Module, BOS & Installation, Use phase and EoL Module)

2.4 Key parameters, assumptions, sources and reference flows of PV model

2.4.1 Overview of PV system and model

Three sc-Si technologies were studied which are namely the Al-BSF (2010 & 2020), the PERC (2020) and the HJT (2020). Table 2.3 describes the major characteristics and key parameters of each technology. For each major process/stage, key parameters and sources are detailed as well as major assumptions. PV model process tree (Figure 2.2) as well as Table 2.2 could help for a better understanding of this section.

Tables 2.3 present the general parameters of the four PV system under study in this project.

Table 2.3: Major characteristics of PV system for each technology

process ID	Information	Unit	Al-BSF 2010	Al-BSF 2020	PERC 2020	HJT 2020
3.	PV system output	kWp	3			
2.	module type	-	laminante (glass/backsheet)			
2.0	Number and type of cells	-	60 M2 sc-Si Al-BSF cells	60 M2 sc-Si Al-BSF cells	120 half-cut G1 sc-Si PERC cells	120 half-cut M6 sc-Si HJT cells
2.	Module area	m ²	1.6	1.6	1.685	1.839
2.	Module efficiency	%	14.0	19.0*	20.0*	21.75
2.	Output power	Wp	224	304*	337*	400
2.	Module weight	kg	24.7	21.23	19.125	19.7
0.4	Wafer type	-	M2	M6*	M6*	M6
0.4	Wafer thickness	μm	270	170	170	170
0.4	Wafer/Cell area	cm ²	244.32	274.15	274.15	274.15
0.4	Wafer weight	g	15.37	10.86	10.86	10.86
2.1	Solar glass	kg/m ²	10.1	8.81	7.92	7.46*
2.4	Aluminium Frame	kg/m ² module	2.63	2.13	1.36	1.25*
2.5	Encapsulant (EVA/POE)	g/m ² module	1000	875	849	849*
R_wafer	wafer area per cell	m ² wafer/m ² cell	1.06	1.03	1.03	1.03
R_cell	Cell area	m ² cell / m ² module	0.932	0.935	0.976	0.894
R_module	module area per PV system	m ² module / PV system	21.9	16.1	15.3	14.1
R_BOS	BOS/PV system		1	1	1	1
RF_use	fulfill FU	PV system/1kWh	1/E_total	1/E_total	1/E_total	1/E_total
0.8	Electricity consumption	kWh/m ² wafer	151.95	58.05	58.05	58.05
1.8	Electricity consumption	kWh/m ² cell	30.24	17.70	13.51	12.00
2.8	Electricity consumption	kWh/m ² module	4.71	13.98	1.44	4.77
.8	Electricity consumption	-	European electricity mix for cell, module, BOS, use, end-of-life Chinese electricity mix for the wafer production			
.9	Inputs/Outputs	-	RER (RoW when not available) for cell, module, BOS, use, end-of-life Rest of the World (RoW) data for wafer			
4.	Hypothesis energy produced	-	Irradiance I= 1391 kWh/m ² *year Performance Ratio PR = 0.75 Lifetime = 30 years			
.10	Materials transport (RER)	-	230 km by truck (>32t, EURO4) 240 km by train (average freight train) 87 km by ship (barge)			
.10	Materials transport (RoW)	-	18 000 km by ship (transoceanic container) 1000 km by truck (>32t, EURO4)			

* adjusted data based on CSEM knowledge and/or own calculations. Other data sources are indicated in Figure 4.9.

Literature review sources for PV technology are very diverse and represent datashape such as product technical data sheets, Excel databases, Ecoinvent database, pdf reports with tables and other reports. Figure 4.9 represent the main sources used to implement in Simapro the models of each PV system technology.







	Technology	Al-BSF 2010	Al-BSF 2020	PERC 2020	HJT 2020
	Wafer	a	b	b	b
	Cell	a	b	c	e,f,g
	Module	a	b,d	c,d	d,e,f
	BOS + Installation	a	b	b	b
	Use phase	a	b	b	b
	End-of-Life	a	b	b	b

Figure 2.7: Data sources for major PV system building blocs and technologies

- (a) Ecoinvent 3.7.1
- (b) IEA-PVPS task 12 LCI [29]
- (c) AMPERE D.2.4 data [34]
- (d) PERC module European manufacturer A data
- (e) CSEM data [38]
- (f) HJT cell and module European manufacturer B data
- (g) Louwen data [35]

Each data sources cited above are evaluated according to various parameters : time validity, completeness, ecoinvent compatibility, simapro and excel transfer in the appendix section.

2.4.2 Wafer

2.4.2.1 General knowledge and description

A wafer is a thin slice of crystalline silicon semi-conductor material which plays the role of the bulk of the solar cell by absorbing light and converting it into electricity. Silicon wafers are obtained from quartz sand through multiple transformation processes. Quartz sand is transformed into metallurgical silicon (MG-Si), which is then refined to Poly-silicon ingots (also called Solar Grade Silicon: SoG) through Siemens process. SOG-Si is transformed into monocrystalline silicon through Czochralski process (CZ-Si), and CZ-Si ingots are cut with diamond wiring and cleaned to give individual silicon wafers. Figure 2.8 illustrates the process necessary to produce a monocrystalline silicon wafer.

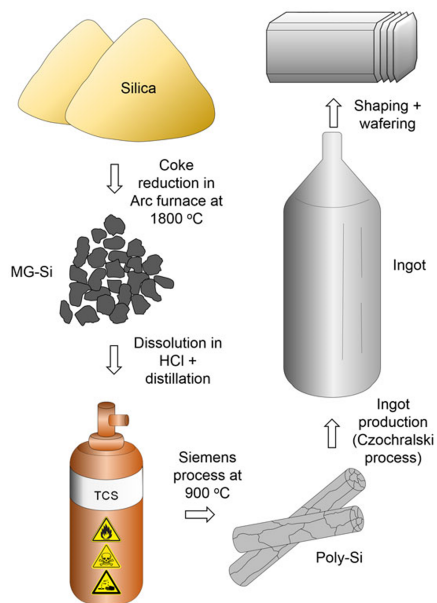


Figure 2.8: Schematic of Single-Si wafer production

The wafer production consumes a lot of energy and is an important contributor to the PV-system impact. Solar wafer market evolves rapidly and has been dominated by Chinese companies since 2018 (95% of wafer production and 58% of Poly-Silicium production) according to IEA[29]. In 2020 Poly-Silicon production was dominated by Chinese companies (83% of the top six world companies) due to low production costs of Poly-Silicon [39]. Therefore, the assumption of 100% Chinese-made wafers was chosen in our study. Furthermore, the wafer size is rapidly evolving towards larger and larger dimensions under the pressure of Chinese manufacturers, superfast as described in Figure 2.9 from ITRPV 2021 [6].

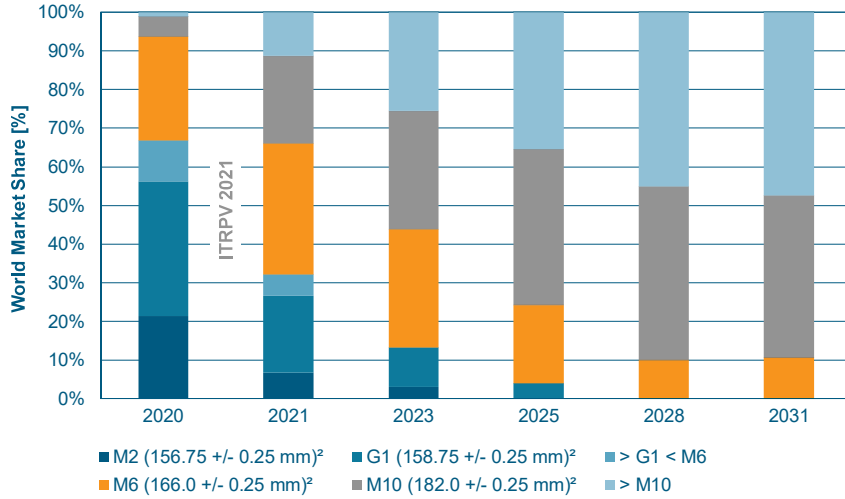


Figure 2.9: Wafer size trends from ITRPV 2021 report

2.4.2.2 Parameters and assumptions for Al-BSF, PERC and HJT technologies

Table 2.4 gathers all key parameters and assumptions used for the wafer building block throughout our study.

Table 2.4: Key parameters and assumptions for sc-Si wafer

Process ID	Information	Unit	Al-BSF 2010	Al-BSF 2020 PERC 2020 HJT 2020
0.4	Wafer type	-	M2	M6
0.4	Wafer thickness	μm	270	170
0.4	Kerfloss and additional losses	μm	191	85.5
0.4	Wafer area	cm^2	244.32	274.15
0.4	Wafer weight	g	15.37	10.86
0.1	MG-Si	kWh/kg	11	11
0.2	SoG-Si	kWh/kg	110	49
0.3	CZ-Si	kWh/kg	85.6	32
0.4	Wafering	kWh/m ²	8	4.8
0.1	MG-Si	kg Si Sand/kg MG-Si	2.7	2.7
0.2	SoG-Si	kg MG-Si/kg SoG-Si	1.13	1.13
0.3	CZ-Si	kg SoG-Si/kg CZ-Si	1.07	1
0.4	Wafering	kg Cz-Si/m ² wafer	1.07	0.595
0.10	Wafer Transport	-	20 000 km essentially with ship	20 000 km essentially with ship
0.4	Wafer sawing method	-	Slurry based	Diamond wire sawing
0.9	Electricity consumption	-	All process : Chinese electricity mix	All process : Chinese electricity mix
0.	Inputs/Outputs	-	Rest of the World (RoW) data	RoW data

2.4.2.3 Parameters and assumptions for HJT technology upgrade (wafer scenarios)

Table 2.5 summarize all key parameters and assumptions used for the different wafer scenario evaluation to upgrade HJT technology. As a reminder, the main output of wafer building block is 1 m² of wafer delivered in Europe. Four scenarios are compared :

- 270 μm thick wafer produced in China, also called China 2010 wafer
- 170 μm thick wafer produced in China, also called China 2020 wafer
- 170 μm thick wafer produced by Norsun in Norway
- 133 μm thick wafer produced by Norsun in Norway

Table 2.5: Key parameters and assumptions for sc-Si wafer scenario. 270 μm China, 170 μm China, 170 μm Norsun, 133 μm Norsun

process ID	Information	Unit	Wafer 270 μm China - 2010	Wafer 170 μm China - 2020	Wafer 170 μm Norsun - 2020	Wafer 133 μm Norsun - 2020
0.4	Wafer type	-	M2	M6	M6 *	M6 *
0.4	Wafer thickness	μm	270	170	170	133
0.4	Kerfloss and additional losses	μm	191	85.5	Not known (67.5 reused)	Not known (43.5 reused)
0.4	Wafer area	cm^2	244.32	274.15	274.15	274.15
0.4	Wafer weight	g	15.37	10.86	10.86	9.24
0.4	Ingot & Wafering	kg SoG-Si/ m^2 wafer	1.07*1.07	1*0.595	0.653	0.574
0.10	Wafer Transport	-	20 000 km * essentially with ship		2 000 km by truck	
0.4	Wafer sawing method	-	Slurry based	Diamond wire sawing	Diamond wire sawing	
0.9	Electricity source for SoG-Si production	-	Chinese electricity mix (1023 g $\text{CO}_2\text{-eq/kWh}$)		USA electricity mix (654 g $\text{CO}_2\text{-eq/kWh}$) German electricity mix (640 g $\text{CO}_2\text{-eq/kWh}$)	
0.9	Electricity source for ingot and wafer production	-	Chinese electricity mix (1023 g $\text{CO}_2\text{-eq/kWh}$)		Norwegian electricity mix (25 g $\text{CO}_2\text{-eq/kWh}$)	
0.	Inputs/Outputs	-	Rest of the World (RoW) data *		Rest of the World (RoW) data *	

*own calculations based on literature review.

Assumptions and parameters used for Norsun wafers are coming from an environmental product declaration [40] (LCA equivalent). The level of detail is lower than the one of Chinese wafer (which were modeled for this study), and only 3 impact categories (over the five of interest) are modeled for Norsun wafers. Therefore, only results from [40] are compared to LCA results for 2010 and 2020 Chinese wafers for CC, RUF and RUM impact categories in the results section.

2.4.3 Cell

2.4.3.1 General knowledge and description

Processes needed to obtain a solar cell from a wafer are different for each technology. This part is very technical, please refer to [14] for any detail. Nevertheless, a common basis exists and consists to make the following processes:

- **Cleaning, Saw Damage Removal and Texturing (Alkaline process)** : The purpose of this production step is to remove sawing damage, i.e. defects at the surface of the wafer that could otherwise propagate cracks during later handling steps and contaminants rendering the raw wafers unsuitable for good surface passivation. Wafer is cleaned with deionized water before and after each step. Saw damage is usually removed by etching 10 - 15 μm of the material. Texturing is also used to introduce a certain surface texture which is needed to reduce reflection and to trap light.
- **Diffusion of p-n junction (Al-BSF and PERC)**: The main goal of the diffusion step is to form the p-n junction and a highly doped region for lateral conduction in order to conduct the carriers to the contact fingers. It is done with POCl_3 for both PERC and Al-BSF technologies. The doping process proceeds by the growth of a phosphorous silicate glass (PSG) at the surface followed by the drive-in on the dopants.
- **HF dip cleaning (Acidic process)**: Wafers are dipped into an HF solution to remove the PSG formed at the surface of the wafers.
- **Chemical and Physical Vapor Deposition steps**: this process varies a lot for each technology
 - Al-BSF**: silicon nitride (SiN_x) is used to provide an anti-reflective coating and other benefits to the wafer. SiN_x is usually deposited by PECVD on the front side.
 - PERC**: This process is the same as Al-BSF process but in addition an $\text{AlO}_x/\text{SiN}_x$ bilayer is deposited on the rear side by PECVD. Small contact holes are afterwards opened in this bilayer stack, such that electric contacts can be established in the next step (see "Screen-printing").
 - HJT**: intrinsic and p-type hydrogenated amorphous silicon (a-Si:H) layers deposition on the rear side and deposition of intrinsic and n-type a-Si:H layers on the front side. Those processes are done by PECVD. They are followed by the front and rear sputtering of Transparent Conductive Oxide (TCO) whose goal is to transport the carriers to the contact fingers.
- **Screen-Printing (metallization)**: Electric contacts are achieved by screen-printing of different metallisation pastes: silver (Ag) pastes for the front side and aluminium (Al) pastes for the rear side (except for HJT which uses also Ag pastes here). The screen-printing technique used for solar cells is basically the same as the one used for printing pictures on T-shirts. It uses a polymer mesh which has a coating with openings in it. In that way the paste is squeezed through the mesh at well-defined positions.
- **Co-firing/Curing**: For Al-BSF and PERC, the metallizations are heated to 850°C for a few seconds in order to "pierce" the SiN_x layer to make direct contact with the Si wafer. For HJT, process temperature must not exceed 230°C , otherwise the a-Si:H layers will be destroyed, therefore the contacts are simply "annealed" at 200°C to evaporate the organic materials contained in the pastes and obtain acceptable electrical conduction. In this case the term used is "curing".

Table 2.6 represents a summary of major processes used to produce a solar cell from a wafer for each technology.

Table 2.6: Cell production processes by technology

Process ID	Al-BSF	PERC	HJT
	Cleaning/texturing	Cleaning	Cleaning/texturing
		Rear protection dielectric layer (e.g. PECVD)	
		Texturing	
	POCl ₃ diffusion (tube furnace)	POCl ₃ diffusion (tube furnace)	
	PSG etching (HF dip)	PSG & rear dielectric etch	HF dip
	Front SiNx deposition (PECVD)	AlOx/SiNx deposition rear side (e.g. PECVD)	Rear i/p layers deposition (PECVD)
		SiNx deposition front side (PECVD)	Front i/n layers deposition (PECVD)
	-	Laser contact opening rear side	Front/rear TCO (PVD)
	Screen-printing front side (Ag paste)	Screen-printing front side (Ag paste)	Screen-printing front side (Ag paste)
	Screen-printing rear side (Al paste)	Screen-printing rear side (Al paste)	Screen-printing rear side (Ag paste)
	Co-firing	Co-firing	Curing

2.4.3.2 Parameters and assumptions for Al-BSF, PERC and HJT technologies

Table 2.7 summarize the major key parameters and assumptions for cell building block.

Table 2.7: Cell key parameters and assumptions

process ID	Information	Unit	Al-BSF 2010	Al-BSF 2020	PERC 2020	HJT 2020
0.4	wafer type	-	M2	M6	M6	M6
1.	cell/wafer area	cm ²	244.32	274.15	274.15	274.15
1.	wafer area	m ² wafer/m ² cell	1.06	1.03	1.03	1.03
1.5	metallization paste back side (Ag)	g/m ² cell	4.9	1.11	0	6.3
1.5	metallization paste back side (Al)	g/m ² cell	71.9	55.4	12.4	0
1.5	metallization paste front side (Ag)	g/m ² cell	7.4	3.4	4.1	2.7
1.7	energy used for cell production	kWh/m ² cell	30.24	17.70	13.51	12.00
1.8	yield of cell production	%	94.3	97	97	97
1.8	rate of cell production	p/h	1142	3600	3600	3600
1.8	lifetime of cell production factory	years	25	25	25	25

2.4.3.3 Parameters and assumptions for the HJT technology upgrades (cell scenarios)

The high efficiencies demonstrated with HJT devices evidence the ability of this technology to approach the practical efficiency limit of sc-Si-based PV panels while offering advantages in the production process. Additional advantages are the low temperature coefficient of HJT devices and their high bifaciality which might lead to higher energy yield. However, current HJT cells require comparatively large amounts of silver for contact formation [33], and are usually made with indium-tin-oxide (ITO) transparent conductive oxide (TCO) on the front and back to improve lateral conductivity. Because of the high price of these materials, and because of parasitic absorption of light in the ITO layers, metallization and TCO are main research areas for improving the efficiency and lowering the cost of HJT solar cells [35]. R&D in this context focuses on silver consumption reduction by alternative metallization schemes, substitution of silver with copper, predominantly using copper electroplating, and substitution of indium with alternative TCO materials such as Aluminum-doped Zinc Oxide (AZO).

Cell processes treated in this work are the metallization process and Physical Vapor Deposition (PVD) process (TCO). Other process may also be upgraded. In addition, IBC HJT cells can be produced, with all contacts gathered on the rear side.

Metallization upgrades: standard metallization process is described in the section above. As a reminder, for HJT, the electric contacts are achieved by screen-printing of metallization pastes, usually containing silver, more recently a certain amount of copper. As an alternative, the Smart-Wire technology developed by Meyer Burger allows to reduce the quantity of silver used per solar cell. Furthermore, CSEM is developing HJT prototypes using copper electroplating. Assumptions and parameters for the three scenarios analyzed (standard, Smart-Wire, copper plating) are defined in the Table 2.8.

Table 2.8: Metallization scenario parameters for HJT upgrade

process ID	Information	Unit	standard	smart-wire	copper plating
1.5	metallization paste back side (Ag)	mg/M6 wafer	154	70	0
1.5	metallization paste front side (Ag)	mg/M6 wafer	66	30	0
1.5	Copper paste	mg/M6 wafer	0	0	320
1.5	Tin	mg/M6 wafer	0	0	60
1.7	Energy used for metallization process	kWh/m ² cell	0.524	0.524	1.37*
1.	Cell efficiency	%	23.9	23.9	23.9

The environmental impact of the three metallization scenarios (standard, Smart-Wire and copper plating) is presented in the results chapter.

Transparent Conductive Oxide upgrades : TCOs are usually made of indium-tin-oxide (ITO) on the front and back of the cell to improve lateral conductivity. Alternatives exist and the AZO is the most promising one. TCO can be applied on both side of a solar cell. For the specific IBC variation, the TCO is only applied to the front side and all contact are placed on the back side. The two scenarios (AZO vs ITO) are evaluated for IBC cells. The impact for Bifacial (BF) cell (standard) is multiplied by 2 (front & back side) compared to IBC cell (front side only). Table 2.9 represent the main parameters of PVD process for upgraded HJT technology.

Table 2.9: PVD scenario (AZO vs ITO) parameters for HJT upgrade

Process ID	Information	Unit	ITO (IBC)	ITO (BF)	AZO (IBC)	AZO (BF)
1.4	Sputtering target ITO	g/m ² cell	1.01	2.02	0	0
1.4	Sputtering target AZO	g/m ² cell	0	0	0.795	1.59
1.7	Electricity used for PVD process	mg/M6 wafer	0.75	1.5	0.75	1.5
1.8	Cell efficiency	%	23.9	23.9	23.9	23.9

2.4.4 Module

2.4.4.1 General knowledge and description

A PV module is produced from multiple sc-Si cells. Activity starts with sc-Si cell at module production location and ends with the production of sc-Si module at production site. As an optional process, sc-Si cells are cut into half-cells and characterized. sc-Si cells are assembled with a stringer (wire and ribbon) and characterized. The string is deposited on solar glass and encapsulant and cover with backsheet or glass. The lamination process is performed to link all elements. An aluminum frame and a junction box are added, and the PV module is characterized and sorted.

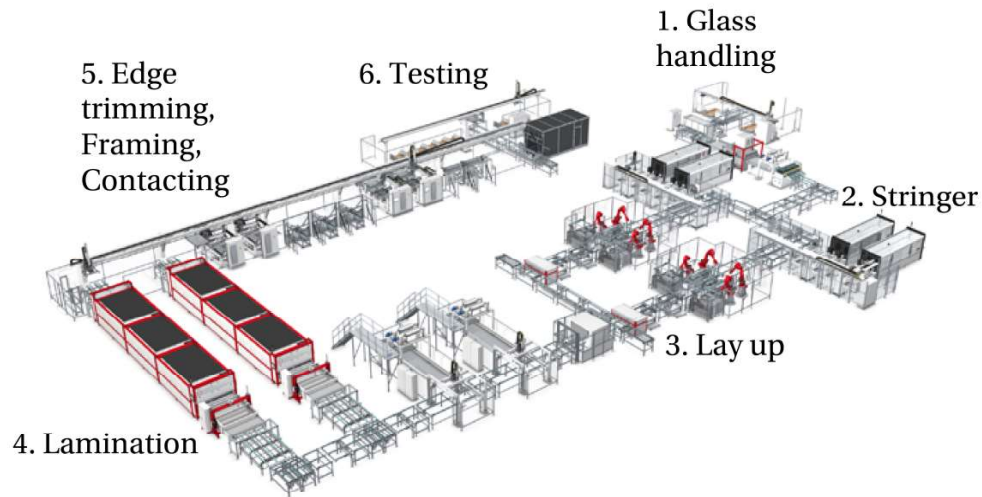


Figure 2.10: Schematic of the process flow of PV module manufacturing

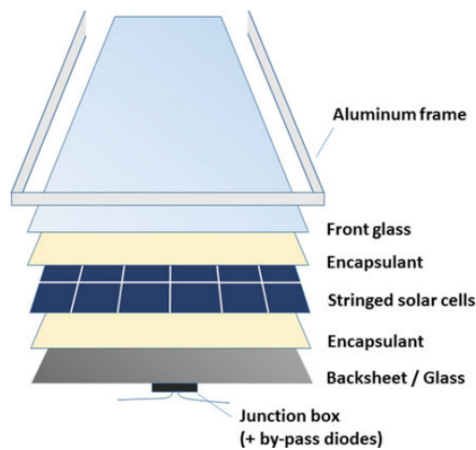


Figure 2.11: Schematic of a solar module structure (glass-backsheet)

2.4.4.2 Parameters and assumptions for Al-BSF, PERC and HJT technologies

Table 2.10: Key parameters and assumptions for PV module

process ID	Information	Unit	Al-BSF 2010	Al-BSF 2020	PERC 2020	HJT 2020
2.	Module type	-	laminate (glass/backsheets)	laminate (glass/backsheets)	laminate (glass/backsheets)	laminate (glass/backsheets)
2.0	Number and type of cells	-	60 M2 sc-Si Al-BSF cells	60 M2 sc-Si Al-BSF cells	120 half-cut G1 sc-Si PERC cells	120 half-cut M6 sc-Si HJT cells
2.	Module dimensions	mm	-	-	1685 x 1000 x 42	1767 x 1041 x 35
2.	Module area	m ²	1.6*	1.6	1.685	1.839
2.	Module efficiency	%	14	19*	20*	21.75
2.	Module output power	Wp	224	304*	337*	400
2.	Module weight	kg	24.7*	21.23	19.125	19.7
2.0	Cell Area	m ² cell/m ² module	0.932	0.935	0.976	0.894
2.1	Solar glass thickness	mm	-	3.2*	3.2	3.2
	Encapsulant thickness	um	-	350-700*	350-700*	350-700
2.1	Solar glass	kg/m ² module	10.1	8.81	7.92	7.46*
	Aluminium frame	kg/m ² module	2.63	2.13	1.36	1.25*
	Encapsulant (EVA/POE)	g/m ² module	1000	875	849	849*
2.8	Electricity consumption	kWh/m ² module	4.71	13.98	1.44	4.77

* own calculations and estimations based on peered PV and literature review

Each technology studied uses different size of cells. To simplify calculations, the quantity of area covered by cells in 1 m² of module is used as a reference, for Al-BSF 2010 and for all recent technologies it refers to a surface of M2, respectively M6 cells of specific technology.

2.4.4.3 Parameters and assumptions for sensitivity analysis

Each PV technology features an intrinsic efficiency limit related to cell and module architecture. The module efficiency strongly depends on the cell efficiency, and represent approximately 90% of the cell efficiency. The current PV trends tends to upgrade cell and module efficiency, therefore it represent a point of interest to observe the potential environmental benefits linked to a cell and module efficiency increase. The standard 2020 and maximum practical module efficiency for the PV technologies studied is set based on CSEM knowledge:

Table 2.11: Standard 2020 and maximum practical module efficiencies for Al-BSF, PERC and HJT technologies

PV technology	Standard 2020 module efficiency [%]	Maximum practical module efficiency [%]
Al-BSF	19.0	20.0
PERC	20.0	22.5
HJT	21.75	24.5

The analysis of efficiency improvements for all technologies (Al-BSF, PERC, HJT) is carried out in the sensitivity results.

2.4.5 Balance of System and installation

The Balance of System (BOS) includes all materials needed to obtain an operational PV-System from a PV module. Installation of the 3 kWp PV system refers to transport from production site to use site as well as installation on a roof top. Thus, for this process, activity starts with the extraction of raw materials needed for BOS production and ends with the installation of the PV system at use site. Therefore, the BOS & Installation includes:

- the production of an inverter amount which is used to convert DC current into AC current. The inverter lifetime is set to 15 years (half of PV system lifetime).
- the production of a mounting structure (usually in aluminium) which is used to set the PV modules on roof top.
- the production of cables which are needed to wire the PV system to the grid.
- the transport of all previous materials and PV modules to the use site.

BOS & Installation building block is not considered for the FU1 (kWp) as this FU focus on the PV module output power only. Battery are not included as the PV-system is grid-connected. The electrical grid to which the PV-system is connected is excluded but its connection (through cables) is included.

Table 2.12 records the diverse parameters used for BOS building block construction

Table 2.12: Balance of System and installation - key parameters

process ID	Information	Unit	Al-BSF 2010	Al-BSF 2020	PERC 2020	HJT 2022
	PV system	kWp	3.00			
	area of module	m ² / PV system	21.9	16.1	15.3	14.1
	mounting system	m ² / PV system	21.9	16.1	15.3	14.1
	aluminium alloy	kg / m ² mounting system	2.84			
	inverter 2.5 kW	p/ PV system	2.40			
	electric installation (cables)	p/ PV system	1.00			
0.10	Materials transport (RER)	-	230 km by truck (>32t, EURO4) 240 km by train (average freight train) 87 km by ship (barge)			
0.10	Materials transport (RoW)	-	18 000 km by ship (transoceanic container) 1000 km by truck (>32t, EURO4)			
0.	Inputs/Outputs	-	RER when possible, RoW/GLO otherwise			
0.9	Electricity consumption	-	dependent of the location RER/RoW			

2.4.6 Use phase

The use phase is the longer stage of the PV system. Its main activity is the production of AC current from incoming solar radiations according to the characteristics of the PV system. Activities included are

- the electricity production of AC current
- the maintenance of the PV system, washing PV modules with water
- the repair / replacement of components of the PV system

AC electricity production AC electricity production is defined by the following equation:

$$E_{produced} = I * A * r * PR$$

$E_{produced}$ = Energy produced [kWh/year]

I = Annual average solar irradiance [kWh/(m²*year)]

A = Area of PV system [m²]

r = Efficiency of PV module [%]

PR = Performance Ratio [%] = (1-losses)*100[%]

$A * r$ represents the output peak power of the PV system, which is set to 3 kWp in this analysis. As the efficiency of PV module differs from one technology to another, the area of PV system vary between technology for the same output power delivered (3 kWp).

The performance ratio includes all internal and external losses and its value is comprised between 0.5 and 0.9 with an average value of 0.75 [41]. As a global observation, many LCA studies [32] use a performance ratio of 75%. Internal losses are related to the losses occurring between the PV module output to the PV system output: inverter conversion from DC to AC current, cables, etc. External losses are losses resulting from inclination/azimut of the PV modules, extreme temperature, shadings and low irradiance, weather (dust or snow). Losses are very hard to determine without in-field data, thus a constant PR (0.75) is chosen for this study, giving an approximation of reality. The total energy produced by the PV system is expressed by:

$$E_{total} = \sum_{i=1}^n E_{produced}(i)$$

E_{total} = total energy produced [kWh]

n = lifetime [years]

Losses are not constant through the life cycle of the PV system and PV module peak power varies within time with important losses during the first year of installation (0.5 to 2%), followed by a constant loss in the rest of the lifetime (0.25 to 0.5% each year). Taking the average yearly energy produced over PV system lifetime, the previous formula can be simplified to:

$$E_{total} = E_{produced} * n$$

The calculation of energy produced by a PV system directly determines the kWh FU and a variation of the performance ratio, solar irradiance or lifetime is expected to have a strong influence on PV delivered kWh. The FU1 kWp is not influenced by the use phase as it is not included in its system boundary.

Parameters performance ratio, solar irradiance and module lifetime represent key parameters that are analyzed in the sensitivity section. A specific focus is set for the energy produced as it directly influence the FU kWh.

Three scenarios of solar irradiance in Europe are analyzed:

- maximum irradiance (south of Spain) with 2200 kWh/(m²*year)
- standard irradiance (european average) with 1391 kWh/(m²*year)
- minimum irradiance (north of Norway) with 800 kWh/(m²*year)

The sensitivity results section on energy produced observe the performance ratio and lifetime couple needed to produce the equivalent quantity of electricity of a 3 kWp PV system operating at standard conditions ($I=1391 \text{ kWh}/(\text{m}^2 \cdot \text{year})$, $PR=0.75$, $n=30$ years). The goal is to show the influence of the location on the production of electricity for a PV system (considering FU kWh).

Maintenance of PV system : Water is used to clean the PV panels, an estimation of $2/3 \text{ liters}/(\text{m}^2 \cdot \text{year})$ of solar panel is chosen as presented in Ecoinvent literature based on [42].

Repairing or replacement of components : For this study, an assumption of 2% of PV system replacement along the lifetime of the PV system is chosen as presented in Ecoinvent literature based on [42].

Table 2.13 summarizes the main parameters and assumptions of the use phase of the PV system.

Table 2.13: Use phase key parameters and assumptions

process ID	Information	Unit	Al-BSF 2010 Al-BSF 2020 PERC 2020 HJT 2020
	Lifetime	years	30
	PV system output	kWp	3
	efficiency module	%	see module table
	Area module	%	see module table
	Solar irradiation	$\text{kWh}/(\text{m}^2 \cdot \text{year})$	1391
	Performance ratio (PR)	%	75
	Replacement rate	%	2
	Water used for cleaning	$\text{l}/\text{m}^2 \text{ module}$	20.00
RF_use	Reference flow use	-	1.07 E-5

2.4.7 End-of-Life

2.4.7.1 General knowledge and description

The end-of-life is the last stage of the PV system. It begins when the product in scope and its packaging is discarded by the user and ends when the product is returned to nature as a waste product or enters another product's life cycle (i.e. as a reused or recycled input). End-of-life includes:

- the transport from use site to end-of-life site
- the dismantling of the PV system
- the waste process applied (reuse, recycling or disposal)
- Major contributors for solar panel are: tempered solar glass, aluminium frame, composites and silicium
- Major contributors of the BOS: mounting structure, copper cables and inverter

Due to limited waste volumes so far, c-Si PV modules are mainly treated in recycling plants designed for treatment of laminated glass, metals or electronic waste. Only the bulk materials (glass, aluminium and copper) are recovered, while the cells and other materials such as plastics are incinerated [29]. IEA report [43] shows the latest trends for PV module recycling, Which tends to achieve 95% of mass recycled. Nevertheless, very poor informations are available for the end-of-life of the BOS, therefore End-of-Life of BOS is not treated in this work.

European PEF guidance (page 67) [27] defines the Circular Footprint Formula (CFF) for end-of-life modelling. The CFF (detailed in appendix) is a combination of "material + energy + disposal" for a specific material. This formula is used by [29] to take into account the benefits or burdens of the waste scenario (recycling, disposal, burned). This complex formula is used to represent the complexity of End-of-Life reality: various waste scenario to apply to a specific material. To simplify calculations, CFF is not used for End of Life (EoL) in this project but three major scenario are detailed based on [29] research.

Three major scenario are considered for the EoL of PV module:

- **Disposal scenario:** disposal in landfill (glass, aluminium) and municipal incineration (copper, plastics).
- **Recycling without benefits scenario:** recycling of glass, copper and aluminium frame, disposal and incineration of plastics.
- **Recycling with benefits scenario:** same as second scenario but with benefits and burdens linked to the replacement of primary materials by secondary materials produced from recycling process.

The boundary for each of the three PV module EoL scenario is depicted in the Figure 2.12.

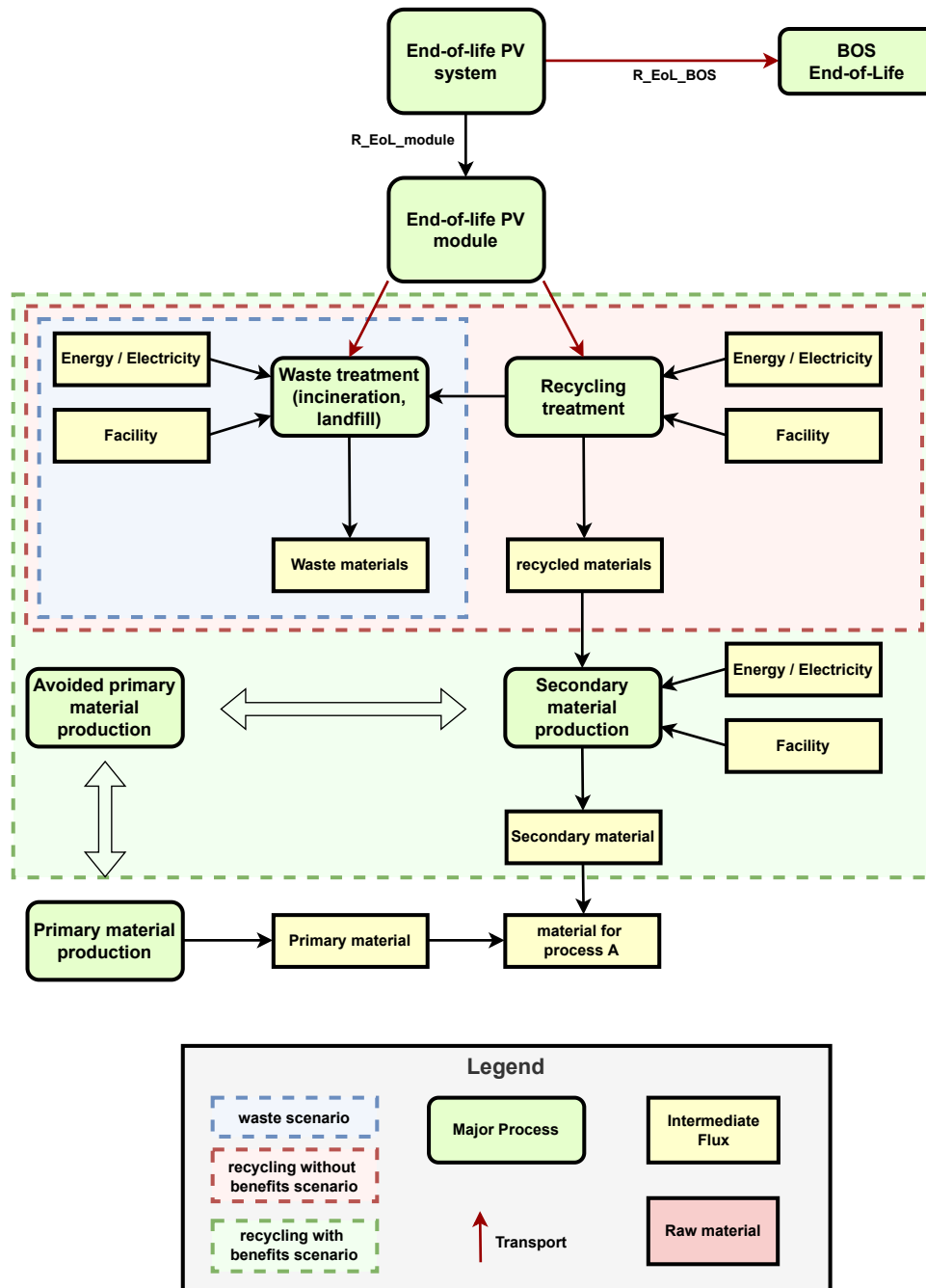


Figure 2.12: Process tree for the End-of-Life of PV system

The environmental impact of the three PV moduel EoL scenario is treated for HJT technology in the results chapter.

Assumptions and key parameters set in [29] for end-of-life are adapted to the quantity of materials used in PV modules,i.e the same composition is assumed for all PV technologies, but the quantity treated for EoL scenarios are dependent of the PV module weight specific to each PV technology.

A progressive implementation of PV system recycling solutions is expected with the increasing number of PV system deployed worldwide. Eco-design should be performed to increase the ease of recuperation of different PV module components, which can nowadays be recycled up to 94% according to Soren [44].

Chapter 3

Results and Discussion

The results and discussion chapter evaluates the environmental impact of the four PV system types studied (namely the Al-BSF 2010, Al-BSF 2020, PERC 2020 and HJT 2020) with a specific focus on HJT technology improvement. In each section, the results are presented considering both FU with the environmental impact per kWh and per kWp. A major concern of this project is to provide advices for PV manufacturers, therefore data for kWp are more detailed as they mainly concern the production and manufacturing processes (wafer, cell, module) on which PV manufacturers have a strong influence. The results chapter is divided in four sections:

- **Environmental impacts:** presents the major results along the 16 impact categories for four PV systems and for both FU: kWp and kWh;
- **Carbon footprint:** evaluates the impact on the Climate Change impact category for the four PV systems studied. Results are shown per kWp and per kWh;
- **Sensitivity analysis:** shows the response of the four PV system to multiple variations of key parameters such as module efficiency, wafer thickness;
- **Upgrade of HJT PV technology towards reduced environmental impacts:** looks in detail at each building block impact (wafer, cell, module, BOS & Installation, Use, End-of-Life) specifically for HJT technology and evaluates alternative scenarios to mitigate the environmental impacts of some of those building blocks.

It is important to remind that results are strongly influenced by hypothesis of the PV system model. All hypothesis selected are described in the methodology chapter. The major hypothesis which are chosen for this study are detailed in the table 2.3 and are the following: Chinese wafer, European cell and module, inclusion of BOS & Installation, use phase in Europe with solar irradiance : $1391 \text{ kWh}/(\text{m}^2 \cdot \text{year})$; lifetime 30 years ; Performance Ratio $PR = 0.75$).

To easily read the various graphs presented in this chapter, the following color code is applied (in most cases) for all results figures.

■ Use phase ■ BOS+Installation ■ Module ■ Cell ■ Wafer

3.1 Environmental impacts

The environmental impacts categories are described in Table 4.6. The results obtained are split into two subsections : impacts per kWh and per kWp. Nevertheless, the discussion of the results may combine both FU as subsection results are highly correlated.

3.1.1 Environmental impacts per kWh produced electricity

The kWh is the FU considered in this subsection. Its definition is depicted in the Scope and goal. Figure 4.12 represents the relative impact per kWh of the four PV system compared to the maximum impact per impact category. Please refer to the methodology to obtain results for any methodological detail about calculations.

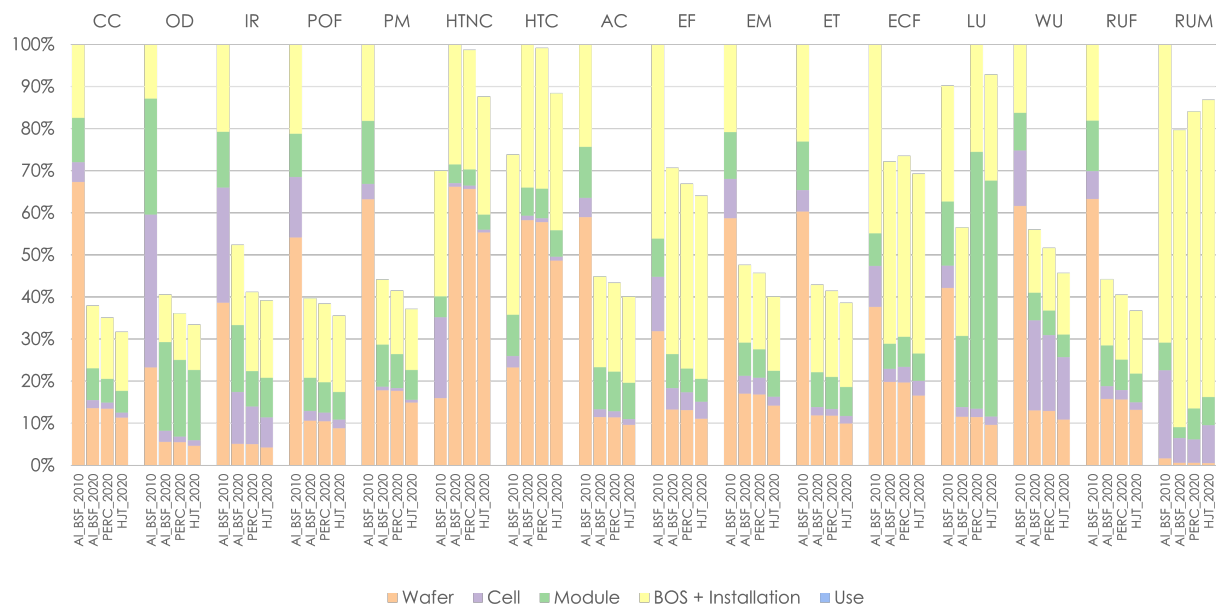


Figure 3.1: Relative environmental footprint per kWh of a 3kWp PV system for four c-Si technologies (Al-BSF 2010 ($\eta=14.0\%$), Al-BSF 2020 ($\eta=19.0\%$), PERC 2020 ($\eta=20.0\%$) and HJT 2020 ($\eta=21.75\%$)). EF 3.0 impact assessment methodology used. Activities included : wafer production in China (2010: 270 μm ; 2020: 170 μm), transport to Europe, Cell and Module manufacturing in Europe, BOS & Installation manufacturing, use phase in Europe ($I=1391 \text{ kWh}/(\text{m}^2 \cdot \text{year})$, $PR=0.75$, $n=30$ years), end-of-life modeled separately. Chinese electricity mix: 1023 g $\text{CO}_2\text{-eq}/\text{kWh}$; European electricity mix: 418 g $\text{CO}_2\text{-eq}$.

For all technologies analyzed, the use phase has a very small influence, representing less than 0.1% of the impact per kWh produced as depicted in Figure 4.12. This result is expected as no or very little inputs are needed for the PV system to operate (mainly maintenance and water to clean the modules), whereas the manufacturing phase (wafer, cell, module, BOS production) needs a lot of materials and energy leading to a more important environmental impact.

All 2020 technologies, which are the Al-BSF 2020, PERC 2020 and the HJT 2020, have a notably lower impact on the 16 impact categories compared to the Al-BSF 2010. In addition, the HJT 2020 presents the lowest impacts compared to PERC 2020 and Al-BSF 2020 for main impact categories. The following question emerges: could this impact be explained only by module efficiency differences or are there other key parameters influencing those impacts differences ? This concern will be studied in detail in the sensitivity analysis section.

As observed in Figure 4.12, Al-BSF 2010 has a higher impact per kWh than the other three PV technologies for all impact categories except LU, HTNC and HTC categories. Furthermore, BOS & Installation

are very similar for all the PV technology studied for those impact categories.

Figure 4.12 shows that the BOS & Installation represents an important contributor (>70%) to the impact on RUM for all technologies evaluated. The main components responsible of the BOS & Installation impact are evaluated in the last section of this chapter. Furthermore, for the impact on the RUM, the HJT 2020 impact is superior to PERC 2020 impact which is superior to Al-BSF 2020 impact. This is a surprising result as efficiency of Al-BSF is inferior to PERC efficiency itself inferior to HJT efficiency, which shows that technology specificities may also influence the environmental impact, and that high efficiency concept do not necessarily result in low environmental impact.

3.1.1.1 End-of-Life

End-of-Life modeling is described in the EoL methodology and the environmental impacts per kWh are treated separately as various End-of-Life scenarios can be applied. The detailed results are shown in the subsection End-of-Life of the section Upgrade of c-Si PV technology of the results chapter.

3.1.2 Environmental impacts per kWp nominal power

Focusing on the kWp FU (which excludes the BOS & Installation and the use phase) gives a better overview of manufacturing processes (wafer, cell, module) differences present between the PV technologies. Figure 3.2 represents the relative impact of the studied PV technologies compared to Al-BSF 2010 (set to 100% of impact). The impact of the Al-BSF is always clearly higher than the three other 2020 PV technologies except for the LU, HTC and HTNC impact categories. In particular, the impacts of the Al-BSF 2020 and PERC 2020 represent 180% of Al-BSF 2010 impact on HTC and HTNC impact categories ; for HJT 2020, this impact is comprised between 150 and 160% of Al-BSF impact. This higher impact is mainly due to the wafer building block as depicted in Figure 3.3. For the impact on LU, Figure 3.2 shows an impact of PERC 2020 and HJT 2020 slightly superior to the one of Al-BSF 2010, on the opposite, Al-BSF 2020 impact on LU represent 50% of Al-BSF 2010 impact on LU. Wafer and Module building blocks have the major influence on this impact for all technologies as depicted in figure 4.12.

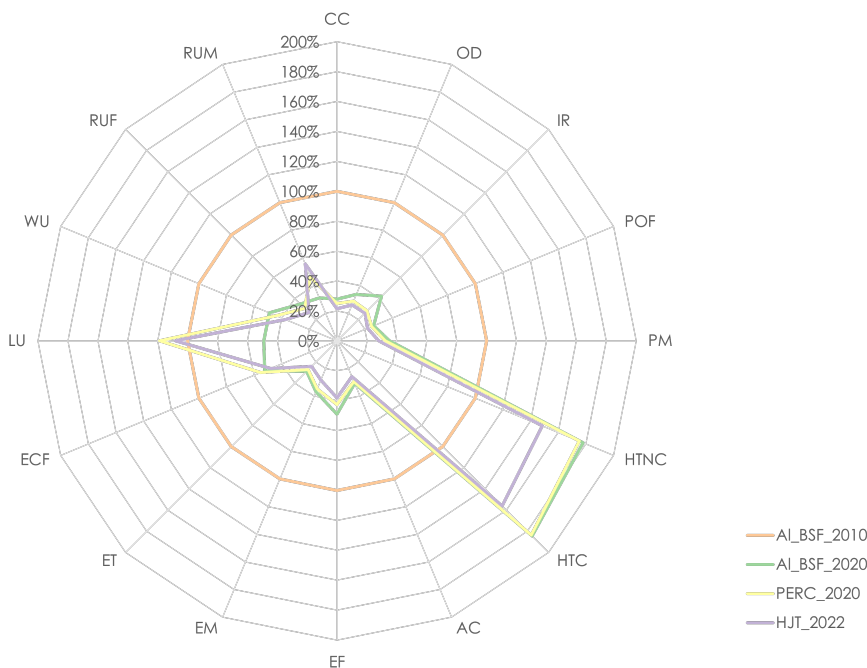


Figure 3.2: relative Environmental impact (along 16 impact categories) per kWp of a 3kWp PV system for four c-Si technologies (Al-BSF 2010 ($\eta=14.0\%$), Al-BSF 2020 ($\eta=19.0\%$), PERC 2020 ($\eta=20.0\%$) and HJT 2020 ($\eta=21.75\%$)). EF 3.0 impact assessment methodology used. Activities included : wafer production in China (2010: 270 μm ; 2020: 170 μm), transport to Europe, Cell and Module manufacturing in Europe, end-of-life modeled separately. Activities excluded: BOS & Installation manufacturing, use phase. Chinese electricity mix: 1023 g CO₂-eq/kWh ; European electricity mix: 418 g CO₂-eq. Al-BSF 2010 is set to 100%

The impact per kWp of the three 2020 PV technologies represents less than 60% of the Al-BSF 2010 impact on all the impact categories except LU, HTC and HTNC. Figure 3.3 represents the relative impact per kWp of the four technologies compared to the maximum impact per impact category. A finer granulometry of analysis is achieved by detailing the wafer and module building blocks. Therefore, previous results can be further detailed.

The impact on HTNC and HTC of the 2020 PV technologies is mainly due to the Czochralski process occurring during the wafer manufacturing. Their higher value compared to Al-BSF 2010 is due to the actualization of pollutants produced during the Cz process, which were only partially taken into account for 2010 wafers used for the Al-BSF 2010 modeling. Despite thinner 2020 wafers, the impacts of the Cz process still represent nearly 87% and 82% of the total impact on HTNC and HTC, respectively, for all 2020 technologies. Figure 3.3 shows that the wafer building block is responsible for more than 60% of the total Al-BSF 2010 impact on LU, which is no more the case for 2020 technologies. The component "other

module" has the major share (>60%) for PERC 2020 and HJT 2020 impact on LU. This impact on LU of "other module" is mainly due to the use of additional wood pallets which are required for the transport of modules, as recent PERC and HJT modules are larger than old Al-BSF ones, owing to the increasing wafer size (see Table 2.10. Nevertheless, the difference observed seems a little larger than expected and further work is required to refine the modeling.

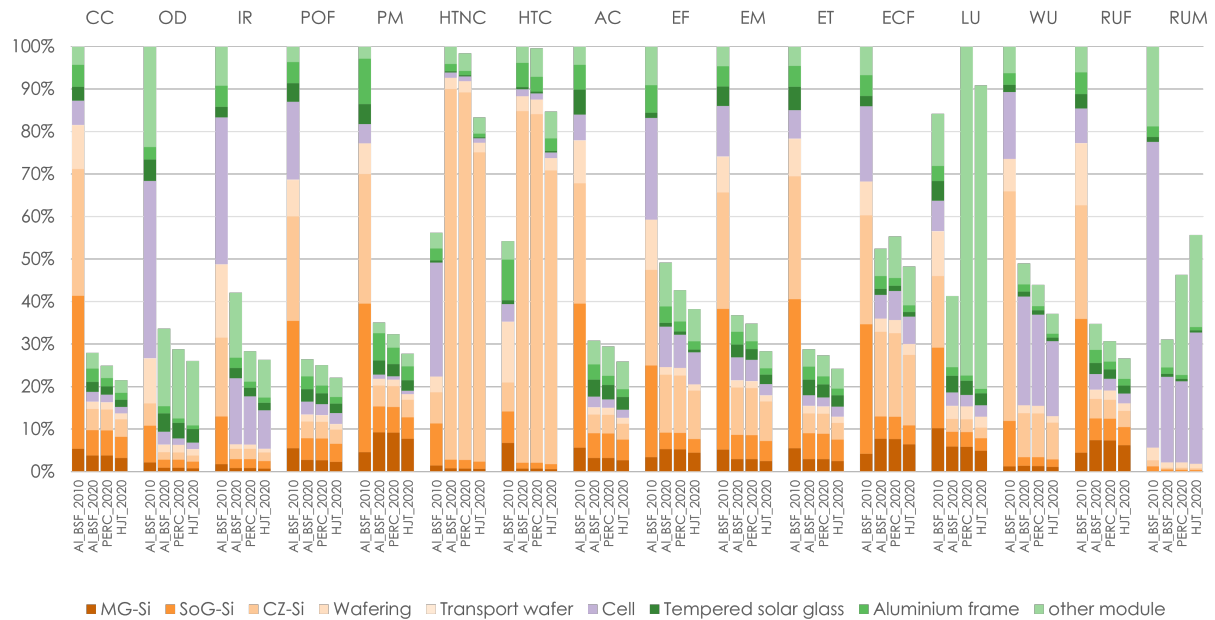


Figure 3.3: Relative environmental impact (along 16 impact categories) per kWp of a 3kWp PV system for four c-Si technologies (Al-BSF 2010 ($\eta=14.0\%$), Al-BSF 2020 ($\eta=19.0\%$), PERC 2020 ($\eta=20.0\%$) and HJT 2020 ($\eta=21.75\%$)). EF 3.0 impact assessment methodology used. Activities included : wafer production in China (2010: 270 μm ; 2020: 170 μm), transport to Europe, Cell and Module manufacturing in Europe, end-of-life modeled separately. Activities excluded: BOS & Installation manufacturing, use phase. Chinese electricity mix: 1023 g CO₂-eq/kWh ; European electricity mix: 418 g CO₂-eq.

To summarize, Figure 3.3 and 4.12 shows that the change from 2010 wafer to 2020 wafer results in an environmental impact reduction for all impact categories except HTC and HTNC, leading to lower environmental footprint of 2020 PV technologies compared to Al-BSF 2010. As an example, wafer impact on PM drops from 77% for Al-BSF 2010 to 22% for Al-BSF 2020. Nevertheless, the total reduction of environmental impact may also be influenced by module efficiency improvements (from 14% Al-BSF 2010 to 19% Al-BSF 2020). Those topic will be studied in the following sections.

3.2 Carbon footprint

Climate Change (CC) represents the impact category the most studied in LCA in general and also specifically for PV LCA [32]. Thus, CC will be studied in detail for both FU (kWp and kWh) in this section. As a reminder, carbon footprint is the denomination of the impact on the Climate Change impact category, also known as Global Warming Potential (GWP).

3.2.1 Carbon footprint per kWh produced electricity

Figure 3.4 presents the carbon footprint (expressed in g CO₂-eq) per kWh of the four PV technologies studied.

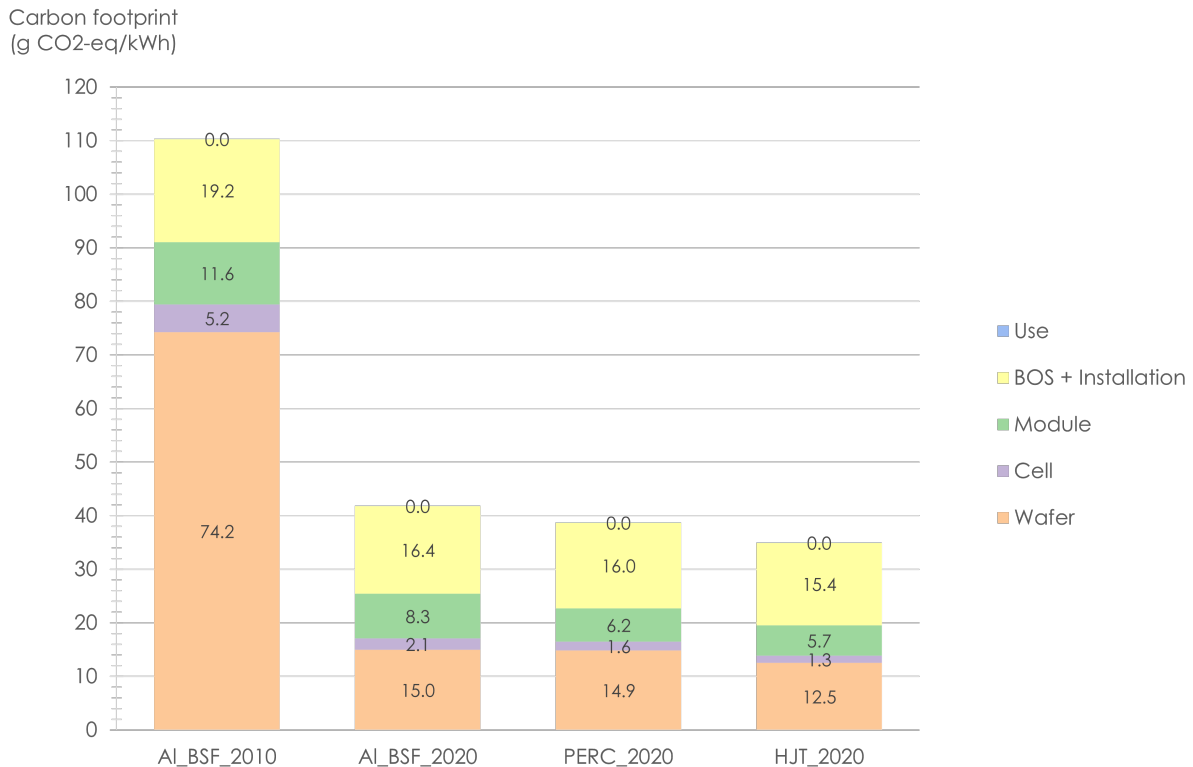


Figure 3.4: Carbon footprint per per kWh of a 3kWp PV system for four c-Si technologies (Al-BSF 2010 ($\eta=14.0\%$), Al-BSF 2020 ($\eta=19.0\%$), PERC 2020 ($\eta=20.0\%$) and HJT 2020 ($\eta=21.75\%$)). EF 3.0 impact assessment methodology used. Activities included : wafer production in China (2010: 270 μm ; 2020: 170 μm), transport to Europe, Cell and Module manufacturing in Europe, BOS & Installation manufacturing, use phase in Europe ($I=1391 \text{ kWh}/(\text{m}^2 \cdot \text{year})$, $PR=0.75$, $n=30$ years), end-of-life modeled separately. Chinese electricity mix: 1023 g CO₂-eq/kWh ; European electricity mix: 418 g CO₂-eq.

The major results found are dependent of major hypothesis described in table 2.3:

- Al-BSF 2010 has a carbon footprint of 110.2 g CO₂-eq/kWh
- Al-BSF 2020 has a carbon footprint of 41.8 g CO₂-eq/kWh
- PERC 2020 has a carbon footprint of 38.7 g CO₂-eq/kWh
- HJT 2020 has a carbon footprint of 34.9 g CO₂-eq/kWh

Those results can be compared with literature review, nevertheless, one may keep in mind that study hypothesis strongly influence the PV system and therefore its carbon footprint. The study from Jungbluth et al. [45] found a carbon footprint of 100-138 g CO₂-eq/kWh for Al-BSF 2010 technology, which is consistent with the 110.2 g CO₂-eq/kWh found here for the Al-BSF 2010.

A more recent study from Muller [33] established the carbon footprint of PERC 2020:

- 25.9 g CO₂-eq/kWh considering a whole Chinese scenario for wafer, cell and module, excluding BOS & Installation and including the same use phase parameters.
- 15.2 g CO₂-eq/kWh considering a whole European scenario for wafer, cell and module, excluding BOS & Installation and including the same use phase parameters.
- Those results can be put in parallel to this study results: 14.9 g CO₂-eq/kWh for the wafer (Chinese), 7.8 g CO₂-eq/kWh for the cell and module (European) which gives a value of 22.7 g CO₂-eq/kWh which is comprised between both values found by Muller. The results tend to be closer to the full Chinese scenario of Muller due to the important influence of the wafer building block.

Another study on PERC technology [46] shows a carbon footprint of 29.2 g CO₂-eq/kWh with hypothesis of 17% module efficiency, mc-Si wafer and excluding BOS & Installation. This is comparable to 22.7 g CO₂-eq/kWh found in this study (excluding BOS & Installation) as the carbon footprint is expected to decrease with an increase of module efficiency (from 17% to 20%). Nevertheless, the use of sc-Si instead of mc-Si (less pollutant than sc-Si) should compensate the benefits of module efficiency increase, which is not observed between this study and Luo results.

In 2016, Louwen [35] performed a major study on HJT and found an impact of approximately 35 g CO₂-eq/kWh for HJT technology. Even if this result is identical to ours, the hypothesis chosen diverge as Louwen considered a solar irradiance of 1700 kWh/(m²*year) while here it is 1391 kWh/(m²*year). Furthermore, the module efficiency has been improved during the last years (18.4% for Louwen to 21.75% for this study), compensating the smaller solar irradiance selected for this study. Louwen detailed the influence of the different building blocks, allowing a more detailed comparison to this study results as presented in figure 3.5.

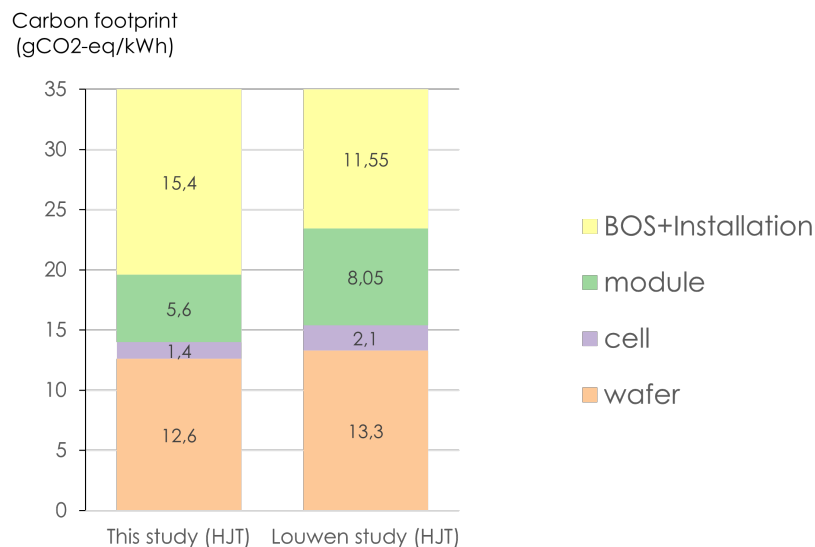


Figure 3.5: Carbon footprint per kWh of HJT (this study versus Louwen [35])

Following previous results, the wafer impact is found to decrease between 2010 and 2020 technologies mainly due to updates of the wafer process and thickness reduction. Nevertheless, this impact remains significant (12.5-15.0 g CO₂-eq/kWh) for 2020 technologies. The differences between 2020 technologies seems to be based on efficiency upgrades (19% for Al-BSF 2010, 20% for PERC 2020, 21.75% for HJT 2020). Finally, BOS & Installation is an important contributor to PV system carbon footprint, representing between 15.4 g CO₂-eq/kWh and 16.4 g CO₂-eq/kWh for 2020 technologies.

3.2.2 Carbon footprint per kWp nominal power

Figure 3.6 presents the carbon footprint (expressed in g CO₂-eq) per kWp of the four PV technologies studied. The major results found are dependent of major hypothesis described in table 2.3:

- Al-BSF 2010 has a carbon footprint of 2850 kg CO₂-eq/kWp
- Al-BSF 2020 has a carbon footprint of 796 kg CO₂-eq/kWp
- PERC 2020 has a carbon footprint of 711 kg CO₂-eq/kWp
- HJT 2020 has a carbon footprint of 612 kg CO₂-eq/kWp

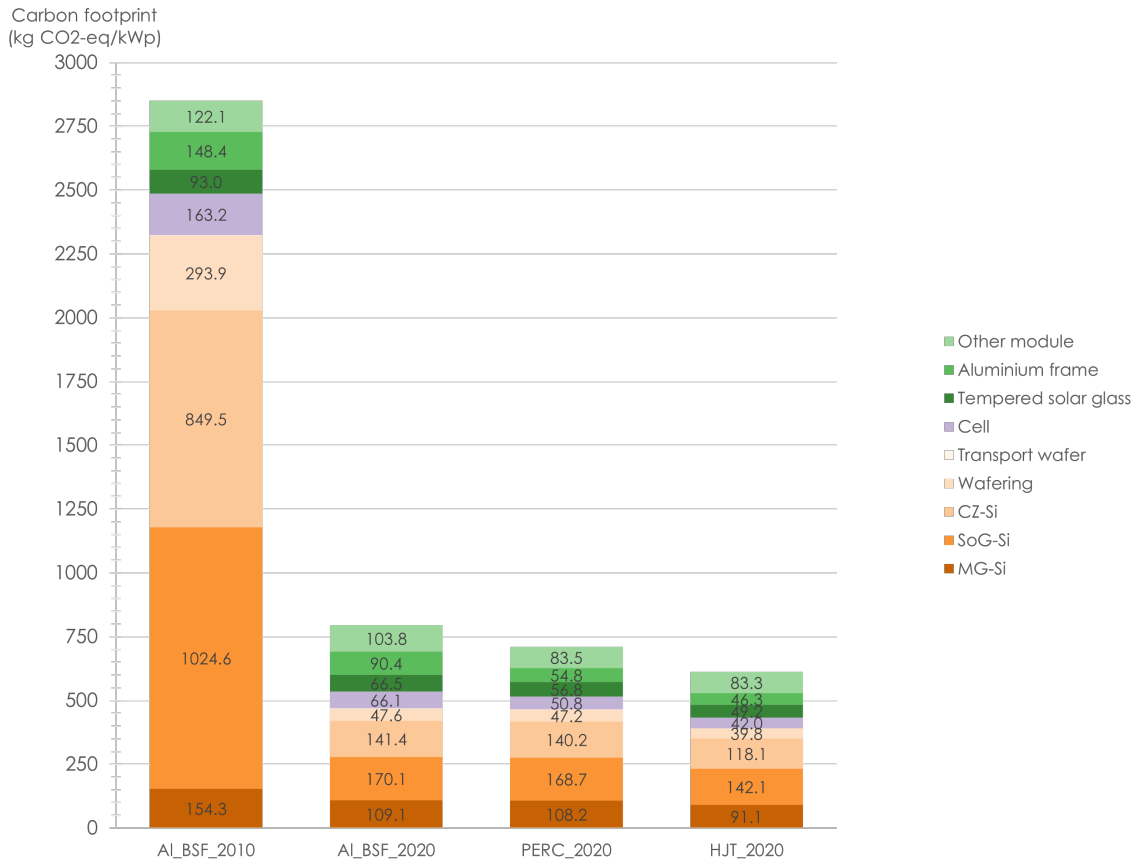


Figure 3.6: Carbon footprint per kWp of a 3kWp PV system for four c-Si technologies (Al-BSF 2010 ($\eta=14.0\%$), Al-BSF 2020 ($\eta=19.0\%$), PERC 2020 ($\eta=20.0\%$) and HJT 2020 ($\eta=21.75\%$)). EF 3.0 impact assessment methodology used. Activities included : wafer production in China (2010: 270 μm ; 2020: 170 μm), transport to Europe, Cell and Module manufacturing in Europe, end-of-life modeled separately. Activities excluded: BOS & Installation manufacturing, use phase. Chinese electricity mix: 1023 g CO₂-eq/kWh ; European electricity mix: 418 g CO₂-eq.

The detailed results for PERC 2020 are compared in figure 3.7 with the recent study from Muller [33] establishing the carbon footprint of PERC 2020 (with hypothesis very similar to the one used in this study).

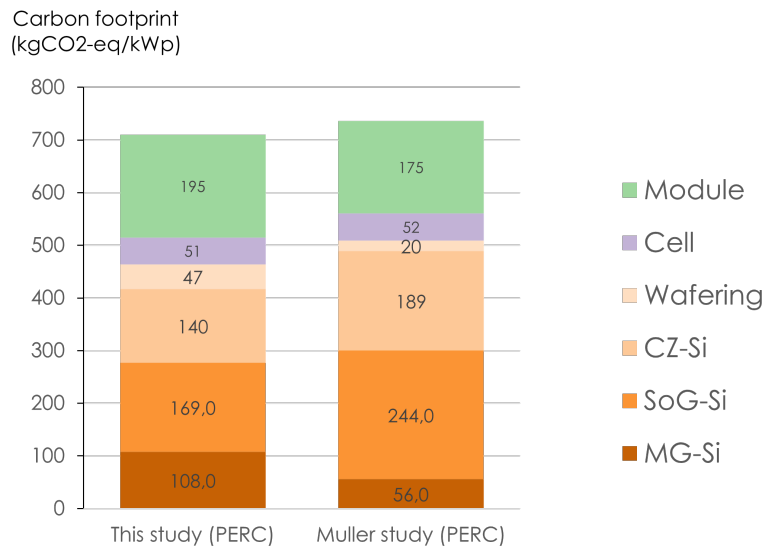


Figure 3.7: Carbon footprint per kWp of PERC technology (This study versus Muller [33])

The major variations observed occur in the wafer building block, nevertheless the total impact of this building block has a similar order of magnitude (464 kg CO₂/kWp for this study and 509 kg CO₂/kWp for Muller). Globally, the results are very similar for the total carbon footprint per kWp, which reinforce the validation of this study results.

For all technologies, the wafer building block represents more than 60% of the total carbon footprint per kWp. Notheworthy, the aluminium frame used for module has alone a higher carbon footprint than all processes needed for the cell production for all the technology studied. For all technologies, the combined impacts of tempered solar glass and aluminium frame represent more than 50% of the carbon footprint of the module. Considering carbon footprint, Cz-Si production is more impacting than SoG-Si production which is itself more impacting than MG-Si production, being more impacting than the wafering process. The transport of wafer shows a small impact (0.5 kg CO₂-eq/kWp for HJT 2020) which could be neglected. The detail of each building block impact will be studied in the section Upgrade of c-Si technology.

3.3 Sensitivity analysis

The results obtained in the previous section represent a strong interest for knowledge. Nevertheless, the results differences observed between technologies are linked to multiple parameters, such as module efficiency, wafer thickness, glass quantity used and so on. Therefore, it is crucial to identify the stability of the PV model against a selected variation of the key parameters. It may indicate on which data the focus must be set to ensure relevant results.

3.3.1 Climate Change and Resource use, minerals and metals

This section analyses the response of the PV system to a variation of +/- 10% of the following key parameters: (i) performance ratio, solar irradiance or module lifetime, (ii) module efficiency, (iii) wafer thickness, (iv) surface of mounting structure, (v) inverter number, (vi) module frame thickness and (vii) module glass thickness. Each key parameter refer to a building block of PV system: (i) is a use phase parameter ; (ii), (vi) and (vii) are module parameters ; (iii) is a wafer parameter ; (iv) and (v) are BOS & Installation parameters. Nevertheless, the influence of these parameters are not limited to their respective building blocks. Parameters (iii),(iv),(vi) and (vii) influence the weight of material needed, leading to an influence on the quantity of material ((v) directly influence quantity) needed to fulfill the FUs. Results are represented only for Climate Change and Resource use, minerals and metals impact categories as the PV system response for PM, WU and RUF is very close to the response for CC impact category. Results are also presented for FU (kWh) and FU1 (kWp). Figure 3.10, 3.11, 3.8 and 3.9 represent the PV model resilience to key parameters ((i) to (vii)) variations for (a) CC impact category, FU kWh ; (b) RUM impact category, FU kWh ; (c) CC impact category, FU1 kWp ; (d) RUM impact category, FU1 kWp respectively.

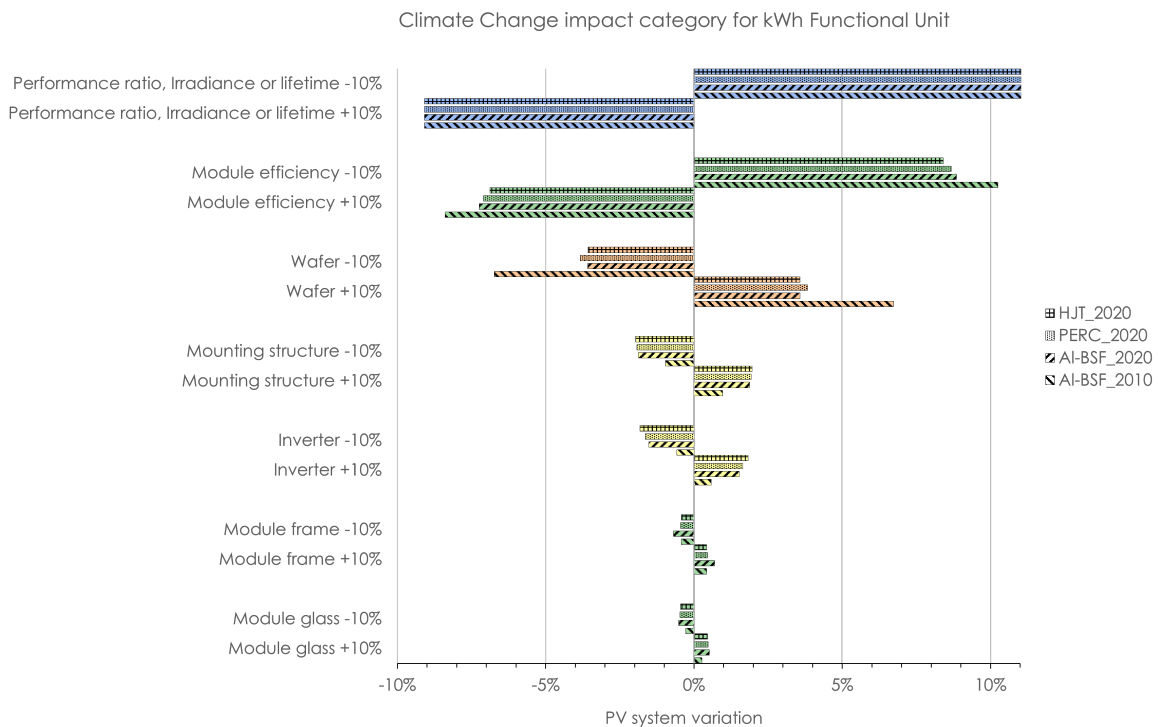


Figure 3.8: Carbon footprint (per kWh:FU) sensitivity (to key parameters variations) of a 3kWp PV system model for four c-Si technologies (Al-BSF 2010 ($\eta=14.0\%$), Al-BSF 2020 ($\eta=19.0\%$), PERC 2020 ($\eta=20.0\%$) and HJT 2020 ($\eta=21.75\%$)). EF 3.0 impact assessment methodology used. Activities included : wafer production in China (2010: 270 μm ; 2020: 170 μm), transport to Europe, Cell and Module manufacturing in Europe, BOS & Installation manufacturing, use phase in Europe ($I=1391 \text{ kWh}/(\text{m}^2 \cdot \text{year})$, $PR=0.75$, $n=30$ years), end-of-life modeled separately. Chinese electricity mix: 1023 g $\text{CO}_2\text{-eq}/\text{kWh}$; European electricity mix: 418 g $\text{CO}_2\text{-eq}$.

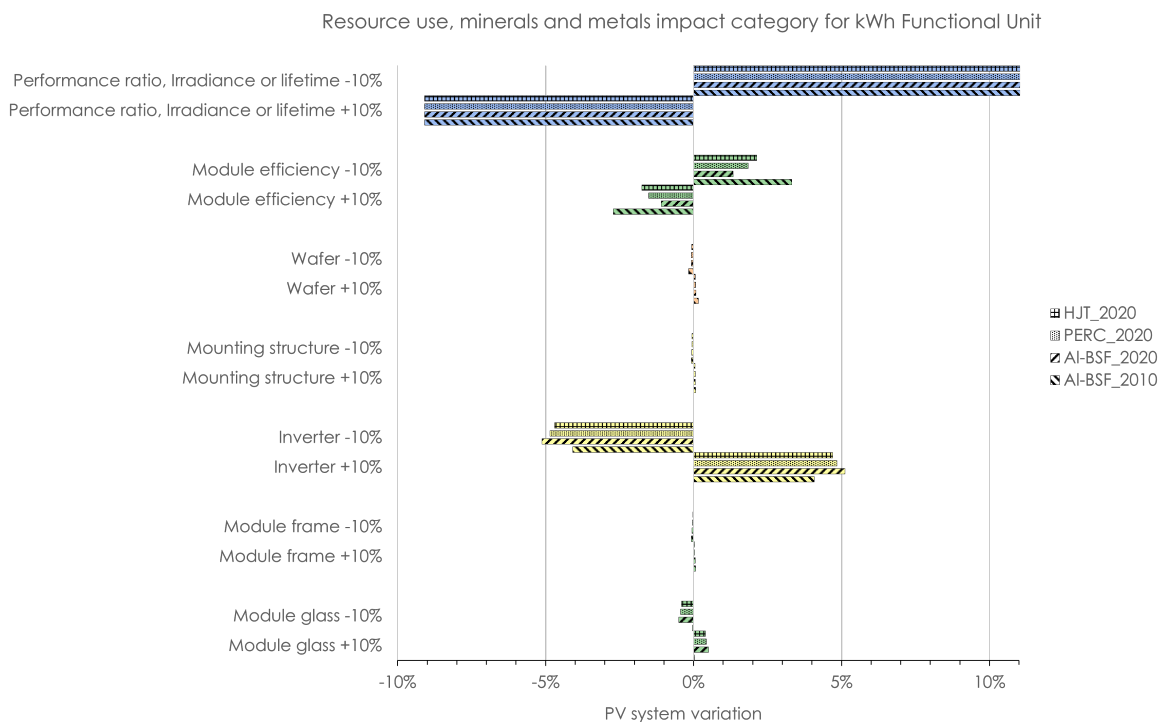


Figure 3.9: RUM impact (per kWh:FU) sensitivity (to key parameters variations) of a 3kWp PV system model for four c-Si technologies (Al-BSF 2010 ($\eta=14.0\%$), Al-BSF 2020 ($\eta=19.0\%$), PERC 2020 ($\eta=20.0\%$) and HJT 2020 ($\eta=21.75\%$)). EF 3.0 impact assessment methodology used. Activities included : wafer production in China (2010: 270 μm ; 2020: 170 μm), transport to Europe, Cell and Module manufacturing in Europe, BOS & Installation manufacturing, use phase in Europe ($I=1391 \text{ kWh}/(\text{m}^2 \cdot \text{year})$, $PR=0.75$, $n=30$ years), end-of-life modeled separately. Chinese electricity mix: 1023 g $\text{CO}_2\text{-eq}/\text{kWh}$; European electricity mix: 418 g $\text{CO}_2\text{-eq}$.

- Obviously, variations of parameters (i): solar irradiance, performance ratio, PV system lifetime and /iv) and (v): mounting structure and inverter number, does not influence the PV system for FU1 kWp as they concern the use phase and BOS & Installation building blocks, (which are not considered for kWp FU).
- Variations of solar irradiance, performance ratio and PV system lifetime have an identical strong influence on the PV system for all technologies (+11%/-9% per kWh). Those parameters are used to assess the total electricity produced for each technology, directly influencing the kWh functional unit and all reference flows related to kWh FU. This result is expected as the formula used gives the same weight to all of those parameters.
- The module efficiency has a strong influence on the PV system for both FUs. With a reduction of 10% (relative) of efficiency, one observe an augmentation (8% to 11%) of environmental impacts. This influence is the same for all technologies for FU1 kWp as it represents the main key parameter of the reference flows. Module efficiency influence per kWh decreases with the increase of module efficiency, HJT 2020 (21.7%) is less influenced by module efficiency variation than Al-BSF 2010 (14%), which owes to the reduced carbon footprint per kWp of wafer (60% HJT versus 80% for Al-BSF).

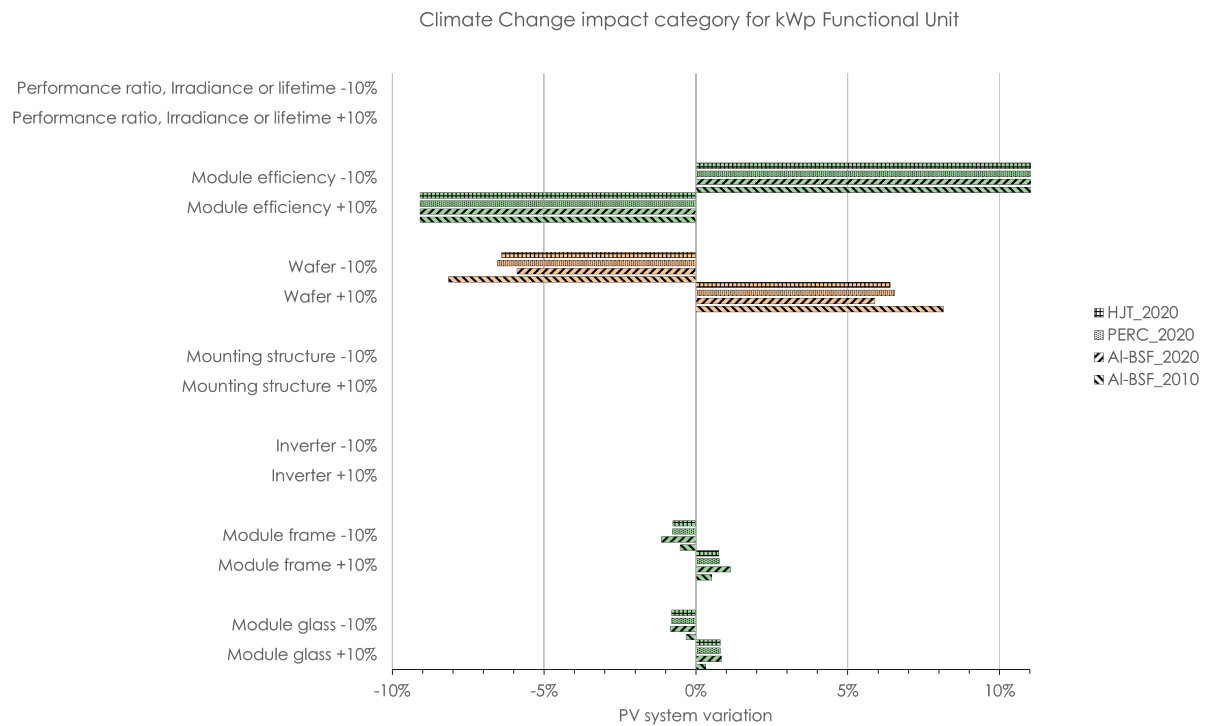


Figure 3.10: Carbon footprint (per kWp:FU1) sensitivity (to key parameters variations) of a 3kWp PV system model for four c-Si technologies (Al-BSF 2010 ($\eta=14.0\%$), Al-BSF 2020 ($\eta=19.0\%$), PERC 2020 ($\eta=20.0\%$) and HJT 2020 ($\eta=21.75\%$)). EF 3.0 impact assessment methodology used. Activities included : wafer production in China (2010: 270 μm ; 2020: 170 μm), transport to Europe, Cell and Module manufacturing in Europe, end-of-life modeled separately. Activities excluded: BOS & Installation manufacturing, use phase. Chinese electricity mix: 1023 g CO₂-eq/kWh ; European electricity mix: 418 g CO₂-eq.

- The wafer thickness influences only the wafer building block. Its influence is stronger for Al-BSF 2010 due to more important environmental impact (except for LU, HTNC and HTC) of 2010 wafers compared to 2020 wafers used for 2020 PV technologies. Wafer thickness variations influences more strongly the PV system for kWp FU (+/- 6% to +/- 8%) than for kWh FU (+/- 3.5% to +/- 7%) as wafer building block is more significant for kWp FU (considering only wafer, cell and module) than for the full system (kWh FU).
- Furthermore, wafer thickness variations influences more strongly the Climate Change impact category than RUM for kWh FU. In contrast, the influence of inverter number is stronger for RUM than CC impact category. Those results are expected as BOS (containing the inverter) contributes to the majority of RUM impact for all technologies and wafer as a much stronger impact on CC than on RUM is observed (see figure 4.12).

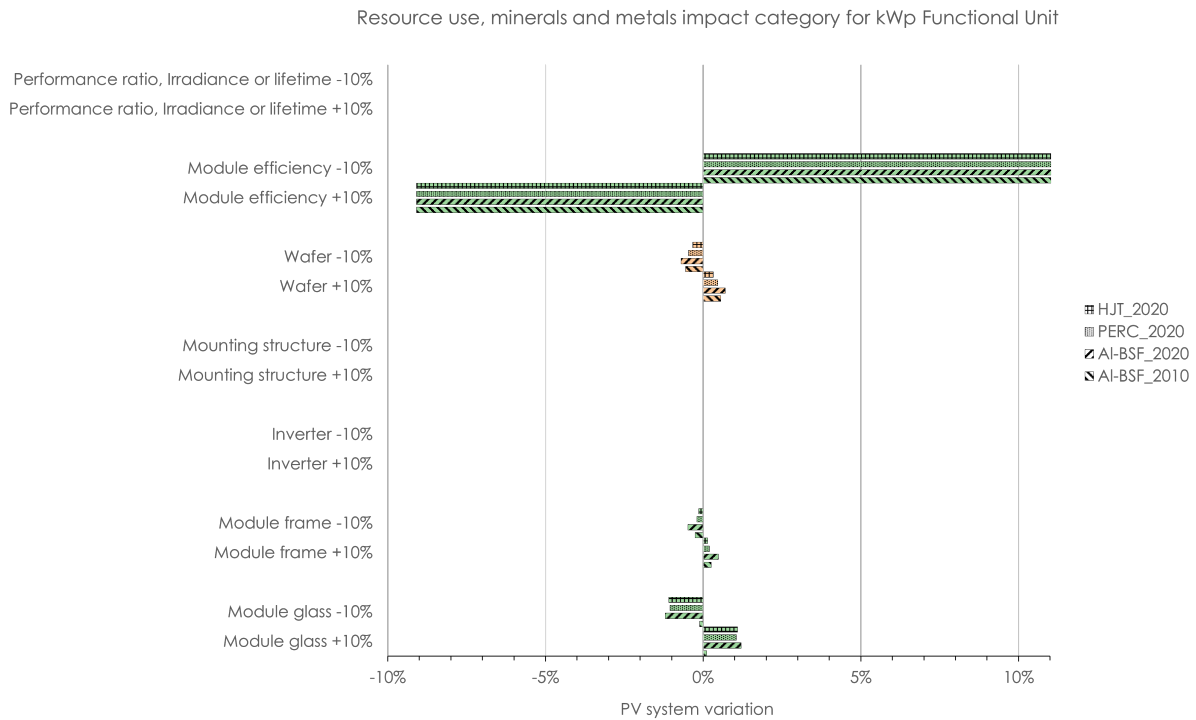


Figure 3.11: RUM impact (per kWp:FU1) sensitivity (to key parameters variations) of a 3kWp PV system model for four c-Si technologies (Al-BSF 2010 ($\eta=14.0\%$), Al-BSF 2020 ($\eta=19.0\%$), PERC 2020 ($\eta=20.0\%$) and HJT 2020 ($\eta=21.75\%$))

- The PV system response is symmetric to vertical axis for a variation of key parameters influencing quantity of material such as (iii) wafer thickness, (iv) mounting structure surface, (v) inverter number, (vi) module frame thickness, (vii) module glass thickness. Other parameters have a strong influence on the reference flows (see methodology chapter), resulting in non-linearity.
- Variations of the key parameters (v) inverter and (iv) mounting system of the BOS & Installation building block have more influence ($\pm 2\%$) than variations of the key parameters (vi) and (vii) influencing the frame, respectively glass quantities of the Module building block ($< \pm 1\%$) for the 2020 PV technologies on CC impact category for FU kWh. Their influence is much smaller than wafer influence for Al-BSF 2010 which is expected due to the strong impact on CC of the 2010 wafer.

The different observations described above can be compared with sensitivity analysis results from [33] study focusing on PERC technology, which evaluates variations for CC, PM and RUM categories for the kWp FU. Module efficiency shows identical results to PV system, nevertheless wafer influence appears to be stronger for the PV system of this study ($\pm 6\%$ vs $\pm 2\%$ for Muller); it is mainly due to the use of German wafers (with a lower carbon footprint than Chinese wafer) for Muller's study. Module glass shows similar influence (inferior to $\pm 1\%$ on the PV model for kWp).

Furthermore, the energy requirement of the key parameters was also studied in the [33] study and shows an important impact ($\pm 5\%$ variations of PV model impact for a $\pm 10\%$ variation of the key parameter) for CC (kWp). It is also important to notice that the energy mixes used are from the Ecoinvent database, which is outdated (2013) for Chinese electricity mix, possibly resulting in a more import impact than real PV impact. This topic is further discussed in the limitations section.

3.3.2 Maximum technology module efficiency

In this subsection, a specific sensitivity analysis on module efficiency is performed as module efficiency strongly influences the environmental impact of the PV system (as described in the previous section). As a reminder, each PV technology features an intrinsic efficiency limit related to cell and module architecture. The standard 2020 and maximum practical module efficiency for the PV technologies studied is set based on CSEM knowledge: Al-BSF: 19.0% (2020), 20.0% (maximal) ; PERC: 20.0% (2020), 22.5% (maximal); HJT:21.75% (2020), 24.5% (maximal).

Figure 3.12 presents the reduction of environmental impact of the three 2020 PV technologies going from standard 2020 to maximal module efficiency for Al-BSF (frame), PERC (dots) and HJT (lines) PV technologies along CC, PM, WU, RUF and RUM impact categories.

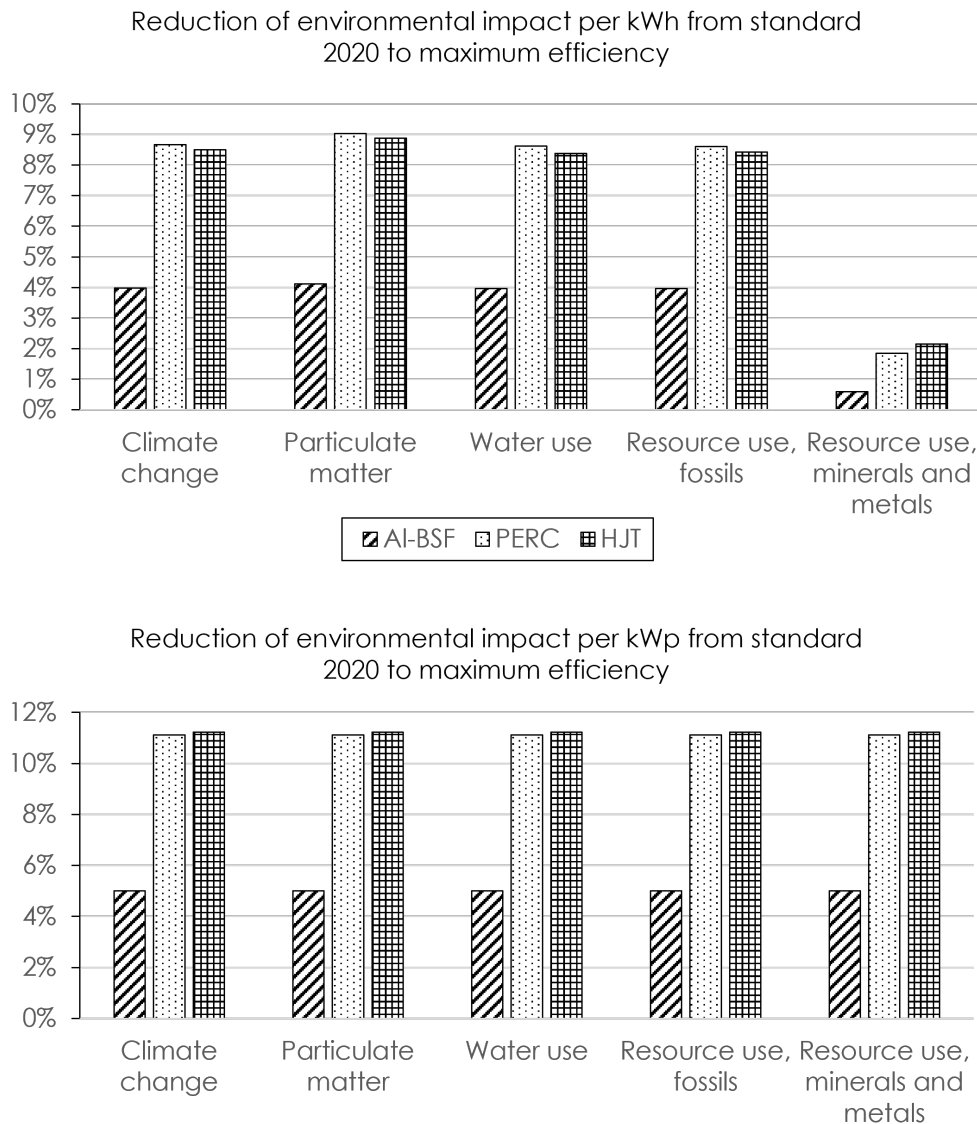


Figure 3.12: Potential environmental impact reduction going from standard 2020 to maximal module efficiency for the three PV technologies. Upper plot for kWh FU and lower plot for kWp FU.

- HJT and PERC are the two technologies with the strongest environmental impact reduction potential (11% for all impact categories for kWp FU) compared to Al-BSF (5% for all impact categories for kWp FU). Results for PERC and HJT for kWp and kWh FU are very similar to the one representing a rise of 10% (relative) of module efficiency in the previous section. All the impact categories studied in Figure 3.12 have identical results (for FU1 kWp) for one selected technology: 5% reduction for Al-BSF, 11% for PERC and HJT.

- Al-BSF can only reduce its carbon footprint per kWh by 4% while achieving its maximum module efficiency. Even with its maximal potential module efficiency, Al-BSF has a carbon footprint (40.2 g CO₂-eq/kWh) superior to the one of PERC (38.7 g CO₂-eq/kWh) and HJT (35.0 g CO₂-eq/kWh), both based on standard 2020 module efficiency as depicted in Figure 3.13.
- PERC with maximal module efficiency has a carbon footprint (35.4 g CO₂-eq/kWh) still slightly superior to the one of HJT standard 2020 module efficiency (35.0 g CO₂-eq/kWh) as depicted in Figure 3.13. Therefore, it gives a clear advantage in the environmental aspect to nowadays HJT technology even in case of efficiency improvement of the PERC technology in the coming years.
- The reduction of environmental impact for kWh FU is always lower than for kWp FU for all impact categories and technologies. The change in efficiency influences more the system for kWp FU than kWh FU (as seen in previous section) because it influences less (for kWh) the quantity of BOS needed. Indeed, higher efficiency means less square meter to obtain a PV system set to 3kWp, which means less material and less mounting structure needed for the PV system, but same quantity of inverter or cables to connect the 3kWp PV system to the grid.
- RUM reduction is very low for kWh (<=2% for all technologies). The major part of the impact on RUM is due to the BOS & Installation building block that is not considered in the kWp FU while it is taken into account in the kWh FU. Many materials (inverter, cable) of the BOS & Installation building block are not influenced by module efficiency changes (as described in the previous section) leading to a less important reduction for all technologies for FU kWh.

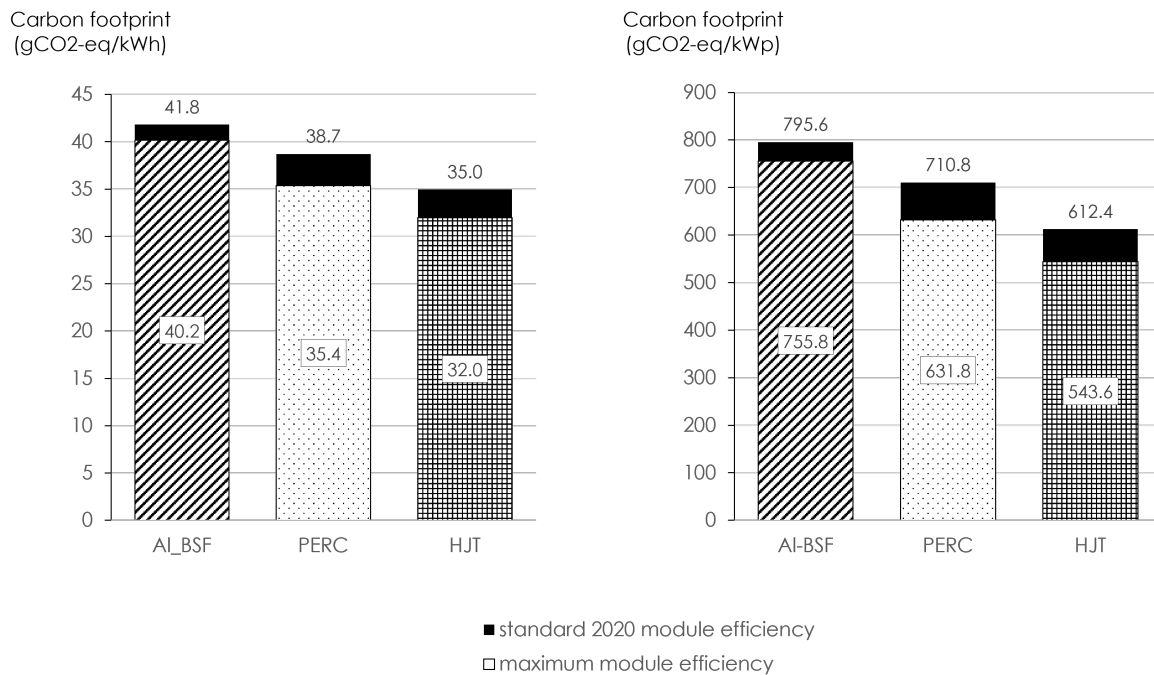


Figure 3.13: Carbon footprint [g CO₂-eq/kWh] and [kg CO₂-eq/kWp] of a 3kWp PV system for three c-Si technologies: Al-BSF (2020 standard $\eta=19.0\%$, maximum $\eta=20.0\%$), PERC (2020 standard $\eta=20.0\%$, maximum $\eta=22.5\%$) and HJT (2020 standard $\eta=21.75\%$, maximum $\eta=24.5\%$). EF 3.0 impact assessment methodology used. Activities included for kWh FU : wafer production in China (170 μm), transport to Europe, Cell and Module manufacturing in Europe, BOS & Installation manufacturing, use phase in Europe ($I=1391 \text{ kWh}/(\text{m}^2 \cdot \text{year})$, $PR=0.75$, $n=30$ years), end-of-life modeled separately. For kWp FU1: same as kWh FU but BOS & Installation and use phase are excluded. Chinese electricity mix: 1023 g CO₂-eq/kWh ; European electricity mix: 418 g CO₂-eq.

3.3.3 Use phase

The use phase is the longest stage of the PV lifetime, nevertheless it is also the less pollutant as shown in environmental impacts results. Key parameters used for the use phase are described in the use phase methodology chapter. The calculation of energy produced by a PV system directly determines the kWh FU and a variation of the performance ratio, solar irradiance or lifetime has a strong influence on PV delivered kWh as observed in sensitivity analysis. The FU1 kWh is not influenced by the use phase as it is not included in its system boundary.

Three scenarios of solar irradiance in Europe are analyzed: maximum irradiance (south of Spain) with 2200 kWh/(m²*year), standard irradiance (european average) with 1391 kWh/(m²*year) and minimum irradiance with 800 kWh/m²*year (north of Norway). Figure 3.14 shows the performance ratio versus lifetime needed to produce the equivalent quantity of electricity of a 3 kWp PV system operating at standard conditions (I=1391 kWh/(m²*year), PR=0.75, n=30 years).

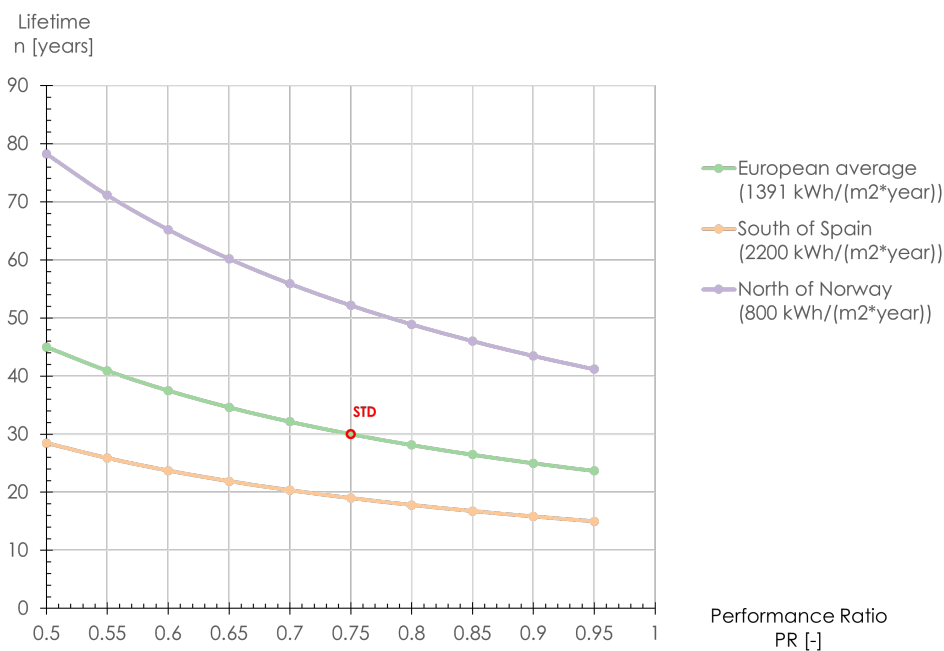


Figure 3.14: Performance ratio and lifetime combination needed to produce equivalent electricity of a 3 kWp operating at standard conditions (I=1391 kWh/m², PR=0.75, n=30 years).

- As a reminder, variations of performance ratio, PV system lifetime and solar irradiance have the same influence on the total electricity produced, influencing the use phase. Module efficiency (η) does not influence the energy production (use phase) as the output power of PV system is fixed to 3 kWp. It influences the area of module needed and thus all the other building blocks.
- The red point with the name STD above at the center of Figure 3.14 represents the standard conditions. For a PR set at 0.75 (supposing same losses due to weather conditions, orientation of panels, and so on), PV system installed in the north of Norway will take 52 years to produce the same amount of electricity as a PV system operating in South of Spain for 19 years. It will take 30 years with an European average irradiance.
- Figure 3.14 illustrates that the production of the same amount of energy for fixed lifetime of 30 years cannot be achieved by a PV system placed in the north of Norway, even if its PR is optimal (0.95). On the opposite, a panel placed in south of Spain would produce the same amount of energy with a PR slightly inferior to 0.5 which is the worst case scenario for PR.
- Figure 3.14 shows that differences between European optimal (south of Spain) and worst (north of Norway) locations result in 3.6 more time for Norway location to produce the same amount of energy for a same PR as south of Spain location, which is a significant difference.

3.3.4 Energy use

Overall, energy requirements variations (+/-10%) influences significantly the PV system (+/- 6% for FU1 kWp) for PERC glass-glass and glass-backsheet modules[33]. Energy requirements variations was not addressed by this work due to its complexity, nevertheless, Muller study [33] managed to provide interesting results for PERC technology, that are also relevant for this study (for PERC and can be expected for HJT) as this study and Muller study [33] shown similar results.

The relative contributions of the PERC processing steps, module components and electricity to the final GHG emissions are depicted in Figure 3.15 (for FU1 kWp) with the width of the flow corresponding to the magnitude of emissions. Electricity is the major driver of carbon emissions throughout the entire process chain (52%–69%), while other upstream process inputs have only little impact (12–23%).

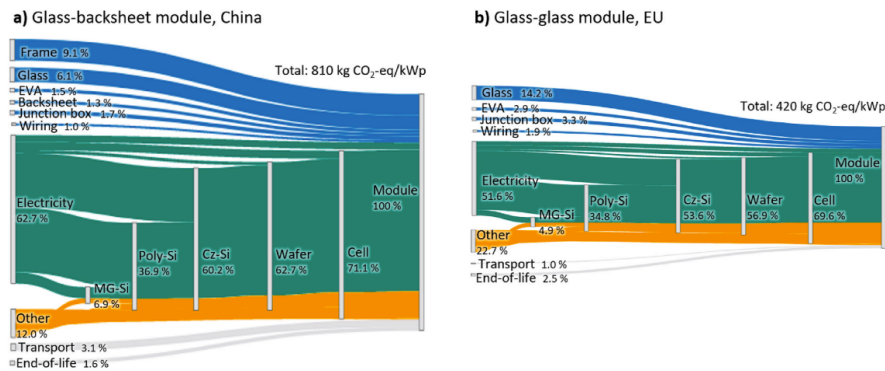


Figure 3.15: Figure from Muller study [33]: Climate change: Sankey diagram of percentual contributions of module production steps, module components and electricity to the indicator Global Warming Potential (GWP) using IPCC 2013 100-year method for 1 kWp of glass-backsheet sc-Si PERC module ($P = 366 \text{ Wp}$, $\eta = 19.79\%$) produced in China (a) and glass-glass sc-Si PERC module ($P = 359 \text{ Wp}$, $\eta = 19.40\%$) produced in EU (b). Including production, transport and end-of-life. Excluding BOS, installation and operation. Thickness of flows corresponds to magnitude of emissions

The differences in results for each environmental impact category are mainly caused by the different composition of the countries' electricity mixes according to Muller [33]. Ecoinvent 3.7.1 [37] provides country electricity mix: swiss electricity mix (97.6 g CO₂-eq/kWh [47]), European electricity mix (418 g CO₂-eq/kWh), Chinese mix (1023 g CO₂-eq/kWh). Therefore, the carbon footprint of PV system would be considerably lowered with a full swiss production for all the processes necessary to build a PV system (wafer, cell, module, BOS & Installation). Nevertheless, this assumption seems utopian nowadays as PV market is mainly dominated by Chinese company, but could lead to an important diminution of PV system carbon footprint.

3.4 Upgrade of HJT PV technology towards reduced environmental impacts

This results section focuses on the upgrade of sc-Si technology through the prism of HJT technology. The results presented in this section show environmental impact of some scenario analyzed that may also apply to other sc-Si technologies for all building blocks. Climate Change, Particulate Matter, Water use, Resource use, fossils and Resource use, minerals and metals are the five categories analyzed in detail. Specific analyses are performed for each building block of the HJT PV system and are presented in the different subsections.

3.4.1 Environmental impacts of HJT

Environmental impacts of HJT technology along CC, PM, WU, RUF and RUM are presented in Figures 3.16 and 3.17 for kWh FU and kWp FU1 respectively. The 100% threshold represents the total contribution to the impact category and the different contributions are labeled on the histogram data.

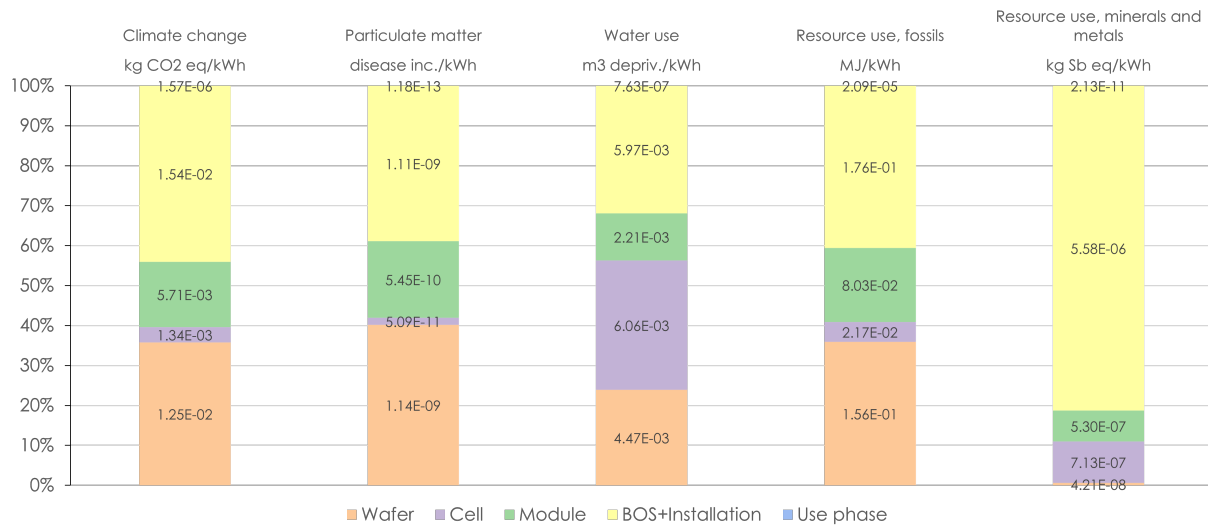


Figure 3.16: Environmental impacts per kWh of HJT ($\eta=21.75\%$) technology along CC, PM, WU, RUF and RUM impact categories. EF 3.0 impact assessment methodology used. Activities included : wafer production in China (170 μm), transport to Europe, Cell and Module manufacturing in Europe, BOS & Installation manufacturing, use phase in Europe ($I=1391 \text{ kWh}/(\text{m}^2 \cdot \text{year})$, $PR=0.75$, $n=30$ years), end-of-life modeled separately. Chinese electricity mix: 1023 g CO₂-eq/kWh ; European electricity mix: 418 g CO₂-eq.

- Figure 3.16 shows that BOS & Installation represent more than 30% of the total system impact per kWh for all five impact categories analyzed. Wafer building block is also responsible of more than 30% of impact for CC, WU and RUF impact categories, nevertheless, it has a very small influence ($<1\%$) on RUM. Therefore, those two building blocks (wafer, BOS & Installation) should be analyzed in detail as they largely contribute ($>50\%$ for all impact categories) to HJT environmental impact.
- Nevertheless, cell and/or module production are the one/two main building block(s) performed by PV manufacturers and observing at which level environmental impacts are produced for cell and/or module represent a strong interest for R&D and PV companies (as the CSEM). Selecting kWp FU offers a more detailed overview of the cell and module contribution to the environmental impacts as depicted in Figure 3.17. Cell processes appear to be responsible of 55% of HJT impact on RUM for kWp FU. Furthermore, water use mainly occurs during the cells processes, being responsible of 48% of HJT impact on WU. 31% of HJT impact on RUF is due to module building block, which is responsible of 41% of HJT impact on RUM (not due to aluminium frame or solar glass) as depicted in figure 3.17.

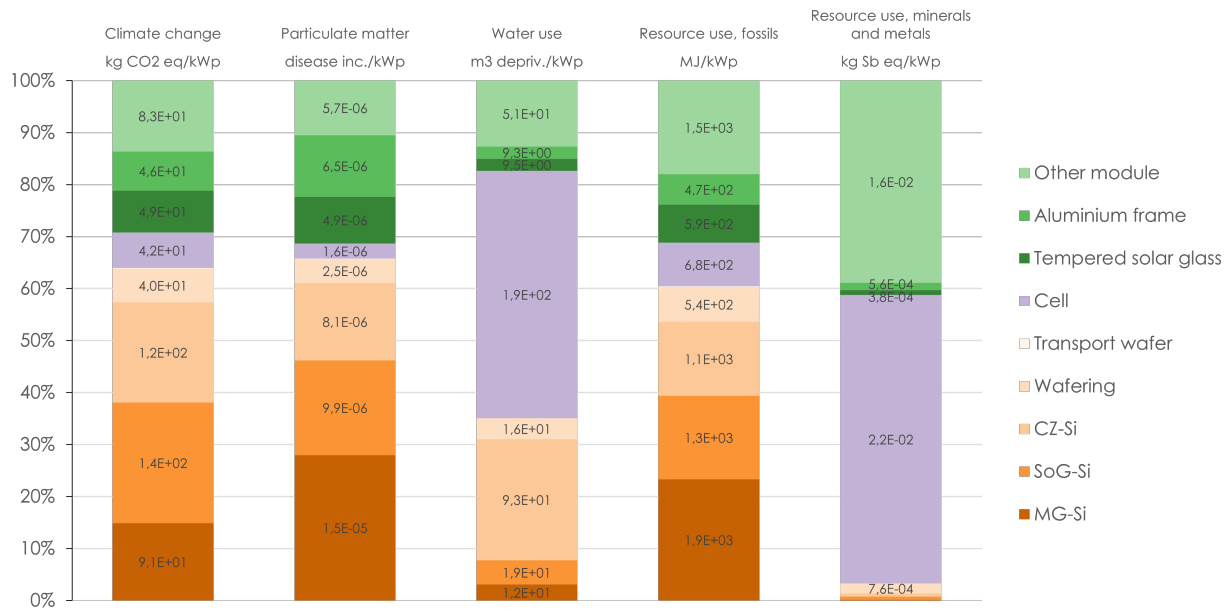


Figure 3.17: Environmental impacts per kWp of HJT ($\eta=21.75\%$) technology along CC, PM, WU, RUF and RUM impact categories. EF 3.0 impact assessment methodology used. Activities included : wafer production in China ($170 \mu\text{m}$), transport to Europe, Cell and Module manufacturing in Europe, end-of-life modeled separately. Activities excluded: BOS & Installation manufacturing, use phase. Chinese electricity mix: $1023 \text{ g CO}_2\text{-eq/kWh}$; European electricity mix: $418 \text{ g CO}_2\text{-eq}$.

All building blocks are analyzed in more details in their respective sections wafer, cell, module, BOS & Installation, End-of-life and alternatives are proposed to ensure a lower environmental impact of HJT technology.

3.4.2 Wafer

Wafer building block is detailed in the wafer methodology section. As a reminder, the main output of wafer building block is 1 m² of wafer delivered in Europe. Four scenarios are compared :

- 270 μm thick wafer produced in China, also called 2010 wafer
- 170 μm thick wafer produced in China, also called 2020 wafer
- 170 μm thick wafer produced by Norsun in Norway
- 133 μm thick wafer produced by Norsun in Norway

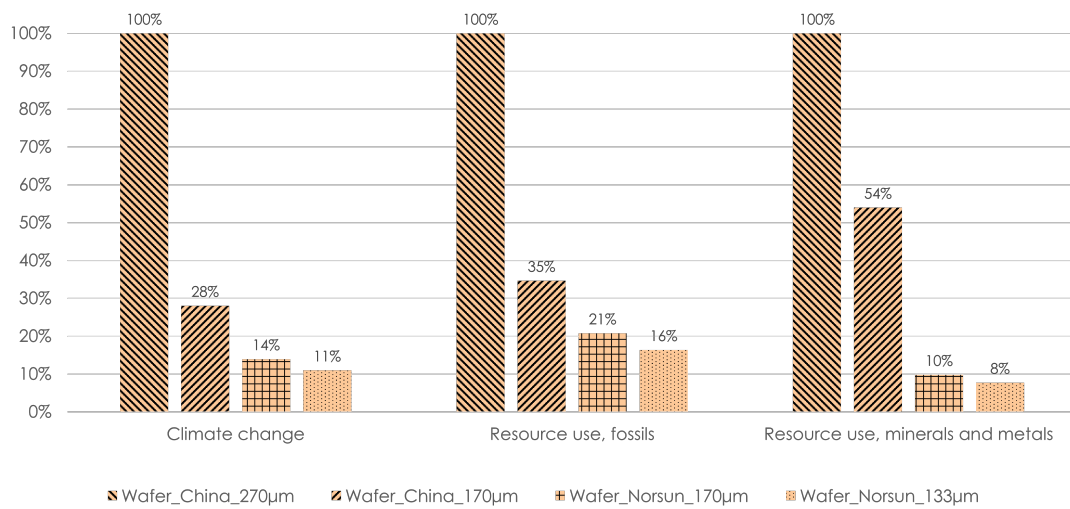


Figure 3.18: Wafer relative impact on CC, RUF and RUM for four wafer scenario. Scenario 1: China 270 μm, scenario 2: China 170 μm, scenario 3: Norsun 170 μm, scenario 4: Norsun 133 μm. Activities includes: MG-Si production, SoG-Si production, CZ-Si production, Ingots and wafering, transport to Europe. Refer to table 2.5 for energy mixes and detailed assumptions.

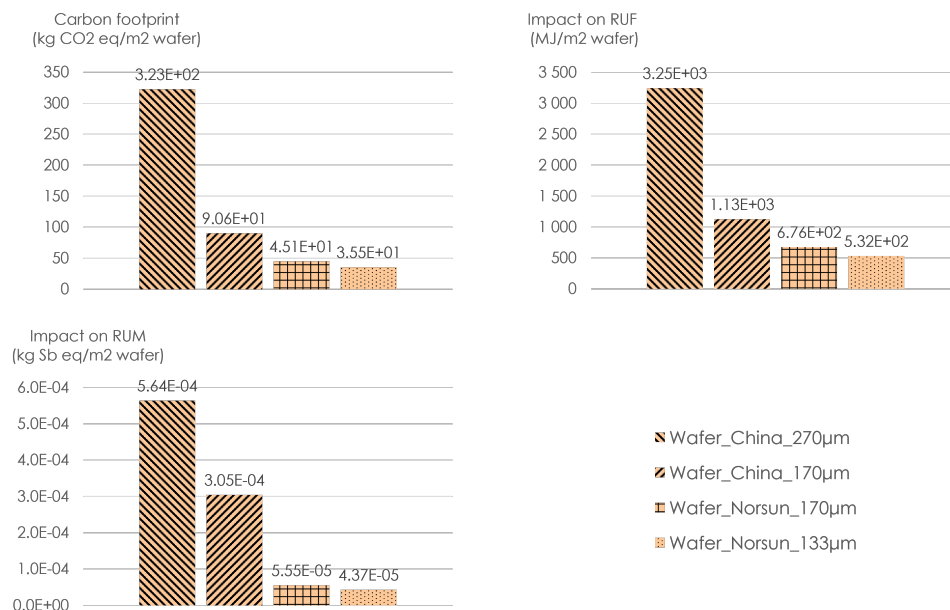


Figure 3.19: Wafer impact per m² of wafer delivered in Europe on Climate Change, Resource use Fossils and Resource use, minerals & metals

- Norsun wafers show a 50% lower impact than Chinese ones for the same thickness (170 μm). This is due to the use of a cleaner electricity mix (mainly hydro power) than the Chinese one for mc-Si ingots production and wafering. Furthermore, the internal reuse of mc-Si waste is modeled for Norsun, which is not the case for Chinese wafers, resulting in a 5 times lower impact for Norsun than Chinese wafer in RUM category (see Figure 3.18).
- Transport accounts for less than 2% for all scenarios, despite the important transport distance (20 000 km) from China to Europe for Chinese wafers.
- For Chinese wafers, all environmental impacts are at least divided by 2 considering 2020 wafer instead of 2010 wafer (see figure 3.18). This reduction is stronger for CC and RUF than for RUM. This reduction is explained by two main factors: (i) the wafer thickness and losses variation (45% reduction) going from 270 + 191 μm for 2010 wafer to 170 + 85.5 μm for 2020 wafer; (ii) the upgrade of the wafer processing in production, notably the reduction of electricity consumption and improvement of sawing process.

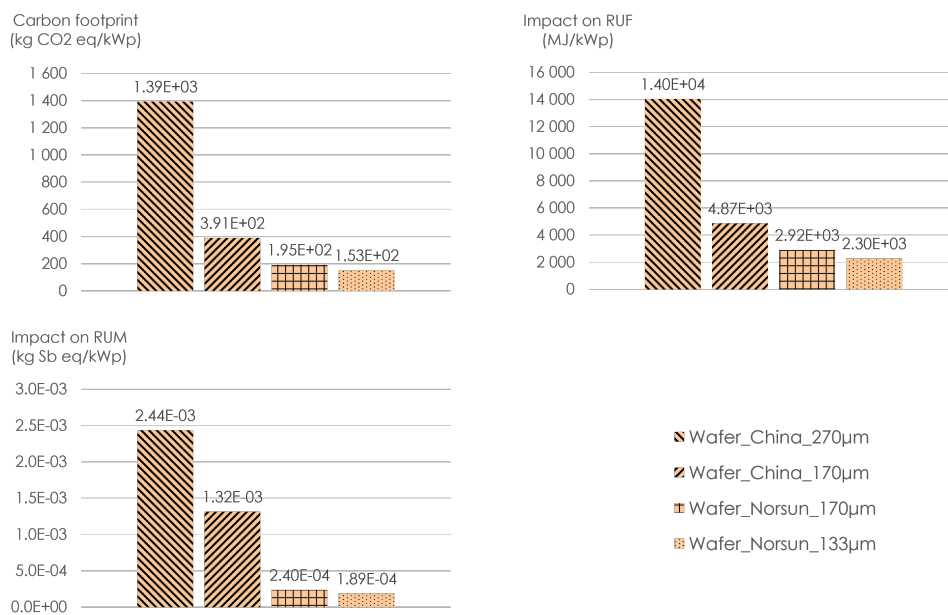


Figure 3.20: Wafer impact per kWp of HJT module produced on Climate Change, Resource use Fossils and Resource use, minerals & metals

The Figure 3.20 show the impact of wafer building block in different units (per m² of wafer, per kWp and per kWh) on CC, RUF and RUM impact categories. No change of relation between the four scenario impacts is expected for the different units studied as only HJT technology is considered.

Imposing a 170 μm thickness for wafer and a switch from Chinese to Norsun wafers results in going from a carbon footprint of 12.5 to 6.2 g CO₂-eq/kWh. This change reduces the carbon footprint of HJT PV system from 35.0 to 28.8 g CO₂-eq/kWh, which has twice the impact of setting the maximal module efficiency (24.5%) of HJT (32.0 g CO₂-eq/kWh).

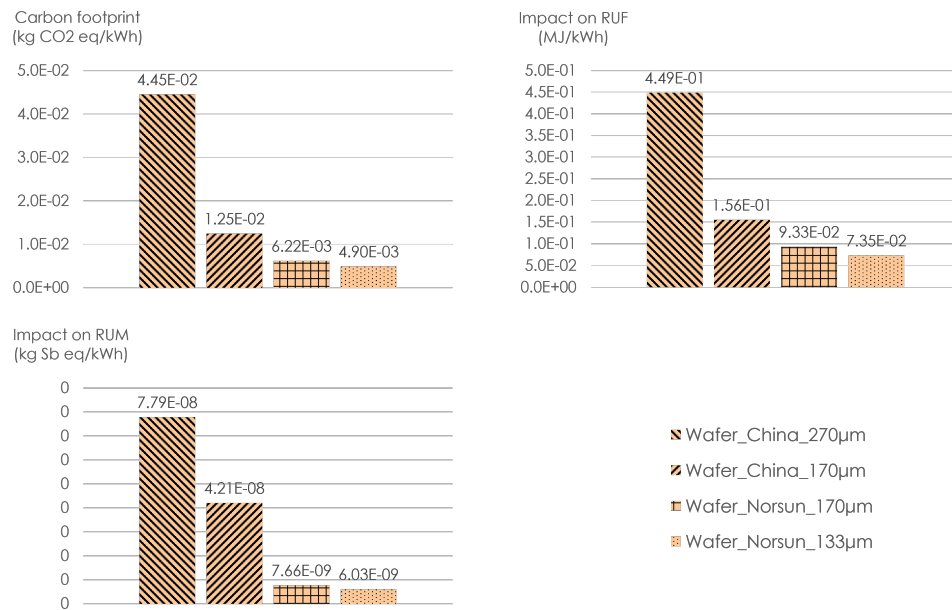


Figure 3.21: Wafer impact per kWh of HJT PV system on Climate Change, Resource use Fossils and Resource use, minerals & metals

3.4.3 Cell

Cell processes are various for different technologies (PERC, Al-BSF, HJT) as described in the cell methodology part. Here, the focus is set on HJT cell production processes and RUM impact category is analyzed with specific attention. As mentioned in figure 3.17, the impact of cell building block represents less than 8% of carbon footprint per kWp but 55% impact on RUM for kWp FU. Figure 3.22 shows the distribution of HJT cell processes responsible of its environmental impact per kWp.

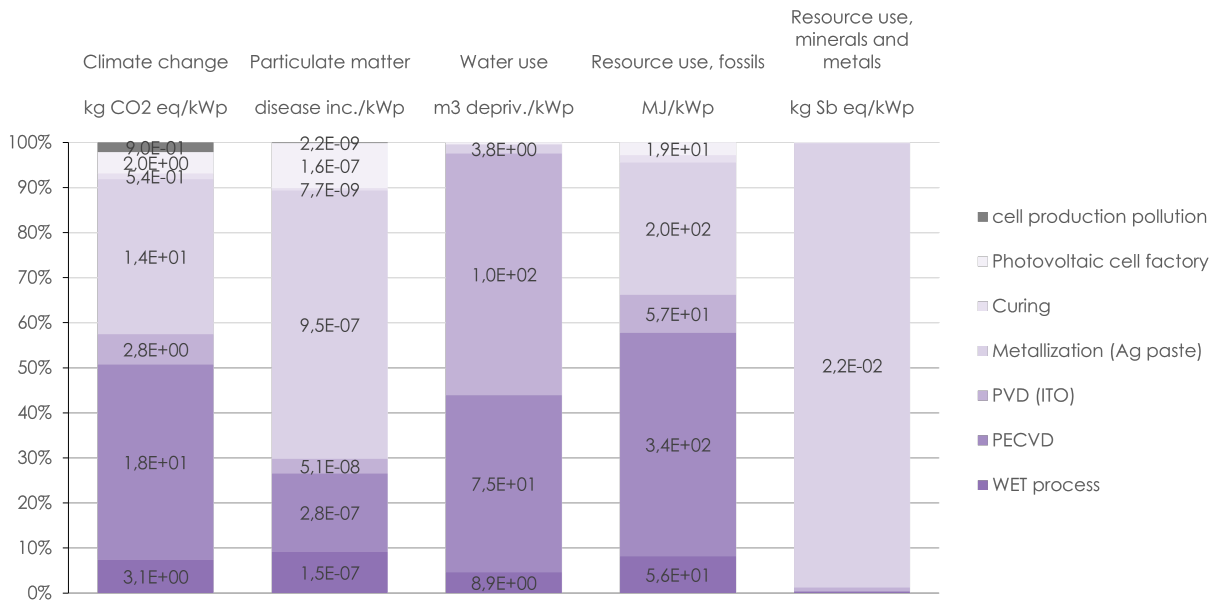


Figure 3.22: Cell environmental impacts per kWp of HJT ($\eta=21.75\%$) technology along CC, PM, WU, RUF and RUM impact categories. EF 3.0 impact assessment methodology used. Activities included for a c-Si bifacial cell production in Europe: Wet processes, PECVD, PVD (ITO), metallization (standard Ag-paste), curing. European electricity mix: 418 g CO₂-eq.

- Five major contributors to HJT cell environmental impacts are Wet bench, Metallization, PECVD, PVD and the cell factory. PECVD, PVD and metallization represent more than 80% of cell impact for all impact categories studied (CC, PM, WU, RUF and RUM).
- Metallization is responsible of 98% of HJT cell impact on RUM. PECVD represent more than 40% of HJT cell impact per kWp for CC, WU and RUF. 50% of HJT cell impact on WU is due to PVD process.
- Louwen study [35] established the distribution of HJT cell processes carbon footprint. Results from Louwen study and this current study are thus compared. This study results are mentioned as "results" while Muller results are mentioned as "(results)". Overall carbon footprint of HJT cell is 42 (67) kg CO₂-eq/kWp. This study uses more recent efficiency of HJT module and cells than Muller study [33], resulting in a lower impact per kWp (less HJT cells are needed to produce a kWp system). Nevertheless, Muller predicted a carbon footprint of 35 kg CO₂-eq/kWp in 2020, which is closer to results obtained in this study. Furthermore, the percentage distribution can be compared between both studies.
- PECVD is the major HJT cell carbon footprint contributor with 43 (36)%. Metallization and PVD showed together an impact of 42 (58) % with a much more important impact of Metallization for this study (35%) than for Louwen study (25%). Cleaning and texturing shows an impact of 6 (7)% of the HJT cell carbon footprint. In addition to compute the full cell process impacts, this study considers the use of a photovoltaic cell fab which shows a carbon footprint of 5% and was not taken into account in Louwen study.

3.4.3.1 Metallization

In this subsection, the focus is put on metallization process. Three scenario are analyzed: standard HJT metallization (Ag-print), Smart-wire (Ag-print) and Copper plating as described in the cell methodology.

Figure 3.23 presents the metallization process of HJT cell production for CC, PM, WU, RUF and RUM impact categories. The three scenarios described above are analyzed.

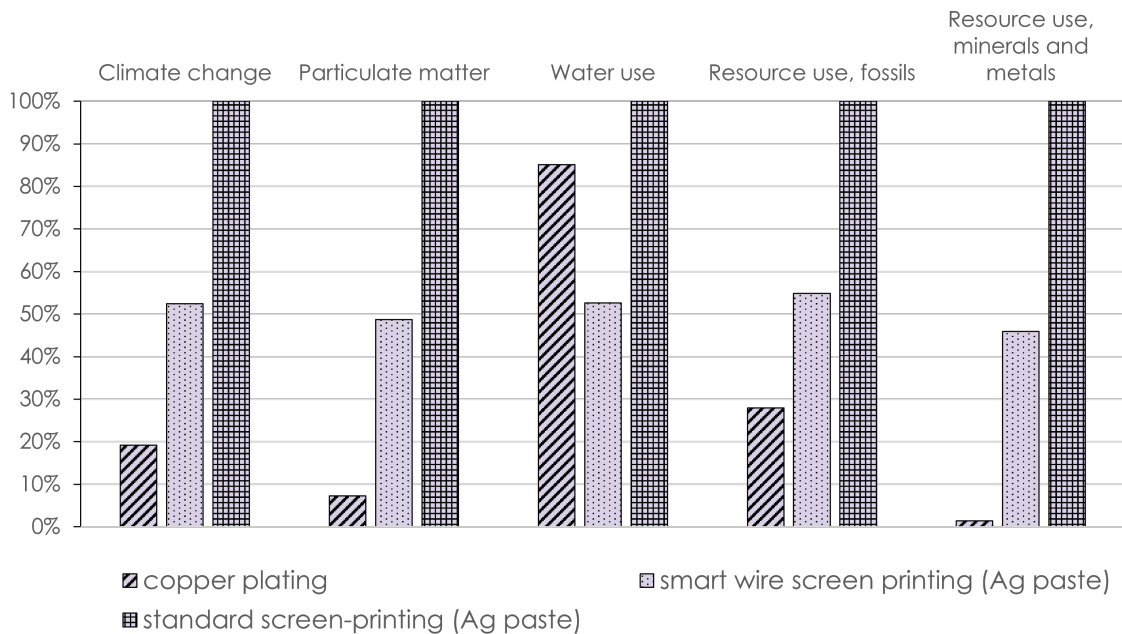


Figure 3.23: Metallization environmental impacts per kWp of c-Si cell of HJT technology along CC, PM, WU, RUF and RUM impact categories. 3 scenario analyzed: standard metallization (220 mg/M6 wafer of Ag-paste), smart-wire metallization (100 mg/M6 wafer of Ag-paste) and copper plating scenarios (320 mg/M6 wafer of Cu-paste). European electricity mix: 418 g CO₂-eq.

- Smart wire impacts represent only 50% in average of standard metallization impacts. This trend is expected as silver paste (responsible of the majority of metallization process) quantities are divided by 2.2 between standard and smart-wire metallization process (100 mg/ M6 wafer for smart-wire).
- Copper plating is the best solution except for WU impact category. The WU impact of copper plating is mainly due to the water used for the production of hydroelectricity needed for tin extraction. Copper plating impact on RUM represent less than 2% of the standard metallization process for HJT cell, which can significantly reduce the Cell building block impact on RUM for HJT technology.

3.4.3.2 TCO

As introduced in the introduction, Critical Raw Material CRM must be limited to ensure sufficient stock of materials for the future generations. ITO (Indium-Thin oxide) is the main TCO used in HJT cell PVD process, indium being an important CRM, an other option known as AZO is analyzed. Note that, TCO is applied for both side for BF cells but only on one side for IBC cells. Figure 3.25 shows results for ITO and AZO considering IBC cells per kWp. Standard HJT cells are BF cells, resulting in double impact (compared to IBC cells) and thus twice more marked differences between the two scenarios.

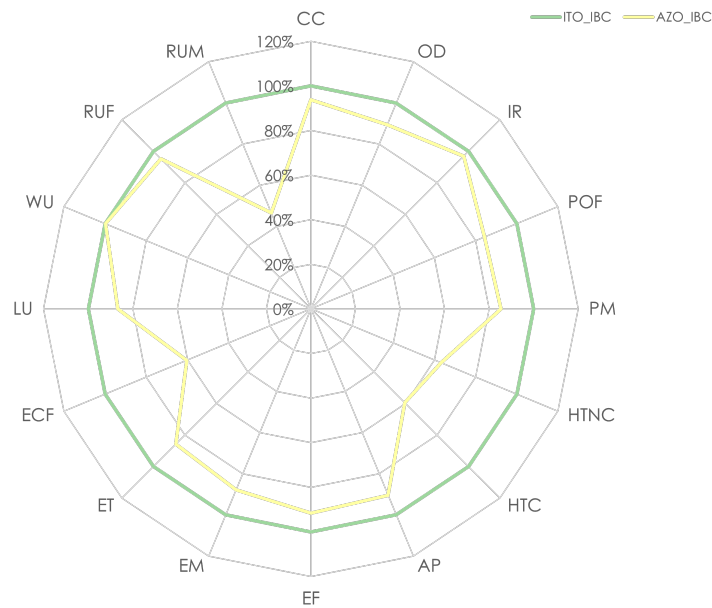


Figure 3.24: Spider plot of two PVD scenario (ITO vs AZO) for IBC HJT cell and for the 16 impact categories. ITO for IBC HJT cell is set as reference scenario (100% impact).

- For all impact categories, AZO is better than ITO scenario as observed in Figure 3.24 while suppressing the use of a notable CRM (indium) for PVD process.
- Sputtering target strongly influence (>97%) RUM category for both ITO and AZO as depicted in Figure 3.25. Therefore upgrade on this domain will result in RUM impact reduction.
- PVD electricity consumption reduction will stongly impact CC, PM and RUF categories as its influence is marked on those impact categories.
- When considering bifacial (BF) cells, impacts are doubled (one TCO layer on each side) compared to IBC cells (one TCO layer only on one side) for all impact categories (see figure 3.25). As an exemple, the AZO impact on RUM category will represent 23% of ITO impact on RUM category for BF cells.

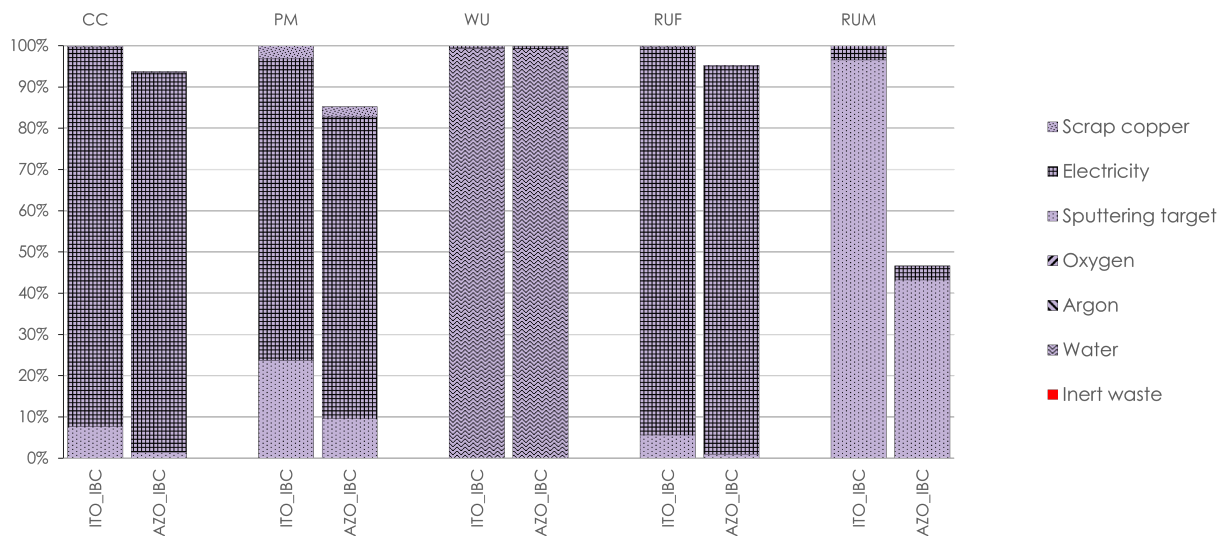


Figure 3.25: Cell PVD environmental impact per kWp on CC, PM, WU, RUF and RUM impact categories for ITO and AZO scenario applied for IBC HJT cell (one TCO layer on one side).

Environmental impact of HJT cell can be reduced thanks to update of metallization process (limit silver paste quantities and if possible, replace it with copper plating). For PVD process, AZO would limit the use of CRM and lower the environmental impact compared to ITO. Both updates represent a better environmental impact in the five impact categories studied (CC, PM, WU, RUF and RUM), except for WU of Copper plating.

Processes for HJT cell require lower temperature of execution than PERC-like technologies (200 °C vs > 700 °C). Nevertheless, the time of HJT cell processes are sometimes longer than for other technologies. It leads to a change of electricity use (more longer but at lower power), leading usually to a reduction of electricity demand: 12 kWh/m² of cell for PERC vs 10 kWh/m² cell for HJT technology. Nevertheless, the electricity use depends highly on PV manufacturers and their optimization (or not) of production processes.

3.4.4 Module

The module building block is described in the methodology chapter. Figure 3.26 details the distribution of module environmental impacts per kWp through its various components for CC, PM, WU, RUF and RUM impact categories.

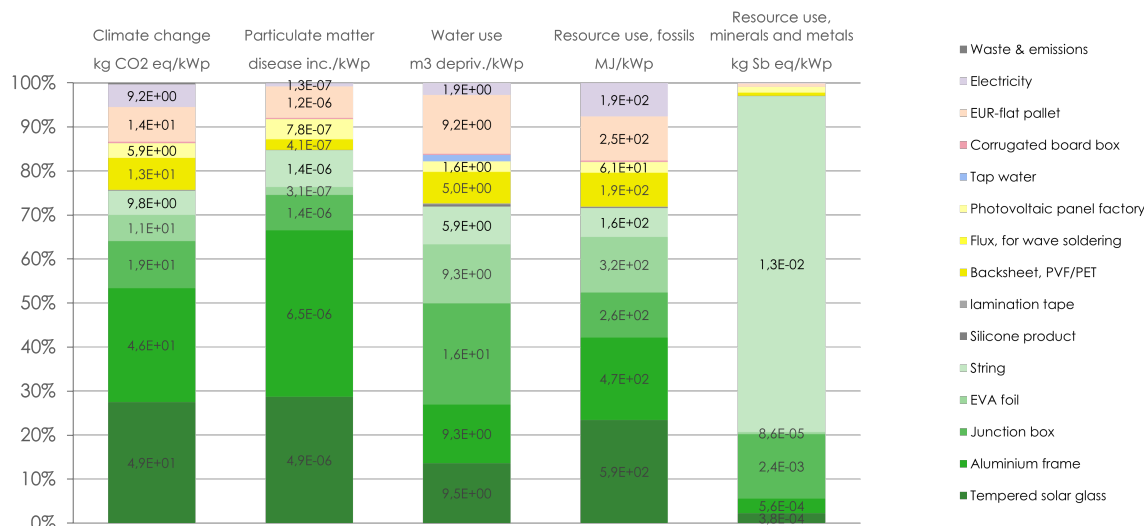


Figure 3.26: Module impact per kWp on CC, PM, WU, RUF and RUM impact categories for HJT technology

- Solar glass, aluminium frame, backsheet, encapsulant (EVA) and string are the five major contributors to module environmental impact per kWp, with more than 60% of total module impact for all impact categories.
- String is responsible of 75% of module impact on RUM category, which is mainly explained by the use of metals to solder cells together.
- Aluminium frame impact is equal or higher than solar glass impact for all impact categories. The module considered for this study are glass-backsheet modules using glass and backsheet with a aluminium frame to maintain the whole. Another option is to produce glass-glass modules, which do not need aluminium frames nor backsheets but weight 150-170% of glass-backsheet module weight. The study of [33] evaluates the two scenarios and showed a environmental impact for glass-glass module lower than glass-backsheet module which match this study results.
- HJT module carbon footprint is 179 kg CO₂-eq per kWp as depicted in 3.26. The PERC module carbon footprint was evaluated to be 175 kg CO₂-eq/kWp. Distribution of module impact per kWp can be compared between this study and Muller results as total module carbon footprint are close and module production process are very similar between HJT and PERC¹. Figures 3.7 mentioned present "this study" vs (Muller) results. Solar glass (49 (46) kg CO₂-eq/kWp) and Aluminium frame (46 (67) kg CO₂-eq/kWp) were the two major contributors to the carbon footprint of the module for Muller and this study. A lower quantity of aluminium (1.25 vs (1.51) kg/m² of module) explain the main difference for aluminium frame results between this study and Muller. Otherwise, junction box, energy use & infrastructures, backsheet and EVA show very similar results between this study and Muller study, ensuring the consistency of results obtained.

¹HJT module processes were mainly modelled thanks to PERC process data due to a lack of data for HJT module production processes. Temperature must remain below 700 celsius degrees to avoid damages of PERC cells. However, HJT module processes must limit the temperature of processes under 200 celsius degrees to not damage HJT cells. Therefore, different components may be used to ensure processes below this temperature threshold. Additionally smart-wire technology was developed by CSEM and an industrial partner to limit consumption of metals for the wiring (stringing) of HJT cells. Due to lack of time, this process was not modeled but should result in a diminution of the environmental impact of wiring process for HJT module production.

3.4.5 BOS & Installation

BOS & Installation is described in methodology chapter and is only considered for the kWh FU. Figure 3.16 shows that BOS & Installation is responsible of 30% (WU) to 80% (RUM) of total PV system impact on the five impact categories studied (CC, PM, WU, RUF and RUM). Figure ?? shows the distribution of environmental impact per kWh for the BOS & Installation building block on the five impact categories analyzed.

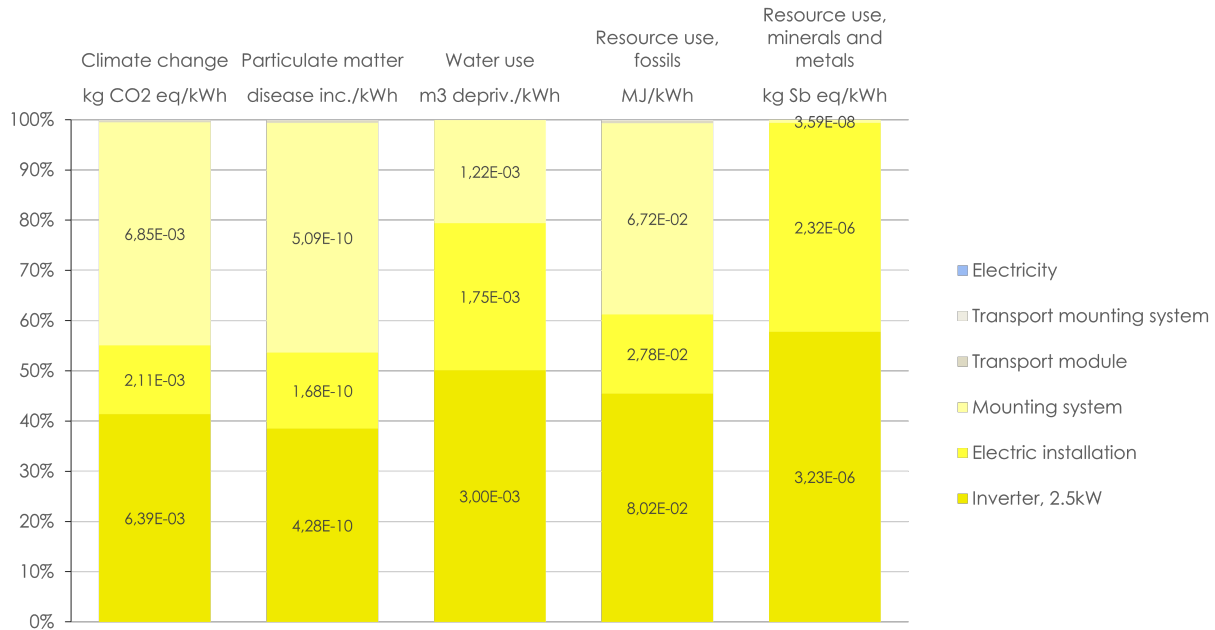


Figure 3.27: BOS & Installation impact per kWh on CC, PM, WU, RUF and RUM.

- Three major materials/processes responsible of BOS impact are the inverter (DC/AC converter), the photovoltaic mounting system (metallic structure) and the electric installation (cables).
- CC, PM, RUF impact categories are similarly influenced by the three major materials/processes.
- RUM is influenced mainly by inverter (57.8%) and electric installation (41.5%) due to use of metals (copper, aluminium, steel). Mounting system impact is reduced on RUM as a fraction of aluminium used comes from recycled scraps instead of primary aluminium.

3.4.6 Use phase

The use phase is the longest stage of the PV lifetime, nevertheless it is also the less pollutant as shown in environmental impacts results. Key parameters used for the use phase are described in the methodology chapter. The calculation of energy produced by a PV system directly determines the kWh FU and a variation of the performance ratio, solar irradiance or lifetime has a strong influence on PV delivered kWh as observed in the sensitivity analysis section. The FU1 kWp is not influenced by the use phase as it is not included in its system boundary.

3.4.7 End-of-Life

End-of-Life (EoL) is modeled separately from other processes as various scenarios can apply, resulting in environmental impacts or benefits. EoL building blocks is defined in the methodology section. Nevertheless, only module End-of-Life was studied due to poor data available for BOS EoL. As a reminder, three scenarios are analyzed for PV module End-of-Life:

- **Disposal scenario:** disposal in landfill (glass, aluminium) and municipal incineration (copper, plastics).
- **Recycling without benefits scenario:** recycling of glass, copper and aluminium frame, disposal and incineration of plastics.
- **Recycling with benefits scenario:** same as second scenario but with benefits and burdens linked to the replacement of primary materials by secondary materials produced from recycling process.

Figure 3.28 shows the environmental impact per kWp of HJT module for the three EoL scenarios (disposal, recycling without benefits, recycling with benefits).

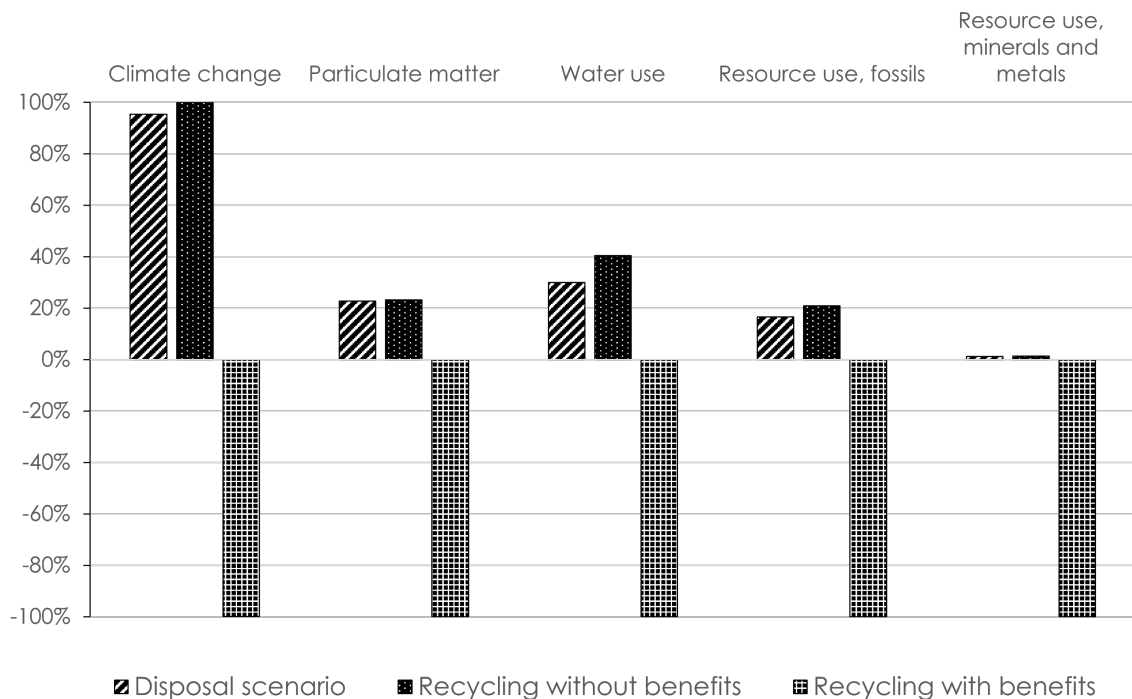


Figure 3.28: Environmental impact per kWp of HJT module end-of-life scenarios (disposal, recycling without benefits, recycling with benefits) for CC, PM, WU, RUF and RUM impact categories.

- Without considering benefits from recycled materials, recycling and disposal impacts are very similar for the five studied Impact categories. Nevertheless, recycling (with benefits) is better than disposal and contributes to a benefit on the categories observed. This is due to the non-fabrication of primary materials, replaced by secondary materials obtained from recycled materials through lower-impact processes.
- Recycling (with benefits) scenario has an overall environmental benefit on all impact categories analyzed. However, this scenario possesses also environmental impacts (containing recycling without benefits impacts), linked for example to transport or energy required to recycle materials. Impacts and benefits must be distinguished in the results discussion.
- Transport has an important influence on the end-of-Life building block environmental impact, representing more than 60 and 40% of impact on PM, respectively RUF and RUM category for all EoL scenarios. Avoiding primary copper production is responsible of 97% of environmental benefits of the recycling (with benefits) scenario for RUM impact category.

- Recycling with benefits shows a negative carbon footprint per kWp equivalent to the disposal and recycling (without benefits) carbon footprint (22 kg CO₂-eq/kWp) as depicted in figure 3.28. Over the whole kWp FU, HJT module disposal represents 3.6% of the total PV model impact. By performing a recycling (with benefits) instead of a disposal, the total carbon footprint goes from 634 kg CO₂-eq/kWp (612+22) to 590 kg CO₂-eq/kWp (612-22), representing a reduction of 7% of the carbon footprint per kWp for HJT technology.

Chapter 4

Recommendations & Conclusion

The environmental footprint (and more specifically the carbon footprint) of PV systems must be reduced, while the number of PV system in use should be increased to achieve the sustainable development of electricity production. First, a summary of the major results, advice and recommendations obtained in this work is provided to PV manufacturers to produce the lowest carbon footprint PV-system with current market trends. Additionally, advice is provided to perform relevant LCA studies on PV system and area for improvement of this study will be tackled. Finally the conclusion section shows the major outcomes of this work and possible future developments.

4.1 Recommendations

4.1.1 Key findings & recommendations for European PV manufacturers

Through this work and literature review, many results were found and presented and detailed in the Results & discussion chapter. Highlights are presented in this section:

- Figures 4.12 and 3.3 shows that HJT technology has the lowest environmental impact compared to PERC 2020, Al-BSF 2020, and Al-BSF 2010 for all impact categories except for HTNC, HTC, LU and RUM impact categories.
- Figures 3.4 and 3.6 shows that HJT 2020 has the lowest carbon footprint for both FU (35g CO₂-eq/kWh and 612kg CO₂-eq/kWp) compared to other PV systems analyzed: PERC 2020 (39g CO₂-eq/kWh and 711kg CO₂-eq/kWp), Al-BSF 2020 (42g CO₂-eq/kWh and 796kg CO₂-eq/kWp), Al-BSF 2010 (110g CO₂-eq/kWh and 2850kg CO₂-eq/kWp). Moreover, our results are consistent with the literature review [33][35].
- The upgrade of processes (materials and electricity use) to produce wafers is the major reason of the reduction of the carbon footprint (per kWh and per kWp) of 2020 technologies (Al-BSF 2020, HJT 2020, PERC 2020) compared to Al-BSF 2010 as depicted in Figures 3.4 and 3.6 . Another factor influencing this diminution is the rise of module efficiency (14% to 19% for Al-BSF).
- For 2020 technologies, BOS + Installation represent the major contributor (30% to 80%) of the environmental impact of PV system per kWh for all impact categories. Furthermore, BOS + Installation represent more than 70% of the PV impact on RUM category for all technologies, its impact being split between inverter and electric cables for RUM impact category as shown in Figure 3.27. Focus should be set by PV manufacturers on this building block to limit environmental footprint of PV systems.
- For kWh FU, PV system is very sensitive to module lifetime, performance ratio and solar irradiance for all impact categories. As an example, with fixed performance ratio, a PV system located in the north of Norway will take 3.6 times more time to produced the same amount of energy than the same PV system located in the south of Spain as depicted in Figure ?? . On the other hand, for kWp FU, PV system is more sensitive to module efficiency variations than wafer thickness variations for all impact categories as depicted in Figure ??.

- Observing Table 3.13 and Figure 3.21, the change of wafer provider (Norsun instead of China) reduces twice more the carbon footprint compared to develop HJT module efficiency up to its limit of 24.5% (current 21.75%).

Looking more closely at the upgrade of HJT technology, major scenarios are detailed in the Methodology chapter and presented in the Results & Discussion chapter. The following paragraph treats of two HJT technology scenarios: standard versus best practice (combination of scenario analyzed in the results). The Figures 4.1 and 4.2 represent the environmental footprint per kWh, respectively kWp of HJT technology (standard vs best practice) for CC, RUF and RUM impact categories. Best practice is defined as: the use of a 170 μm thick Norsun wafer instead of 170 μm thick Chinese wafer (standard) ; HJT cell is IBC instead of Bifacial (standard) with an AZO as TCO instead of an ITO (standard) and finally, for cell metallization, copper plating is used instead of silver paste (standard). All the other parameters not mentioned are identical to standard HJT technology.

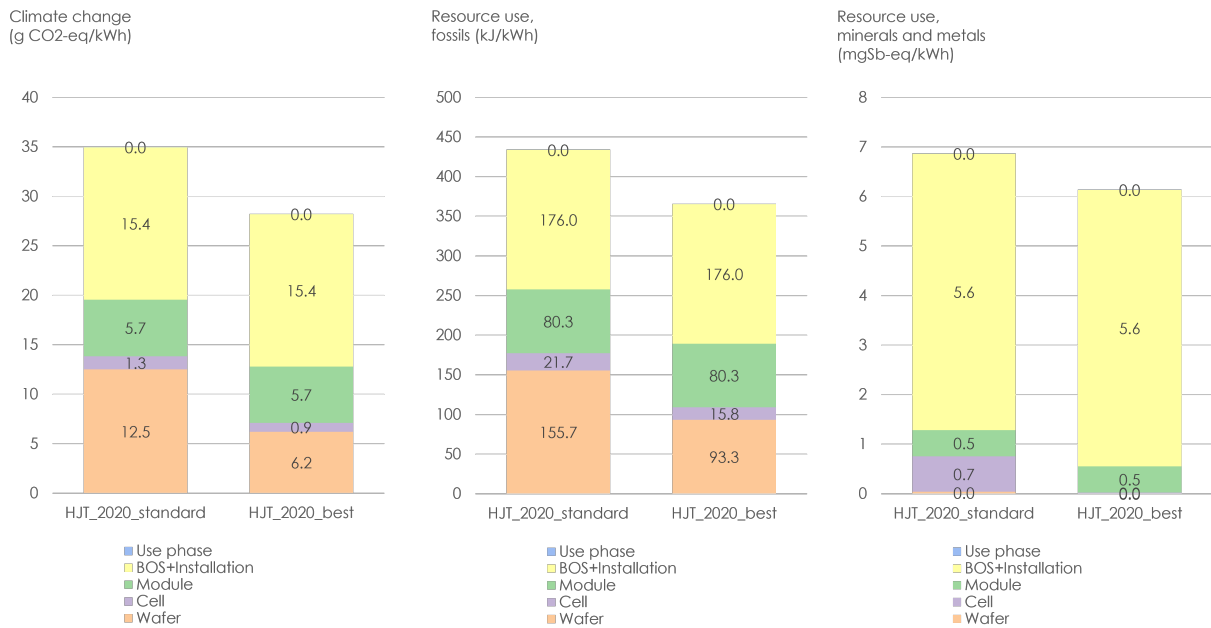


Figure 4.1: Environmental footprint per kWh of HJT technology (standard vs best practice) for CC, RUF and RUM impact categories. EF 3.0 impact assessment methodology used. Activities included : wafer production and transport, Cell and Module manufacturing in Europe, BOS & Installation manufacturing, use phase in Europe ($I=1391 \text{ kWh}/(\text{m}^2 \cdot \text{year})$, $PR=0.75$, $n=30$ years), end-of-life modeled separately. Chinese electricity mix: 1023 g CO₂-eq/kWh ; European electricity mix: 418 g CO₂-eq. Standard: China 2020 wafer (170 μm), sc-Si bifacial HJT cell, Ag paste for metallization (220 mg/ M6 wafer), ITO for TCO, module efficiency $\eta=21.75\%$. Best practice: Norsun wafer (170 μm), sc-Si IBC HJT cell, copper plating for metallization, AZO for TCO, module efficiency $\eta=21.75\%$. All other parameters are identical to standard.

As a major observation:

- Figures 4.1 and 4.2 show that the standard HJT 2020 carbon footprint (35g CO₂-eq/kWh and 612kg CO₂-eq/kWp) can be reduced for both FU (28.2g CO₂-eq/kWh and 400kg CO₂-eq/kWp) using best practices available in 2020.
- Figures 4.1 and 4.2 shows that RUF impact of standard HJT is reduced thanks to the change of wafer provider (China replaced by Norsun) and changes in cell processing for PVD process (ITO replaced by AZO) and metallization process (Ag-paste replaced by copper plating). The modification of wafer provider (Norsun vs China) influences strongly the carbon footprint reduction, while the change in cell processing (metallization and TCO) affects mainly the Resource Use impact category of Cell building block.
- Reduction observed per kWh is comprised between 10% for RUM and 20% for CC. Even if this reduction seems low, one has to remind that the two most important building blocks (BOS + In-

stallation and Module representing more than 60% of total PV system impact), remain unchanged and represent all the remaining impact of PV system for HJT 2020 best practice for RUM impact category. Regarding impacts in kWp, the reduction observed from standard HJT to best practice HJT is more marked, especially for the RUM impact category (-57.5%) where the impact of cell manufacturing went from 22.3 gSb-eq/kWp to 0.5 gSb-eq/kWp mainly owing to the use of copper plating instead of silver paste for the metallization process.

- In addition, Muller study [33] on PERC technology shows that glass-glass modules have a lower carbon footprint than glass-backsheet modules (modeled for this study). Therefore by doing glass-glass modules, the carbon footprint of HJT technology might be reduced further than the presented "best-practice" of this study.
- Furthermore, implementation of a regulation to recycle PV modules will lead to a reduction of this carbon footprint as presented in EoL results section.



Figure 4.2: Environmental footprint per kWp of HJT technology (standard vs best practice) for CC, RUF and RUM impact categories. EF 3.0 impact assessment methodology used. Activities included : wafer production and transport, Cell and Module manufacturing in Europe, end-of-life modeled separately. Activities excluded: BOS & Installation manufacturing, use phase. Chinese electricity mix: 1023 g CO₂-eq/kWh ; European electricity mix: 418 g CO₂-eq. Standard: China 2020 wafer (170 μ m), sc-Si bifacial HJT cell, Ag paste for metallization (220 mg/ M6 wafer), ITO for TCO, module efficiency $\eta=21.75\%$. Best practice: Norsun wafer (170 μ m), sc-Si IBC HJT cell, copper plating for metallization, AZO for TCO, module efficiency $\eta=21.75\%$. All other parameters are identical to standard.

4.1.2 Limits of this study and recommendations for improved LCA studies on PV

Despite the promising results obtained in this work, the following points represent an interest to ensure a better quality of this study and, more generally, for LCA studies on PV:

- The formulae used for the use phase is a good approximation but do not reflect the complexity of the PV system production of energy depending on various internal (module degradation, inverter efficiency, cable losses) and external parameters (inclination, weather conditions, temperature);
- The End-of-Life model might also be upgraded with the inclusion of BOS +Installation end-of-life as well as the consideration of the Circular Footprint Formula (CFF) available in appendix and suggested by PEF [27];

- Other indicators used for energy production technology comparison such as Energy Payback Time and Cumulative Energy Demand may also be considered. This might provide interesting values to compare PV technology with other LCA researches on energy and electricity production technologies. Furthermore, evaluation in detail of the 16 impact categories available on the LCIA methodology might provide a more detailed environmental impact, but may not be very relevant for all impact categories for the PV domain.
- An important topic to tackle is to ensure a better data quality evaluation of the various sources used and put a specific focus on time validity evaluation that may be very short in the PV domain. As an example, data present on the Ecoinvent database for the electricity mix per country is outdated and may lead to biased results as described by Muller [33].
- The main challenge to improve the spread of this project is to refine the PV system model to tends to match the reality as much as possible while keeping it simple to understand for PV manufacturers.
- Other LCA of PV system should follow the major recommendations from IEA [7] as well as PEF recommendations [27]. Furthermore, the use of recent and relevant data should represent the main focus of the work. Very interesting and pertinent LCA studies on PV domain are mainly [35, 33, 29, 32] which provides complementary vision to tackle the subject in addition to future PV trends evaluated by ITRPV [6].

4.2 Conclusion

The environmental footprint (and more specifically carbon footprint) of PV system must be reduced to achieve a sustainable deployment of TW scale PV technology while limiting our impact on the environment (and more specifically on climate change). In this context, the major motivation of this work was to fill the gap of the state-of-the-art on environmental footprint of the future major PV technology: Heterojunction (HJT). Providing relevant results exploitable to reduce environmental footprint of HJT technology for European PV manufacturers (and more specifically for Photovoltaic Business Unit of CSEM and its industrial partners) was thus a major objective of this project. Globally this goal was tackled by performing the following points:

1. Putting in place a methodology and constructing a PV system model based on LCA recommendations and reviews;
2. offering a recent and robust database for LCA calculations thanks to literature review and industrial partners collaboration;
3. using this database allowed to produce results (per kWp and per kWh) to compare current environmental impact of major technologies of the PV market: Al-BSF and PERC with HJT technology;
4. evaluating the stability of PV systems to multiple variations of key parameters such as module efficiency, wafer thickness, solar irradiance.
5. providing major recommendations to PV manufacturers (in particular HJT manufacturers) thanks to the overview and multiple scenario analysed for each of the PV system building blocks (wafer, cell, module, BOS & Installation, Use phase, End-of-life) for HJT technology;
6. detailing the PV impact on 5 impact categories (Climate change, Particulate Matter, Resource use, fossils, Resource use, minerals and metals) over the 16 impact categories.

In addition to those promising results, limitations of this study as well as recommendations to improve future work and quality of other LCA studies on PV were tackled in the recommendations section. Overall, this project provides a recent and qualitative data to orient PV manufacturer choices for HJT technology while considering environmental footprint of PV system. It also generated a strong interest from industrial partners as well as other groups of the photovoltaic division of CSEM. Therefore, future work is scheduled and will focus on the development of an internal LCA tool (independent from Simapro) to evaluate environmental footprint of PV technologies. Furthermore, integration of costs consideration such as the LCOE (and integrate LCA results with a carbon tax) may also be useful to integrate durably LCA as an important driver for PV technology development in the world of PV manufacturers.

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Appendix

Appendix A - LCA methodology

This section describes the general methodology of the Life Cycle Analysis or Life Cycle Assessment (LCA). LCA is a method employed to analyze the environmental impact of an action, a product, a service or a system over its complete or partial life cycle based on a specific function. Simapro [22], OpenLCA [23] and GaBi [24] are the 3 major professional tools used to perform LCA [25]. A complete life cycle includes the following stages: Raw material extraction, Manufacturing, Distribution, Use phase, End-of-Life (disposal or recycling). LCA makes it possible to identify the aspects and different stages of a product that are harmful to the environment or, on the contrary, those that are less harmful. According to the ISO 14040 and 14044 standards, the LCA is carried out in 4 phases: definition of targets (Goal and Scope), inventory of emissions and extractions (LCI), impact analysis (LCIA) and interpretation. LCA applications are numerous and could be for product development, marketing or public policy. This methodology is also useful to compare different products or process while considering the same functional unit, orienting decision-making from an environmental point of view.

International standard ISO14040

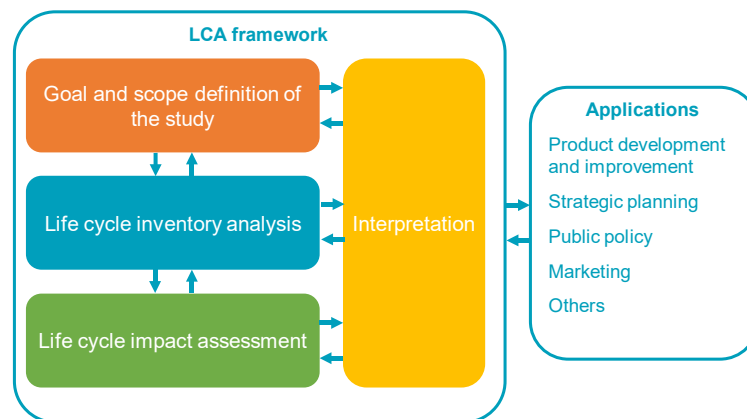


Figure 4.3: LCA methodology

A.1 Goal & Scope

: **Definition of targets:** this first part defines the objectives and field of study:

- the function of the system under study
- its functional unit which defines the amount of material required to carry out the action
- the boundaries of the system

All scenarios are compared on this common basis and all the flows are related to the quantity of product needed to fulfil the function.

For example, for a lamp, the function is to light, its functional unit is to light at 50 Watts for 1'000 hours. Regarding the system boundaries, the processes with the greatest impact need to be considered. Generally, the following stages are taken into account: extraction of raw materials, infrastructure, transport, manufacture of the product, its use, waste treatment and recycling (if any).

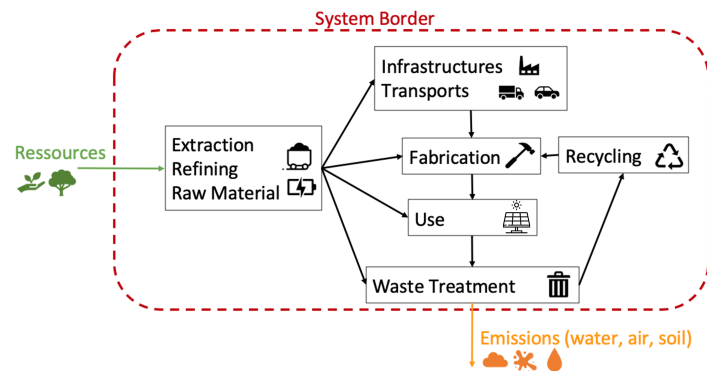


Figure 4.4: General System Boundary in the Life Cycle Analysis

A.2 Life Cycle Inventory

Inventory of emissions and extractions: quantifies emissions to air, water and soil, raw material extraction and land use necessary to achieve the function of the system. An inventory of all elemental flows (all material, energy and pollutant flows crossing the system boundary) is carried out. This inventory includes all quantities of pollutants and resources extracted during the product's life cycle.

A.3 Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) assesses the environmental impact of the emissions and extractions listed in the LCI.

This stage is divided into five phases (the last two are optional because they are based on a social value judgment within the meaning of ISO 14044):

- **The classification** is used to distribute emissions from the inventory according to the categories of impact they will affect (Climate Change, Human Toxicity, Land Use, etc.).
- **The midpoint characterisation:** the word "midpoint" means that emissions are between the inventory of the emissions and the endpoint categories. The midpoint characterisation is used to weight the emissions within each midpoint category. This is done by grouping the inventory results with similar effects (e.g. all substance flows that influence Global Warming) into midpoint categories. For each midpoint category a midpoint indicator is defined in order to compare the substance flows in that category. To do this, each flow in the inventory is multiplied by a midpoint characterization factor that characterizes its contribution to the midpoint category. For example CH_4 emissions are converted in $\text{kg CO}_2\text{-eq}$ thanks to a midpoint characterisation factor.
- **The endpoint characterisation:** this section is used to assess the contribution of midpoint categories to one or more endpoint categories on a subject to be protected. A damage factor is applied to each midpoint emission to group midpoint categories into endpoint categories. Example: a damage factor is applied to mineral extraction and non-renewable energy to form the damage category resources.
- **The normalisation** is carried out when the relative contribution of a product to the total effect of a given geographical area is needed according to a selected environmental impact category.

- **The weighting** is carried out in order to compare different endpoints with each other using a single score. The common unit is the point (Pt). A social value is assigned to each endpoints category.

Figure 4.5 represents the different phases of LCIA. The left red arrow represents the two first stages, the middle red arrow the third and fourth stages and the right red arrow the last stage.

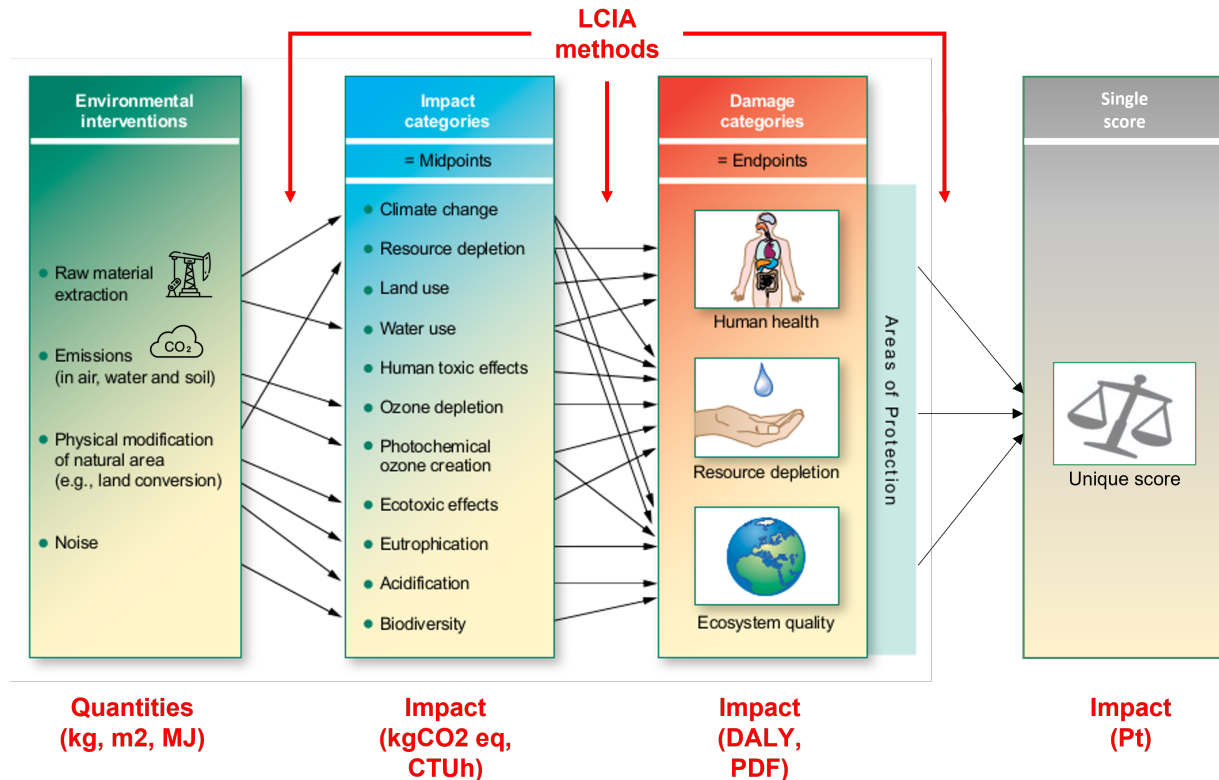


Figure 4.5: Life Cycle Impact Assessment scheme

Following European Commission recommendations for LCA of products, **the impact assessment methodology EF 3.0** published in 2019 [36] was used for this project. The more recent adaptation (June 2021) of this methodology on Simapro 9.2 was preferred to ensure consistent and exploitable results for the LCIA thanks to the database.

The impact analysis carried in this study focuses only on the two first stages (classification and midpoint characterisation) as further stages are based on a social value judgment within the meaning of ISO 14044 [26].

EF 3.0 classifies elemental flows from LCI in 16 (midpoint) Impact categories [36]. The midpoint characterisation factors are available on the description of EF 3.0 methodology on the Simapro software. Impact categories (and their acronyms) are described in the figure 4.6 based on information from Ecochain [48] and European Platform on LCA [49]:

LCIA Impact categories	Unit	Description	LCIA Impact subcategories
Acidification (AP)	mol H ⁺ eq	Indicator of the potential acidification of soils and water due to the release of gases such as nitrogen oxides and sulphur oxides. Accumulated Exceedance (AE) characterizing the change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances deposit.	-
Climate change (CC)	kg CO ₂ eq	Indicator of potential global warming due to emissions of greenhouse gases (GHG) to air. All GHG are converted into the well known CO ₂ gas. Radiative forcing as Global Warming Potential (GWP100) baseline model of the IPCC 2013. Divided into 3 subcategories based on the emission source: (1) fossil resources, (2) bio-based resources and (3) land use change.	Biogenic
			Fossil
			Land use and land use change
Ecotoxicity, freshwater (ECF)	CTUe	Impact on freshwater organisms of toxic substances emitted to the environment. Comparative Toxic Unit for ecosystems (CTUe) unit is calculated based on USEtox consensus multimedia model (see Human toxicity).	Inorganics
			Metals
			Organics
Eutrophication, freshwater (EF)	kg PO ₄ eq	Indicator of the enrichment of the fresh water ecosystem with nutritional elements, due to the emission of nitrogen or phosphor containing compounds, expressed in phosphorus equivalent. Only valid for Europe.	-
Eutrophication, marine (EM)	kg N eq	Indicator of the enrichment of the marine ecosystem with nutritional elements, due to the emission of nitrogen containing compounds, expressed in nitrogen equivalents.	-
Eutrophication, terrestrial (ET)	mol N eq	Indicator of the enrichment of the terrestrial ecosystem with nutritional elements, due to the emission of nitrogen containing compounds.	-
Human toxicity, cancer (HTC)	CTUh	Impact on humans of toxic substances emitted to the environment. Divided into non-cancer and cancer related toxic substances. Comparative Toxic Unit for human (CTUh) are calculated based on USEtox consensus multimedia model. It spans two spatial scales: continental and global scale both split into six compartment (urban air, rural air, agricultural soil natural soil, freshwater, costal marine water).	Inorganics
			Metals
Human toxicity, non-cancer (HTNC)	CTUh		Organics
			Inorganics
			Metals
			Organics
Ionising radiation (IR)	kBq U-235 eq	Damage to human health and ecosystems linked to the emissions of radionuclides. This indicator quantifies the impact of ionizing radiation on the population (Ionizing Radiation Potentials), in comparison to Uranium 235.	-
Land use (LU)	Pt	Measure of the changes in soil quality (Biotic production, Erosion resistance, Mechanical filtration). CFs set was re-Calculated by JRC starting from LANCA® v 2.2 as baseline model.	-
Ozone depletion (OD)	kg CFC11 eq	Indicator of emissions to air that cause the destruction of the stratospheric ozone layer (Ozone Depletion Potential) over a time horizon of 100 years.	-
Particulate Matter (PM)	disease incidence	Indicator of the potential incidence of disease due to particulate matter (PM _{2.5}) emissions. The indicator is calculated applying the average slope between the Emission Response Function (ERF) working point and the theoretical minimum-risk level. Exposure model based on archetypes that include urban environments, rural environments, and indoor environments within urban and rural areas.	-
Photochemical ozone formation (POF)	kg NMVOC eq	Indicator of emissions of gases that affect the creation of photochemical ozone in the lower atmosphere (smog) catalysed by sunlight. This indicator is only valid for Europe.	-
Resource use, fossils (RUF)	MJ	Indicator of the depletion of natural fossil fuel resources (ADP-fossil), based on lower heating value. ADP for energy carriers, based on van Oers et al. 2002 as implemented in CML, v. 4.8 (2016). Depletion model based on use-to-availability ratio. Full substitution among fossil energy carriers is assumed.	-
Resource use, minerals and metals (RUM)	kg Sb eq	Indicator of the depletion of natural non-fossil resources (ADP). ADP for mineral and metal resources, based on van Oers et al. 2002 as implemented in CML, v. 4.8 (2016). Depletion model based on use-to-availability ratio. Full substitution among fossil energy carriers is assumed. Subnational regions are assigned the national characterization factor.	-
Water use (WU)	m ³ deprived	Indicator of the relative amount of water used, based on regionalized water scarcity factors. Relative Available Water REMaining (AWARE) per area in a watershed, after the demand of humans and aquatic ecosystems has been met. CF are recommended for characterization of blue water consumption only, where consumption is defined as the difference between withdrawal and release of blue water. Therefore, green water, fossil water, sea water and rain water are not to be characterized with this CFs set.	-

Figure 4.6: Impact categories from EF 3.0 LCIA methodology

A.4 Interpretation

Interpretation: is the last phase used to test and validate the assumptions made, to interpret the results obtained and to assess uncertainties. Positive points and areas for improvement at the product level are highlighted. More detailed information on the Life Cycle Analysis method can be found in this reference [50].

Appendix B - LCA tools

B.1 Ecoinvent database

The Ecoinvent database contains around 18'000 reliable life cycle inventory datasets, covering a range of industrial sectors as agriculture, construction, chemicals, metals [37]. All of those process datasets are split in different categories: Material, Energy, Transport, Treatment, Use, Waste scenario and Waste treatment. Furthermore, each activity in the ecoinvent database is attributed a geographic location.

Table 4.1 shows the major useful nomenclature of Ecoinvent database:

Table 4.1: Major Ecoinvent nomenclature

Concern	Ecoinvent name	Signification
Nomenclature	Cut-off U	Ecoinvent model used : allocation, cut-off by classification (Cut-off), Unit (U)
Nomenclature	Market	product as available on the market (including its production and transport)
Nomenclature	Transformation (production)	production / transformation of the product
Location	RoW	used in transformation, represent the (rest of the) world (RoW) production
Location	GLO	used in market, represent the world market : Global (GLO)
Location	RER	used in transformation/Market, represent the (rest of the) europe (RER) production/market
Location	CN	China
Location	DE	Germany
Location	CH	Switzerland
Location	NO	Norway

Processes are sets of interacting activities that transform inputs into outputs. Two types of processes exists namely **Unit (U)** and **System (S)**. The S process refers to the system as a black box, with given incomes and given outcomes whereas the U process keeps the detail of the flows entering and exiting each unit processes present in the main process. Therefore, S type is useful to speed up the calculation time of the software while U type allows to change some subprocesses within the main process.

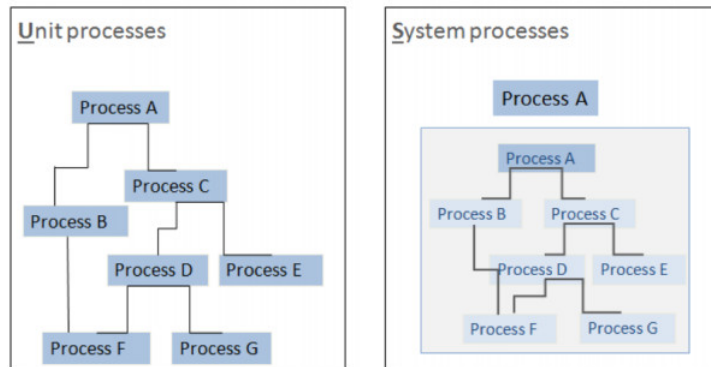


Figure 4.7: Unit (U) versus System (S) processes

For this work, it is important to note that datasets processes for PV system available on Ecoinvent refers to an old technology which is the Al-BSF dating from 2010 (referred as Al-BSF 2010) since there was no actualization of the database since then. Thus, the creation of new processes is needed to model the more recent technologies studied in this work. In this aim, U type was chosen as it enables a better understanding of each process and simplifies its modification.

Three system models exist for the Ecoinvent database more recent than Ecoinvent 3.1 [51]:

- **Allocation (default)** : this system model uses the average supply of products, without taking into account the possible scarcity of the supply.
- **Allocation, cut-off by classification**: this system model is based on the Allocation system, but does not take into account any benefit related to the recycling of a material.

- **Consequential:** this system model is intended to reflect the sector future trends by taking into account the constraints that apply at small-scale and long-time horizon.

For this work, the model "Allocation, cut-off by classification" is selected with unit process: (**Ecoinvent 3.7.1 - Allocation, cut-off by classification - unit**). Therefore default end-of-life processes are not taking into account any benefit due to the recycling of materials, which therefore represents an overestimation of the end-of-life environmental impact.

B.2 Simapro software

Simapro [22], OpenLCA [23] and GaBi [24] are the three major professional tools used to perform LCA [25]. Simapro version 9.2 was used for this project with an EPFL academic license. The Simapro software is built on life cycle thinking and enables the user to perform a complete LCA. The four stages of LCA can be found on the left column of the left figure 4.8:

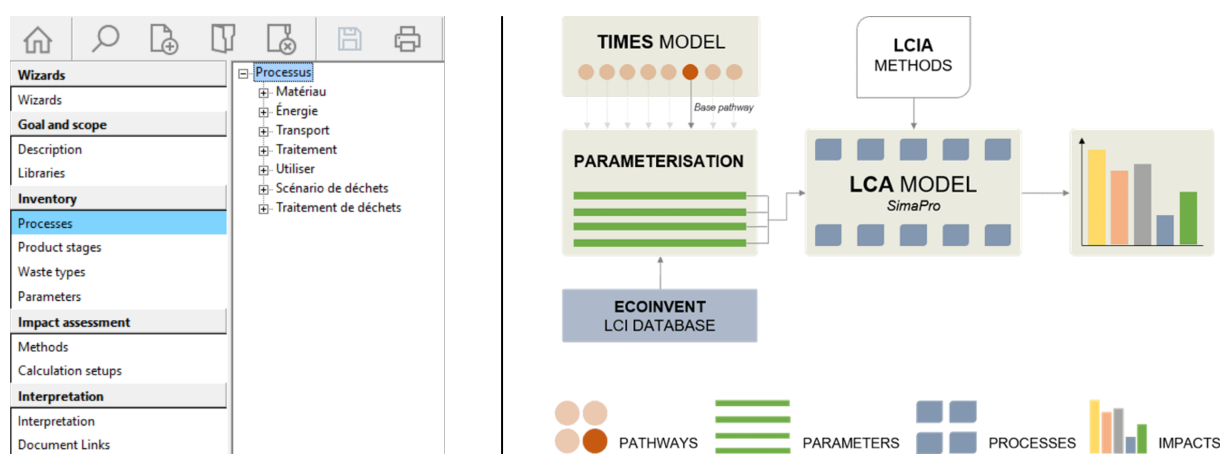


Figure 4.8: Simapro screen print | Simapro working principle

Figure 4.8 right shows the working principle of Simapro which is mainly used for two reasons:

- the creation of new datasets with existing LCI database.
- the visualisation of environmental impacts of a process/product stage (after choosing a LCIA method).

Processes: All processes from Ecoinvent dataset are split in different categories: Material, Energy, Transport, Treatment, Use, Waste scenario and Waste treatment as depicted in Figure 4.8 left. Simapro allows the production of new process based on existing Ecoinvent database. A process should include all inputs (energy, natural resources, other processes) and outputs (main product, polluting emissions, waste). As mentioned previously, for PV systems, dataset available on Ecoinvent refers to the old ALBSF 2010 technologies. Thus new processes need to be created based on the available processes from the Ecoinvent database.

Product stages: also known as **Assembly** represent a combination of different processes or assemblies. This option is used to have a better visualization of results as by default Simapro shows only the top process without detailing the impact of the subprocesses used.

Parameters: In this section of Simapro, general parameters of the project can be added. Nevertheless, specific parameters can be added for each process (on the process parameters).

Methods: contains all the available LCIA methodologies compatible with the Simapro software. A specific LCIA methodology can be set for the whole project.

Impact Assessment Results: is one of the strength of the Simapro software. It allows to show results in rough numbers according to impact categories but also for end-point categories or single score. Furthermore, data can be visualized with figures.

Appendix C - Data sources evaluation

Literature review sources for PV technology are very diverse and represent datashape such as product technical data sheets, Excel databases, Ecoinvent database, pdf reports with tables and other reports. Figure 4.9 represent the main sources used to implement in Simapro the models of each PV system technology.







STEP \ Technology	Al-BSF 2010	Al-BSF 2020	PERC 2020	HJT 2020
 Wafer	a	b	b	b
 Cell	a	b	c	e,f,g
 Module	a	b,d	c,d	d,e,f
 BOS + Installation	a	b	b	b
 Use phase	a	b	b	b
 End-of-Life	a	b	b	b

Figure 4.9: Data sources for major PV system building blocs and technologies

(a) Ecoinvent 3.7.1

(b) IEA-PVPS task 12 LCI [29]

(c) AMPERE D.2.4 data [34]

(d) PERC module European manufacturer A data

(e) CSEM data [38]

(f) HJT cell and module European manufacturer B data

(g) Louwen data [35]

For each process, quantities (kg, MJ, m²) of inputs and outputs need to be converted in the Ecoinvent database. Building a dataset compatible with ecoinvent database is different for each source of data, depending on their time period validity, completeness and Ecoinvent compatibility as depicted in Table 4.2. The five levels of Ecoinvent compatibility are defined as :

- 1/5 Ecoinvent data does not exist
- 2/5 data needs to be converted into exploitable quantities or fluxes (kg, MJ, m²)
- 3/5 data needs to find an equivalent in Ecoinvent database
- 4/5 data are linked with Ecoinvent database
- 5/5 data are already Ecoinvent data

A similar scale is applied for completeness to Simapro transfer and Excel transfer with 5/5 representing a very complete, respectively easy to transfer dataset and 1/5 representing a incomplete, respectively very hard to transfer dataset.

Table 4.2: Major PV system dataset

Data source \ Information	Nomenclature	Time	Completeness	Ecoinvent compatibility	Simapro transfer	Excel transfer
Ecoinvent	a	2010	4/5	5/5	5/5	4/5
IEA-PVPS	b	2020	5/5	4/5	3/5	5/5
AMPERE ; manufacturer A	c;d	2020	3/5	3/5 ; 2/5	2/5	3/5
CSEM; manufacturer B	e:f	2022	3/5 ; 2/5	2/5 (1/5)	1/5	2/5

Appendix D - Process example: MG-Si

Inputs and outputs of a process are identified by a name, a location, if they are an infrastructure or not and their unit. The two last columns shows the matching of a input or output with Ecoinvent (or own) dataset. Quantities of input/output are defined in the blue columns. Those numbers are obtained from literature data, and/or calculations. Extra columns not shown in Table 4.3 shows data source, hypothesis and data validity (if available).

In addition to inputs and outputs of a process, extra information are added (if available):

- specific process parameters
- process description and schematic
- detailed calculations

Other data such as key parameters are also recorded on a separate sheet of the Excel file for each of the PV building blocks.

As an example, Table 4.3 represents the Process 0.1 "Metallurgical grade Silicium (MG-Si)".

Table 4.3: MG-Si process

Category	Name	Location	Infra-structure	Unit	MG-Silicon production {CN}	MG-Silicon production {NO}	Matching	Name
Product	MG-Silicon, at plant	CN	0	kg	1	0	PV_CSEM	MG-Silicon, at plant {CN}
	MG-Silicon, at plant	RER (NO)	0	kg	0	1	PV_CSEM	MG-Silicon, at plant {NO}
Input technosphere (materials/flux)	wood chips, production mix, wet, measured as dry mass, at forest road & at sawmill	RoW	0	kg	3.25E-03	0.00E+00	Ecoinvent 3.7.1	Wood chips, wet, measured as dry mass {RoW} market for Cut-off, U
	wood chips, production mix, wet, measured as dry mass, at forest road & at sawmill	RER w/o CH	0	kg	0.00E+00	3.25E-03	Ecoinvent 3.7.1	Wood chips, wet, measured as dry mass {Europe without Switzerland} market for Cut-off, U
	hard coal coke, at plant	CN	0	MJ	2.31E+01	0.00E+00	Ecoinvent 3.7.1	Hard coal {CN} market for Cut-off, U
	hard coal coke, at plant	RER w/o RU, TR	0	MJ	0.00E+00	2.31E+01	Ecoinvent 3.7.1	Hard coal {Europe, without Russia and Turkey} market for hard coal Cut-off, U
	graphite	RoW	0	kg	1.00E-01	0.00E+00	Ecoinvent 3.7.1	Graphite {RoW} production Cut-off, U
	graphite	RER	0	kg	0.00E+00	1.00E-01	Ecoinvent 3.7.1	Graphite {RER} production Cut-off, U
	charcoal, at plant	GLO	0	kg	1.70E-01	1.70E-01	Ecoinvent 3.7.1	Charcoal {GLO} market for Cut-off, U
	petroleum coke, at refinery	RoW	0	kg	5.00E-01	0.00E+00	Ecoinvent 3.7.1	petroleum coke {RoW} petroleum coke production, petroleum refinery operation Cut-off, U
	petroleum coke, at refinery	RER	0	kg	0.00E+00	5.00E-1	Ecoinvent 3.7.1	petroleum coke {Europe without Switzerland} petroleum coke production, petroleum refinery operation Cut-off, U
	silica sand	CN	0	kg	2.70E+00	0.00E+00	Ecoinvent 3.7.1	Silica sand {RoW} production Cut-off, U
	silica sand	DE	0	kg	0.00E+00	2.70E+0	Ecoinvent 3.7.1	Silica sand {DE} production Cut-off, U
	oxygen, liquid, at plant	RoW	0	kg	2.00E-2	0.00E+00	Ecoinvent 3.7.1	Oxygen, liquid {RoW} market for Cut-off, U
	oxygen, liquid, at plant	RER	0	kg	0.00E+00	2.00E-2	Ecoinvent 3.7.1	Oxygen, liquid {RER} market for Cut-off, U
	transport, transoceanic freight ship	OCE	0	tkm	2.55E+0	2.55E+0		
	transport, freight, lorry, fleet average	RER	0	tkm	0	1.56E-1	Ecoinvent 3.7.1	Transport, freight, lorry >32 metric ton, euro4 {RER} market for transport, freight, lorry >32 metric ton, EURO4 Cut-off, U
	transport, freight, lorry, fleet average	RoW	0	tkm	1.56E-1	0	Ecoinvent 3.7.1	Transport, freight, lorry >32 metric ton, euro4 {RoW} market for transport, freight, lorry >32 metric ton, EURO4 Cut-off, U
	transport, freight, rail	CN	0	tkm	6.90E-2	0.00E+00	Ecoinvent 3.7.1	Transport, freight train {CN} market for Cut-off, U
transport, freight, rail	RER	0	tkm	0.00E+00	6.90E-2	Ecoinvent 3.7.1	Transport, freight train {RER} market for Cut-off, U	
silicone plant	RoW	1	p	1.00E-11	0.00E+00	Ecoinvent 3.7.1	Silicone factory {RoW} construction Cut-off, U	
silicone plant	RER	1	p	0.00E+00	1.00E-11	Ecoinvent 3.7.1	Silicone factory {RER} construction Cut-off, U	
Input technosphere (electricity/heat)	electricity, medium voltage, at grid	CN	0	kWh	1.10E+01	0.00E+00	Ecoinvent 3.7.1	Electricity, medium voltage {CN} market group for Cut-off, U
	electricity, medium voltage, at grid	NO	0	kWh	0.00E+00	1.10E+01	Ecoinvent 3.7.1	Electricity, medium voltage {NO} market group for Cut-off, U
Output (air, unspecified)	Heat, waste	-	-	MJ	7.13E+1	7.13E+1	Ecoinvent 3.7.1	Heat, waste
	Arsenic	-	-	kg	9.42E-9	9.42E-9	Ecoinvent 3.7.1	Arsenic
	Antimony	-	-	kg	7.85E-9	7.85E-9	Ecoinvent 3.7.1	Antimony
	Cadmium	-	-	kg	3.14E-10	3.14E-10	Ecoinvent 3.7.1	Cadmium
	Chromium	-	-	kg	7.85E-9	7.85E-9	Ecoinvent 3.7.1	Chromium
	Cyanide	-	-	kg	6.87E-6	6.87E-06	Ecoinvent 3.7.1	Cyanide
	Hydrogen sulfide	-	-	kg	5.00E-04	5.00E-04	Ecoinvent 3.7.1	Hydrogen sulfide
	Hydrogen fluoride	-	-	kg	5.00E-04	5.00E-04	Ecoinvent 3.7.1	Hydrogen fluoride
	Lead	-	-	kg	3.44E-07	3.44E-07	Ecoinvent 3.7.1	Lead
	Mercury	-	-	kg	7.85E-09	7.85E-09	Ecoinvent 3.7.1	Mercury
	NM VOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	9.60E-05	9.60E-05	Ecoinvent 3.7.1	NM VOC, non-methane volatile organic compounds, unspecified origin
	Nitrogen oxides	-	-	kg	9.74E-03	9.74E-03	Ecoinvent 3.7.1	Nitrogen oxides
Particulates, >10 um	-	-	kg	7.75E-03	7.75E-03	Ecoinvent 3.7.1	Particulates, >10 um	
Sulfur dioxide	-	-	kg	1.22E-02	1.22E-02	Ecoinvent 3.7.1	Sulfur dioxide	
Tin	-	-	kg	7.85E-09	7.85E-09	Ecoinvent 3.7.1	Tin	
Output (air, low pop)	Aluminium	-	-	kg	1.55E-6	1.55E-6	Ecoinvent 3.7.1	Aluminium
	Boron	-	-	kg	2.79E-7	2.79E-7	Ecoinvent 3.7.1	Boron
	Calcium	-	-	kg	7.75E-7	7.75E-7	Ecoinvent 3.7.1	Calcium
	Fluorine	-	-	kg	3.88E-8	3.88E-08	Ecoinvent 3.7.1	Fluorine
	Iron	-	-	kg	3.88E-06	3.88E-06	Ecoinvent 3.7.1	Iron
	Potassium	-	-	kg	6.20E-05	6.20E-05	Ecoinvent 3.7.1	Potassium
	Silicon	-	-	kg	7.51E-03	7.51E-03	Ecoinvent 3.7.1	Silicon
Sodium	-	-	kg	7.75E-07	7.75E-07	Ecoinvent 3.7.1	Sodium	
Output (air, high pop)	Carbon monoxide, biogenic	-	-	kg	6.20E-4	6.20E-4	Ecoinvent 3.7.1	Carbon monoxide, biogenic
	Carbon monoxide, fossil	-	-	kg	1.38E-3	1.38E-3	Ecoinvent 3.7.1	Carbon monoxide, fossil
	Carbon dioxide, biogenic	-	-	kg	1.61E+0	1.61E+0	Ecoinvent 3.7.1	Carbon dioxide, biogenic
	Carbon dioxide, fossil	-	-	kg	3.58E+0	3.58E+0	Ecoinvent 3.7.1	Carbon dioxide, fossil
	Chlorine	-	-	kg	7.85E-8	7.85E-8	Ecoinvent 3.7.1	Chlorine
Output (waste to treatment)	disposal, slag from MG silicon production, 0% water, to inert material landfill	GLO	0	kg	2.50E-2	2.50E-2	Ecoinvent 3.7.1	Slag from metallurgical grade silicon production {GLO} market for Cut-off, U

Appendix E - Energy indicators for PV LCA

The energy payback time (EPBT) is defined as the time it takes for a PV system to produce the same amount of energy that it consumed during its whole lifecycle.

$$EPBT = CED/E_{total}$$

EPBT = Energy Payback Time [year]

CED = Cumulative Energy Demand [MJ]

E_{total} = Energy produced by the PV system over its lifetime [MJ]

$$CED = E_{prod} + E_{trans} + E_{insta} + E_{use} + E_{EoL}$$

where E represent the energy for each step of the LCA (production, transport, installation, use, end-of-life).

The interest of EPBT (and CED) indicators is to show how much PV system are effective to compensate the energy used during their lifetime.

Appendix F - Circular Footprint Formula

European PEF guidance (page 67) [cite](#) defines the Circular Footprint Formula (CFF) for End-of-life modelling. The CFF is a combination of "material + energy + disposal" for a specific material which is expressed as:

$$Material = (1 - R_1)E_V + R_1 * (AE_{recycled} + (1 - A)E_V * \frac{Q_{Sin}}{Q_p}) + (1 - A)R_2 * (E_{recyclingEoL} - E_V^* * \frac{Q_{Sout}}{Q_p})$$

$$Energy = (1 - B)R_3 * (E_{ER} - LHV * X_{ER,heat} * E_{SE,heat} - LHV * X_{ER,elec} * E_{SE,elec})$$

$$Disposal = (1 - R_2 - R_3) * E_D$$

With the different factors:

A: allocation factor of burdens and credits between supplier and user of recycled materials.

B: allocation factor of energy recovery processes. It applies both to burdens and credits.

Q_{Sin} : quality of the ingoing secondary material, i.e. the quality of the recycled material at the point of substitution.

Q_{Sout} : quality of the outgoing secondary material, i.e. the quality of the recyclable material at the point of substitution.

Q_p : quality of the primary material, i.e. quality of the virgin material.

R_1 : it is the proportion of material in the input to the production that has been recycled from a previous system.

R_2 : it is the proportion of the material in the product that will be recycled (or reused) in a subsequent system. R2 shall therefore take into account the inefficiencies in the collection and recycling (or reuse) processes. R2 shall be measured at the output of the recycling plant.

R_3 : it is the proportion of the material in the product that is used for energy recovery at EoL.

$E_{recycled}$: specific emissions and resources consumed (per functional unit) arising from the recycling process of the recycled (reused) material, including collection, sorting and transportation process.

$E_{recyclingEoL}$: specific emissions and resources consumed (per functional unit) arising from the recycling process at EoL, including collection, sorting and transportation process.

E_V : specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material.

E_V^* : specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials.

E_{ER} : specific emissions and resources consumed (per functional unit) arising from the energy recovery process (e.g. incineration with energy recovery, landfill with energy recovery, etc.).

$E_{SE,heat}$ and $E_{SE,elec}$: specific emissions and resources consumed (per functional unit) that would have arisen from the specific substituted energy source, heat and electricity respectively.

E_D : specific emissions and resources consumed (per functional unit) arising from disposal of waste material at the EoL of the analysed product, without energy recovery.

$X_{ER,heat}$ and $X_{ER,elec}$: the efficiency of the energy recovery process for both heat and electricity.

LHV: lower heating value of the material in the product that is used for energy recovery.

Appendix G - Additional plots and examples for data visualization

Different data visualization exists and process to obtain them is described in the methodology chapter. Sensitivity analysis plot (Figure 4.10), spider plot (Figure 4.11) and stacked column plot (Figure 4.12) can be shown below

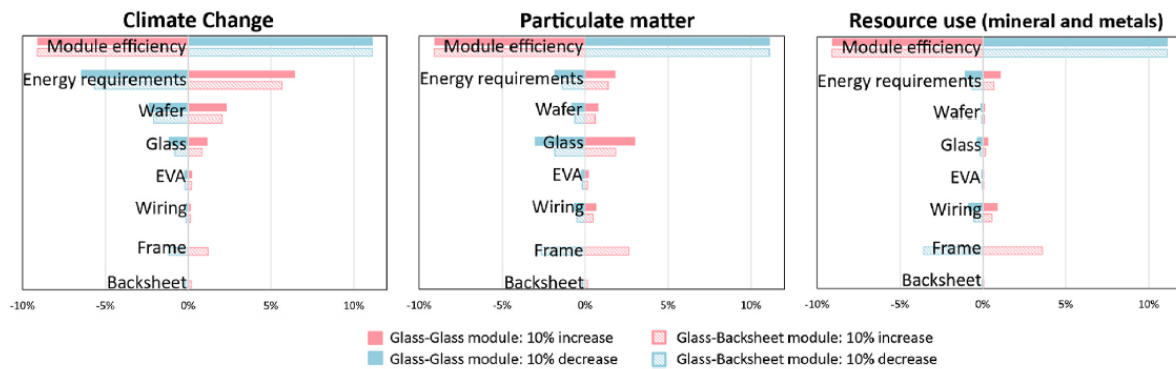


Figure 4.10: Figure from Muller study [33]: Sensitivity analysis of various module parameters for the impact categories climate change, particulate matter and resource use (mineral and metals) for glass-glass and glass-backsheet modules produced in Germany. Each parameter is increased or reduced by 10%. The results indicate the percentual changes of the overall impact for the environmental indicator. The plot for module efficiency is asymmetric because the calculation divides by this parameter, resulting in nonlinearity.

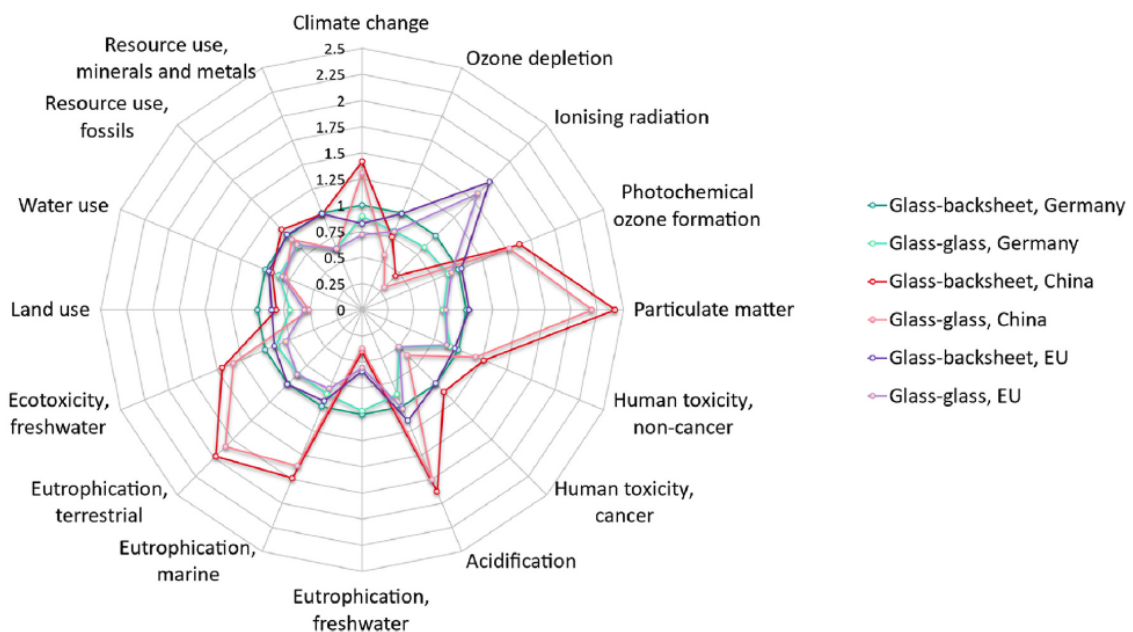


Figure 4.11: Figure from Muller study [33]: Results of environmental assessment of 1 kWp sc-Si glass-backsheet and glass-glass modules produced in China, Germany or the EU for the 16 EF environmental indicators recommended by IEA PVPS and EU PEFCR [13,14]. Glass-backsheet modules: $P = 366$ Wp, $\nu = 19.79\%$. Glass-glass modules: $P = 359$ Wp, $\nu = 19.40\%$. Including production, transport and end-of-life. Excluding BOS, installation and operation. Results of glass-backsheet modules produced in Germany are scaled to 1.

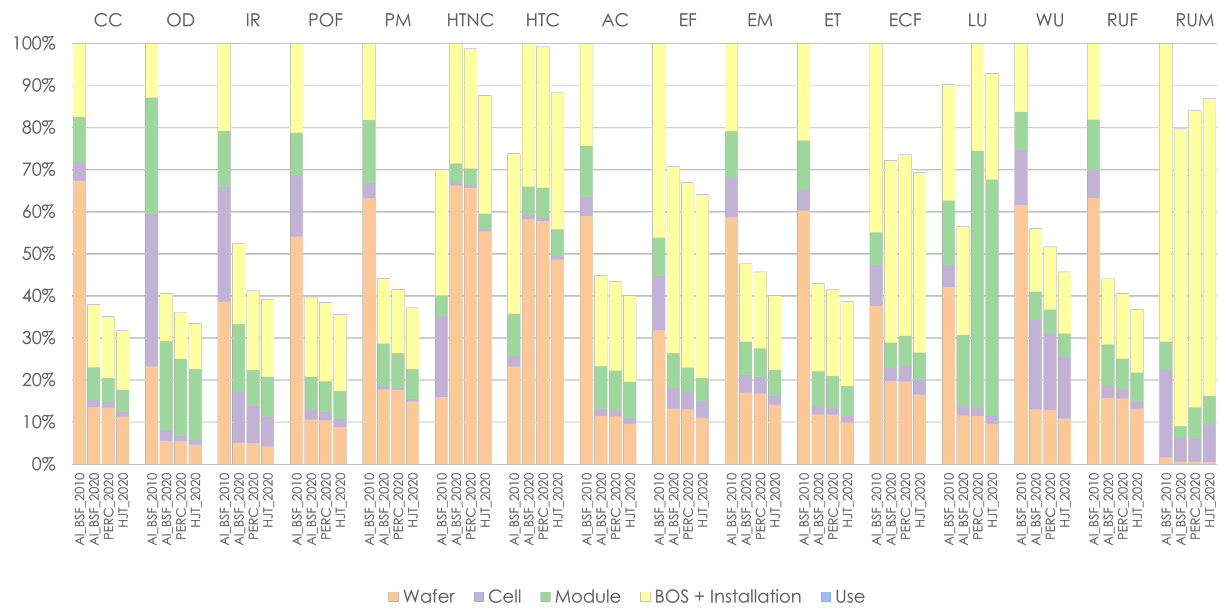


Figure 4.12: Relative environmental footprint per kWh of single-Si technologies