Life Cycle Assessment of a PV System with Silicon Heterojunction modules

Current and Prospective scenarios based on manufacturing in the Netherlands

SET3901: GraduationProject

Shashank Bhardwaj

Delft University of Technology

Life Cycle Assessment of a PV System with Silicon Heterojunction modules

Current and Prospective scenarios based on manufacturing in the Netherlands

by

Shashank Bhardwaj
5704146

to obtain the degree of Master of Science at Delft University of Technology,

Student number:	5704146
Project Duration:	January 9,2024 - August 29, 2024
Thesis Supervisor:	Prof.dr. A.W. (Arthur) Weeber
Thesis Committee:	Dr. M.R. Vogt
	Dr. V.A. (Vera) Popovich

Cover Image by:- DALL-E-2

TU Delft

Acknowledgment

This thesis signifies the completion of my graduation project, which extended for a duration of nine months.

I would like to begin by expressing my gratitude and appreciation to my supervisor, Prof.dr. A.W. (Arthur) Weeber, for providing me the opportunity to work on this thesis project under his guidance. Your invaluable expertise, patience, and unwavering belief throughout this phase has been of incredible support to me, without which this project would not have been possible. Your knowledge and critical feedbacks have played a crucial role in influencing and structuring this work. I would like to express my sincere gratitude to Dr. M.R. Vogt for his exceptional knowledge and invaluable insights during the course of this study.

I would also like to express profound gratitude to my family for their constant support, understanding, and motivation during this endeavour. Your unwavering faith in me has consistently served as a powerful driving force. I would like to extend my gratitude to my friends Shubham Choudhary and Samit Goud for their consistent support and encouragement during this journey. I immensely appreciate the multitude of ways in which your friendship has provided me with strength and motivation throughout this journey.

Lastly, I would like to express my admiration for Aaradhya Bansal, who has served as both a friend and a senior to me. Your assistance and support throughout the duration of this thesis, starting from the very beginning, has been remarkable. Thank you for your presence and willingness to help me at the most difficult times during this thesis work.

Shashank Bhardwaj
Delft, August 2024

Abstract

As sustainable energy technologies continue to attract growing interest worldwide, comprehending their environmental implications becomes essential. Along with cost optimisation and enhancing efficiencies, it is equally important to reduce a wide range of environmental impacts, which is crucial for attaining global sustainability goals. Silicon Heterojunction (SHJ) solar panels are one such example of a growing sustainable energy technology that are anticipated to take up a considerable share of the global PV market in the coming years, owing to its high achievable efficiency.

The goal of this study was to conduct a Life Cycle Assessment on a PV system consisting of Silicon Heterojunction solar cells and modules in order to gain insights for the environmental impacts of such a PV system based on manufacturing in the Netherlands. The study included the production steps of SHJ cells and modules, from raw material to final product and use phase until end of life time. Recyling processes were not included. Inverters and mounting structures were also used to complete the PV system.

4 impact categories were analyzed in this study for a rooftop PV system with SHJ cells in 2024. The results for these impact categories were: 22 g CO_2-Eq/kWh for Climate Change; 14 g 1.4-DCB-eq/kWh for Ecotoxicity Freshwater; 17.5 g 1.4-DCB-eq/kWh for Ecotoxicity Marine and 0.0016 $\mathrm{m}^2\ \mathrm{crop}-\mathrm{eq}$/kWh for Land Use. Similarly the results for the future scenarios were also reported: Climate change impacts will reduce by more than 10 g CO_2-Eq/kWh ; Ecotoxicity impacts will reduce by around 0.6 g 1.4-DCB-eq/kWh and land use by 0.0006 $\mathrm{m}^2\ \mathrm{crop}-\mathrm{eq}$/kWh over the course of a decade. Then, the contribution analyses were presented for these categories, representing the components and process steps that were major contributors to each of these categories. Finally, two sensitivity analyses were conducted, to see how the environmental impacts change by changing certain parameters.

The results gathered in this study, and upon comparing them with the LCA results from earlier published studies showed that the SHJ cell and module manufacturing was more environment friendly than some of the other technologies, along with certain room for improvement. Improving the manufacturing processes and with a change in Dutch electricity mix, in the future scenarios, showed that the environmental impacts will further reduce, making this PV technology highly acceptable and implementable.

Contents

List of Figures

List of Tables

List of Abbreviations

- **LCA** - Life Cycle Assessment
- **SHJ** - Silicon Heterojunction
- **BoS** - Balance of System
- **IAM** - Integrated Assessment Models
- **SSP** - Shared Socioeconomic Pathways
- **PECVD** - Plasma Enhanced Chemical Vapor Deposition
- **TCO** - Transparent Conductive Oxide
- **Cz-Si** - Czochralski Silicon
- **MG-Si** - Metallurgical Grade Silicon
- **GWP** - Global Warming Potential
- **PV** - Photovoltaic
- **EVA** - Ethylene-vinylacetate
- **RCP** - Representative Concentration Pathway
- **RE** - Renewable Energy
- **CCS** - Carbon Capture and Storage
- **PR** - Performance Ratio
- **ISE** - Fraunhofer Institute for Solar Energy Systems
- **1.4-DCB** - 1,4-Dichlorobenzene (used as an equivalence for ecotoxicity)
- **kWh** - Kilowatt-hour
- **kWp** - Kilowatt peak
- **STC** - Standard Test Conditions
- **ITRPV** - International Technology Roadmap for Photovoltaic
- **PERC** - Passivated Emitter Rear Cell / Passivated Emitter and Rear Cell
- **GHG** - Greenhouse Gas
- **GMST** - Global Mean Surface Temperature
- **GSA** - Global Sensitivity Analysis
- **RER** - Representative Europe
- **GLO** - Global
- **SiC** - Silicon Carbide
- **H2O** - Water (used chemically)
- **PH3** - Phosphine
- **B2H6** - Diborane
- **SiH4** - Silane
- **In2O3** - Indium Tin Oxide
- **ELCD** - European Reference Life Cycle Database
- **USLCI** - United States Life Cycle Inventory Database
- **Cu-Eq** - Copper Equivalent

- **Co-60-Eq** - Cobalt-60 Equivalent
- **SO2-Eq** - Sulfur Dioxide Equivalent
- **NOx-Eq** - Nitrogen Oxides Equivalent
- **CFC-11-Eq** - Chlorofluorocarbon-11 Equivalent
- **PMFP** - Particulate Matter Formation Potential
- **IRP** - Ionising Radiation Potential
- **HFOp** - Photochemical Oxidant Formation Potential: Human Health
- **FEP** - Freshwater Eutrophication Potential
- **MEP** - Marine Eutrophication Potential
- **TAP** - Terrestrial Acidification Potential
- **METP** - Marine Ecotoxicity Potential
- **FETP** - Freshwater Ecotoxicity Potential
- **LOP** - Land Occupation Potential
- **SOP** - Surplus Ore Potential
- **pLCA** - Prospective Life Cycle Assessment
- **M6** - A standard size for silicon solar cells (156 mm x 156 mm)
- **c-Si** - Crystalline Silicon
- **ITO** - Indium Tin Oxide
- **Ag** - Silver
- **SiOx** - Silicon Oxide
- **nc-Si** - Nanocrystalline Silicon
- **KOH** - Potassium Hydroxide
- **LCI** - Life Cycle Inventory
- **LCIA** - Life Cycle Impact Assessment
- **CML** - Center of Environmental Science of Leiden University
- **TRACI** - Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
- **ReCiPe** - A method for life cycle impact assessment that harmonizes the midpoint and endpoint approaches
- **MFA** - Material Flow Analysis
- **IPCC** - Intergovernmental Panel on Climate Change
- **IMAGE** - Integrated Model to Assess the Global Environment
- **REMIND** - Regional Model of Investments and Development
- **CdTe** - Cadmium Telluride
- **CIS/CIGS** - Copper Indium Selenide / Copper Indium Gallium Selenide
- **multi-Si** - Multicrystalline Silicon
- **BSF** - Back Surface Field
- **mono-Si** - Monocrystalline Silicon
- **CSEM** - Centre Suisse d’Electronique et de Microtechnique
- **IEA** - International Energy Agency
- **PVPS** - Photovoltaic Power Systems Programme
- **HZB** - Helmholtz-Zentrum Berlin
- **Al BSF** - Aluminum Back Surface Field

- **ZnO** - Zinc Oxide
- **SiCx** - Silicon Carbide
- **TOPCon** - Tunnel Oxide Passivated Contact
- **NREL** - National Renewable Energy Laboratory
- **GW** - Gigawatt
- **GWp** - Gigawatt peak
- **ISO** - International Organisation for Standardisation
- **m2*a crop-Eq** - Square Meters Agricultural Land Occupation Equivalent
- **CO2-Eq** - Carbon Dioxide Equivalent
- **m2 crop-eq** - Square Meters Crop Equivalent
- **M10** - A standard size for silicon solar cells (182 mm x 182 mm)

1 Introduction

The primary sources of energy that have been used to meet the ever-growing global energy demand are fossil fuels and natural gas, which are also referred to as non-renewable energy sources. These sources are finite, and their extraction and use result in significant environmental problems, despite their capacity to provide large quantities of energy[1]. These issues include, for example, ecological destruction, global warming, and ecotoxicity. There is increasing agreement on the need for sustainable and renewable energy technologies, which have shown the potential to be an economical alternative to traditional energy sources as the adverse effects of the latter become more noticeable. The transition to renewable energy sources has been identified as a key solution to these issues, with solar energy being one of the most promising alternatives.

Sustainable energy technologies have emerged as plausible alternatives to address the drawbacks of non-renewable energy. Renewable energy sources, including solar, wind and geothermal energy, are abundant in nature and have the potential to reduce adverse environmental impacts [2].The percentage share of global electricity generation from sustainable energy sources has increased, as illustrated in Figure 1.1 below [3]. The global proportion of sustainable energy technologies has been steadily increasing since 2012, suggesting that the relevant authorities have recognized them as one of the most viable solutions to the environmental challenges facing the world today. Although the rate of growth might not seem to be as rapid as one might anticipate, these sources are now highly competitive with non-renewable sources due to technological advancements and economies of scale [4].

Solar energy is particularly important in the transition to a sustainable energy future. It provides a nearly infinite supply of renewable energy by using photovoltaic cells (PV) to capture the power of the sun. Technological advancements have significantly improved the efficiency and cost-effectiveness of solar installations. For example, NREL reports that the efficiency of commercial solar panels has increased from approximately 15% to more than 22% in recent years [5] and the cost of solar power has fallen, making it one of the cheapest sources of new electricity generation [6]. On a similar note, the latest edition of ITRPV also predicts the growth rate of efficiencies of different types of silicon-based solar PV from 2023 to 2034 as shown in the figure 1.2 below. It can be seen that the stabilized cell efficiency, which was in the range of 23.5% to 25% in 2023 has been predicted to increase to as high as 31% for certain tandem-based PV cells in 2034. This prediction has been devised based on a historical year on year learning rate, starting from around 9 percent in 1980 to about 15% in 2011 and 21.2% over the next decade [7].

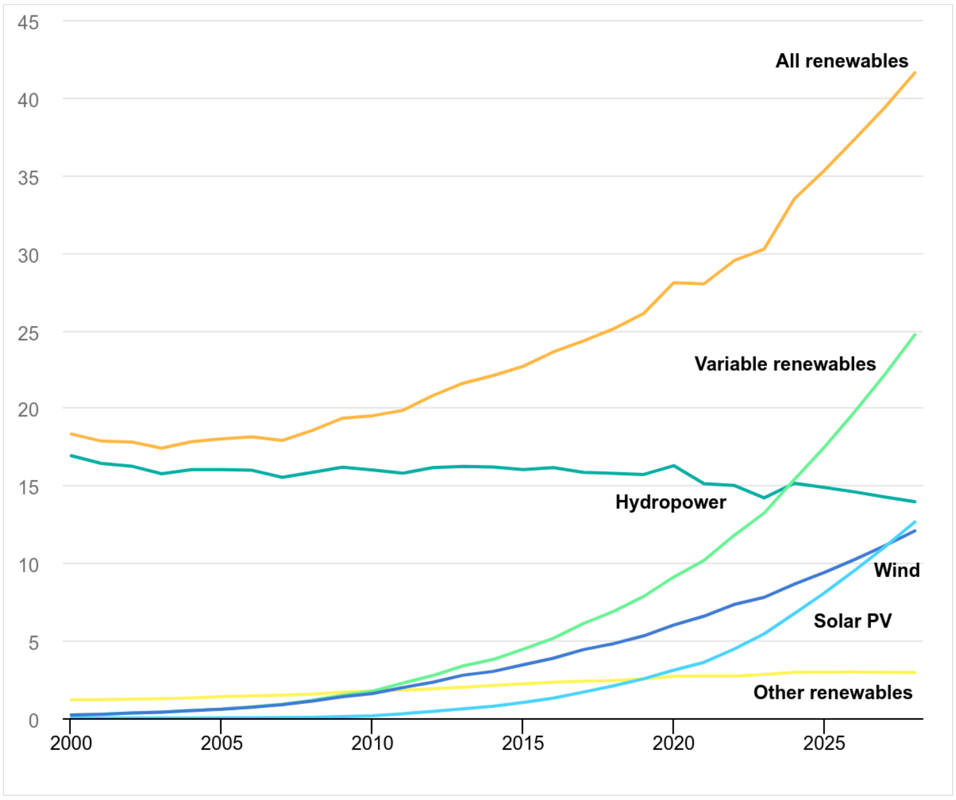

Figure 1.1: Increase in different renewable energy generation by percentage [3]

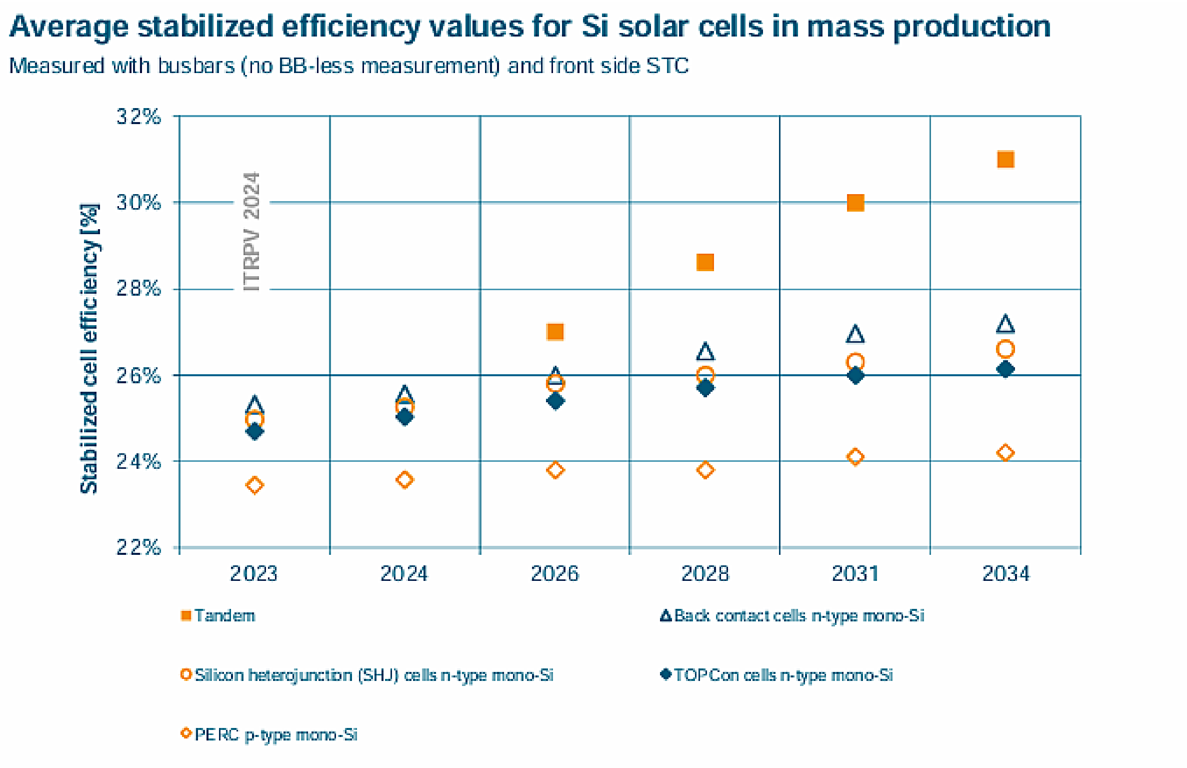

Figure 1.2: Average cell efficiencies' prediction [7]

.

However, there are many process steps involved in harnessing solar energy, starting from raw material extraction, photovoltaic cell and module manufacturing, transportation involved and more. All of these steps are not completely devoid of emissions. To continue progress toward a more sustainable future, it is important to account for all the emissions and environmental impacts that might occur at any stage of a photovoltaic system's lifetime. This is why a Life Cycle Assessment(LCA) of the PV technology is important. An LCA study helps in informing the actual environmental impacts that occur throughout the lifetime of a product, and helps identify the hotspots and areas for improvement, ensuring that technological improvement can make these PV technologies more sustainable and environmentally friendly.

Therefore, the goal of this study is to analyze the Life Cycle of one such particular PV technology, Silicon Heterojunction (SHJ) solar cells and modules. SHJ technology has been chosen for this study because of its increasing market interest, driven by the high achievable efficiencies (as can been seen in figure 1.2) and better performance in low-light conditions [8]. These benefits not only improve the yield but also make this photovoltaic technology acceptable for a wide range of climatic conditions. As SHJ modules gain the attention in the PV industry, analyzing their impacts on the environment over the life time becomes essential to optimize their role in the shift towards sustainable energy.

1.1. Evolution of PV

Since its introduction, the market for PV Technology has undergone substantial growth and transformation. The first practical photovoltaic cell was invented at Bell Labs in 1954, which marked the beginning of the development of PV technology [9]. Although, these were related to high cost and limited reachable efficiency, the vast potential of PV technology has resulted in constant improvements in materials and manufacturing processes to improve the cell structure, which in-turn helps achieve a higher level of efficiency and generate an increasing amount of energy.

In the early 2000s, the cumulative global PV market gained momentum, thanks to the growing environmental consciousness, subsidies, and governmental policies[1]. An exponential growth was seen in the market. The global market rose from around 100 GW in 2012 to exceeding 945 GW by 2021 [10]. The cumulative PV installations further increased to 1,581 GW by the end of 2023 as reported in the Photovoltaic Report, ISE [11]. The compound annual growth rate of PV installations has been reported at almost 26% from 2013 to 2023 [11]. This rapid growth was facilitated by major advancements in solar cell technologies like, the switch from traditional aluminium back surface field (Al BSF) solar cells to more advanced technologies such as Passivated Emitter and Rear Cells (PERC), and in recent years to TOPCon[12]. It can be seen from the figure 1.3 below how the market share has changed over the years, and the n-type c-Si solar cells are predicted to be dominant in the coming decade. [1]

[1] The sales report in [13] and [14] suggest that the sales of TOPCOn have been increasingly high in 2023 and in the first half of 2024, taking over the the sales of PERC. This suggests that the market share and anticipated growth rate may be more faster than the one shown in figure1.3 at industrial level.

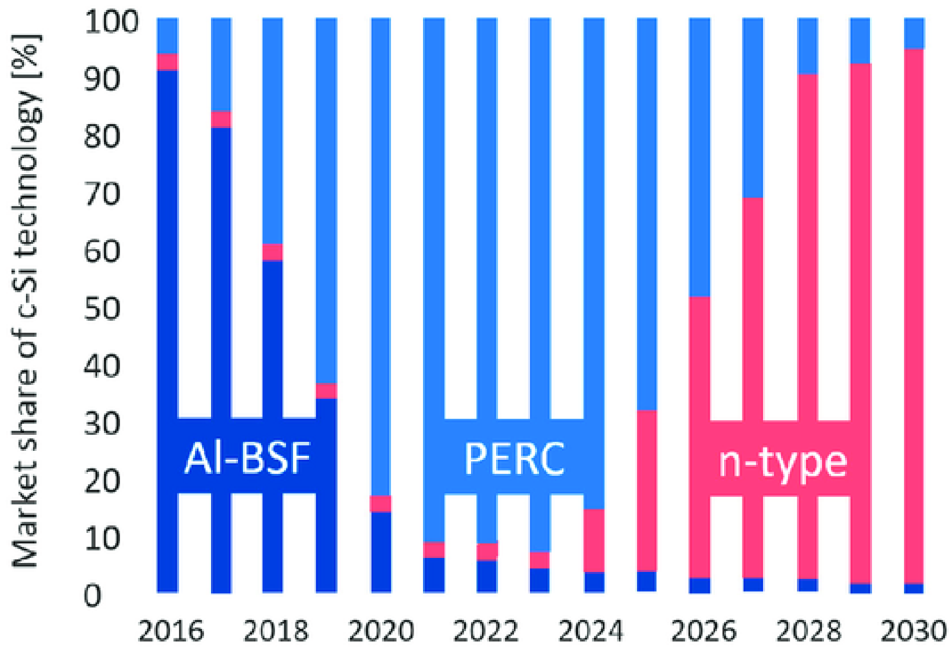

Figure 1.3: Market Share trend for PV technologies over the years, with future projections [15]

The figure 1.4 below shows the increase in PV technologies' global annual production volume over the year in gigawatt peak (GWp). It represents the scale of expansion the PV industry has seen across the globe, and especially in Asia, in recent decades, particularly after 2020. Even for Europe, the total cumulative PV installations have amounted for almost 20% [11].

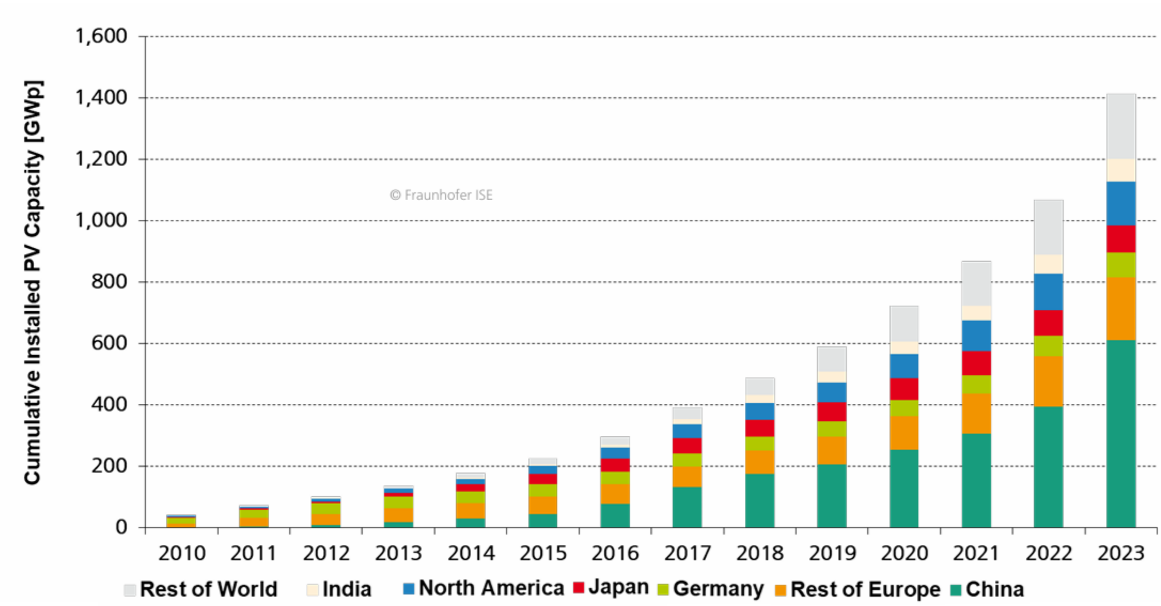

Figure 1.4: Global Annual Production of PV[11]

1.2. SHJ-Cell type

Silicon heterojunction (SHJ) solar cells are a recent development in the industrial photovoltaic (PV) technology that combines the features of thin-film and crystalline silicon technologies. A crystalline silicon wafer is sandwiched between layers of amorphous silicon in SHJ cells, which reduces recombination losses and passivates the surface [16]. SHJ cells demonstrate exceptional performance and have shown the potential to attain high efficiencies as a result of their distinctive structure. When compared to traditional c-Si solar cells, the manufacturing process for SHJ cells is relatively simple and straightforward. It takes place at a relatively lower temperature ($180°$C $- 200°$C), which can result in a reduction in production cost and could even reduce environmental impacts [17]. LONGi held the world record for the highest recorded efficiency of SHJ cells at 27.09%, making them one of the most efficient solar cell types available [18] . This cell is Back Contact type, where all the electrical contacts are placed at the back end of the cell, thereby eliminating the shading losses of the front metal grid and thus enhancing the light absorption and overall cell efficiency. In tandem solar cell applications, SHJ cells act as effective bottom cells. They work alongside top cells with higher bandgaps to capture a broader range of the solar spectrum, thus enhancing the overall conversion efficiency[19].

The high levels of efficiency that can be reached and the progress made in technology have shown that SHJ cells can be widely used [20]. All these factors have helped SHJ technology gain significant attraction in the PV market [12]. These cells are an attractive option for future large-scale PV systems and an essential focus for current and future studies in solar energy due to their high efficiency and ease of manufacturing (especially because of the low temperature operation). The increasing interest from industries and relevant authorities is evident from the increasing market share of SHJ. This technology is already expected to acquire around 10% of the global market share by the end of 2024 and the projections show further growth in the coming decade, as illustrated in figure 1.5 [21].

However, there are still aspects that need to be analysed before this PV technology can be deemed truly environmentally friendly. For instance, the production of SHJ solar cells, as for any other c-Si PV technology, may not be entirely free of adverse environmental effects. Raw material extraction, manufacturing processes, and end-of-life disposal are critical stages in the lifecycle of these products that can contribute to greenhouse gas emissions, resource depletion, and other environmental burdens that are not considered when only the use phase is studied. Moving from the concept of renewable to sustainable solar PV requires more than just capturing the sun's limitless energy; it demands that all phases of solar panel manufacturing, installation, and disposal are conducted in an environmentally friendly, cost-effective, and socially fair manner. This holistic approach guarantees that solar energy will continue to be a genuinely sustainable resource for generations to come.

Therefore, this study aims to conduct a comprehensive Life Cycle Assessment (LCA) of a PV system consisting of SHJ modules. It is essential to identify the critical areas that are having a negative impact on the environment and to formulate strategies to reduce or eliminate these impacts. By doing so, it can be assured that SHJ technology is not only cost-effective and efficient, but also in accordance with global sustainability targets, such as those stated in the Paris Climate Agreement, which aims to keep the global temperature rise well below 2°C [22].

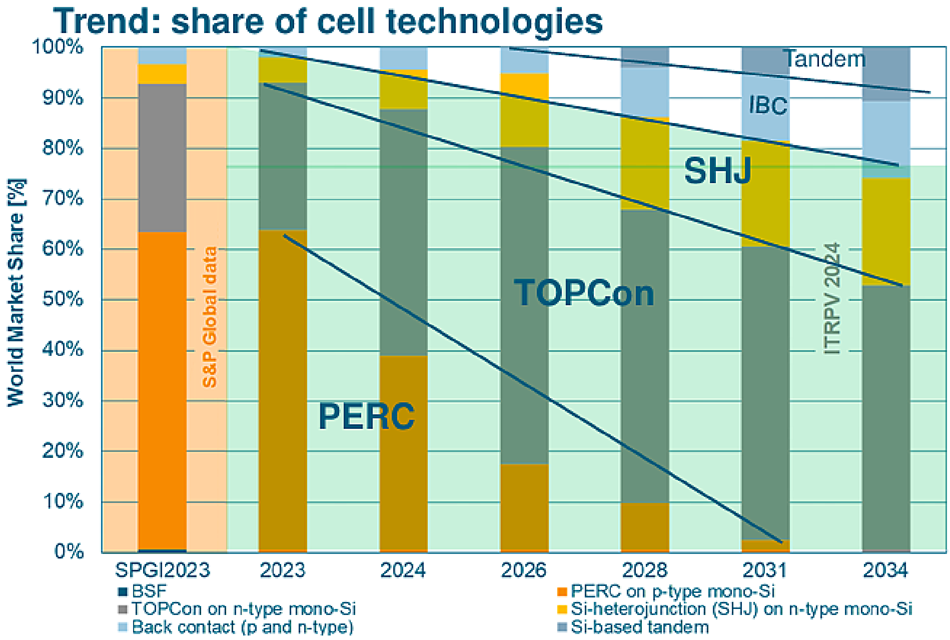

Figure 1.5: Market Share Trends of Different PV Cell Technologies (2023-2034) [21]

1.3. Life Cycle Assessment

A Life Cycle Assessment (LCA) is an effective method for evaluating the environmental impact of products such as PV panels. LCA is a comprehensive approach that involves the quantification of material and energy flows, thereby assessing the full environmental impact of a product over every stage of its life, from the extraction of raw materials to disposal. The entire lifecycle of a product can have an impact on the environment in a variety of ways, including resource depletion, human health, and ecosystem degradation [23]. LCA offers a comprehensive framework for evaluating these impacts, thereby facilitating the development of environmentally sound products and processes.

LCA can be implemented for a variety of purposes, including the development of new products with reduced environmental impacts and the optimisation of existing products by reducing material and energy consumption during production or by selecting sustainably sourced materials. The insights obtained from LCA can be used to identify the parts of the process that have the greatest environmental impacts, thus directing decision-making to create more sustainable products and assisting in the achievement of carbon footprint reduction objectives.

Furthermore, LCA results can be employed for marketing purposes, demonstrating a product's reduced environmental impact in order to attract investors. It also functions as a comparative instrument to identify products with the least environmental impact, thereby facilitating decision-making processes in both government and industry [24].

The importance of conducting Life Cycle Assessments (LCA) for renewable technologies has become increasingly evident in recent decades and has grown significantly in recent years. This is primarily due to the recognition that the adoption of more sustainable technologies and the optimisation of energy production processes are both necessary for the purpose of meeting established emission standards. For instance, while solar energy is considered a highly sustainable solution, the production and transportation of solar panels can have substantial environmental impacts. If these panels are manufactured in one part of the world and transported using non-renewable fuel sources, the overall emissions may not be minimised, highlighting the need for a holistic approach to sustainability. LCA offers a thorough examination of the entire life cycle of a product, including the extraction of materials, production processes, use phase, and end-of-life administration. This comprehensive evaluation assists in the identification of areas that require enhancement, thereby guaranteeing that renewable technologies are as sustainable as possible throughout their entire life cycle.

Reliability, consistency and comparability are important factors for any LCA studies. For this, the International Organisation for Standardisation (ISO) has developed standards to ensure a structured methodology to be followed to carry out LCAs. The two most important standards are ISO 14040 and ISO 14044. ISO 14040 describes the principles and framework to be followed for an LCA. The four stages, that is, the objective and scope, the life cycle inventory, the life cycle impact assessment, and the interpretation, are defined under this standard. The requirements and guidelines for LCA are specified in ISO 14044. This includes the preparation, conduct, and critical review of the LCA study. These standards are implemented to ensure that the LCA is comprehensive, transparent, and scientifically robust [25].

1.4. Report Structure

This report consists of 6 chapters. chapter 2 defines problem statement for this study. It consists of the research questions along with the objectives that will be answered and explored along the study.

chapter 3 is about the literature review that was conducted in order to successfully complete this study. It begins with an overview of the SHJ solar cells, followed by the concepts and phases of LCA. It also presents discussions about different LCA softwares available to conduct the analysis and the detailed conceptual understanding for prospective LCA, which means the LCA for future scenarios. Finally, a section on LCA results from previous studies are presented, which shows the emission values of different relevant studies that have been conducted in the past, which sets a good base for comparison of results of this study, to conclude the literature review.

chapter 4 is about the methodology followed in the study for the LCA of SHJ solar cells based PV system, starting with defining the goal and scope of this study. Then the Life Cycle Inventory is discussed, where all the process steps are defined and articulated along with the details for the amount of each and every step that consumes energy in one way or the other. For the inventory, the focus has been kept on the cell manufacturing process and not on the module and BoS manufacturing. Once the created inventory has been discussed, the next section focuses on the implementation of the collected datasets to the LCA software to get the results.

chapter 5 is about the results and discussions, where the impact assessment is carried out. It represents the results for some of the most important imapct categories, and discussions are presented for the important observations that may have been the reasons for the results. A sensitivity analysis is also conducted, where certain parameters are altered by the support of reasonable arguments, and the results are compared to the original results.

Finally in chapter 6, a conclusion is presented relative to the overall study conducted and the results obtained. The final section is for future work, where the possibilities of improvements and developments that can be adopted in the future work related to this study are shown.

2
Goal and Scope

2.1. Problem Statement

The photovoltaic (PV) technology has been significantly advanced by Silicon Heterojunction (SHJ) solar cells, which combines the properties of crystalline silicon with the superior passivation properties of thin-film technologies. This combination results in high-efficiency solar cells. In addition to high achievable efficiencies, this photovoltaic technology also has shown the potential of reduced costs [26]. Another PV technology that exhibit similar benefits is the TOPCon [27]. Owing to such benefits, it is imperative that concerned authorities want to switch from the current dominant PV technologies, like PERC to these upcoming technologies at largest scale possible.

However, the production and implementation of SHJ solar cells may have significant environmental implications, despite their potential for a reduced environmental impact during operation. The extraction of raw materials and energy utilizing manufacturing processes may contribute to the depletion of resources and the emission of greenhouse gases. In order to overcome these concerns, it is imperative to conduct an extensive Life Cycle Assessment (LCA) to assess the overall environmental performance of PV system consisting of SHJ solar cells and modules.

Therefore, the goal of this study is to conduct an LCA of a PV system consisting of SHJ solar cells and modules produced in the Netherlands, assessing both current production processes and prospective scenarios for the year 2035. The scope of this study is defined by:-

- **Geographical Focus:** The production processes assessed in this study are based in the Netherlands. This means that the Dutch electricity mix will be incorporated in the production process. It is also understandable that not all the prerequisite material and components can always be produced in the Netherlands and therefore for such cases, the specific components are assumed to have been produced at a different part of the world, and then transportation to the Netherlands have been considered. The installation and usage of the PV system is also based in the Netherlands.
- **Time Frame:** The study encompasses a comparative analysis of the current LCA, which is the 2024 scenario, and prospective LCAs (pLCA) for the year 2035.
- **Technological Coverage:** The analysis includes the environmental impacts of the complete PV system, including cells, modules, and the Balance of System (inverters and mounting structure), but the emphasis remains on the SHJ cell production.
- **Environmental Assessment:** By employing life cycle assessment techniques, this research investigates the environmental impacts across multiple categories, including global warming potential and eco-toxicity.
- **Scenario Analysis:** Different Integrated Assessment Models (IAM) and Shared Socioeconomic Pathways (SSP) are used to project and analyze future environmental impacts.

2.2. Research Question and Objectives

The most important research questions that will be addressed by this study are:

1. **Which impact categories make the most significant contribution to the overall environmental impact assessment?**
   This question aims to identify which environmental impact categories (e.g., global warming potential, eco-toxicity) are most significantly affected by the production and lifecycle of SHJ PV system.
2. **Which activities in the cell and module manufacturing process have the highest contribution in different impact categories?** This question seeks to pinpoint specific stages or components within the manufacturing process that contribute the most to various environmental impacts.
3. **In what ways do the various IAM and SSP scenarios differ in terms of their environmental impacts for the year 2035?** This question evaluates how future scenarios, modeled through different IAMs and SSPs, affect the environmental impacts of SHJ solar cells, providing information on potential future developments and challenges.
4. **How does changing certain parameters affect the overall impact assessment, for both current and future LCA scenarios?** This question concerns the sensitivity analysis of the LCA results to variations in crucial parameters (such as material consumption) in order to comprehend how different assumptions affect the environmental impact assessment. This also entails the reasons for the inaccuracy or unavailability of the data for analysis.

Data Collection:-
For the collection of datasets (although a crucial step for an LCA) the most recent industrial data is difficult to collect. This is because of the industrial norms,and policies pertaining to the confidentiality of the data. Therefore in this work, the datasets have been accumulated from the limited available open source data and from those available from the research organizations such as IEA and ITRPV. In this way, it has been ensured that the data being used is validated from recognized organizations and research institutes.

2.3. Implication of the Study

The findings from this study will help in identifying critical areas that significantly impact the environment and possibilities to reduce or eliminate these impacts. It will also answer the question if the SHJ based PV system, in the current state, is environmentally friendly or not. By understanding the full life cycle environmental impacts of SHJ solar cells and modules, this research will contribute to the development of more sustainable production processes to assist the large scale sustainable implementation of this PV technology.

3

Literature Review

Before conducting the Life Cycle Assessment (LCA) for a PV system consisting of Silicon Heterojunction (SHJ) cells and modules, it is essential to thoroughly research the existing knowledge regarding the manufacturing processes, market availability, and the methodology for performing an effective LCA.

For SHJ, various manufacturing techniques exist, such as the addition of new layers to improve cell efficiency. Additionally, the feasibility of large-scale production needs to be explored. This chapter will discuss some of the details about SHJ cells and its structure. This background will help in selecting a specific cell structure for this study in the subsequent chapter.

Following this, a discussion on LCA will be presented, starting with a clear definition and outlining the steps involved. Finally, different possible scenarios, including Integrated Assessment Models (IAM) and Shared Socioeconomic Pathways (SSPs), will be discussed. This will facilitate the prospective LCA (pLCA) and aid in selecting future scenarios for the analysis.

3.1. Silicon Heterojunction PV Technology

3.1.1. SHJ solar cells

Silicon heterojunction solar cells belong to the c-Si family of photovoltaic technologies. The SHJ cells are a significant advancement in the PV industry, as they combine the high efficiency of crystalline silicon cells with the exceptional passivation properties of thin-film technologies. The absorber layer of SHJ cells is a crystalline silicon wafer that is sandwiched between thin layers of amorphous silicon. This is the fundamental structure of the cell. This distinctive configuration significantly decreases recombination losses at the surface, thereby improving the overall efficiency of the cell [28].

In comparison to photovoltaic cells like Al BSF and PERC, which also use thin-film layers for passivation, the SHJ solar cells possess benefits, such as a lower temperature coefficient, improved performance in low-light conditions, contact passivation, and increased efficiency [29]. These advantages render SHJ cells more appropriate for a diverse array of environmental conditions. SHJ cells are expected to acquire a substantial market share in the years ahead, as indicated by the International Technology Roadmap for Photovoltaic (ITRPV) data (figure 3.1)[21]. SHJ cells occupied approximately 5% of the market in 2023 and is expected to acquire about 20% of the market by 2034, which is indicative of their increasing significance and widespread adoption in the PV industry [21]. The development of SHJ cells commenced in the 1990s and has since undergone substantial evolution, with ongoing enhancements resulting in increased cost-effectiveness and efficiency. In the solar industry, SHJ cells are currently acknowledged for their capacity to outperform the other silicon-based technologies, making them a promising candidate for widespread adoption [30].

There has been an annual improvement in SHJ cell efficiency, which has increased by about 0.5-0.6%. Additionally, the intrinsic characteristics of SHJ cells make them ideal for serving as the bottom cell in tandem solar cell setups [31], bolstering their attractiveness. While current findings indicate that TOPCon cells may also be viable for tandem uses, the distinct benefits of SHJ cells, including their superior performance compared to other silicon-based technologies, make them a strong contender for future photovoltaic systems.

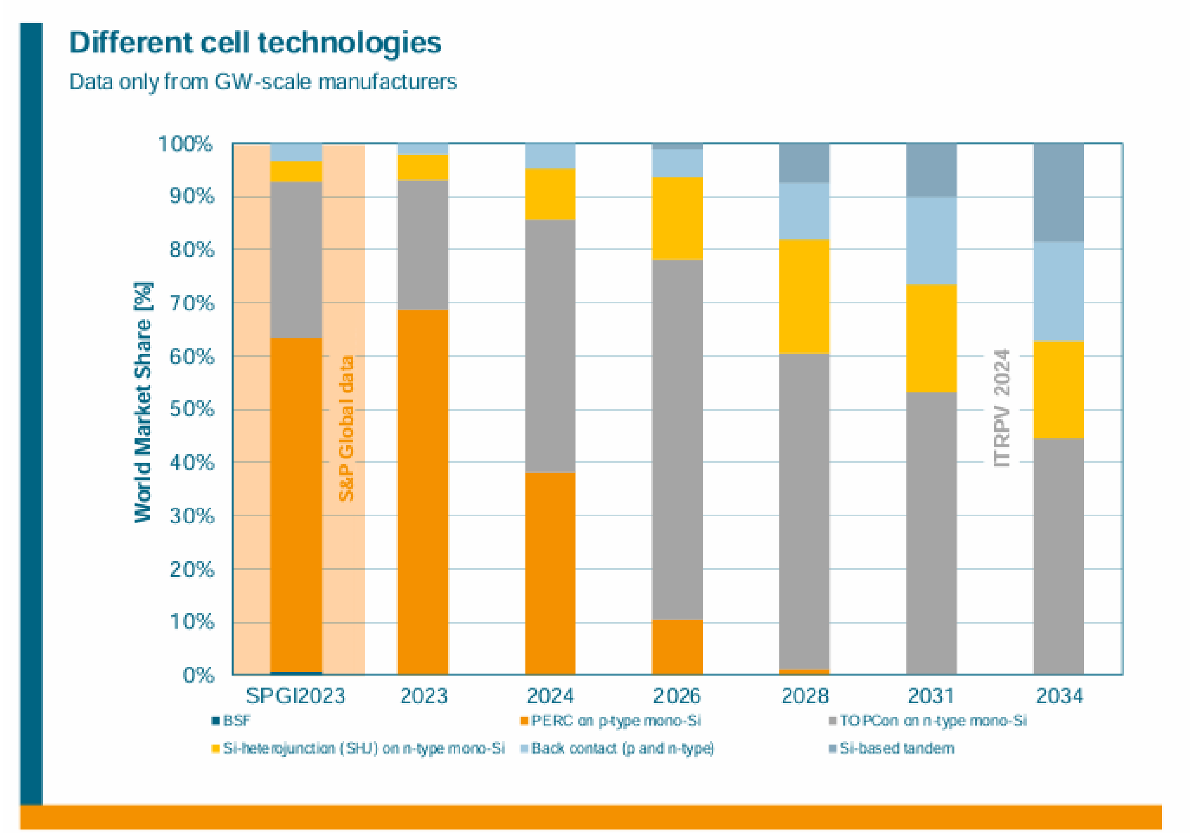

Figure 3.1: Market Share Trends of Different PV Cell Technologies (2023-2034) [21]

3.1.2. Evolution of SHJ

In the early 1990s, pioneering research initiated the development of Silicon Heterojunction (SHJ) technology. Initially, SHJ cells achieved high efficiencies by employing a straightforward structure that included a crystalline silicon wafer and thin amorphous silicon layers. Sanyo (now Panasonic)'s foundational work in the late 1990s and early 2000s was a significant milestone, as their HIT (Heterojunction with Intrinsic Thin layer) technology achieved efficiencies exceeding 20% [28]. This innovation illustrated the capacity of SHJ cells to surpass conventional silicon-based technologies.

The efficiency and performance of SHJ cells have been further optimised by researchers over the past few decades by focusing on a variety of aspects. The introduction of intrinsic hydrogenated amorphous silicon layers for improved passivation and the use of transparent conductive oxides (TCOs) to enhance electrical conductivity have been critical innovations. Continuous research is being conducted to achieve even higher efficiency levels, as these advancements have allowed SHJ cells to achieve efficiencies exceeding 26% [32]. Advanced materials and designs are integrated into the cutting-edge SHJ technology to optimise reliability and efficiency. For example, the utilisation of tandem cells and multi-junction configurations, in which SHJ cells are coupled with other high-efficiency cells such as perovskites, has demonstrated the potential to achieve even higher efficiency rates [33]. Furthermore, there is ongoing research to create innovative passivation techniques and materials, including silicon carbide (SiCx) and silicon oxide (SiOx), which improve the overall performance of cells and further reduce surface recombination losses[32]. However, most of these structural advances are still naive and are not yet being used on an industry scale. Figure 3.2 below shows the one of the basic structures of an SHJ cell, and this is most widely used structure in today's market.

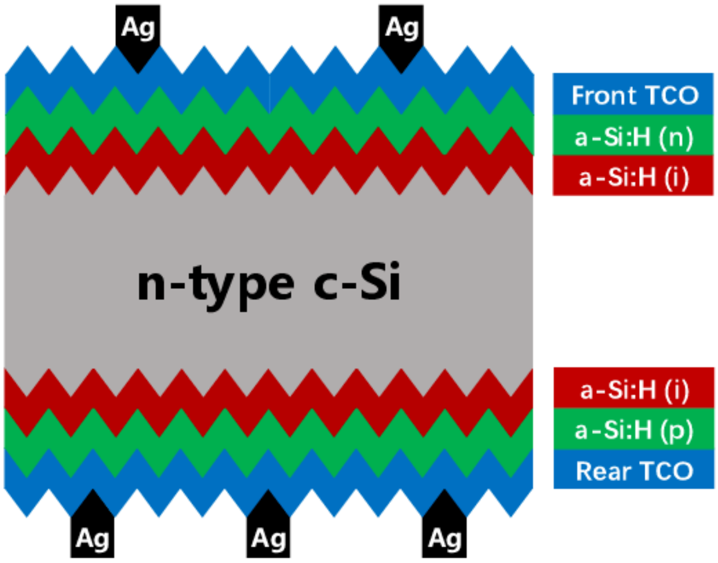

Figure 3.2: Silicon Heterojunction cell structure [34]

3.1.3. Cell Structure

The design of Silicon Heterojunction (SHJ) solar cells is distinctive, as it integrates amorphous silicon layers with crystalline silicon to attain exceptional performance and efficiency. Following is a comprehensive analysis of the structure of SHJ solar cells [35]:

1. **Crystalline Silicon Wafer**: This superior n-type crystalline silicon wafer acts as the main light-absorbing layer and serves as the core of the SHJ cell. In SHJ cells, n-type wafers are employed, which exhibit greater resistance to light-induced degradation and feature extended carrier lifetimes [36]. Consequently, this results in better performance and increased longevity for solar cells, while also allowing SHJ cell manufacturing at relatively lower temperatures.
2. **Intrinsic Amorphous Silicon Layers**: The undoped (intrinsic) hydrogenated layers of amorphous silicon functions as buffer, thereby improving surface passivation and decreasing carrier recombination. This is applied to both the sides of the n-type wafer.
3. **Doped Amorphous Silicon Layers**: Doped amorphous silicon layers are applied to both the sides. One side is doped with phosphorus, and the other with boron. These layers offer exceptional surface passivation and also act as electron- and hole-transfer layers thereby substantially mitigating the recombination losses at the interface between the amorphous and crystalline silicon.
4. **Transparent Conductive Oxide (TCO) Layers**: These layers are typically composed of materials such as Zinc Oxide (ZnO) or Indium Tin Oxide (ITO), which facilitate the transmission of electricity while permitting the passage of light. This layer is essential for the collection and transportation of charge carriers that are produced by the cell to the metal contacts and is applied on both the sides of the wafer.
5. **Metallization contacts**: These layers are typically composed of metals, such as silver, and serves as a pathway for the collected charge carriers to exit the cell. The electrical circuit of the cell is completed by these layer.

3.2. Life Cycle Assessment

A products life cycle is defined by the following 5 stages as depicted in figure 3.3 [37]:

1. Raw Material Extraction
2. Manufacturing & Processing
3. Transportation

4. Usage & Retail
5. Waste Disposal

Figure 3.3: Life stages of a product [37]

A Life Cycle Assessment can be conducted incorporating some or all of these life cycle stages, according to the need of the analysis. Figure 3.4 shows the most common life cycle models that can be formulated using these stages:-

1. **Cradle-to-grave**: Assessing a product's effects over all five stages of its lifecycle is known as cradle-to-grave. This approach starts with obtaining raw materials (the cradle) and concludes with the disposal of the product (the grave).
2. **Cradle-to-gate**: A cradle-to-gate assessment evaluates a product only until it leaves the factory and is prepared for shipment to the consumer, thus leaving out the usage and disposal phases. This form of analysis can significantly streamline an LCA, providing faster insights, especially into internal processes.
3. **Cradle-to-cradle**: Cradle-to-cradle is often referenced within the Circular Economy framework. It transforms the cradle-to-grave method by substituting the disposal phase with a recycling process, enabling materials to be reused in new products, thereby "closing the loop." Consequently, it is also referred to as closed-loop recycling [38].

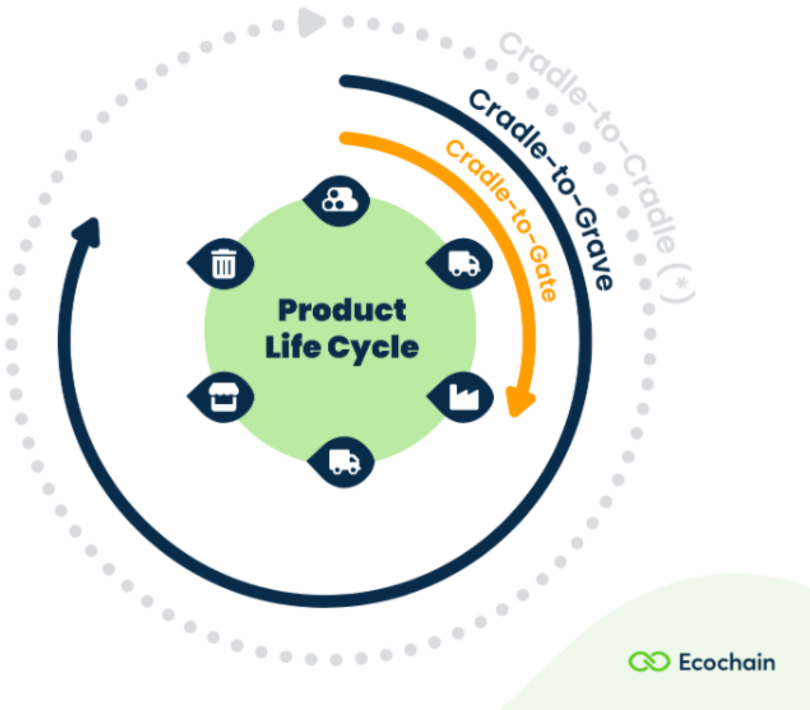

Figure 3.4: Types of LCA [38]

The ISO14040 and ISO14044 standards serve as the guidelines for conducting a Life Cycle Analysis (LCA). According to these standards, an LCA includes four main phases, as illustrated in figure 3.5: the goal and scope definition phase, the life cycle inventory (LCI) phase, the life cycle impact assessment (LCIA) phase, and the interpretation phase[38].

3.2.1. Phase 1: Goal and Scope

Goal and Scope Definition:
In the first phase of an LCA, the goal and scope of the study are established. This stage involves defining the study's aim, the audience it targets, and the planned objective of the results. The goal sets the purpose of the LCA and what it seeks to achieve. Reasons for undertaking an LCA could include comparing the environmental impacts of different products, identifying significant production processes to improve a product, or informing policy-making. The target audience might be government entities, NGOs, or industry participants[39].

The scope outlines the product system subject to examination, covering its functions, functional unit, and system boundaries, as illustrated in Figure 3.6. The functional unit is a crucial component as it acts as a benchmark for comparing inputs and outputs. It allows for performance quantification and ensures that comparisons with other LCA studies are valid. The system boundary specifies the processes included in the study, ensuring transparency of assumptions and the extent of analysis. For example, an LCA could be a cradle-to-grave assessment, which includes the entire lifecycle of the product from raw material extraction to disposal, or a cradle-to-gate assessment, which covers processes up to the factory gate, excluding use and end-of-life stages.

When outlining the scope of the study, it is essential to define its geographic and temporal limits, as these factors can significantly influence the outcomes. The level of detail depends on both data availability and the study's objectives. The life cycle starts with the procurement and processing of materials for production, moves through the product's usage phase, and ends with its disassembly and disposal [37].

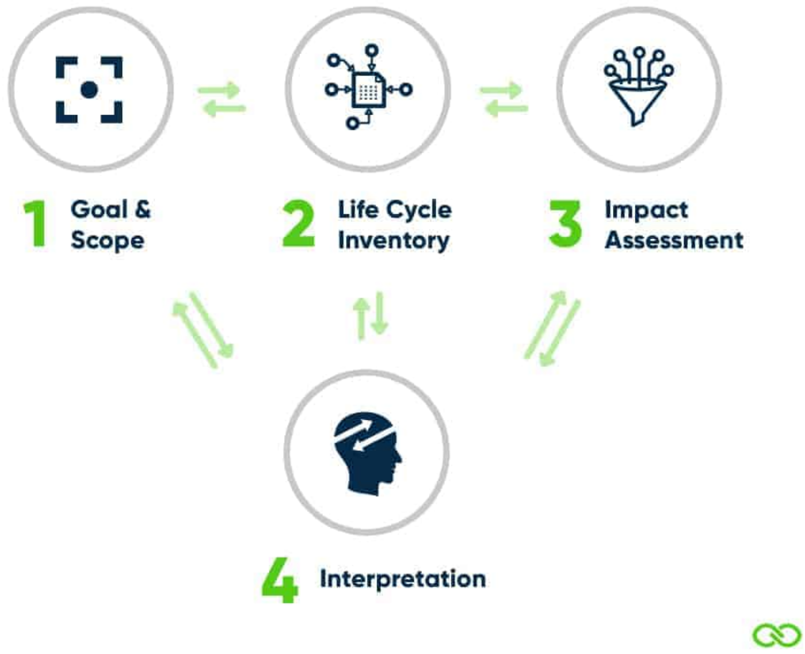

Figure 3.5: Phases of LCA [38]

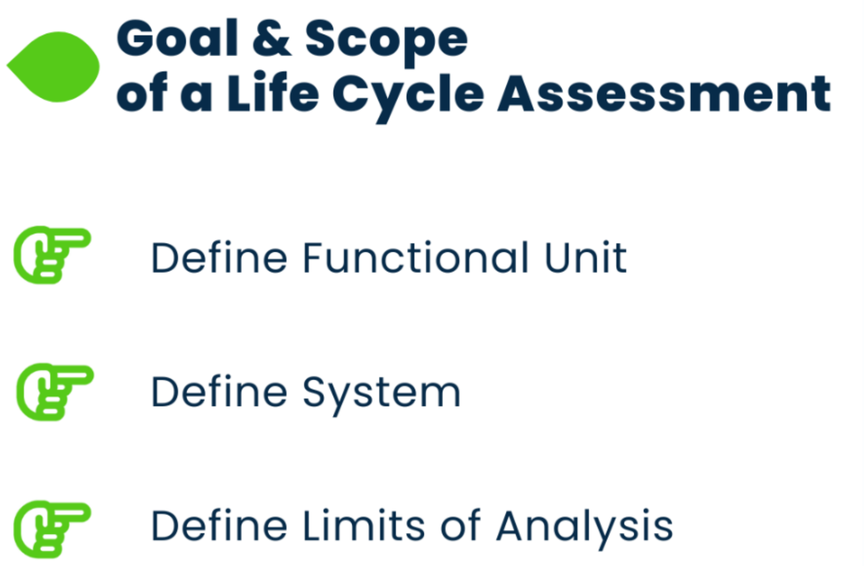

Figure 3.6: Defining Goal and Scope of an LCA [38]

3.2.2. Phase 2: Life Cycle Inventory

The second stage of an LCA is the life cycle inventory (LCI) analysis. In this stage, a comprehensive list of key inputs and outputs for the product system is created throughout its life cycle. Inputs include all energy-consuming processes such as raw material extraction and other resources, whereas outputs encompass waste products and emissions to air, water, and soil. Every unit process within the system's boundary is assessed through inventory analysis.

The LCI phase involves extensive data handling and requires the collection and verification of information. Data sources include production facilities, academic publications, databases such as ecoinvent, and estimations. Assessing the validity and quality of this data is essential, considering its technological and geographical relevance. The data collection process is usually repetitive, with evolving requirements as more details about the system are discovered.

A distinction is made between foreground and background processes. Foreground processes are directly involved in the production of the product and occur within the system boundary. On the other hand, background processes, although they might lie outside the system boundary, supply inputs to the foreground processes. These include the production of energy and basic materials [40].

3.2.3. Phase 3: Impact Assessment

The third phase in the life cycle impact assessment (LCIA) evaluates the potential environmental impacts of the inventory data. The LCIA phase comprises several stages:

1. **Selecting Impact Categories:** The selection of relevant impact categories is guided by the study's goals and scope. Common categories include resource depletion, acidification, eutrophication, and global warming potential.
2. **Classification:** Inventory data are classified based on the chosen impact categories; for example, carbon dioxide emissions fall under global warming potential.
3. **Characterization:** This stage quantifies the impact contributions of various emissions to each category, such as determining the global warming potential of methane in terms of carbon dioxide equivalents.

The LCIA methodology chosen should align with the study's goals and scope. Various methodologies, such as CML, TRACI, or ReCiPe, offer different impact categories and characterization factors [41].

3.2.4. Phase 4: Interpretation

During the final phase of an LCA, known as the interpretation phase, the results of the LCI and LCIA are analyzed to draw conclusions and offer recommendations. This interpretation must align with the objectives and boundaries established in the study, and it should also take into account any assumptions made during the LCI phase as well as any limitations discovered throughout the analysis.

The main steps in the interpretation phase include:

- **Recognizing Key Issues:** Identify and prioritize the life cycle stages and processes that have the most significant impact on the environment.
- **Evaluating Results:** Examine the consistency, sensitivity, and comprehensiveness of the results. This step may involve conducting uncertainty and sensitivity analyses to validate the findings.
- **Drawing Conclusions and Making Recommendations:** Formulate conclusions on the product's environmental performance and suggest improvements or alternative strategies based on the assessment outcomes to reduce its environmental impact.

The interpretation stage ensures that the LCA provides decision-makers with straightforward and actionable insights, thereby guiding efforts towards more sustainable practices. [42].

3.3. LCA Softwares

The complex and comprehensive nature of LCA studies necessitates the use of sophisticated software tools that assist in the collection, analysis, and interpretation of data. Various LCA software tools are widely used in both industry and academia, each providing distinct advantages and features. Here are some of the most commonly used software:

1. **SimaPro**
   SimaPro is a widely recognized and frequently used tool for conducting LCA. It offers a user-friendly interface and a comprehensive range of features, making it ideal for detailed LCA studies. SimaPro supports multiple impact assessment methods, including ReCiPe, Eco-indicator 99, and TRACI, and integrates with extensive databases like Ecoinvent and USLCI [43].
2. **GaBi**
   GaBi software is a leading LCA tool used in sustainability and lifecycle engineering for products. It offers extensive modeling features and is supported by rich databases covering various sectors and industries. GaBi allows users to create detailed models and carry out comprehensive analyses of environmental impacts [44].
3. **OpenLCA**
   OpenLCA is a cost-free LCA software equipped with robust modeling and analysis capabilities. It connects with multiple databases, including ecoinvent, offering users a flexible and adaptable platform for conducting LCAs. OpenLCA is a preferred choice among researchers and practitioners who support open-source solutions [45].
4. **Umberto**
   Umberto is a versatile tool for life cycle assessment (LCA) and material flow analysis (MFA), allowing users to create, assess, and optimize production systems. It integrates LCA with economic and process data, providing a comprehensive solution to assess sustainability and enhance resource efficiency [46].
5. **Brightway 2.0**
   Brightway2 is a powerful, open-source LCA tool designed for advanced users seeking flexibility and customization. Written in Python, it facilitates the development of complex LCA models, integration with a range of tools, and comprehensive data analysis. The graphical interface provided by Activity Browser improves result interpretation [47].

The table 3.1 shows an overview of the comparison of different LCA softwares:

Feature	**SimaPro**	**GaBi**	**OpenLCA**	**Brightway2**
User Interface	User-friendly	User-friendly	Moderate	Advanced
Database Integration	Ecoinvent, USLCI	Ecoinvent, GaBi DB	Ecoinvent, ELCD	Ecoinvent, custom
Impact Assessment Methods	ReCiPe, Eco-indicator 99, TRACI	ReCiPe, CML, TRACI	ReCiPe, CML	ReCiPe, TRACI
Customization	Limited	Moderate	High	Very High
Cost	Commercial	Commercial	Free/Open-source	Free/Open-source

Table 3.1: Comparison of LCA Software[43][44][45][46][47]

3.4. Prospective LCA

3.4.1. Overview

To improve the quantification and comparison of LCA results, it is essential and advantageous to model future scenarios. These scenarios entail performing an LCA for a product over an upcoming period, such as a decade or 15 years or even beyond 20 years, by adjusting key parameters derived from significant estimations based on past data and expected future developments. This process also considers possible variations due to the adoption of different policies over time.

To achieve this, a prospective life cycle assessment (pLCA) is conducted. Prospective Life Cycle Assessment represents an innovative approach in LCA, aimed at assessing the potential future environmental impacts of products, technologies, or systems. Unlike traditional LCA, which focuses on current or historical data, pLCA incorporates future scenarios to predict and analyze environmental effects over an extended timeframe. This method facilitates more informed decision-making by anticipating changes in technology, market conditions, and regulatory landscapes. Including future scenarios in LCA is crucial for achieving long-term sustainability goals and making well-informed choices regarding new technologies [48].

pLCA commonly utilizes two types of cases: foreground and background system changes. Foreground system pertain to the particular technology or product under analysis and encompass anticipated advancements in technology, manufacturing techniques, and operational changes. In contrast, background system involve a wider spectrum of economic, social, and environmental elements that influence the context in which the product or technology operates. These aid in comprehending the interactions within the product system and external influences, thus providing a comprehensive outlook on possible future impacts.

3.4.2. Integrated Assessment Models

There are several instruments that can be used to simulate future scenarios. One such tool is Integrated Assessment Models (IAMs). The IAMs are used to study the link and interaction between human, technology and the eco-system. It is a tool that incorporates data from various sectors like energy, land use, economy, etc., and provides an in-depth understanding of the plausible effects of socio-economic and environmental progressions. This helps to evaluate the effectiveness of different policies and strategies, like the Paris Climate Agreement, that have been put in place to face the global challenges like climate change and sustainable development [49].

Integrated Assessment Models (IAMs) can be utilised across several sizes, including local, regional, and global levels. They employ a wide range of methodologies to simulate future developments. Each of these varied spectrums is classified as a distinct scenario, encompassing assumptions regarding technological advancement, economic fluctuations, and policy implementations. Through the comparison of various scenarios, Integrated Assessment Models (IAMs) assist in the identification of strategies to achieve long-term sustainability objectives and effectively address environmental concerns [49].

The models often include a range of modules that represent key components of the system being studied. For example, they may include detailed representations of energy systems, land use patterns, economic activities, and climate processes. By integrating these modules, IAMs can provide insights into the trade-offs and synergies between different policy objectives, such as reducing greenhouse gas emissions, promoting economic growth, and preserving natural ecosystems.

IAMs are widely used in international assessments and policy-making processes, including those conducted by the Intergovernmental Panel on Climate Change (IPCC) and various national governments. They play a crucial role in informing decisions about climate mitigation and adaptation strategies, as well as broader sustainability initiatives [49].

1. **IMAGE: Integrated Model to Assess the Global Environment)**: IMAGE is a comprehensive IAM designed to assess the complex interactions between human and natural systems, focusing on long-term environmental and sustainability issues. The model integrates various subsystems, including climate, energy, land use, and water, to provide a holistic view of the environmental impacts of different policies and development pathways. IMAGE operates on a global scale with regional detail, allowing for detailed analysis of regional and global environmental changes. The model incorporates data on demographics, economic development, technological advancements, and policy measures to simulate future scenarios. These scenarios help in understanding the potential outcomes of different strategies for achieving sustainability goals, such as reducing greenhouse gas emissions, preserving biodiversity, and managing natural resources. IMAGE is widely used in environmental research and policy-making to explore the implications of various socio-economic and environmental changes on global sustainability [50].
2. **REMIND (Regional Model of Investments and Development)**: REMIND is an IAM that combines macroeconomic growth, energy system dynamics, and climate change to evaluate long-

term energy strategies and their environmental impacts. The model integrates detailed representations of the global economy, energy markets, and climate system to provide insights into the trade-offs and synergies between economic development and climate mitigation. REMIND operates on a global scale with detailed regional resolution, allowing for the analysis of region-specific policies and their global implications. The model considers various factors, such as technological progress, resource availability, policy interventions, and behavioral changes, to simulate future energy pathways and their environmental impacts. REMIND is particularly useful for assessing the costs and benefits of different climate policies, such as carbon pricing, renewable energy deployment, and energy efficiency measures. By exploring a range of scenarios, REMIND helps policymakers identify robust strategies for achieving climate goals while ensuring economic growth and energy security [51].

3.4.3. Shared Socioeconomic Pathways

Shared Socioeconomic Pathways (SSPs) Shared Socioeconomic Pathways (SSPs) are scenarios used in climate research to explore different trajectories of societal development and their impacts on climate change mitigation and adaptation. Developed by the climate research community, SSPs provide a framework to analyze how global socioeconomic trends might influence greenhouse gas emissions and the capacity to address climate change. There are five distinct SSP narratives (figure 3.7), each describing a different pathway of societal development:

1. **SSP1: Sustainability (Taking the Green Road)**:
   SSP1 envisions a world that progresses towards sustainability, with an emphasis on inclusive development and environmental protection. Economic growth is balanced with social equity and environmental goals, leading to a reduction in resource use and emissions. This pathway assumes strong international cooperation and significant investments in green technologies and infrastructure [52].
2. **SSP2: Middle of the Road**:
   SSP2 represents a continuation of current trends, with moderate economic growth, technological development, and social progress. Inequalities and environmental challenges persist, but they do not worsen significantly. This pathway assumes that incremental policy changes and technological improvements are implemented to address climate issues without major societal shifts [53].
3. **SSP3: Regional Rivalry (A Rocky Road)**
   SSP3 depicts a fragmented world characterized by regional conflicts, nationalism, and limited international cooperation. Economic development is uneven, and there is a focus on energy security and self-sufficiency, often at the expense of environmental protection. This pathway results in high emissions and limited capacity to address climate change due to regional disparities and lack of global collaboration [53].
4. **SSP4: Inequality (A Road Divided)**
   SSP4 describes a world with high levels of inequality, where a wealthy global elite drives technological advancements and economic growth, while large segments of the population are left behind. Environmental policies and investments are fragmented, leading to uneven progress in mitigating climate change. This pathway assumes significant disparities in access to resources and technologies, with substantial environmental and social consequences [53].
5. **SSP5: Fossil-fueled Development (Taking the Highway)**
   SSP5 envisions a world with rapid economic growth driven by the exploitation of fossil fuels. Technological advancements and high energy demand lead to significant increases in greenhouse gas emissions. This pathway assumes that climate change impacts are addressed primarily through technological solutions rather than reducing fossil fuel use. The focus is on maximizing economic output, with less emphasis on environmental sustainability [53].

Each SSP provides a distinct narrative that helps researchers and policymakers understand the potential impacts of different socioeconomic trajectories on climate change and the effectiveness of mitigation and adaptation strategies.

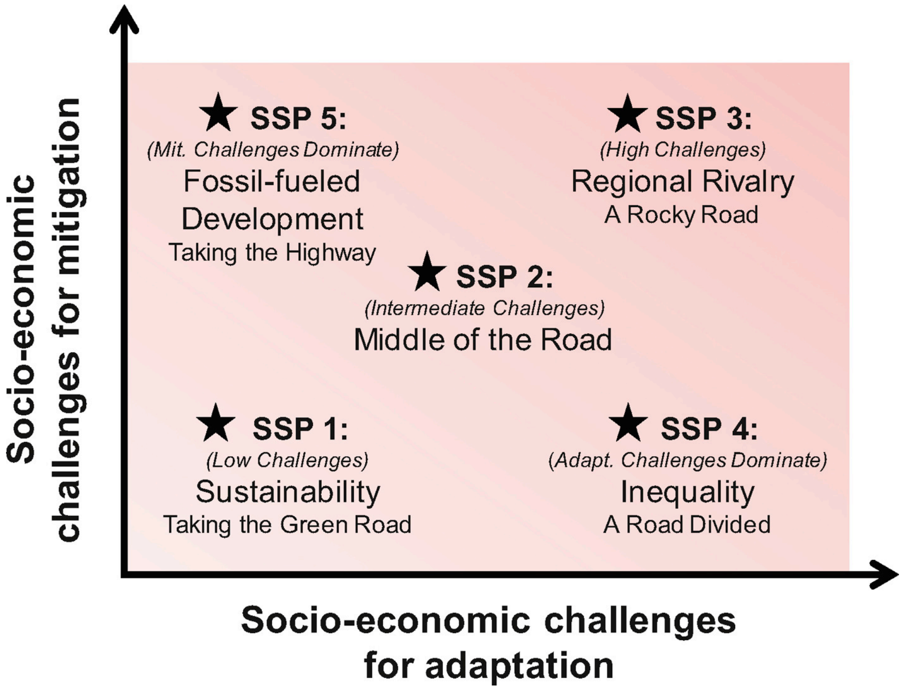

Figure 3.7: Different SSP scenarios [53]

3.4.4. Premise

Premise stands for ”PRospective EnvironMental Impact asSEment”. It is an open source python library which incorporates the ecoinvent database and Wurst library in order to make different transformations to the LCI database, as seen in figure 3.8 below. This helps in the implementation of prospective Life Cycle Assessments (pLCAs) that accurately represent anticipated technical and regulatory modifications in crucial industries such as electricity generation, manufacturing industries, and transportation [54].

The ”Premise” platform is compatible with many IAMs and produces prospective Life Cycle Inventory (pLCI) datasets that are in line with different socio-economic scenarios and climate objectives. This helps in the adaptability of databases and their ability to be exported to various LCA applications, thereby assisting the production of results compatible with LCA platforms. It is especially helpful for analysing industries that require a significant amount of materials and energy and are expected to undergo rapid developments as a result of stringent environmental regulations.

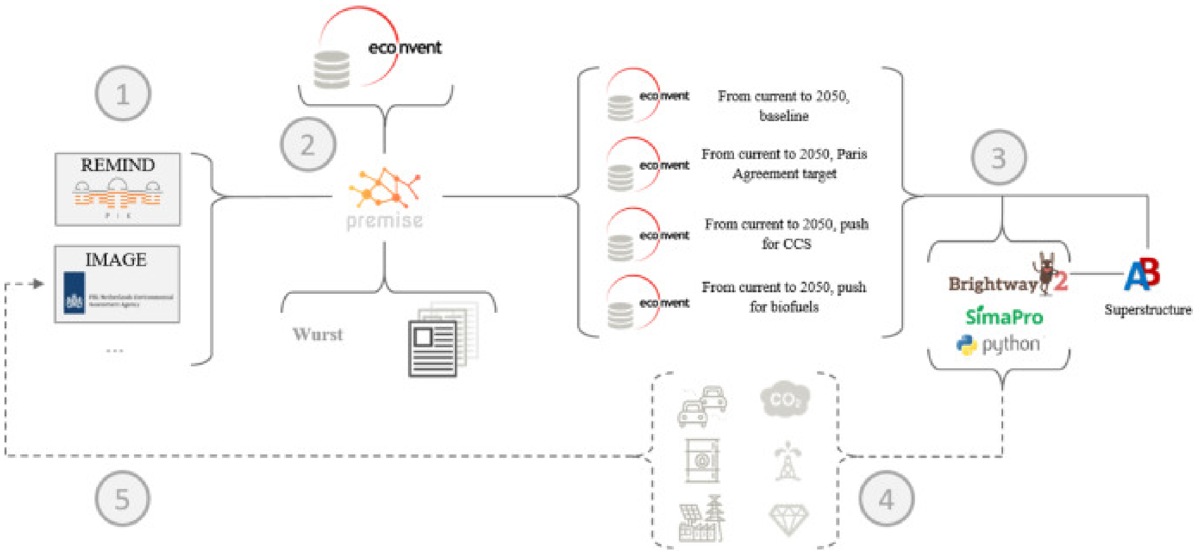

Figure 3.8: Workflow of premise [54]

3.5. Previous LCA studies

Over the past decades, numerous Life Cycle Assessments have been conducted for various photovoltaic technologies worldwide. For a thorough comparison for this Life Cycle Assessment (LCA) on Silicon Heterojunction (SHJ) PV technologies, table 3.2 shows the results for some up-to-date findings on the Global Warming Potential (GWP) from LCA studies on different PV technologies.

Technology	Emissions Recorded (GWP) g CO_2-eq/kWh	Module Efficiency	Year	Source
CdTe	26.5	18%	2019	IEA PVPS Task 12 [55]
CIS/CIGS	36.3	16%	2010	IEA PVPS Task 12 [55]
multi-Si, BSF	42.3	18%	2019	IEA PVPS Task 12 [55]
mono-Si BSF	42.5	19.5%	2019	IEA PVPS Task 12 [55]
PERC	25.7	21.16%	2024	IEA PERC [56]
PERC	12.5 (Without BoS)	21.75%	2023	S.I. Kommers [57]
SHJ	34.9	21.5%	2022	A. Barrou (CSEM) [58]
SHJ	35	18.4%	2014	A. Louwen [59]
SHJ	40.6(Without BoS)	22%	2014	M. Roffeis [60]

Table 3.2: GWP potential of different LCA studies

The table above represents the LCA results for one of the impact categories, climate change, in terms of g CO_2-Eq/kWh. The greenhouse gas emissions recorded for mono-Si, BSF in the [55] are for the data from the year 2019, with a module efficiency of 19.5%. For the CIS/CIGS panels, it is 17% and the data are for the year 2010, for multicrystalline silicon BSF it is 18% for 2019 and for CdTe it is 18% for 2019. All the emissions reported by IEA PVPS task 12 include the modules and balance of system, that is, the inverters and mounting structures, and are for the rooftop installations.

Similarly, the most recent report published by the IEA on PERC LCA in 2024 [56] reported GWP at 25.7g CO_2-Eq/kWh, which also includes the modules and the balance of the system.

As for SHJ-based PV systems, the work done by A. Barrou at CSEM [58] reported the emissions to be 35 g CO_2-Eq/kWh in 2022 for the module efficiency of 21.5% and A. Louwen [59] reported that the emissions were 35 g CO_2-Eq/kWh at a cell efficiency of 18.4%. Finally the study by M. Roffeis at HZB[60], used a SHJ module efficiency of 22% and the GWP potential reported was 40.6 g CO_2-Eq/kWh, in a system not include the BoS.

All of these values above establish the basis for this study, as they will help draw critical conclusions about the results obtained in this study and will also help verify the validity of the results.

4 Methodology

As seen in the previous chapter 3, for a successful LCA, the four phases namely, goal and scope definition, Life Cycle Inventory, Life Cycle Impact Assessment and Interpretation, needs to be conducted. This chapter presents the methodology implemented to carry of the LCA of a PV system consisting of SHJ solar modules. Thus, the first two stages will be covered in this chapter. Firstly, goal and scope of the study is defined. After this, an inventory is created which lists the quantities of each and every material or energy input for the production and usage phase.

The section of Life Cycle Inventory is divided into multiple subsections. Initially the details for the inputs of cell manufacturing and module manufacturing are discussed. Then the details of how the LCA software is used, is presented. Finally, the modelling of the prospective scenarios are also discussed.

4.1. Goal and Scope of this LCA

4.1.1. Goal definition

The objective of this study is to perform a comprehensive life cycle assessment for a photovoltaic system consisting of silicon heterojunction solar modules. The assessment focuses on evaluating and analyzing the environmental impacts of the SHJ PV system both for the current and future scenarios, which will be based on the year 2035. By comparing these scenarios, the study aims to understand potential changes and advancements in environmental performance over time, and under different IAM and SSP scenarios.

This study is crucial as it acts as a method to investigate the possibilities of larger-scale deployment of SHJ-based PV systems. While the SHJ photovoltaic technology is not yet as prevalent worldwide, acquiring only about 5% of the global PV market until 2023, as seen in chapter 1 (which is still higher compared to thin film PV technologies), the growing interest from industries and research institutions is evident. Consequently, conducting an LCA on this technology at an early stage in its life cycle will provide valuable insights into its overall potential environmental impacts and provide insights for the possible improvements that may be adopted to ensure the sustainable implementation of this technology over further, larger scales and see an increment in the percentage share of the global PV market in the coming decade.

4.1.2. Scope definition

Functional Unit

The functional unit for this analysis is defined as ”1 kilowatt-hour (kWh) of electricity produced”. Thus the impacts are quantified as units/kWh of generated electricity. This implies that the total electricity generated by the installed PV system can fluctuate over time and under different conditions, however, the findings will be analyzed per kWh of electricity generated.

System Boundary

This study uses a cradle-to-grave Life Cycle Assessment (LCA) methodology, which encompasses all phases of the photovoltaic (PV) system, from raw material extraction to the lifetime, with the exception of recycling processes. The omission stems from a current deficiency in comprehensive, industry-scale data on recycling processes and their efficiency for the materials under scrutiny. Moreover, despite some industries are adopting downcycling methods to manage material waste, dependable and consistent data on these approaches remain scarce. In light of these data limitations, including recycling or downcycling would considerably elevate the uncertainty in this study's environmental impact assessments. Hence, to preserve the accuracy of the outcomes, these end-of-life stages have been intentionally excluded from the analysis.

The SHJ cell manufacturing process is the primary focus of this study, as it plays a critical role in determining the environmental impact and feasibility of SHJ technology. The term cell manufacturing here includes each and every process right from the raw material extraction to the final manufactured cell. Thus the process like quartz mining, production of MG-Si, Cz-Si ingot growth, wafer sawing, PECVD process and cleaning and texturing, to name a few, are all the steps included in cell manufacturing. The SHJ cell manufacturing process is the basis of the analysis, with the entire PV system, including BoS components such as inverters and mounting structures, being evaluated. This focus is essential because the study is designed to assess the environmental feasibility of the production of SHJ cells, and analyze the significance of these on the overall system's sustainability and performance.

However, it is crucial to incorporate the entire PV system into the assessment in order to offer a thorough analysis of the environmental effects. The inclusion of the BoS components ensures that the results reflect the real-world application of SHJ cells within a complete PV system. This method enables a more precise and elaborate analysis, which facilitates a more accurate comparison with other PV technologies and informs future enhancements in SHJ cell manufacturing.

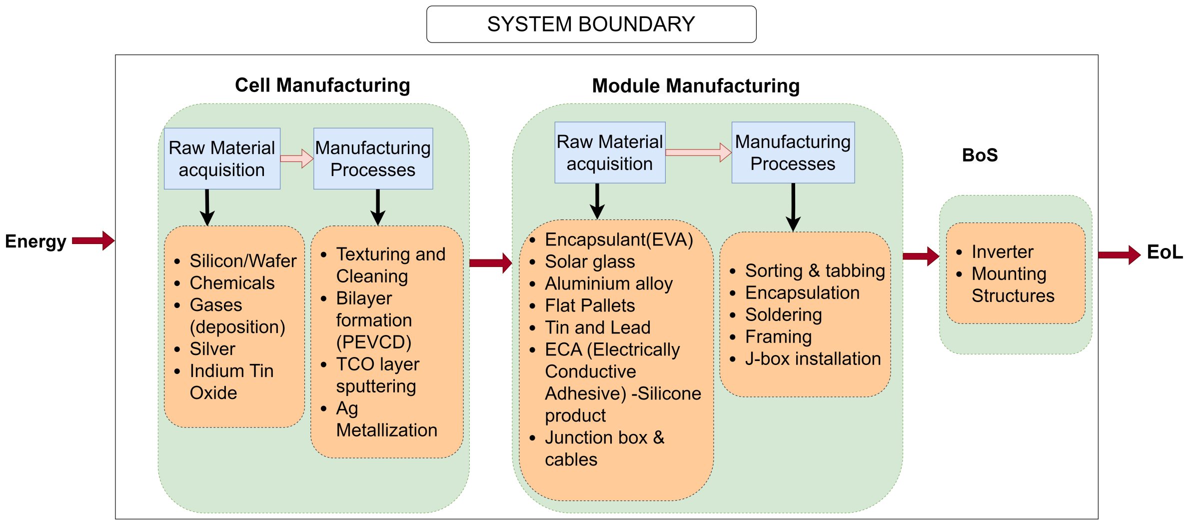

Figure 4.1: System Boundary of this LCA study

The figure 4.1 depicts the system boundary for this study. On the far right, an energy component lies outside this boundary. This indicates that any energy-consuming processes, such as the establishment of a factory or lab for the manufacture of cell or module, are excluded from the scope of this study. About the system boundary:

- **Production:**
  - **Cell Manufacturing:** Includes raw material extraction and materials and energy required for the manufacturing process like PECVD.
  - **Module Manufacturing:** Involves raw material extraction for the module components and manufacturing steps such as encapsulation, curing, tabbing and framing.

- **Balance of System (BoS):**
  - For a manufactured module to be operational, a balance of system is required, including inverters and mounting structures.
- **End-of-Life:**
  - The recycling process and disposal are not included in this study.

The system boundary outlines a clear framework to evaluate the environmental impacts of the SHJ PV system, emphasizing the production and operational stages and omitting the initial setup and recycling phases.

Regarding the pLCA, the system boundary will be unchanged, but adjustments in the foreground and background will be made to enhance the accuracy and reliability of the results.

4.2. Life Cycle Inventory

Like other photovoltaic technologies, silicon heterojunction (SHJ) solar modules have undergone development of various cell structures by different research institutions and industries, each showing different efficiency levels. Among the leading designs is the one by LONGi, achieving an impressive 27.09% cell efficiency with back contact solar cells [18].

Delft University of Technology has also made significant contributions to realizing high-efficiency SHJ solar cells. Notably, the work by Y. Zhao presents one of the SHJ cell structures with an efficiency of 24.18%[29]. While different layer stacks are applied to the cell structure in order to obtain the higher efficiency, the cell design remains straightforward, providing an ease of manufacturing [61].Therefore this LCA study incorporates the cell structure developed in Zhao's research, with a cell efficiency of 24.18%, extending it to an industrial level by using existing SHJ LCA studies, such as the work done by A. Louwen in 2014 [26].

This research utilizes a Silicon Heterojunction (SHJ) solar cell configuration that features a double-layer design aimed at increasing efficiency and performance. The n-type crystalline silicon wafer (c-Si) plays a crucial role in absorbing light and generating charge carriers. Encasing this wafer are hydrogenated intrinsic and doped amorphous silicon layers (a-Si)—notably, an i/n a-Si layer on the front side and an i/p a-Si layer on the rear side. These layers offer superior surface passivation, reduce recombination losses and also forms the PN junction for charge separation. The Transparent Conductive Oxide layers on both the front and rear facilitate efficient charge carrier collection and light passage. Silver (Ag) is used for the front and back contacts to provide high electrical conductivity. This layered configuration is intended to enhance the efficiency of the SHJ cell by integrating the advantages of crystalline silicon with the excellent passivation qualities of amorphous silicon.

Before diving into the specifics of cell manufacturing and constructing the life cycle inventory, it is essential to establish certain parameters for the cells and modules, which will guide the creation of the inventory. The table 4.1 below outlines the main parameters and serves to facilitate calculations and dataset scaling, when necessary.[1]

[1] ITRPV predicts that the SHJ cell efficiency of almost 25% by 2024 [21]. However during the research phase of this study, it had been possible to gather the cell manufacturing data from the research work of Y. Zhao[29] and therefore the cell efficiency achieved by Y. Zhao has been used in this study.

Parameter	Value
Cell Efficiency	24.18%
Thickness	120 μm
Single Cell Size	182 $\times$ 182 mm^2 (M10)
Time Frame	2024
Lifetime	30 years
Module Size	2 m^2
Cell Configuration/Module	7 $\times$ 8
Functional Unit	1 kWh

Table 4.1: Main Parameters for the SHJ Solar Cell and Module

From the point of view of LCA, data collection is an important step. Despite the fact that the order of the manufacturing steps is not the main focus, it is crucial to consider the energy-consuming processes and the number of components used in each step. A thorough examination is guaranteed by precise data regarding energy consumption and materials. Each manufacturing process is described in the following subsections, with an emphasis on the energy requirements, inputs, and outputs that are essential for the successful completion of each stage.

4.2.1. Cell Manufacturing

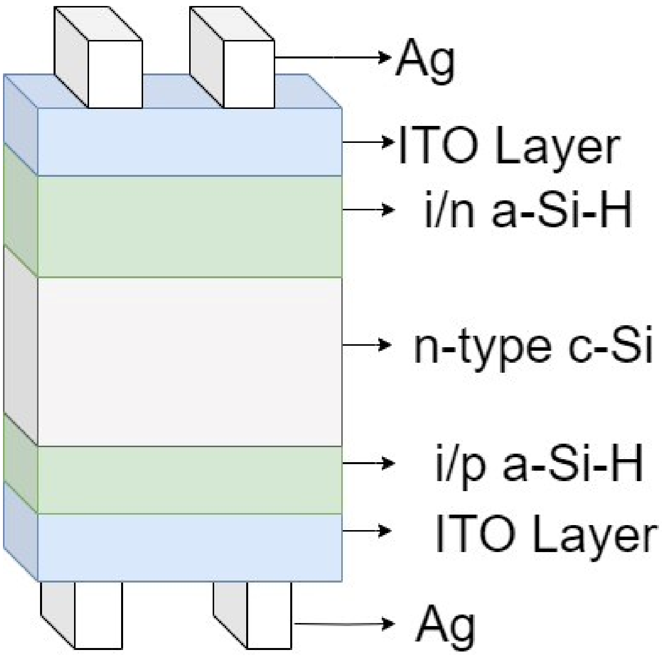

Figure 4.2: SHJ cell structure for this study

The figure 4.2 above describes depicts an SHJ cell structure. It is clear from the figure that an SHJ cell has an n-type c-Si layer in between two a-Si layers. On both the sides of the cell the TCO layers are implemented (ITO) over which there is a silver metal's bars.

Wafer manufacturing

Figure 4.3 shows an overview of the processes involved in the manufacturing of silicon wafers from quartz.

1. **Raw Material Extraction**
   - Silica is obtained from sand or quartz.
2. **Reduction to Metallurgical Grade Silicon (MG-Si)**
   - The obtained silica is then processed and converted into metallurgical-grade silicon (MG-Si).
3. **Purification to Solar-Grade Silicon**
   - In order to eliminate impurities, MG-Si is subjected to chemical purification through procedure such as:
     - **Siemens Process:** MG-Si is converted to high-purity solar-grade silicon.
4. **Ingot - Czochralski Process (Cz Process)**
   - The Czochralski process is employed to convert the purified solar grade silicon into a single crystal ingot.
5. **Ingot to wafer**
   - Uniformly trimmed ingots are now sliced into thin wafers of desired thickness using diamond wire sawing.

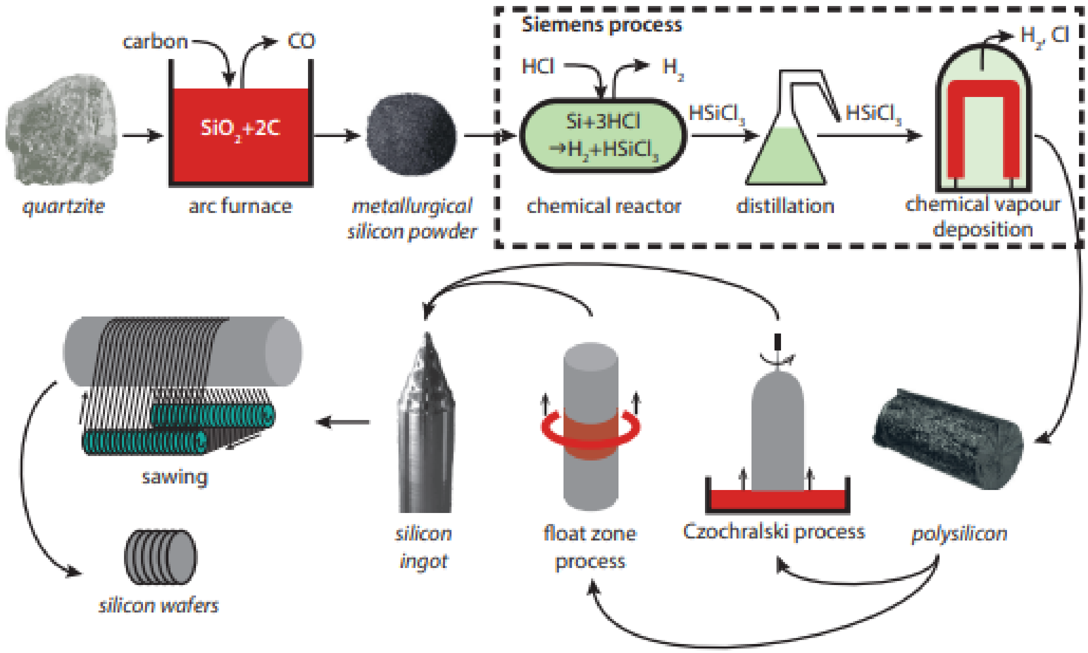

Figure 4.3: Wafer Manufacturing overview [62]

The aforementioned process steps outline a general process for the production of a silicon wafer. The eco-invent database was employed to obtain the input data for the Single-Si wafer production in this study. This database includes each and every material required, along with the electricity usage in correct amounts for the production of a single-Si wafer that covers a surface area of 1 square metre. However, the set of data used here are specifically for the square wafers with a thickness of 270 um and a dimension of $156 \times 156\,\text{mm}^2$.

According to the 15th Edition of the ITRPV [21], the M10 wafer, which is a mono-crystalline silicon (mono-Si) wafer with dimensions of 182 mm $\times$ 182 mm, currently dominates the silicon wafer market.

The kerf loss for 120-μm thickness, which is one of the most prevalent cell thicknesses in the market for 2024, is approximately 55 μm, according to ITRPV. As a result, M10 wafers with a thickness of 120 μm were chosen for this study.

In order to guarantee precise and relevant data analysis, it is essential to modify the current database of Eco invent to correspond with the specifications of the M10 wafer. This was accomplished by employing a straightforward linear scaling method to convert the data from the Eco-Invent database to align with the designated wafer specifications. The conversion process is illustrated below, along with the data in table 4.2, to guarantee that the analysis is consistent with the current market standards and offers precise insights for the investigation.

Property	**EcoInvent (μm)**	**Current (μm)**
Thickness	270	120
Kerf Loss	180	55
Total	**450**	**175**

Table 4.2: Comparison of Properties between EcoInvent and Current Market

Scaling Factor:

$$\text{Scaling Factor} = \frac{\text{Total}_{\text{current market}}}{\text{Total}_{\text{EcoInvent}}}$$

$$\text{Scaling Factor} = \frac{175}{450} = 0.388$$

This method guarantees that the database modifications are in accordance with the most recent industry trends and standards, thereby enabling a more accurate and practical examination of the silicon wafer market.

Cleaning and Texturing

For silicon heterojunction solar cells, cleaning and texturing wafers are done to achieve high efficiency. These processes removes saw damage, surface impurities, and contaminants that could degrade solar cell performance. Wet chemical etching is used not only to clean the wafers but also to improve their light-trapping abilities by texturing the surface.

Sodium Hydroxide (NaOH) is commonly employed in the etching process to eliminate saw damage and generate a textured surface that improves light-trapping properties. This technique entails a wet alkaline etch, where NaOH diluted in deionized water reacts with the silicon wafer to create a random pyramid structure, thereby reducing reflectivity and enhancing light absorption. After texturing, an RCA cleaning procedure is performed, incorporating hydrogen peroxide (H_2O_2) and hydrochloric acid to remove any remaining organic and inorganic contaminants. Lastly, the wafer is subjected to a hydrofluoric acid (HF) dip to dissolve any residual oxide layers formed in previous stages, ensuring a clean, oxide-free surface ready for further processing.

Material and Energy Use:

The table 4.3 below provides an overview of the materials and energy consumption involved in the cleaning and texturing stages for silicon heterojunction solar cells, drawing on data from prior LCA studies. Since the process of cleaning and texturing takes place over the surface area of the wafer, the data below has been linearly scaled according to an M10 wafer area, as being used in this study.

Material/Process	Value	Unit	Source
Hydrogen Fluoride (HF)	0.0802	kg/m^2	PERC [56]
Nitric Acid (HNO_3)	0.086	kg/m^2	PERC [56]
Compressed Air	0.25	m^3/m^2	Louwen [59]
Sodium Hydroxide (NaOH)	0.156	kg/m^2	Louwen [59]
Hydrogen Peroxide (H_2O_2)	0.012	kg/m^2	PERC [56]
Hydrochloric Acid (HCl)	0.0141	kg/m^2	PERC [56]
Ammonia (NH_3)	0.0127	L/m^2	PERC [56]
Water (H_2O)	33.43	L/m^2	Louwen [59]
Electricity	0.647	kWh/m^2	Louwen [59]

Table 4.3: Material and Process Values

PEVCD Process

Plasma Enhanced Chemical Vapor Deposition (PECVD) which is used in the manufacturing of silicon heterojunction (SHJ) solar cells, primarily involves the deposition of amorphous silicon layers. This process uses silane (SiH_4) as the primary gas to deposit the amorphous silicon. In addition, gases such as phosphine (PH_3), diborane (B_2H_6), and hydrogen (H_2) are used for doping and improving the process. These gases were quantified based on the research work done Zhao in [29] (lab scale). The thickness of intrinsic and doped layers on both the sides were reported to be 8nm and 2nm, respectively. To adapt this data for industrial-scale production, linear scaling of data was applied to estimate the required quantities accurately by refering and incorporating the data used A. Louwen's work in [59]. Other than the gases and chemicals used for the deposition of layers, electricity and water is also required, for which the data has been directly used from A. Louwen's work in [59]. Figure 4.4 depicts the pictorial representation of a standard PECVD process, and table 4.4 shows the values used as inputs for the inventory for this process. More about this can be found in the Appendix A.

Material/Process Input	Value	Unit	Source
Silane (SiH_4)	0.00108	kg/m^2	[29],[59]
Diborane (B_2H_6)	0.002117	kg/m^2	[29],[59]
Phosphine (PH_3)	0.000138	kg/m^2	[29],[59]
Hydrogen (H_2)	0.003548	kg/m^2	[29],[59]
Water	192.97	L/m^2	[59]
Electricity	3.228	kWh/m^2	[59]

Table 4.4: Material and energy inputs for PECVD process.

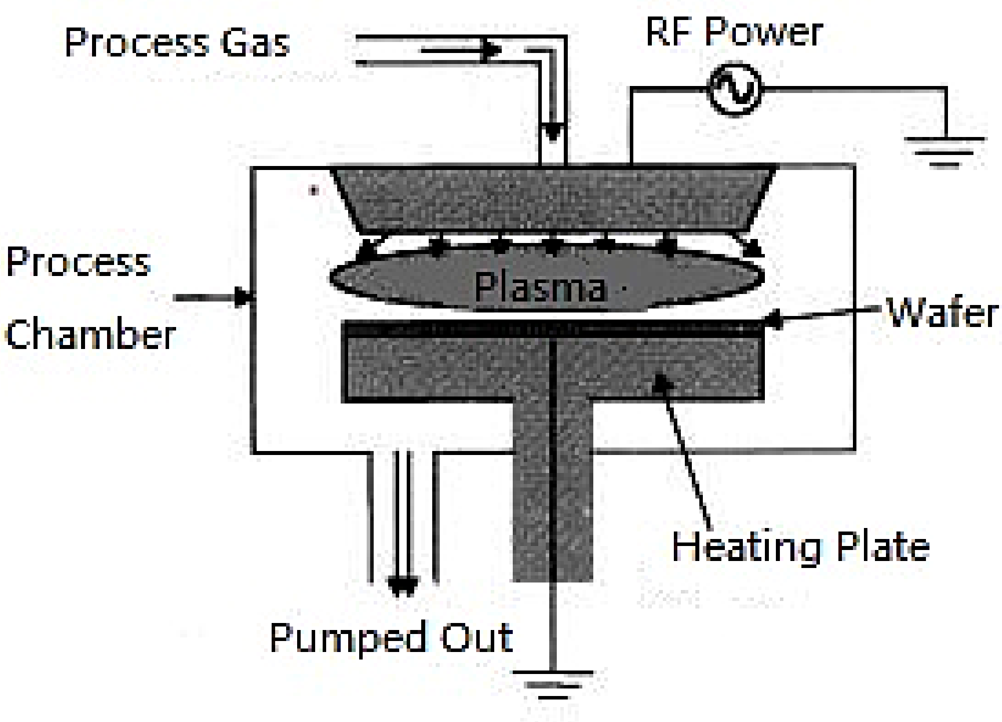

Figure 4.4: PECVD Process [63]

TCO Layer
Transparent Conductive Oxide (TCO) layers function as transparent electrodes that facilitate electrical conduction and allow light to penetrate the cell. In this study, Indium Tin Oxide(ITO) is used as the TCO layer due to its exceptional optical transparency, low electrical resistivity, and strong chemical stability. In addition to this, ITO also possesses the properties of anti Reflection coating (ARC), which help reduce light reflection and enhance overall cell efficiency.

Different fabrication techniques, such as nebulizer spray pyrolysis (NSP), spray pyrolysis, pulsed laser deposition, thermal evaporation, chemical sol-gel methods, magnetron sputtering, and vapor deposition, can be utilized to produce ITO thin films. In this research, the data for the sputtering method is used because it is one of the most widely used techniques globally to obtain a TCO layer. Optimized Sn-doped In_2O_3 (ITO) has shown to be an effective TCO material for SHJ solar cells owing to its outstanding physicochemical properties like high transmittance, electrical conductivity, mobility, bandgap, stability and low refractive index. The table 4.5 below is the inventory list used for TCO layer application in this study.

Material/Process Input	Value	Unit	Source
Indium Tin Oxide (In_2O_3)	0.00256	kg/m^2	Louwen [59]
Water	511.82	L/m^2	Louwen [59]
Electricity	6.07	kWh/m^2	Louwen [59]

Table 4.5: Material and energy inputs for TCO process.

The ITO value of 0.00256 kg/m^2 has been calculated referring to the study done by A. Louwen [59]. The thickness of the ITO layers on both the sides is assumed to be 75nm. Linear scaling has been followed as a standard here as well as in all the other process steps.

Metallization

Screen printed Ag metallization, cured at low temperature is crucial in silicon heterojunction (SHJ) solar cells for forming both front and rear electrical contacts. It ensures high electrical conductivity, facilitating efficient current collection and transfer. The paste adheres well to silicon surfaces, provides mechanical stability, and endures thermal cycling. Designed for low-temperature processing, it meets the specific requirements of SHJ technology. Furthermore, silver paste aids in light management and maintains durability throughout the cell's lifespan, which is vital for the efficiency and reliability of SHJ solar cells. Despite being a rare metal, silver remains the most commonly used paste for SHJ cells in commercial applications, and thus, silver paste is employed in the current scenario.

The information concerning the usage of silver paste has been sourced from ITRPV [21]. It indicates that for an M10 cell, the total silver consumption for the front and back side together in 2024 is around 140mg/cell. This translates to almost 4.22 g/m^2 for an M10 cell that is an area of 182mm*8182mm. The following table 4.6 provides data specific to the M10 surface area wafer to determine the adequate amount of silver paste for the SHJ cell in this study.

Material/Process Input	**Value**	**Unit**	**Source**
Silver Paste-front	0.00211	kg/m^2	ITRPV [21]
Silver Paste-back	0.00211	kg/m^2	ITRPV [21]
Compressed Air	511.821	m^3/m^2	Louwen [59]
Electricity	0.524	kWh/m^2	IEA PVPS [10]

Table 4.6: Material and energy inputs for the metallization process.

Assumptions

-The cell structure described in Zhao's work includes both nc-Si and nc-SiOx layers. Nonetheless, these layers are not implemented into the LCA for this study due to the unavailability of deposition process data. For instance, information regarding the additional electricity required for the deposition of these layers is missing. As a result, the structure has been simplified, and it is assumed that the efficiency will remain at 24.18% even without these additional layers. Appendix C presents LCA results that incorporate these layers as well, with any unavailable data being linearly scaled based on the thickness of the new layers.

- The size of the module and cell configuration has been assumed based on the SHJ data sheets available form different manufacturers. Various SHJ datasheets were investigated, and the most common module size, that is 2m^2 was chosen and accordingly the number of cells were decided.

- In the cleaning process, for etching KOH can also be used. NaOH has been used because of the detaield data availability for this.

-RCA cleaning might not be used in the industries, however it is a process being done in laboratories, and thus, owing to the data availability, this process has been used.

- For Cz growth, the ecoinvent database does not explicitly distinguish between the n-type data and p-type data. Therefore, it is assumed that the environmental impacts from Cz growth will be similar for both p-type and n-type.

-For PECVD process, an assumption has been taken that the chemicals and gases consumed in the process scale directly according to the learning rate of the wafer, and not with the individual layer thickness. This has been done because of the lack of availability electricity and water usage data at lab scale and the difference in throughput values between lab and industry, both of which were unknown. Since these are important information for going from lab scale to industry scale, and it was not possible to collect such complicated data, it was assumed that the values used in [59] would scale linearly along the wafer thickness learning rate.

4.2.2. Module and BoS

In this analysis, an in-depth inventory for the production of Silicon Heterojunction (SHJ) photovoltaic modules was not specifically performed. The main aim of this research is to assess the complete life cycle impacts of SHJ photovoltaic systems, which encompasses the modules, but the core focus is on the cell technology. Moreover, there is a significant shortage of publicly accessible datasets that pertain to the inventory for SHJ module production. Consequently, this study utilizes the data provided for PERC modules in the IEA PVPS PERC LCA report released in 2024 [56].

Reasons for utilizing IEA's module inventory for PERC as a proxy for SHJ modules:

- Focus on Cell Technology: This study primarily aims to evaluate the environmental impacts and advantages of SHJ cell technology. SHJ cells mark a considerable technological leap with possible enhancements in efficiency and performance. Therefore, the main focus is on the cells themselves instead of the module level.
- Similarity in Module Production: The production processes and materials for PV modules among different cell technologies, such as SHJ and PERC, are mostly similar. This includes the use of encapsulants, glass, frame materials, and other components and processes like lamination, framing, and encapsulation. These resemblances ensure that the environmental impacts linked to module production are comparable. Therefore, the inventory list for a PERC module can be effectively employed as a proxy for an SHJ module. [2]
- Availability of Reliable Data: Extensive and reliable inventory data for PERC modules can be easily accessed from reputable sources such as the International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS). Utilizing this data offers a solid foundation for the research.

The following table 4.7 shows the inventory used for modules of this study:

The IEA PVPS PERC LCA inventory accounts for a module with a size of 2.17m^2 and an efficiency of 21.16%. Each module comprises 144 half-cut M6 cells. In this SHJ study, the module size was considered to be 2m^2 with an efficiency of 22.18% and 56 cells (7x8 configuration) in each module [56].

4.2.3. Details for BoS

For this study, the balance of system(BoS) includes the inverters and mounting structures. The inventory provided in the IEA PVPS task 12 is a very detailed and comprehensive incorporating the details for each and every component required to make an inverter. The list of inventory for both the mounting structures and inverters can be found in the Appendix A [64].

[2]Note: When encapsulated with EVA, SHJ modules face the problem of water ingress, which occurs because the moisture leads to release of sodium ions, which then combine with water to form NaOH, which penetrates through the EVA. This could damage the passivation layer of the cell.

Name	Location	Unit	Amount
Materials			
Aluminum alloy	GLO	kg	1.19E+00
Solar glass	GLO	kg	7.49E+00
Copper	GLO	kg	7.45E-02
Lead	GLO	kg	4.49E-02
Tin	GLO	kg	7.67E-03
Ethylene-vinylacetate, foil	GLO	kg	1.67E+00
Polyethylene, film	GLO	kg	3.84E-02
Polyurethane, rigid foam	GLO	kg	4.13E-02
Granulate	GLO	kg	4.54E-01
Silicone products	RER	kg	1.14E-01
J-box + cables	GLO	kg	5.92E-01
Anti-reflex coating	GLO	m2	3.92E-01
Packaging material			
Polystyrene	GLO	kg	2.16E-02
Cardboard	RER	kg	2.44E-01
Pallet	RER	kg	2.49E-01
Energy utility			
PV panel factory	GLO	kWh	4.86E+06
Tap water from public supply	RER	kg	3.98E+04
Transport			
Freight train	GLO	tkm	1.06E-04
Freight lorry	RER	tkm	7.77E-03

Table 4.7: Material and energy inputs for SHJ module production [56]

4.3. Methodology: Impact Assessment

4.3.1. LCA Software: Brightway2.0

The third stage of an LCA is that of impact assessment. However, before moving on, it is important to implement all the inventory created in the previous sections in one of the software to get the appropriate results.

Brightway2.0 software has been utilized for this Life Cycle Assessment (LCA). Brightway2.0 is an advanced open-source LCA software written in Python. It offers a variety of powerful tools and a high degree of flexibility, making it ideal for comprehensive environmental assessments [47].

Reasons for Choosing Brightway2.0:-

- **Flexibility and Customisation**: Brightway2.0, in contrast to many commercial LCA tools, provides a high degree of flexibility, enabling the customization of LCA models to meet specific research requirements. This is especially crucial for modeling the distinctive processes involved in the production of Silicon Heterojunction (SHJ) solar cells. In accordance with the selected functional unit, it is also easy and straightforward to use.

- **Advanced Analytical Capabilities**: Brightway2.0 facilitates a diverse array of advanced analytical methodologies, such as Monte Carlo simulations, sensitivity analysis, and contribution analysis. These capabilities enable a more thorough evaluation of environmental effects.
- **Ecoinvent Database Integration**: The software seamlessly integrates with the Ecoinvent database, which offers a wide range of datasets on background processes, thereby guaranteeing a high degree of accuracy in the assessment results. This integration is essential for including various background processes and transportation impacts into the analysis.
- **Prospective Scenario Modelling**: Brightway2 excels in modeling prospective (future) scenarios. This feature is especially beneficial for evaluating the future effects of SHJ solar cell technology in various socio-economic and environmental contexts.
- **Activity Browser**: Finally, the graphical interface used by Brightway2.0 is 'Activity Browser', which is a simple and easy to use interface in order to formulate the results.

4.3.2. ReCiPe

For the Impact Assessment in this research, the ReCiPe model has been utilized. ReCiPe is a detailed life cycle impact assessment (LCIA) method created in 2008 through the partnership of RIVM, Radboud University Nijmegen, Leiden University, and PRé Sustainability [65]. Its purpose is to convert vast amounts of life cycle inventory data into a limited set of indicator scores that represent the extent of environmental effects. ReCiPe assesses impacts at two tiers: 18 midpoint indicators and 3 endpoint indicators, offering a comprehensive and globally applicable view of environmental impacts.

- **Midpoint indicators:** Midpoint indicators are primarily focused on individual environmental issues such as climate change, acidification, and land use. These indicators are generally simpler to evaluate and comprehend, as they are directly associated with the source of the impact. Consequently, they offer a more detailed analysis of the inventory, aiding in the identification of hotspots and opportunities for system-wide improvements [66].
- **Endpoint indicators:** These are the ultimate evaluations of environmental impacts grouped into three main categories: 1) human health, 2) biodiversity, and 3) resource scarcity. Endpoint indicators provide a broader perspective compared to midpoint indicators, as they reveal the final results of environmental changes and facilitate a more integrated and consistent comparison across different impact categories. However, calculating and interpreting endpoint indicators can be more challenging than midpoint indicators, due to the need for additional data, complex modeling, and the inclusion of more uncertainties and subjective assessments[66].

The ReCiPe methodology provides three cultural viewpoints [67]:

- **Individualist:** A short-term perspective with a positive outlook on technological solutions.
- **Hierarchist:** A model based on consensus, often considered the standard.
- **Egalitarian:** A long-term view emphasizing precautionary measures.

Several notable benefits of the ReCiPe framework are its extensive array of midpoint impact categories, worldwide applicability, and the omission of potential future extraction impacts, which are presumed to be included in the inventory analysis. The most recent update, ReCiPe 2016, integrates new data and research and has been developed by the Dutch National Institute for Public Health and the Environment (RIVM), Radboud University Nijmegen, Norwegian University of Science and Technology, and PRé Sustainability.

Given that the 'Midpoint Impact Category' methodology emphasises individual impacts, this study will adopt this method to perform the impact assessment and interpretations for the LCA. The table 4.8 presents the 18 different impact categories, their indicators, and units of measurement.

While every category is crucial for comprehensively evaluating the Silicon Heterojunction (SHJ) photovoltaic (PV) system, this research will concentrate on a handful of key impact categories. In particular, the focus will be on Climate Change, Ecotoxicity: Freshwater, Ecotoxicity: Marine and Land Use.

Impact Category	Indicator	Unit
Climate change	Global Warming Potential (GWP1000)	kg CO2-Eq
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11-Eq
Human health, cancer	Human toxicity potential (HTPc)	kg 1.4-DCB-Eq
Human health, non-cancer	Human toxicity potential (HTPnc)	kg 1.4-DCB-Eq
Particulate matter	Particulate matter Formation(PMFP)	kg PM2.5-Eq
Ionising radiation, human health	Ionising radiation potential (IRP)	kg Co-60-Eq
Photochemical oxidant formation : human health	Photochemical oxidant formation potential: human health(HFOP)	kg NOx-Eq
Acidification: terestrial	terrestrial acidification potential(TAP)	kg SO2-Eq
Eutrophication, freshwater	freshwater eutrophication potential(FEP)	kg oil-Eq
Eutrophication, marine	marine eutrophication potential (MEP)	kg oil-Eq
Ecotixicity Terrestrial	terrestrial ecotoxicity potential	kg oil-Eq
Ecotoxicity, marine	marine ecotixicity potential(METP)	kg oil-Eq
Ecotoxicity, freshwater	freshwater ecotoxicity potential(FETP)	kg 1.4-DCB-Eq
Land use	agricultural land occupation(LOP)	m^2*a crop-Eq
Water use	water consumption potential	m^3
Resource use, minerals and metals	surplus ore potential(SOP)	kg Cu-Eq
Resource use, fossils	fossil fuel potential	kg oil-Eq
Photochemical oxidant formation: terrestrial ecosystem	Photochemical oxidant formation potential: ecosystems(EOFP)	kg NOx-Eq

Table 4.8: 18 Mid Point Impact Categories

4.4. Parameter Explanation

In this research, the initial input data is given in per square meter (m^2) units. However, since the chosen functional unit is per kilowatt hour (kWh), it is crucial to appropriately employ the functional unit in the study. For this purpose, it is required to first calculate the total electricity generated by the chosen photovoltaic (PV) system throughout its lifespan.

The electricity production is calculated using the following formula:

$$E(\text{kWh}) = \text{S.I.}\,(\text{kWh/m}^2/\text{yr}) \times \text{L.T.}\,(\text{years}) \times \text{M.E.}(\%) \times \text{R.A.}\,(\text{m}^2) \times \text{P.R.}\,(\%) \times \text{D.R.}\,(\%)$$

[3] Where:

- **S.I. is Solar Irradiation** (the amount of solar energy received per square metre per year).
- **L.T. is the Lifetime** (refers to the operational lifespan of the PV system).
- **M.E. is the Module Efficiency**(the initial operational efficiency of modules at STC).
- **R.A. is the Rooftop Area** (the surface area available for the PV installation).
- **P.R. is Performance Ratio**(losses due to factors such as shading, temperature variations, and system inefficiencies).

[3]The formula used here is a simplifies and theoretical formula. There are other softwares and tools like PVsyst available to calculate more accurate performance of a PV system.

- **D.R. is Degradation Rate**(Represents the annual percentage decrement in the efficiency of the PV system, because of the factors like environmental conditions).

By entering these parameters, the total electricity generated by the photovoltaic system over its lifetime was calculated. This value is then used to convert all input data from a per square meter basis to a per kilowatt-hour basis.

Afterwards, the software used in this research modifies the data to the per kWh format, guaranteeing that the conclusions are in line with the designated functional unit for this study. This method allows for a more precise evaluation of the environmental effects and efficiency of the Silicon Heterojunction (SHJ) PV system.

The details of each of these parameters are presented in the table 4.9 below:-

PARAMETER	VALUE
Module Efficiency	22.18%
Lifetime	30 Years
Module size	2m^2
Solar Irradiation	1000kWh/m^2
Rooftop area	22m^2
Performance ratio	0.75
Degradation rate 1st year	2%
Degradation rate 2-30 years	0.6%

Table 4.9: Parameters used to determine total electricity production

- **Module Efficiency**: The PV module's efficiency is taken to be at 22.18% at STC. This figure takes into account a 2% decrease from the efficiency at the cell level to the module level.
- **Lifetime**: The PV system's operational duration is considered to be 30 years, in line with the ITPRV 2024 recommendations [21].
- **Module Size**: The PV module's dimensions are given as 2 square meters.
- **Solar Irradiation**: The amount of solar energy received per square meter per year, set at 1000 kWh/m^2. This is the average solar radiation for the Netherlands [68].
- **Rooftop Area**: The PV installation area is presumed to be 22 square meters. This parameter has a significant contribution in the overall impacts, as changes in rooftop area affect the total electricity generation. The selection of 22 m^2 is based on the standard rooftop area needed for a 3 kWp PV system. As per the "Life Cycle Assessment of Photovoltaics: Update of ecoinvent data" report, 22 m^2 is used to maintain consistency in the analysis [69].
- **Performance Ratio**: An efficiency factor accounting for losses due to shading, temperature variations, and system inefficiencies, assumed to be 0.75.
- **Degradation Rate 1st Year**: The efficiency degradation rate during the first year of operation, set at 2% [21].
- **Degradation Rate 2-30 Years**: The annual efficiency degradation rate for the remaining years, set at 0.6%. This gradual reduction in efficiency over time will be factored into the overall electricity production calculations [21].

By accurately defining these parameters, the study can effectively convert input data from a per square meter basis to a per kilowatt-hour basis, ensuring that the findings align with the specified functional unit and providing a comprehensive assessment of the environmental impact and performance of the SHJ PV system.

4.4.1. pLCA

Prospective Life Cycle Assessment (LCA) is a forward-thinking methodology that is intended to evaluate the prospective environmental consequences of products, processes, or systems that are currently in the planning or development phases. In contrast to conventional LCA, which assesses the environmental performance of present products or processes, prospective LCA anticipates future technological advancements, market trends, and regulatory changes. This anticipation enables a more dynamic and predictive evaluation, which incorporates a variety of future scenarios to offer a comprehensive understanding of prospective impacts. Scenario planning is one of the primary characteristics of prospective LCA. This entails the development of numerous future scenarios that are predicated on a variety of assumptions regarding technological advancements, market dynamics, and policy modifications. By examining these scenarios, prospective LCA offers a glimpse into the potential impact of various factors on environmental outcomes. This method not only identifies opportunities for advancement early in the development process but also emphasises potential environmental hotspots.

Another critical component for prospective LCA is the incorporation of dynamic data. The data employed in the evaluation is subject to change as technologies and markets develop. Prospective LCA is a method that estimates prospective environmental impacts by incorporating time-dependent changes in data and predictive models. This guarantees that the evaluation remains applicable and precise, accurately representing the most recent developments and trends in the industry.

pLCA involves the Integrated Assessment Models and Shared Socioeconomic Pathways to create different future scenarios as seen in the section 3.4. For this study, the SSP1 and SSP2 scenarios have been chosen. These are the pathways that follow the sustainability path thus are the most relevant ones in this study. As for the IAM models, the most common pLCA models available, the IMAGE and REMIND models are used. By combining these IAM models and SSPs, three different scenarios, namely, SSP1-Remind, SSP2-Remind and SSP2-Image models are used to conduct the pLCA:

- **SSP2 Image:** The IMAGE model under SSP2 offers a moderate perspective, reflecting a world with continued development. This scenario serves as a plausible baseline for future trends, helping to understand the potential environmental impacts of ongoing developments. The SSP2-IMAGE model identifies challenges and areas needing further effort to improve the sustainability and adoption of SHJ solar cells within a conventional developmental pathway.
- **SSP1 Remind:** The REMIND model under SSP1 emphasizes the importance of global cooperation, robust environmental policies, and rapid technological advancements in transitioning to a low-carbon economy. It underscores the economic benefits of investing in sustainable technologies like SHJ solar cells, demonstrating how these investments can significantly reduce greenhouse gas emissions and promote long-term sustainability.
- **SSP2-Remind:** Under SSP2, the REMIND model provides a view of a world where economic and technological advancements follow historical trends, with only modest efforts toward sustainability. This model predicts the potential performance of SHJ solar cells in typical economic conditions, highlighting incremental advancements in technology and policy. The SSP2-REMIND model helps stakeholders identify key leverage points for enhancing SHJ solar cells' role in an evolving energy market and developing strategies to overcome obstacles even in less ambitious scenarios [70].

SSP Scenario	Model	Climate Policy
SSP1-RCP2.6	REMIND	Paris Agreement objective (1.7°C)
SSP2-RCP2.6	REMIND	Paris Agreement objective(1.6-1.8°C)
SSP2-RCP2.6	IMAGE	Paris Agreement objective(1.6-1.8°C)

Table 4.10: Scenarios for pLCA in this study for the year 2035[70]

4.4.2. pLCA SHJ Foreground and Background changes

There are two ways to conduct pLCA. One by foreground changes, which means the changes in the technology itself over the time-period. For instance, the efficiency of the solar cells may increase in

future (or may be estimated to increase), or the thickness of the cell reduces, thereby reducing the amount of certain materials used for the manufacturing of the cell itself. The other is by background changes, which refers to the shift in the electricity mix, or transportation sector etc., basically anything that does not directly impact the manufacturing process but has its contribution in the hindsight. All these changes will bring certain changes in the environmental impacts, and therefore it becomes important to study these change in the results for the future scenarios, in order to predict how well the development of the SHJ solar cells are going to be, and thus, how much acceptable to the environment these solar cell technologies can be in the coming years.
This study combines both these of pLCA, that is the results for the future are calculated accumulating both the foreground and background changes. As for the background changes, the chosen year for future scenarios is 2035, therefore the energy mix with shift according to the predicted changes in the Netherlands energy mix by the year 2035.

The table 4.10 above depicts the 3 different scenarios chosen to evaluate the environmental impacts. All these 3 scenarios have different changes in the background scenarios in terms of energy mix, transportation involvement, and raw material extraction process depending upon the Climate Policy and the Share-Socioeconomic Pathway.

For the foreground changes, the table 4.11 below depicts the major changes applied to the inventory data listed in the section with current scenario's methodology:

Input	**Data for 2024**	**Data for 2035**	**Source**
Cell thickness	120µm	100µm	ITRPV [21]
Silver Consumption/cell	140mg	80mg	ITRPV[21]
Cell Efficiency	24.18%	26.6%	Zhao[29] & ITRPV [21]
Module Efficiency	22.18%	24.4%	ITRPV [21]
Lifetime	30 years	40 Years	ITRPV [21]
Degradation Rate	2% (1st year), 0.6%(rest)	1% (1st year), 0.5%(rest)	ITRPV [21]

Table 4.11: Foreground changes

4.4.3. Electricity Generation for pLCA

For pLCA, the 'premise' library in python has been used. As explain in the section 3.4.4, it incorporates the ecoinvent database and Wurst library to come up with new LCI databases that follow different IAM scenarios, depending on the climate policies they follow.

Figure 4.5 below shows the expected gross global electricity production mix as predicted by the developers of premise for various years and from various technologies. It can be inferred from the figure that in the Image model, for the year 2035, about 42% contributions come from the renewables and about 30% from the CCS. For the Remind model, the electricity generation will be even higher from the renewables at about 78%.

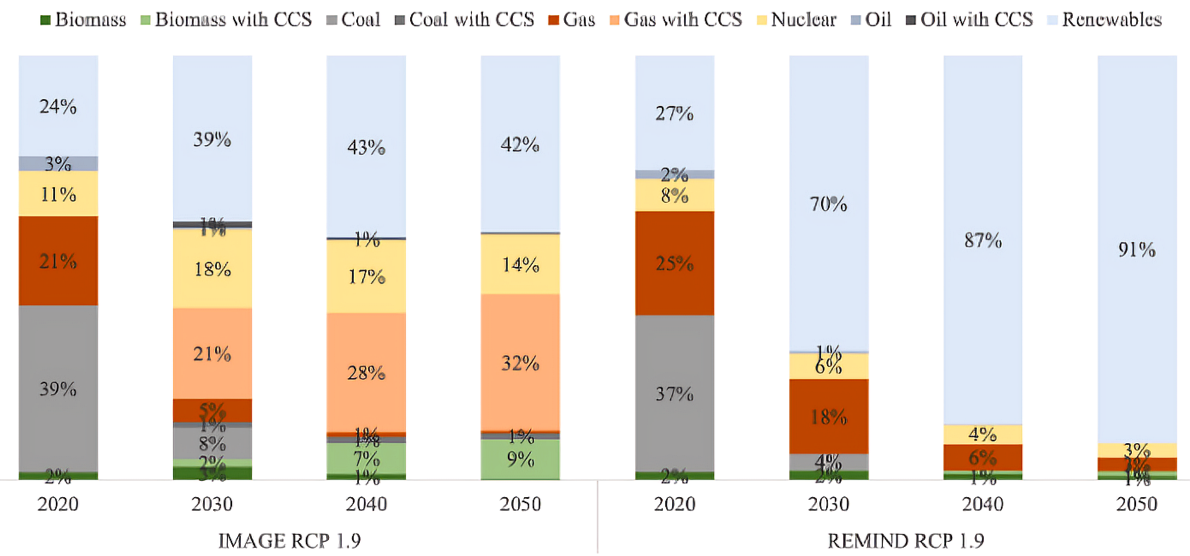

Figure 4.5: Predicted global electricity production by different technologies [54]

Although the prediction here is for the RCP 19 scenarios, and in this study RCP 26 scenarios are used, it can be assumed that the energy mix will remain almost consistent since both follow the same Paris Climate Agreement and the time period is for 11 years (from current to prospective), a big deviation is not anticipated. More details about this can be found in Appendix B.

5
Results and Discussions

In the methodology chapter, the methods adopted to create the inventory for both the current and future scenarios were discussed, followed by the selection of IAM models and SSP scenarios. Finally, all the collected data was used as inputs into the Brightway2.0 software and using the Cutoff (current) and future libraries, the results for all 18 impact categories were obtained.

In this chapter, these results are presented, along with a detailed explanation and comparison of the results for different impact categories between the current and future scenarios. A contribution analysis for the cell manufacturing stage will also be presented to get a better idea of which process step has the highest contribution to different categories. Finally in the section of sensitivity analysis, some parameters are changed according to certain predictions to see how the variation in one particular parameter leads to the overall change in the results. This will give better insight into the most important hotspots in SHJ technology to be considered for future improvements to make the system more sustainable and environment friendly.

5.1. Impact Assessment Results

The table 5.1 below depicts the results for all the 18 impact categories for the current scenario results, serving as the base case for this study.
Although all these impact categories are important, the values obtained for some of them are very small to make a significant impact on the overall study. The categories which show significant results to be analyzed are the climate change, ecotoxicity: freshwater, ecotoxicity: marine and Land Use. In the following sections, this study will look at a more detailed interpretation of the results only for these categories.

For the prospective scenarios, various IAM models and SSP's were discussed in the Literature Review chapter. From all the available options, this study focuses on the following three scenarios:

1. **SSP1-RCP2.6 REMIND:** This scenario is developed based on the Climate Policy that follows the Paris Agreement objective of limiting the Global Mean Surface Temperature (GMST) increase to 1.7°C by 2100. This scenario is modeled using the REMIND IAM.
2. **SSP2-RCP2.6 REMIND:** This scenario aims for a GMST increase of 1.6-1.8°C by 2100, in line with the Paris Agreement objectives. It is also modeled using the REMIND IAM.
3. **SSP2-RCP2.6 IMAGE:** Similar to the previous scenario, this one targets a GMST increase of 1.6-1.8°C by 2100 but is modeled using the IMAGE IAM.

These three scenarios represent the best and most realistic approaches that might be adopted, providing optimistic results for LCA studies. For comparison purposes, the climate change impact category also includes results for the SSP5 base scenario, illustrating the differences if climate policies are not implemented and business continues as usual.

No.	IMPACT CATEGORY	VALUE	UNIT/kWh
1	Climate Change Global Warming Potential (GWP1000)	0.02204	kg CO_2-eq
2	Acidification Terrestrial Terrestrial Acidification Potential (TAP)	8.41E-05	kg SO_2-eq
3	Ecotoxicity Freshwater Freshwater Ecotoxicity Potential (FETP)	0.012231	kg 1.4-DCB-eq
4	Marine Ecotoxicity Potential (METP)	0.015725	kg 1.4-DCB-eq
5	Ecotoxicity: Terrestrial Terrestrial Ecotoxicity Potential (TETP)	0.102259	kg 1.4-DCB-eq
6	Energy Resources: Non-Renewable, fossil Fossil Fuel Potential (FFP)	0.00525	kg oil-eq
7	Eutrophication: Freshwater Freshwater Eutrophication Potential (FEP)	2.25E-05	kg P-eq
8	Eutrophication Marine Marine Eutrophication Potential (MEP)	1.11E-06	kg N-eq
9	Human Toxicity: Carcinogenic Human Toxicity Potential (HTPc)	0.003195	kg 1.4-DCB-eq
10	Human Toxicity: Non-Carcinogenic Human Toxicity Potential (HTPnc)	0.153638	kg 1.4-DCB-eq
11	Ionising Radiation Ionising Radiation Potential (IRP)	0.001783	kg Co-60-eq
12	Land Use Agricultural Land Occupation (LOP)	0.001457	m^2* crop-eq
13	Material Resources: Metals/Minerals Surplus Ore Potential (SOP)	0.000959	kg Cu-eq
14	Ozone Depletion Ozone Depletion potential (ODPinfinite)	8.88E-09	kg CFC-11-eq
15	Particulate Matter Formation Particulate Matter Formation potential (PMFP)	4.12E-05	kg PM2.5-eq
16	Photochemical Oxidant Formation: Human Health Human Health (HOFP)	6.45E-05	kg Nox-eq
17	Photochemical Oxidant Formation: Terrestrial Ecosystems Terrestrial Ecosystems (EOFP)	6.68E-05	kg Nox-eq
18	Water Use Water Consumption Potential (WCP)	0.00031	cubic meter

Table 5.1: Environmental impacts per kWh for all 18 the impact categories in current (2024) scenario

5.2. Impact Assessment: by Impact Category

5.2.1. Climate Change

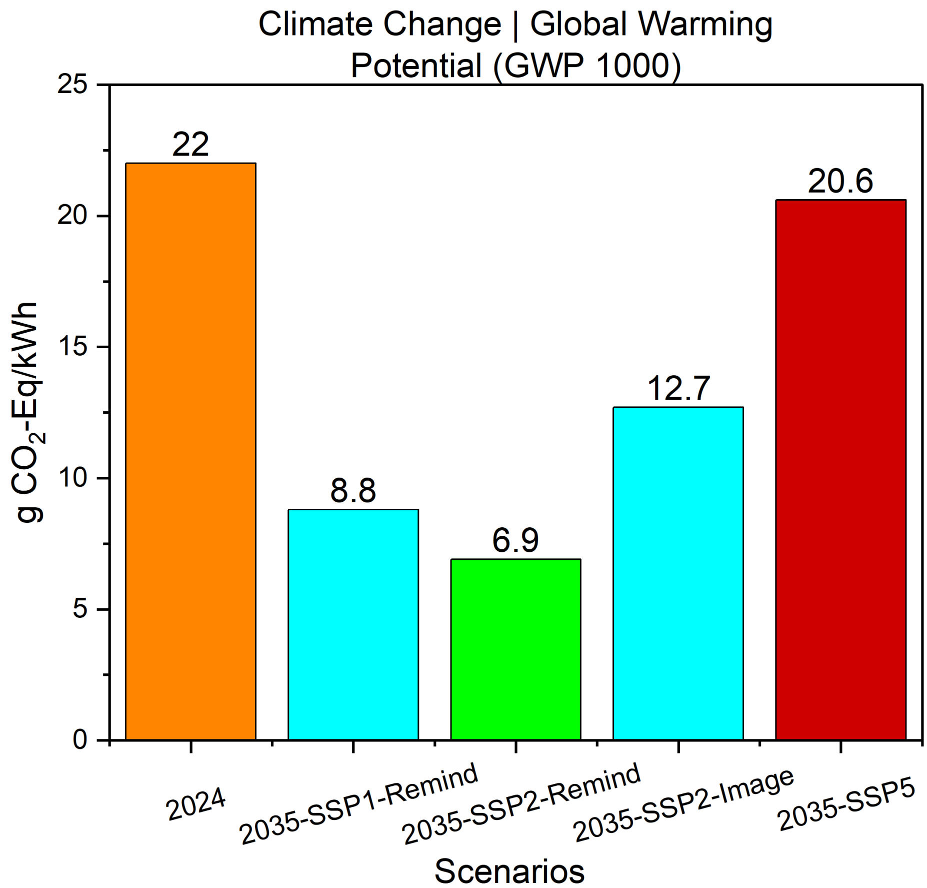

Figure 5.1: Results of Climate Change impact category for the 5 scenarios (with BoS)

Climate change is one of the most common and widely used category to evaluate the environmental impacts. The figure above shows the results for this impact category.

The graph 5.1 above illustrates the global warming potential (GWP) measured in kg CO_2-equivalent (kg CO_2-Eq) for four different scenarios:

- **2024 (Base Scenario):** The GWP is 22.04 g CO_2-Eq/kWh
- **2035 SSP1-Remind:** This scenario, reflecting the optimistic SSP1 pathway, shows a reduced GWP of 8.75 g CO_2-Eq/kWh.
- **2035 SSP2-Remind:** The REMIND model for SSP2 in 2035 shows the lowest GWP at 6.91 g CO_2-Eq/kWh, indicating significant reductions in emissions possibly due to strong climate policies and changes in the electricity mix. Even the equipment used in the processes involved, like raw material extraction may become more efficient thereby decreasing the emission values.
- **2035 SSP2-Image:** The IMAGE model for SSP2 in 2035 has a GWP of 12.71 g CO_2-Eq/kWh, higher than REMIND but lower than SSP1 and the base scenario.
- **2035-SSP5:** The SSP5 scenario has the highest impact value amongst all the future scenarios at 20.63 g CO_2-Eq/kWh, which is almost comparable to the base case scenario of 2024.

This analysis underscores the possible decrease in the effects of global warming potential of the SHJ based PV system of this study in various socioeconomic scenarios and climate strategies, with SSP2-REMIND demonstrating the most favorable outcomes for reducing climate change.

As explained before, the prospective scenarios, SSP1-2035 of the REMIND model, SSP2-2035 of the IMAGE and REMIND model, all are dependent on different learning rates from the recent past (determined by the developers of the Premise software). All of these scenarios follow the path developed according to the Paris Climate Agreement and thus show the decrement in global warming potenial by a considerable margin over the course of 11 years.

On the other hand, the last prospective scenarios, that of SSP5 for 2035, is the scenario which does not follow any of the climate policies. In addition to this, unlike the other aforementioned scenarios, this scenario does not follow a sustainable path. Instead, SSP5 follows the pathway which uses fossil fuel to the maximum limit in the future. This means that whatever development that will take place will be powered by fossil fuel as much as possible. Therefore, it is understandable for the high amounts of global warming potential,as seen in the graph for this scenario.

To gain clearer insights into the GWP reduction depicted in the graph above, the following contribution analysis is provided. The balance of system, such as inverters and mounting structures, is excluded from the contributional analysis to focus primarily on the SHJ cells and modules. This approach will provide more precise information about the components within SHJ modules that exhibit the most significant changes in emission values across various scenarios. Since, the results of overall GWP for SSP5 came to be very high, this scenario will not be discussed in the contriutional analysis, since this pathway naturally becomes the one that if taken would be very harmful for the future.

Graph 5.2 represents the contribution analysis for this impact category. The graph shows that in all four scenarios, the majority of emissions come from the module production phase. This phase accounts for approximately 40% (from the total of about 9.8g CO_2-Eq/kWh) in the 2024 scenario. The module production process encompasses any part necessary to complete the module, excluding solar cells, such as aluminum alloy production, solar glass, etc.

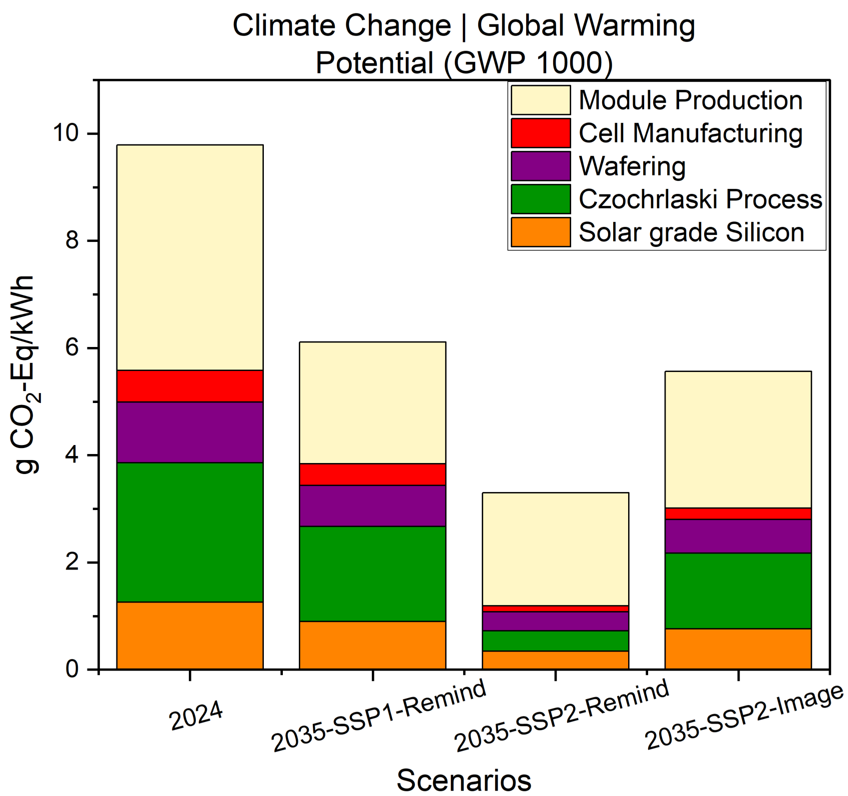

Figure 5.2: Contribution analysis from climate change impact category (without BoS)

Amongst the cell manufacturing steps, the major contributors are from the solar grade manufacturing, wafering and in particular the Czochralski process. These three process steps make up about 50% of the total impact of climate.

2024 Scenario

- **Solar Grade Silicon (13%):** In the production of solar grade silicon, the major contributors to CO_2 emissions are from the process used to convert the MG-Si to solar grade silicon, which incorporates raw material extraction, use of MG-Si and the emissions from Siemens process.
- **Czochralski Process (27%):** The overall contribution to GHG emissions from Cz-Si process itself is quite high, even when the solar grade silicon production step is not included here. It is notable for its energy-intensive process, which escalates electricity usage during the growth of silicon crystals.
- **Wafering (12%):** In the analysis of single silicon wafer contributions, emissions associated with Cz-Si are excluded to prevent double counting the data. Consequently, at this stage, only the emissions from the manufacturing processes that transform Cz-Si into single-Si wafers are considered, also known as wafering. Of the 12%, the main contributors are the production and market of silicon carbide, as well as electricity usage. This electricity usage likely encompasses processes like wafer sawing and polishing. [1]
- **Cell Production (6%):** The overall GHG emissions see an increase of merely 5% from the manufactured wafer stage to the final cell manufacturing. This indicates that the cell manufacturing processes make a minimal contribution. Hence, steps in cell manufacturing such as PEVCD and TCO sputtering add only a small portion to the total GHG emissions.
- **Module Production (43%):** Significant contributor because of the substantial electricity needed for processes and material sourcing. The production of aluminum alloy for the module frame and solar glass are the main contributors. Flat glass production accounts for over 80% of solar glass. Over 35% of module production emissions come from electricity usage, aluminum alloy production, and solar glass production.

2035 SSP1-REMIND

All the process involved in the cell production phase in this scenario have about 30-32% reduction in GHG emissions from the base case scenario of 2024.

- **Solar Grade Silicon:** During the production phase of solar grade silicon, there has been a some decrement in emissions. There is almost a 30% reduced emissions from the base case, which is primarily due to the alterations in the Netherlands' electricity mix, which led to approximately 16% lower emissions from electricity consumption across all processes (such as the Siemens process). However, the percentage of GHG emissions associated with the use of MG-Si to obtain Cz-Si remains nearly identical to the 2024 scenario.
- **Czochralski Process:** The significant reduction (about 32% from the 2024 scenario) in the percentage for the Cz-Si process step is due to lower emissions from electricity usage and subsequent generation of solar grade silicon. Therefore, enhanced energy efficiency and a higher reliance on renewable energy sources help in decreasing emissions.
- **Similar trends in Cell Production and wafering:** The lowered emissions in the cell production and the wafering processes like wafer slicing, indicate that these process are not only optimized by the use of greener electricity but also by the raw material extraction processes involved in these stages.
- **Module Production:** Module production has the highest reduction in emissions, of about 40%. The production process of aluminium alloy for the module frames have a significant reduction in the emissions, attributing to the advancements in material extraction and manufacturing processes).

[1] In recent years, diamond wire sawing is being used instead of SiC. This might bring some difference in the emissions, however the ecoinvent database still uses the SiC as an assumption for data.

2035 SSP2-REMIND

- **Czochralski Process and cell manufacturing**: There is a significant reduction in emissions from the Cz-Si phase, approximately 85% compared to the 2024 scenario. The largest decrease is observed in emissions from electricity usage. Furthermore, the impact from electronic grade silicon has diminished, suggesting that both the electricity mix and raw material extraction processes have become more optimized and efficient. This points to a substantial transition towards sustainable practices and renewable energy. Its contribution to the overall emissions is only 12%. The cell manufacturing phase also exhibits similar trends, with a minimal contribution of just 3% to the total emissions in this context.
- **Solar Grade Silicon and wafering**: Both these stages have shown a reduction of around 70% in emissions compared to the baseline scenario. The MG-Si production stage for solar grade silicon has seen the largest decline in emissions, while for wafering process, the most significant reduction has been in the silicon carbide market followed by electricity use. These can be attributed to the fact that the resource utilization will be highly efficient in the future under this scenario. Together they contribute to only about 21% of the total emissions in this particular scenario.
- **Module Production :** This remains high in the contribution to the overall impacts (64%), however the emissions decrease to almost 50% of the base case, implying that processes like production of solar glass and aluminium alloy will be further improved.

2035 SSP2-IMAGE

- **Solar Grade**: For the solar grade silicon production process, the reduced emissions are seen because the reduction in electricity is anticipated due to a cleaner electricity mix in 2035, and the MG-Si production sees nearly 35% less GHG emissions, indicating improved raw material extraction and manufacturing processes in this SSP scenario.
- **Czochralski Process and wafering**: Both categories experience approximately a 45% decrease in emissions compared to the values from 2024. The overall reduction in emissions can be attributed to lower emissions from electricity usage, electronic grade silicon production, and silicon carbide production. Combined, these two categories contribute nearly 36% to the total emissions.
- **Cell Production**: Improved but remains a minor contributor.
- **Module Production**: Module production remains the major contributor to the overall emissions, but sees almost 40% reduction from the base case. Similar to the other scenarios, the production of aluminium alloy and solar glass have reduced emissions thereby bringing the emissions from module production down.

Summary of Observations

- **Czochralski Process:** Significant reduction across all scenarios, particularly in SSP2-Remind due to enhanced energy efficiency and renewable energy use.
- **Module Production:** While reductions are observed, it remains the largest contributor due to its inherent energy and material intensity.
- **Solar Grade Silicon:** Consistent reduction in emissions due to advancements in material processing technologies.
- **Cell Production and wafering:** Minor improvements are noted, reflecting general advancements in manufacturing efficiencies.

It is important to note here, the processes involved do not change. For example, the process such as Siemens process, Czochralski process etc., do not change in any of the scenarios. It is anticipated by the models that until 2035 at least, industries are not going to switch to processes like Fluidized Bed reactors (instead of Siemens process), even though they might consume less energy.

Inference

The contribution analysis graph clearly illustrate that the major reductions in global warming potential are primarily driven by improvements in energy efficiency and a shift towards renewable energy sources, particularly in the Czochralski Process and Module Production stages. These advancements are more pronounced in the SSP2-REMIND scenario, showcasing the impact of stringent climate policies and

technological innovations on the environmental footprint of SHJ PV systems.
In the prospective scenarios, the overall emissions have decreased by a considerable amount. This reduction is mainly attributed to the fact that future scenarios will have a different energy mix, and thus the emissions from different manufacturing steps will change.
The least CO_2 emissions is achieved in the Remind Model of SSP2 scenario, followed by remind models's SSP1 scenario. The pattern of contribution amongst these scenarios for the cell manufacturing are still the same, where electricity usage make up the highest percentage of contribution, closely followed by solar grade silicon production. The difference in the emissions value for the future scenarios between the different IAM models are for the following reason: REMIND may predict a quicker implementation of clean technologies and employ stronger mitigation approaches in contrast to IMAGE. REMIND's SSP2 scenario anticipates moderate advancements, whereas IMAGE's SSP2 might predict slower or less efficient policy implementations.

Comparison with other LCA results

The Climate Change impact category is among the most extensively studied, and as demonstrated in the Literature Review chapter, various LCA results are available for this category. Nonetheless, few studies have endeavored to estimate the future impacts of technologies. Consequently, the comparison presented here is limited to the current scenario. The graph 5.3 below, represents the comparison between this LCA studies' result to that of two other LCAs conducted on SHJ. The first and most notable study on SHJ solar cells within PV systems was conducted by A.Louwen in 2014 [59], reporting a module efficiency of 18.4%. For the entire PV system, the results were documented at 35g CO_2-Eq/kWh, encompassing modules, BoS, and cell manufacturing. This study also provided results for the cell manufacturing process alone (67 g CO_2-Eq/Wp); however, due to the functional unit being Watt peaks in this instance, direct comparison is not feasible for the cell manufacturing process alone. With regard to the entire photovoltaic system, the results of this study indicate a substantial reduction in impacts compared to A. Louwen's findings. This implies that enhanced module efficiency plays a critical role in mitigating climate change impacts over the system's lifetime. Even though the solar irradiation taken in this study is significantly lower (1000kWh/yr compared to 1700kWh/yr in A. Louwen's work), the GHG emissions have reduced by over 12 grams because of the better efficiency, advancement in technology and the change of electricity usage to the Dutch electricity mix.

The next LCA study used here for comparison is from the LCA conducted by Barrou at CSEM in 2022 [58]. the GWP emissions reported in here was 34.9 g CO_2-Eq/kWh, which is still significantly higher than the results of this study (22.04 g CO_2-Eq/kWh). The main parameter difference are from the efficiency, wafer thickness and the lifetime taken for the PV system. Solar irradation used in this case in 1391 kWh/yr.

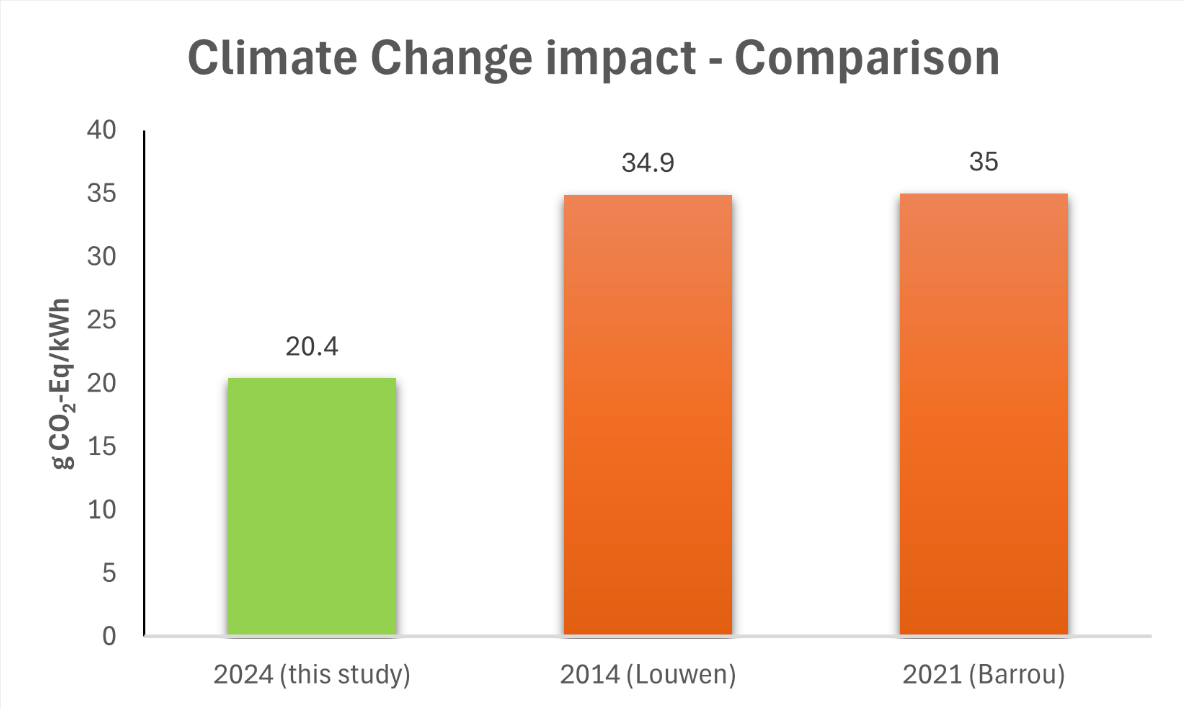

Figure 5.3: Comparison of GWP between different SHJ based studies

As for the other GHG emissions reported in the Literature Review section, the results reported for PERC modules are 12.5 g CO_2-Eq/kWh in the work done by S. Kommers [57]. Since this study reports the emissions of about 9.8 g CO_2-Eq/kWh for SHJ modules, it can be concluded that SHJ has the potential to substitute the PERC global market, which has been very high in recent years. Similarly the results for SHJ PV system at 22.04 g CO_2-Eq/kWh is still lower than the PERC LCA results in the IEA PVPS report [56] (25.7 g CO_2-Eq/kWh).

Another interesting study in [71], shows that the GHG emissions for PERC based PV system to be 14.5 g CO_2-Eq/kWh. However, this is for a large scale PV utility which is different from the rooftop PV system, employed in this study.

5.2.2. Ecotoxicity: Freshwater and Marine

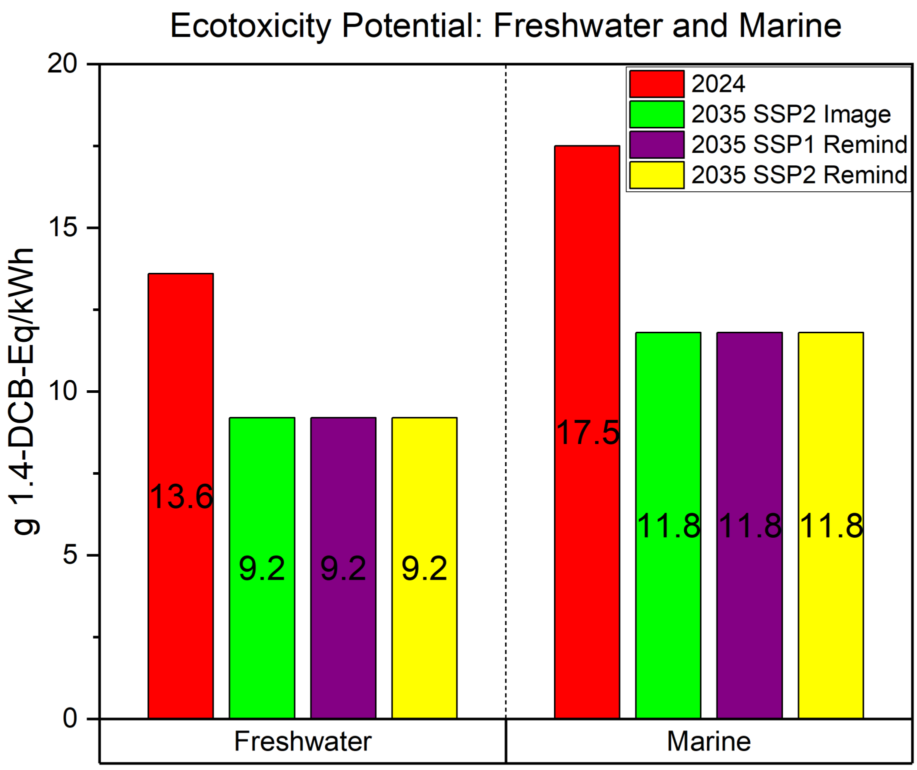

Figure 5.4: Ecotoxicity Potential for freshwater and Marine (with BoS)

Investigating the ecotoxicity potential of freshwater and marine is vital in life cycle assessment (LCA), as it helps to assess the potential negative impacts of pollutants on aquatic ecosystems, which are crucial to the protection of biodiversity and ecological equilibrium. Contaminants can disturb aquatic organisms, accumulate within them, and make their way into the human diet, presenting health dangers. Furthermore, polluted water can contaminate drinking water sources and agricultural lands through irrigation. Therefore, understanding these effects is fundamental for the protection of ecosystem, ensuring food security, and protecting human health.

The graph 5.4 above shows the results of the impact assessment for freshwater excotoxicity and marine ecotoxicity for the SHJ based PV system for the base scenario of 2024 and the three chosen prospective scenarios together. In both impact categories, the overall impacts have decreased significantly in the prospective scenarios of the 2024 case, and all future cases show almost the same impact. Upon further investigation of the results it was realises that in both these impact categories, inverters constitute of a very high percentage value (almost 85% in the all the scenarios), which is out of scope for this study. But in order to examine how a change in production process of cell and module production may have impacted these impact categories, an assessment specific to cells and modules (that is excluding the BoS) has been carried out, the results for which are presented in the graph 5.5 below.

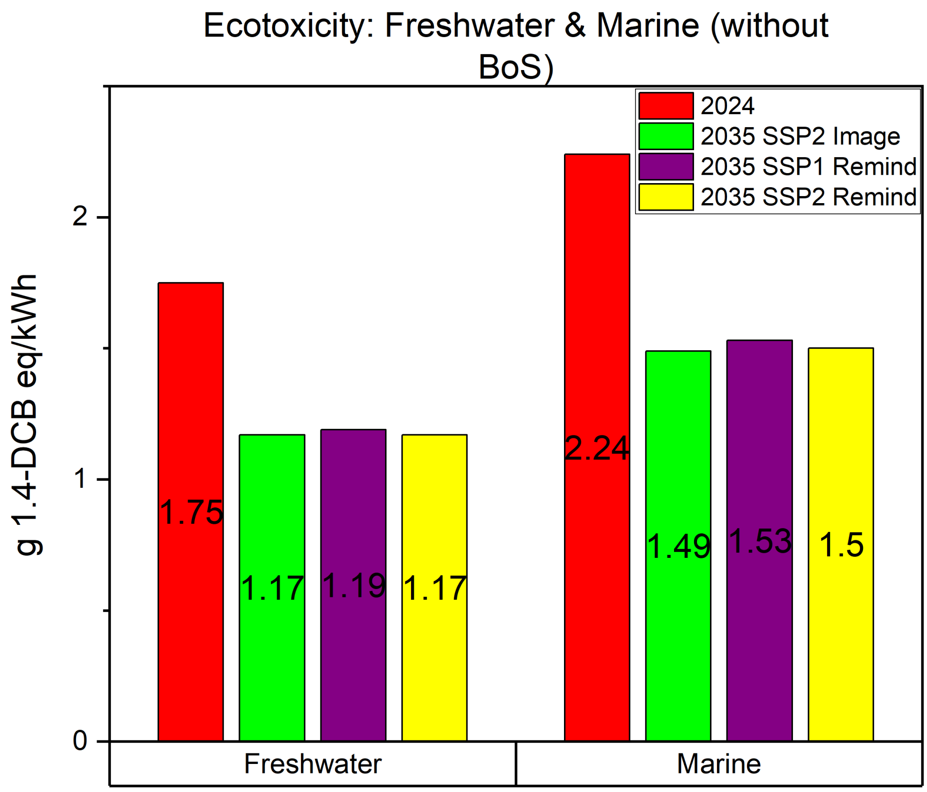

Figure 5.5: Ecotoxicity Potential for freshwater and Marine (without BoS)

It is evident from the impact assessment of the PV system without the BoS, that a similar trend is followed as that of with the BoS. All the results of future scenarios have decreased in the future scenarios compared to the base case, and the impacts are also almost similar for all the prospective cases.

- **2024**
  The major contribution in the 2024 case comes from the copper production process. Of the total impact, almost 25% constitutes the copper mining operation (in which 15% comes from sulfidic acid treatment), used for the extraction and electrowinning process of copper used in the modules. This percentage contribution is almost consistent for both freshwater and marine ecotoxicity. The next major contributor for both these contributions is the metalization paste production process at approximately 10% of the total impact, to which the silver refining process contributes for about 5%. This implies that for both freshwater and marine ecotoxicity, the metal extraction and refining process dominate the impact assessment results.
- **Prospective scenarios**
  In the 2035 SSP 2 Image and Remind scenarios the impact is observed to be slightly less than that of the 2035 SSP 1 Remind model. This is consistent for both the Freshwater and Marine ecotoxicity. This difference is due to the fact that the two main contributors, similar to the 2024 case, namely the extraction and refining processes of copper and silver paste, show a marginally lower contribution in the 2035 SSP2 Image and Remind models. Specifically, the percentage contributions for these processes are approximately 24% and 3% for copper and silver paste, respectively, while in the 2035 Remind SSP1 model, these contributions are around 24.5% and 4% of the overall impact. This slightly reduced impacts for the two SSP2 scenarios make the small difference in the impact results as seen in the graph.

5.2.3. Land Use

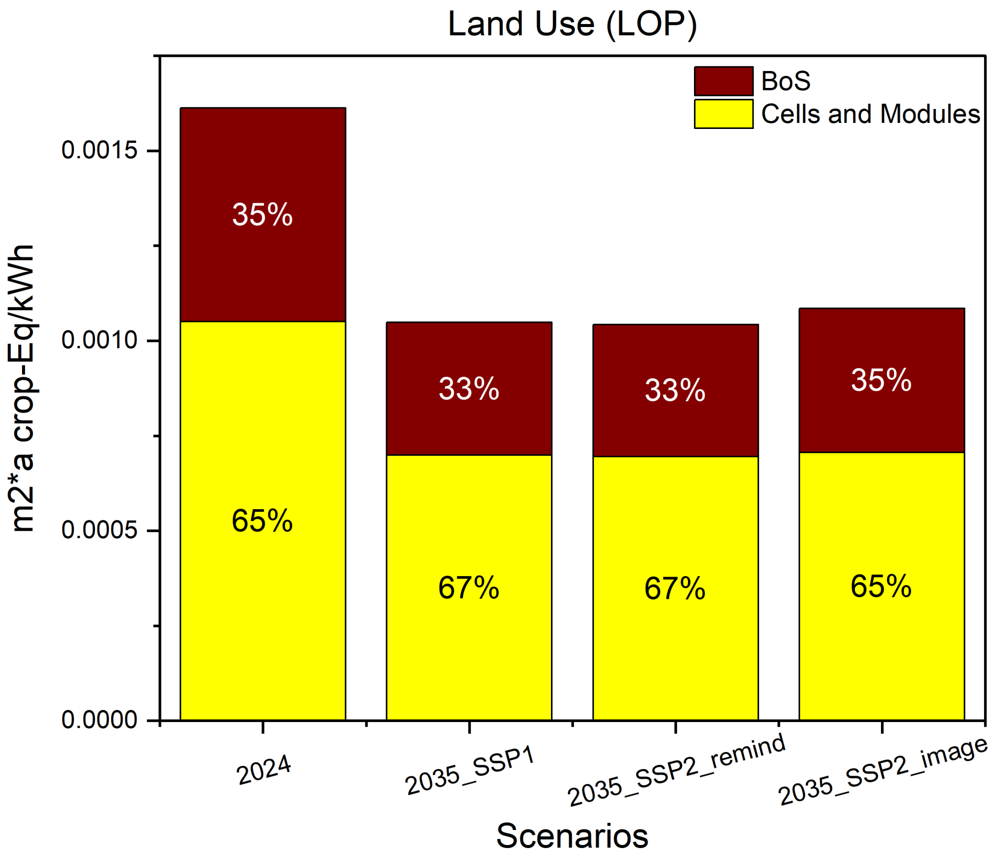

Figure 5.6: Land use imapct category assessment (with BoS)

The 'Land Use' impact category is critical to examine in this LCA because the contribution from cell and module production processes is significantly greater than from the balance of system in all scenarios considered, as can be seen in the graph 5.6. This category encompasses not only the amount of land utilized for a particular technology or process, but also the manner in which the land is used. Hence, it covers two main aspects: the amount of land occupied for a certain duration for product manufacturing and the extent of land transformation necessary to render the land suitable for this production. Consequently, the impact value presented here accumulates both aspects to represent the overall effect on the soil quality over time.

The land impact from the manufacturing stages of cells and modules accounts for roughly 65% in 2024, equating to 0.00105m^2*a crop-Eq/kWh. Notably, the cell manufacturing process itself contributes only 10% of this amount, suggesting that the manufacturing components for the modules are responsible for 90% (0.000941 m^2*a crop-Eq/kWh) of the total impact. Analyzing these high percentage contributions reveals that the production of flat pallets, mainly used for handling, transportation, and storage of the modules, is the predominant contributor to the land use impact, making up approximately 77% of this value. Softwoods such as spruce and pine, which are readily available, cost-effective, lightweight, and easier to work with than hardwoods, are predominantly used for pallet production. Despite being part of sustainable forest management which aims to mitigate environmental effects, the pallet production process still involves activities like planting and harvesting that can significantly affect soil quality over time, altering land structure and consequently increasing the impact in the land use category. Additionally, large areas of land need to be converted into forestry land for growing trees used for softwoods. All these factors collectively lead to the high land use impact under the module production step, thereby amplifying the impact in this category for the entire PV system over its lifespan.

The graph indicates that the land use impact contribution from the cell and module production processes is nearly identical across all three prospective scenarios, decreasing from 0.000941 m^2*a crop-Eq/kWh in 2024 to approximately 0.0007 m^2*a crop-Eq/kWh in each scenario. Additionally, the impacts from the steps within cell and module manufacturing have diminished almost equally in all scenarios, maintaining a similar percentage contribution (around 70%) for each process to the total impact. This phenomenon can be explained by the consistent application of sustainable land use practices in all pLCA scenarios. For example, improvements and advancements in forestry management and agricultural techniques can enhance yield per area. Likewise, better raw material utilization is achievable due to technological advancements in wood processing methods, such as more efficient saw milling processes. When the raw material, in this case, wood, is used more efficiently due to increased process efficiency, it leads to a reduction in waste and, consequently, a decrease in overall impacts.

However, since the contribution of cell and module manufacturing continue to contribute to more than 65% of the overall impacts, there is a wide range of scope available for improvement in this category.

An important point to note here is that the flat pallets (that are made of softwood) that has the highest contribution in this impact category is assumed not be reused. However, in reality, these are resuable, and thus the impacts will be reduced depending upon the number of times each one of such flat pallets are reused over the course of their lifetime before getting discarded. Such resuability has not been accounted in this study because it is not possible to quantify the number of times the product is being reused and therefore it is assumed that it is used only once and then discarded.

5.3. Sensitivity Analysis

Performing a sensitivity analysis is essential for evaluating the robustness and dependability of results within the scope of silicon heterojunction (SHJ) solar modules. This form of analysis enables researchers and stakeholders to grasp how variations in input variables or assumptions influence significant outputs, such as the environmental impacts of SHJ technology.
Considering the intricate nature and interconnected stages involved in the lifecycle of solar modules—from the extraction of raw materials and the manufacturing process to installation, operation, and eventual disposal—a sensitivity analysis proves to be crucial in pinpointing key factors that impact these outcomes. This understanding is essential for streamlining processes, enhancing sustainability, and making strategic decisions throughout the entire lifecycle of SHJ solar modules.

In the context of SHJ solar modules, performing sensitivity analysis is especially relevant due to their sophisticated technological makeup and production demands. Factors such as energy usage during manufacturing, improvements in module efficiency over time, and changes in material supply chains can greatly influence the environmental impact and economic sustainability of SHJ technology. By methodically altering these factors and examining their effects on metrics like energy payback time, carbon emissions, and material consumption, sensitivity analysis helps stakeholders identify opportunities for enhancement and innovation. This iterative process ultimately equips decision-makers in the solar sector to make informed choices that boost sustainability, reduce environmental impact, and improve the market position of SHJ solar modules within the renewable energy industry.

5.3.1. Sensitivity Analysis

In the previous sections, the results present are set based on certain fixed parameters. For the current and more improtantly for the future scenarios, it is important to quantify and analyze the behavior of the impact assessment based on sensitivity analysis. Therefore in the next sections, a sensitivity analysis will be presented to get better understanding of the effect of change of parameters in the overall results.

Performance Ratio

Until now, all the electricity production was calculated based on the performance ratio of 0.75. However, this is a very safe assumption, and generally it can be expected to be as high as 0.85 as well. The Photovoltaics Report, ISE [11] reported a typical PR of 0.83 in 2024. Therefore, in this section the sensitivity analysis with performance ratio of 0.85 is presented for all the 4 scenarios. All the other parameters are kept same as before in order to get a clear interpretation of the affect of performance ratio on the whole system.

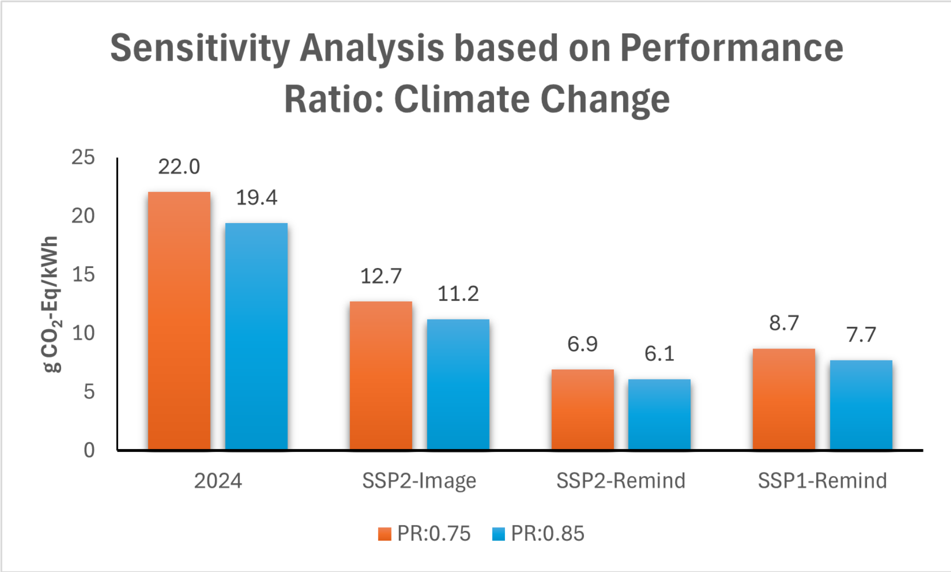

Figure 5.7: Impact of change in PR on Climate Change

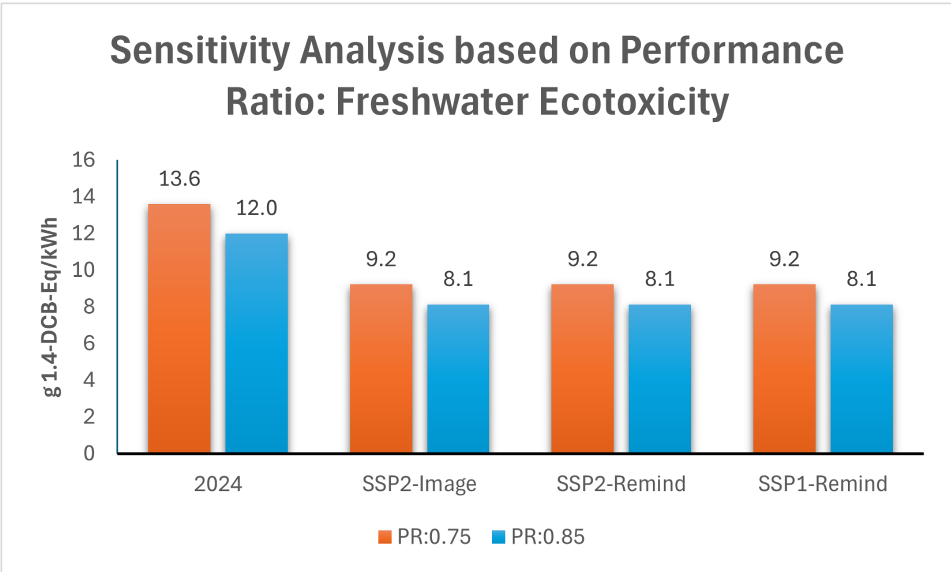

Figure 5.8: Impact of change in PR on Freshwater Ecotoxicity

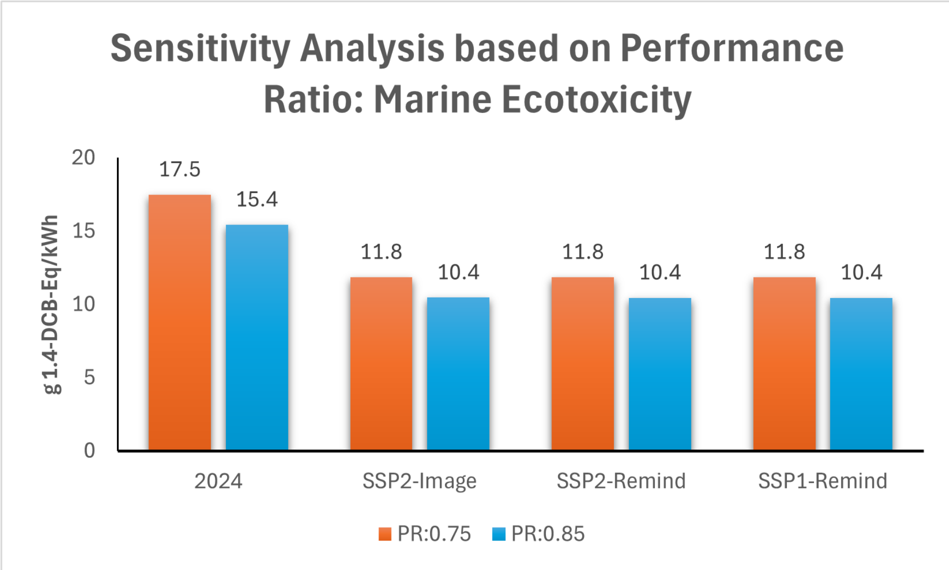

Figure 5.9: Impact of change in PR on Marine Ecotoxicity

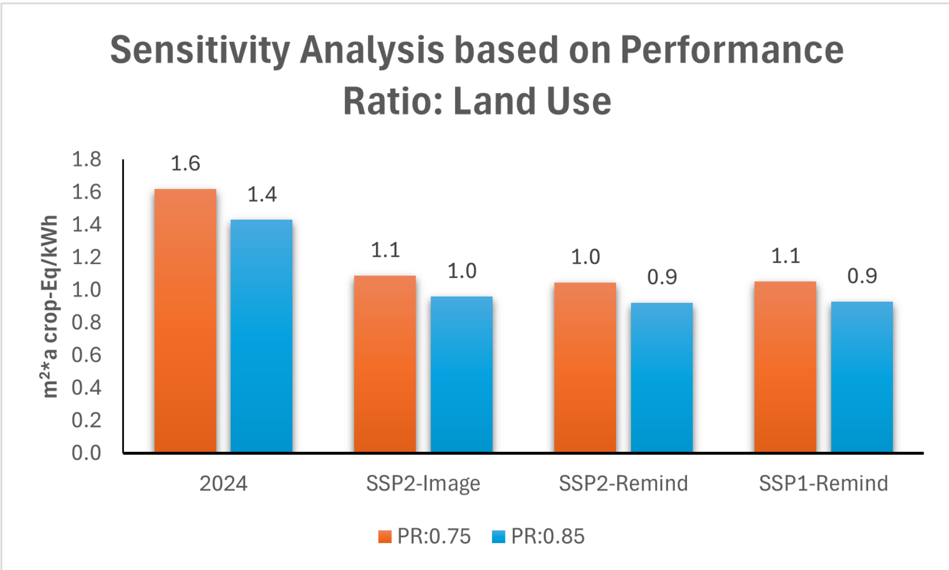

Figure 5.10: Impact of change in PR on Land Use

The results of the sensitivity analysis, as represented in the figures 5.7,5.8, 5.9 and 5.10, clearly demonstrate the impact of improving the performance ratio of silicon heterojunction (SHJ) solar cells from 0.75 to 0.85. Across various environmental impact categories—Climate Change, Freshwater & Marine Ecotoxicity and Land Use impacts—the shift to a higher performance ratio consistently leads to reduced environmental impacts.

Climate Impact: Increasing the performance ratio from 0.75 to 0.85 decreases the climate impact associated with SHJ solar cell production. For instance, original values range from 22.04 to 8.75 g CO_2-Eq/kWh across the 4 scenarios, while new values range from 19.4 to 7.7 g CO_2-Eq/kWh, indicating lower carbon emissions due to increased energy efficiency.

Freshwater Ecotoxicity: Similarly, freshwater ecotoxicity shows reductions in all scenarios. Original values range from 13.59 to 9.213 g 1.4-DCB-Eq/kWh, and new values range from 11.906 to 8.129 g

1.4-DCB-Eq/kWh across the 4 scenarios, reflecting improved water quality outcomes with enhanced solar cell performance.

Marine Ecotoxicity: The impact on marine ecosystems also decreases with a higher performance ratio. Original values range from 17.47 to 11.84 g 1.4-DCB-Eq/kWh, and new values range from 11.996 to 8.129 g 1.4-DCB-Eq/kWh across the 4 scenarios, indicating less harm to marine life due to reduced pollution from production processes.

Land Use: Land Use impact category also sees reductions as well, with original values from 1.62 to 1.053 m2*a crop Eq/kWh across the 4 scenarios, and new values from 1.43 to 0.92 m2*a crop Eq/kWh.

The sensitivity analysis highlights the significant impact of technological advancements in reducing the environmental burdens associated with SHJ solar cell manufacturing. By improving the performance ratio from 0.75 to 0.85, a noticeable reduction in carbon emissions, pollution, and land use is observed across multiple environmental indicators. This clearly indicates that even without the improvement in the cell structure, or any of the component for that instance, the overall impacts can be significantly reduced by improving the process efficiencies, and thereby generating a larger amount of electricity. These results emphasize the necessity for ongoing innovation in solar technology to reach sustainability objectives and lessen the environmental footprint of renewable energy solutions.

Single-Si wafer production

The production process for silicon wafers relies significantly on background data from the Ecoinvent database, which includes comprehensive inputs and process parameters. However, it is important to note that this database was initially created based on data collected in 2005 and last updated in 2011. Since then, the datasets have been periodically reviewed but not significantly updated.

Given technological advancements and the optimization of manufacturing processes in the past decade, it is reasonable to assume that silicon wafer production has become more efficient. To account for these advancements and to understand their potential impact on this Life Cycle Assessment (LCA), a sensitivity analysis will be conducted. This analysis will simulate reductions in energy and material use for silicon wafer production to reflect possible improvements. It includes all the process steps from raw material (like silica) extraction for the wafer, electricity usage, solar grade silicon, Cz-Si growth and finally the wafering process to obtain the single-Si wafer, to be used in the SHJ cell.

The sensitivity analysis will be performed in three stages, with hypothetical reduction in the usage and consumption by 20%, 30%and finally 70%. The 70% reduction scenario is particularly significant, reflecting the nearly 75% reduction in silicon consumption as observed from 2011 to 2023 [11]. These stages will help explore how the environmental impacts might vary under current (2024) conditions if the production processes have indeed advanced. This approach provides a more nuanced understanding of the potential range of impacts in the absence of updated and accurate datasets.

The results of the sensitivity analysis for the climate change impact category are shown in the figure 5.11 below. It depicts the impact of the three levels of reductions in wafer production inputs on the Global Warming Potential (GWP) for overall PV system. The four scenarios analyzed include the original SHJ production values, followed by reductions of 20%, 30%, and 70%.

- **Original SHJ Production**:
  - The GWP for the original SHJ production process, as shown in the previous sections is at approximately 22.04 g CO_2-eq/kWh. This represents the scenario incorporating the data available from the ecoinvent database for wafer production. In this case, the cell manufacturing accounts for 20%, in which 18% emissions come from the steps until the production of wafer.
- **20% Reduction**:
  - Implementing a 20% reduction in the wafer production inputs results in a only a small decrease in GWP to around 21.3 g CO_2-eq/kWh. This reduction reflects moderate technological advancements and process optimizations in the wafer manufacturing process. specifically for the cell manufacturing step, the overall contribution reduced from 20% in the baseline scenario to 17% in this case.

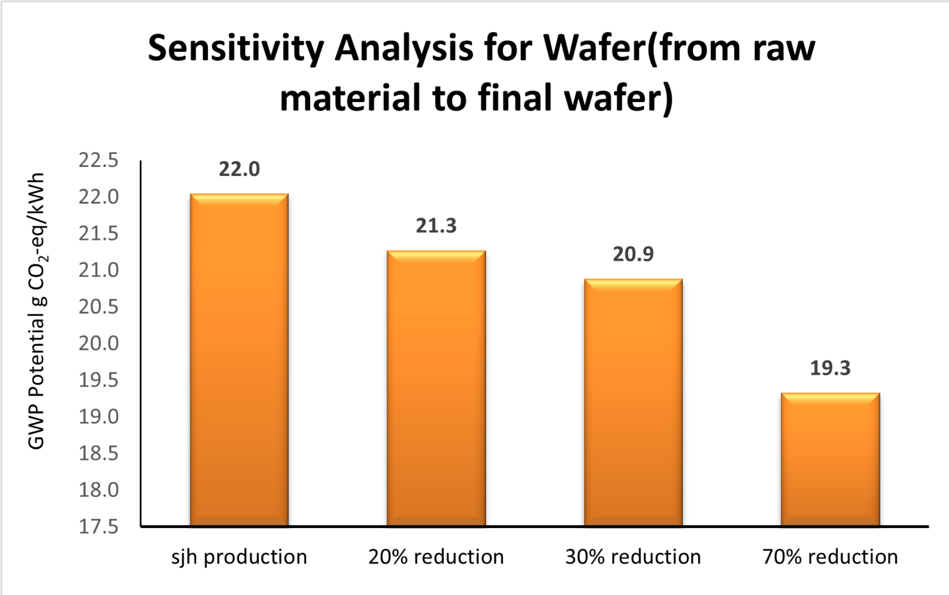

Figure 5.11: Sensitivity analysis based on complete single-Si wafer production process (from raw material to final wafer)

- **30% Reduction**:
  - Further reducing the wafer production data to 30% of the original value shows a decrease of the GWP to approximately 20.9 g CO_2-eq/kWh. The overall emissions from the cell accounted for 16% of the overall emissions in this case.
- **70% Reduction**:
  - The most drastic reduction of 70% in wafer production inputs leads to the overall emissions to be reduced to around 19.3 g CO_2-eq/kWh. This scenario shows an optimistic view of the advancements in wafer production technology. The overall emissions from the manufactured cell accounted fro 15% of the overall, depicting that the technological advancements can and may have had significant impact on the overall PV System.

It is important to note that these percentage reduction values are only an assumption to estimate the changes in the results, and incorporate the technological developments that might otherwise would have gone unnoticed.

5.4. Discussions

In the previous section, the results for the impact assessment have been discussed. In this section, the implication of these results will be discussed, with some possible reasons for the same.

One assumption in this study is that the cell manufacturing has to take place in the Netherlands itself. For this reason the electricity mix used in all the 4 scenarios, that is the base scenario of 2024 and the 3 prospective scenarios all have been made to use the dutch electricity mix. Therefore, for the steps involved in the manufacturing processes have not been accounted for any transportation. If the cell manufacturing is done in any other part of the world, and then installation takes place in the Netherlands, then the transportation for it has to be added in the model (incorporating the 'Market for' data from the ecoinvent database), which may increase the impacts from each impact category.

As for the module and BoS, most of the inventory, whose data has been used from ecoinvent database, had two options, one for only the production, and the other called 'Market For' data. The latter includes the average transport of the particular inventory component from the production site to the country where the PV system has to be installed, which in this study is the Netherlands. Therefore, wherever possible, this 'Market for' data has been used.

By looking at the results, it is evident that the by the improvement of module efficiency from 22.18%

in 2024 to 24.4% in 2035, the results for each impact category have reduced. This, therefore, implies that along with background changes (like the change in the learning curve for electricity mix over time), foreground changes are also important for making this PV system further environment friendly. Since the reduction in impacts is consistent for all the impact categories, the improvement and advancement in technology can be considered to have an important and crucial role in mitigating the negative impacts on the environment.

Moreover, both the IMAGE and REMIND models have exhibited reduced impacts from the usage of electricity. As inferred from [54], in the year 2035, Image model shows to have about 42% contribution in the electricity mix from the renewables. This contribution for Remind model is even higher at about 78%. For the Image model, the electricity CCS also accounts for almost 30% of the overall electricity. This implies that in both the models, the major electricity will be generated from the renewable sources and thus help in justifying the reduction of impacts.

Inverters have been seen to have higher impacts than the cell and module manufacturing process in all the impact categories (expect for the land use category). While examining only the module and cell manufacturing, it was seen that cell manufacturing again had smaller contribution to impacts than the module components. These findings indicate that the production process of Silicon Heterojunction solar cells do not have major contributions to the overall PV system. Thus, even if the cell structure is not improved further to improve the efficiency beyond 26.5%, and the cell structure is kept as simple as the one used in this study for the future scenarios as well, the SHJ cell production can be adopted at global market scale.

As for the impact categories, the following observations and inferences can be made:-

- **Climate Change:**
  The analysis indicated that improvements in cell and module efficiency along with reduction in wafer thickness, the performance of the PV system significantly improves, lowering the global warming potential (GWP). Future scenarios forecasted a notable decrease in GWP due to increased efficiency and a shift towards renewable energy sources. This is in line with the objectives of international climate treaties, like the Paris Climate Agreement suggesting that following these protocols can effectively reduce the climate impact.
- **Ecotoxicity:** The impact of cell and module production on ecotoxicity was relatively small in comparison to other components, such as inverters. Nevertheless, an examination of particular manufacturing procedures showed that certain steps, like the creation of metalization pastes and the application of copper, notably contribute to ecotoxicity. This implies that using less detrimental materials or improving manufacturing methods could further decrease the ecotoxicity effect.
- **Land Use:** Land use effects were mainly linked to the module production stage, especially the utilization of flat pallets for the transport and storage of modules. This highlights the necessity to take into account not only the core manufacturing processes but also the auxiliary elements that add to the total environmental impact. Adopting more eco-friendly approaches in material procurement and waste management within these aspects could greatly reduce the land use effect. One such possibility that is being already employed is the resuse of the flat pallets, which has not been included in this study due to the lack of availability of this reuse data.

  A noteworthy finding, particularly in the realm of climate change impacts, was that the SSP2 REMIND model exhibited the least impacts among the anticipated scenarios. Nevertheless, based on the descriptions of SSP1 and SSP2, it was discerned that SSP1 follows the 'green road,' signifying the most sustainable trajectory. On the other hand, SSP2 adopts the 'Middle Road' strategy, which implies sustainable development guided by historical progress and lessons learned.

  The variation in the outcome relative to its definition arises from the use of a learning curve across all SSP and IAM scenarios. As illustrated in the figures 5.12,5.13 and 5.14 below, the learning curve indicates that the SSP2 REMIND model records the lowest Global Mean Surface Temperature for the year 2035. Although this is only a minor difference of approximately 0.01 and 0.06 degree Celsius compared to the SSP1 Remind model and SSP2 Image respectively, the resulting impacts had a difference in outcomes. This suggests that in 2035, transitioning to greener energy by following SSP2-Remind scenario would be marginally more advantageous than other scenarios, leading to a reduction in impact results.

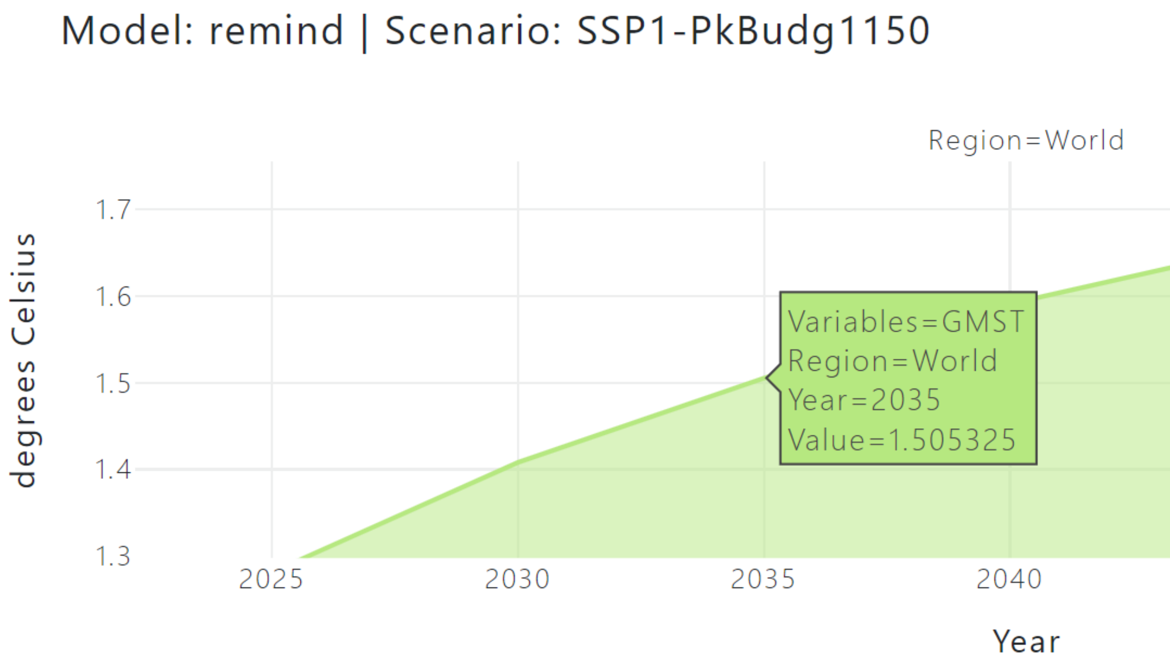

Figure 5.12: GMST 2035-SSP1 Remind Model [70]

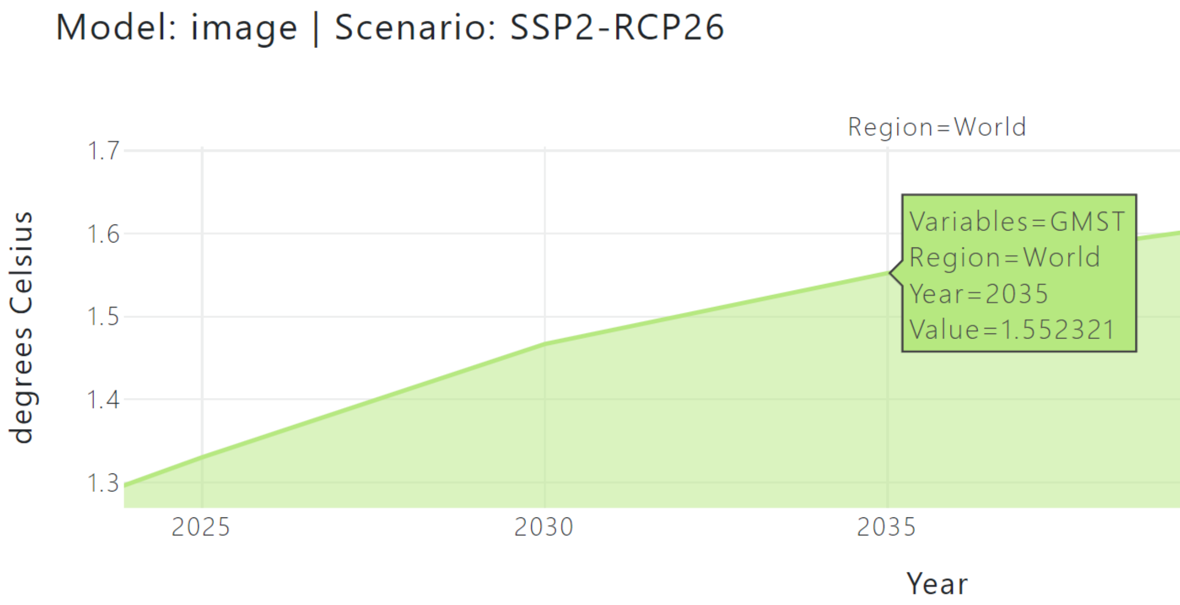

Figure 5.13: GMST 2035-SSP2 Image Model[70]

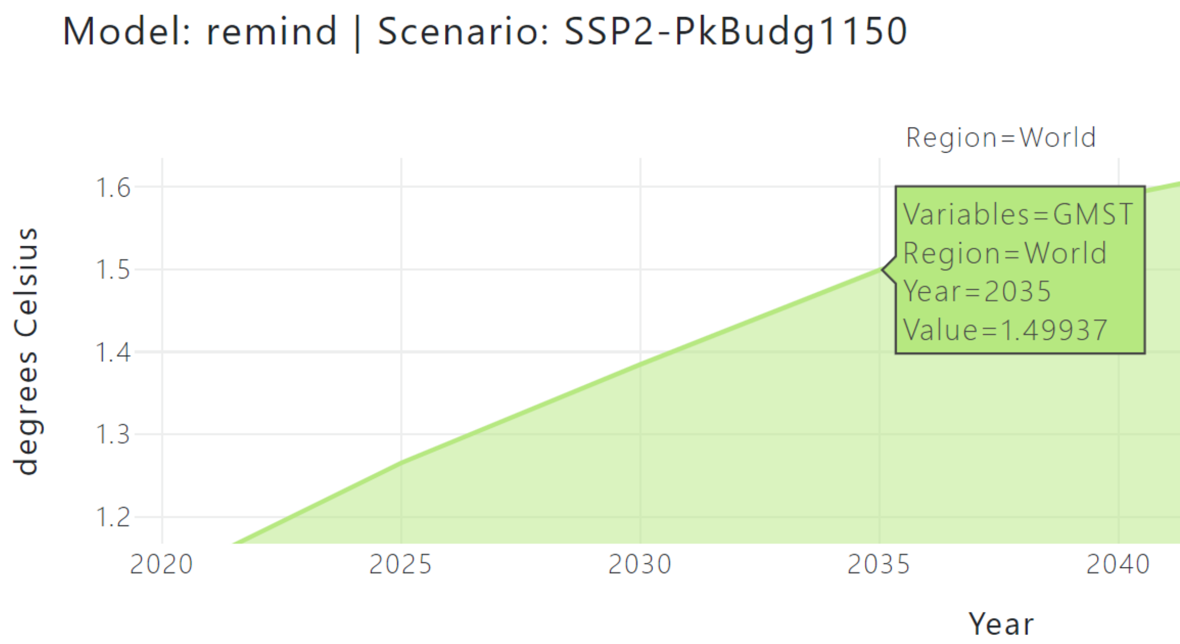

Figure 5.14: GMST 2035-SSP2 Remind Model [70]

6 Conclusion

In this study an LCA was performed on a PV system consisting of silicon heterojunction solar cells and modules based on the production in the Netherlands. The goal of this study was to analyze the environmental impacts of such a PV system over the course of its lifetime. The system was then adjusted to a future timeline of the year 2035, by making the background and foreground changes using various IAM and SSP model combinations and future trends, to get the impacts of this PV system for the year 2035. For this study, the chosen functional unit was 1kWh of electricity produced, and the system boundary consisted of cradle-to-grave, without the end-of-life processes.

6.1. Key Findings

Following are some of the key findings from the study that help to answer the research questions addressed:

1. **Which impact categories make the most significant contribution to the overall environmental impact assessment?**

2. **Which activities in the cell and module manufacturing process have the highest contribution in different impact categories?**

3. **In what ways do the various IAM and SSP scenarios differ in terms of their environmental impacts for the year 2035?**

- Amongst the 18 impact categories possible to be evaluated the results of Climate Change, Ecotoxicity (freshwater and marine) and Land Use were most notable.
- All the impact categories consistently show the domination of impacts from inverters, which accounted for more than 55% in all the categories, barring ’Land Use; impact category.
- Climate Change
  - In the 2024 base scenario, the GWP impact was 22.04 g CO_2 Eq/kWh, in which almost 58% contribution came from inverters and mounting structures. The cell and module manufacturing contributed to only about 42% of the emissions.
  - The major impacts accounted in the cell manufacturing, came from solar grade silicon, Czochralski process and wafering.
  - For the prospective scenarios, the least emission was seen in the 2035 SSP2-Remind scenario, where the overall emissions decreased to 6.9 g CO_2-Eq/kWh, followed by 2035 SSP1-Remind (8.75 g CO_2 Eq/kWh) and 2035 SSP2-Image (12.71 g CO_2 Eq/kWh).

- The reduction in emissions is majorly attributed to the improvement in the efficiency and a shift towards renewable energy technology for the raw material extraction and manufacturing processes together. The implementation of Paris Climate Agreement in the pLCA scenarios also plays a major role in this reduction. This inference is based on the fact that the electricity usage for different purposes have consistently shown decrement in emissions.

• Ecotoxicity

- Freshwater ecotoxicity was initially recorded at 13.59 g 1.4-DCB Eq/kWh and Marine ecotoxicity measured at 17.47 g 1.4-DCB Eq/kWh.
- A significant contribution of over 55% in both categories came from the inverters and balance of system components, which involve materials and processes that have high ecotoxic impacts.
- In cell and module manufacturing, silver paste production was one of the major contributors to both freshwater and marine ecotoxicity. The extraction and processing of copper, utilized extensively in electrical conductors, significantly contributed to ecotoxicity due to the release of toxic substances into water bodies.
- The 2035 SSP2-Remind scenario showed the greatest reductions, with freshwater ecotoxicity decreasing to 8.129 g 1.4-DCB Eq/kWh and marine ecotoxicity to 8.129 g 1.4-DCB Eq/kWh as well.
- Similar reductions were observed in the SSP1-Remind and SSP2-Image scenarios, demonstrating effective mitigation strategies across all prospective scenarios.

• Land Use

- The primary contributors to land use impacts were the manufacturing phases of cells and modules, which were responsible for approximately 65% of the overall effects, equivalent to 0.00105 m^2*a crop-Eq.
- The cell manufacturing phase was responsible for just 10% of this, suggesting that the majority of the impact was due to the module components, notably the fabrication of flat pallets utilized for handling, transporting, and storing.
- The creation of flat pallets, primarily from softwoods such as spruce and pine, was the leading cause, contributing roughly 77% to the land use impacts. This significant portion highlights the substantial land utilization for forestry, essential for pallet manufacturing, which entails notable land conversion and can impact soil quality over an extended period.
- In all three future scenarios projected for the year 2035, the land use impacts associated with the production of cells and modules decreased to around 0.0007 m^2*a crop-Eq.
- This decline remained steady, with these processes consistently accounting for approximately 70% of the contribution in each scenario.
- The decrease in land use effects in future scenarios is due to the adoption of sustainable forest management, enhanced farming methods, and progress in wood processing technologies. These advancements have increased raw material efficiency, resulting in less waste and lower overall impacts.

4. **How does changing certain parameters affect the overall impact assessment, for both current and future LCA scenarios?**

• The sensitivity analysis based on the performance ratio showed that as the performance ratio of the PV system is increase from 0.75 to 0.85, the overall amount for electricity generated increases and eventually the impacts reduce. This indicates that even without improving the cell strcuture and efficiency, if the processes involved are efficient enough, then the overall emissions can be significantly reduced.

• The sensitivity analysis for wafer production data was conducted only on the climate change impact category. In this case all the inventory data from raw material extraction process to the final wafering process was decreased by 20%, 30% and 70%. The reason behind this is that the ecoinvent database used for the single silicon wafer is from the year 2014. Since there is a lack of accurate data for 2024, this sensitivity analysis provides the changes in the results considering the fact that over the time of one decade, the involved process must have become efficient. The results show that as these processes become more and more efficient, thereby using lesser amount of materials, the emissions keep on decreasing.

6.2. Implications

- **Environmental Benefits:** The results of this study show that employing photovoltaic (PV) systems made up of Silicon Heterojunction (SHJ) solar cells and modules offers significant environmental advantages.
- **Comparative Impact:** Upon analyzing the cells and their production method, it becomes clear that the environmental impacts are substantially less than most those of other PV technologies and earlier SHJ research. In the analyzed PV system, inverters had the highest impact in almost all the impact categories. Within the cell and module manufacturing, the production of single silicon wafer, from raw material extraction to final wafer, came up as one of the process with higher impact in climate change impact category. Similarly, the production of flat pallets, which uses softwood, had higher impacts in land use category, and the extraction and mining process of silver and copper (used in both cell and module) had higher impacts in the ecotoxicity (freshwater and marine) category.
- **Efficiency Metrics:** Currently, the technology demonstrates excellent performance with a cell efficiency of 24.18% and is expected to improve to 26.5% in the future, which solidifies its position as a viable global option and particularly in the Netherlands.
- **Scenario Analysis:** Among the various scenarios, the SSP2 REMIND scenario stands out as the most eco-friendly. This is especially evident in projections for the year 2035, where this scenario excels in minimizing environmental impacts. It should be noted that these findings could differ if the evaluation year is altered. Nonetheless, according to the present analysis for the year 2035, the SSP2 REMIND scenario emerges as the most advantageous in terms of environmental impact.
- **Importance of parameters:** The sensitivity analysis that was conducted demostrated the importance of parameters and their value being used in the study. In the initial study, the performance ratio was taken as 0.75 which is very conservative. Therefore a sensitivity analysis with performance ratio of 0.85 was conducted and it the results showed that as the overall system becomes more efficient, and as the energy losses are lowered, the overall generated electricity increases, thereby decreasing the negative environmental impacts. Similar conclusion can be made from the sensitivity analysis where the wafering process has been considered to be 20%,30% and 70% more efficient respectively. In this case as the % increases, the amount of material and energy consumption has been assumed to be reduced linearly. It also showed the decrease in the impacts accordingly.
- **Policy and Decision-making:** The results and conclusion drawn from this thesis work has a great potential to significantly impact policy-making and strategic decisions related to PV system consisting of SHJ solar cells. The detailed information on the environmental impacts of SHJ solar cells can help the policymakers and industry leaders to more accurately evaluate the sustainability of this technology relative to others. This will be essential for creating regulations, incentives, and policies that support the widespread use of SHJ solar cells while addressing environmental concerns.
- **Guiding Industry Practices:** The environmental impact information detailed in this thesis can also provides a beneficial resource for industry stakeholders working to elevate their procedures. Companies that manufacture SHJ solar cells can leverage these findings to enhance their processes, minimize environmental adverse effects, and boost the market appeal for SHJ cells.

6.3. Future Work and Outlook

This study entails the detailed environmental impacts of a PV system with SHJ solar cells for the year 2024 and 2035. It was concluded in the previous section that SHJ, with the simple structure chosen for evaluation, is still environment friendly. The following work can be conducted in the future to take this study forward:

- Silver, being one of the scarce and costly material, can be susbtituted by copper for the metallization contacts. even though, the impacts from silver were not recorded to be very high, this sustitution can eventually make the overall system cheaper, thus making the large scale implementation of such PV system more acceptable.
- For the prospective scenarios, only the IMAGE and REMIND models were used. In future, a new IAM model can be designed to specifically study SHJ cells. This can be made possible by integrating the predictions from various IAM models, and altering the learning curves by well planned assumptions to get more accurate results. This way, a new path can be designed to be opted for this PV system.
- In this study, a very simple structure was evaluated. In principle, SHJ are also used as bottom tandem cells. Evaluating the environmental impacts of such SHJ based tandem cells can be crucial.
- More importantly, since it was seen that SHJ already present high efficiencies, in order to make them globally wide spread, it will be important to study and improve the environmental impacts of the inverters which exhibited very high overall impacts.
- As for the sensitivity analysis, in this work two of the parameters were chosen to obtain the results. One more approach that can be adopted in future is that of GSA (Global Sensitivity Analysis). By the thelp of this, other important paramters can also be obtained.

References

[1] International Energy Agency (IEA), *The world energy outlook 2020*, International Energy Agency, 2020. [Online]. Available: https://www.iea.org/reports/world-energy-outlook-2020.

[2] W. Zhou, C. Lou, Z. Li, L. Lu, and H. Yang, "Current status of research on optimum sizing of stand-alone hybrid solar-wind power generation systems," *Applied Energy*, vol. 87, no. 2, pp. 380–389, 2010. DOI: 10.1016/j.apenergy.2009.09.020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0306261909004206.

[3] International Energy Agency (IEA), *Share of renewable electricity generation by technology, 2000-2028*, International Energy Agency, 2024. [Online]. Available: https://www.iea.org/data-and-statistics/charts/share-of-renewable-electricity-generation-by-technology-2000-2028.

[4] World Energy Council, *World energy scenarios 2024: Transitions to a sustainable world*, World Energy Council, Accessed: 2024-08-16, 2024. [Online]. Available: https://www.worldenergy.org/publications.

[5] National Renewable Energy Laboratory (NREL), *Best research-cell efficiencies*, National Renewable Energy Laboratory, 2021. [Online]. Available: https://www.nrel.gov/pv/cell-efficiency.html.

[6] International Renewable Energy Agency (IRENA), *Renewable power generation costs in 2020*, International Renewable Energy Agency, Jun. 2021. [Online]. Available: https://www.irena.org/publications/2021/Jun/Renewable-Power-Generation-Costs-in-2020.

[7] International Technology Roadmap for Photovoltaic (ITRPV), *Itrpv 15th edition*, International Technology Roadmap for Photovoltaic, 2023. [Online]. Available: https://itrpv.vdma.org/en/documents.

[8] M. D. Sabatino, R. Hendawi, and A. S. Garcia, "Silicon solar cells: Trends, manufacturing challenges, and ai perspectives," *Crystals*, vol. 14, no. 2, p. 167, 2024, Published: 7 February 2024. DOI: 10.3390/cryst14020167. [Online]. Available: https://doi.org/10.3390/cryst14020167.

[9] D. M. Chapin, C. S. Fuller, and G. L. Pearson, "A new silicon p-n junction photocell for converting solar radiation into electrical power," *Journal of Applied Physics*, vol. 25, pp. 676–677, 1954. DOI: 10.1063/1.1721711. [Online]. Available: https://doi.org/10.1063/1.1721711.

[10] International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS), *Pvps trend report 2022*, International Energy Agency Photovoltaic Power Systems Programme, 2022. [Online]. Available: https://iea-pvps.org/wp-content/uploads/2023/02/PVPS_Trend_Report_2022.pdf.

[11] Fraunhofer Institute for Solar Energy Systems, ISE, *Photovoltaics report*, Fraunhofer Institute for Solar Energy Systems, Supported by PSE Projects GmbH, Freiburg, 2024. [Online]. Available: https://www.ise.fraunhofer.de.

[12] A. Allouhi, S. Rehman, M. S. Buker, and Z. Said, "Up-to-date literature review on solar pv systems: Technology progress, market status and rd," *Journal of Cleaner Production*, vol. 362, p. 132 339, 2022, ISSN: 0959-6526. DOI: https://doi.org/10.1016/j.jclepro.2022.132339. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0959652622019436.

[13] A. Bhambhani, *Solar module shipments of top 10 companies grew to 226 gw in h1 2024*, InfoLink Consulting, Published on TaiyangNews, Aug. 2024. [Online]. Available: https://taiyangnews.info/business/solar-module-shipments-of-top-10-companies-grew-to-226-gw-in-h1-2024.

[14] InfoLink, *Cell shipment ranking 1h24: Top 5 reshuffle amid sagging market*, Solar Shipment Ranking, Aug. 2024. [Online]. Available: https://infolink-group.com/energy-article/solar-topic-cell-shipment-ranking-1h24-top5-reshuffle-amid-sagging-market.

[15] R. Kopecek, F. Buchholz, V. Mihailetchi, *et al.*, "Interdigitated back contact technology as final evolution for industrial crystalline single-junction silicon solar cell," *Solar*, vol. 3, pp. 1–14, Dec. 2022. DOI: 10.3390/solar3010001.

[16] K. Masuko, M. Shigematsu, T. Hashiguchi, *et al.*, "Achievement of more than 25% conversion efficiency with crystalline silicon heterojunction solar cell," *IEEE Journal of Photovoltaics*, vol. 4, pp. 1433–1435, 2014. [Online]. Available: https://api.semanticscholar.org/CorpusID:31321943.

[17] Y. Liu, Y. Li, Y. Wu, *et al.*, "High-efficiency silicon heterojunction solar cells: Materials, devices and applications," *Materials Science and Engineering: R: Reports*, vol. 142, p. 100 579, 2020, ISSN: 0927-796X. DOI: https://doi.org/10.1016/j.mser.2020.100579. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0927796X20300371.

[18] LONGi Green Energy Technology Co., Ltd., *Longi sets a new world record of 27.09% for the efficiency of silicon heterojunction back-contact (hbc) solar cells*, LONGi, Dec. 2023. [Online]. Available: https://www.longi.com/en/news/heterojunction-back-contact-battery/.

[19] X. Li, Q. Xu, L. Yan, *et al.*, "Silicon heterojunction-based tandem solar cells: Past, status, and future prospects," English, *Nanophotonics*, vol. 10, no. 8, pp. 2001–2022, 2020. [Online]. Available: https://www.proquest.com/scholarly-journals/silicon-heterojunction-based-tandem-solar-cells/docview/2542501167/se-2.

[20] W. Duan, A. Lambertz, K. Bittkau, *et al.*, "A route towards high-efficiency silicon heterojunction solar cells," *Progress in Photovoltaics: Research and Applications*, vol. 30, no. 4, pp. 384–392, DOI: https://doi.org/10.1002/pip.3493. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/pip.3493. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/pip.3493.

[21] VDMA Photovoltaic Equipment, "International technology roadmap for photovoltaics (itrpv): Results 2023," VDMA Photovoltaic Equipment, Tech. Rep., May 2024.

[22] N. Glanemann, S. N. Willner, and A. Levermann, "Paris climate agreement passes the cost-benefit test," *Nature Communications*, vol. 11, no. 1, p. 110, 2020. DOI: 10.1038/s41467-019-13961-1. [Online]. Available: https://doi.org/10.1038/s41467-019-13961-1.

[23] J. Guinée and R. Heijungs, "Introduction to life cycle assessment," in *Sustainable Supply Chains: A Research-Based Textbook on Operations and Strategy*, Y. Bouchery, C. J. Corbett, J. C. Fransoo, and T. Tan, Eds. Cham: Springer International Publishing, 2017, pp. 15–41.

[24] G. Finnveden, M. Z. Hauschild, T. Ekvall, *et al.*, "Recent developments in life cycle assessment," *Journal of environmental management*, vol. 91, no. 1, pp. 1–21, 2009.

[25] M. Finkbeiner, A. Inaba, R. Tan, K. Christiansen, and H.-J. Klüppel, "The new international standards for life cycle assessment: Iso 14040 and iso 14044," *The international journal of life cycle assessment*, vol. 11, pp. 80–85, 2006.

[26] A. Louwen, W. van Sark, R. Schropp, and A. Faaij, "A cost roadmap for silicon heterojunction solar cells," *Solar Energy Materials and Solar Cells*, vol. 147, pp. 295–314, 2016, ISSN: 0927-0248. DOI: https://doi.org/10.1016/j.solmat.2015.12.026. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0927024815006741.

[27] PV Magazine, *Low prices for topcon solar panels put pressure on perc*, Jun. 2024. [Online]. Available: https://www.pv-magazine.com/2024/06/24/low-prices-for-topcon-solar-panels-put-pressure-on-perc/.

[28] M. Taguchi, "Review—development history of high efficiency silicon heterojunction solar cell: From discovery to practical use," *ECS Journal of Solid State Science and Technology*, vol. 10, no. 2, p. 025 002, Feb. 2021. DOI: 10.1149/2162-8777/abdfb6. [Online]. Available: https://dx.doi.org/10.1149/2162-8777/abdfb6.

[29] Y. Zhao and P. P. et. al., "Strategies for realizing high-efficiency silicon heterojunction solar cells," *Solar Energy Materials and Solar Cells*, vol. 258, p. 112 413, 2023, ISSN: 0927-0248. DOI: https://doi.org/10.1016/j.solmat.2023.112413. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0927024823002349.

[30] J. Haschke, O. Dupré, M. Boccard, and C. Ballif, "Silicon heterojunction solar cells: Recent technological development and practical aspects - from lab to industry," *Solar Energy Materials and Solar Cells*, vol. 187, pp. 140–153, 2018, ISSN: 0927-0248. DOI: https://doi.org/10.1016/j.solmat.2018.07.018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0927024818303805.

[31] G. Paggiaro, "Optimizations of high-efficiency silicon heterojunction solar cells for tandem applications," Available: TU Delft Repository, Master's thesis, Delft University of Technology, Delft, Netherlands, Sep. 2021. [Online]. Available: https://repository.tudelft.nl/record/uuid:367f7b6e-04c4-444b-b2f7-b68b49e9dba5.

[32] Z. Sun, X. Chen, Y. He, *et al.*, "Toward efficiency limits of crystalline silicon solar cells: Recent progress in high-efficiency silicon heterojunction solar cells," *Advanced Energy Materials*, vol. 12, no. 23, p. 2 200 015, 2022. DOI: https://doi.org/10.1002/aenm.202200015. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/aenm.202200015. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/aenm.202200015.

[33] F. Hou, L. Yan, B. Shi, *et al.*, "Monolithic perovskite/silicon-heterojunction tandem solar cells with open-circuit voltage of over 1.8 v," *ACS Applied Energy Materials*, vol. 2, no. 1, pp. 243–249, 2019. DOI: 10.1021/acsaem.8b00926. eprint: https://doi.org/10.1021/acsaem.8b00926. [Online]. Available: https://doi.org/10.1021/acsaem.8b00926.

[34] F. Peng, W. Long, C. Zhou, *et al.*, "Terrestrial study of bifacial silicon heterojunction solar modules," Sep. 2018. DOI: 10.1109/PVSC.2018.8547682.

[35] A. Smets, K. Jäger, O. Isabella, R. van Swaaij, and M. Zeman, *Solar Energy: The Physics and Engineering of Photovoltaic Conversion, Technologies and Systems*, 1st. 2016, Kindle Edition.

[36] SOLAR MAG, *N-type vs. p-type solar panels: An in-depth to both technologies*, Solar Magazine, Jul. 2022. [Online]. Available: https://solarmagazine.com/solar-panels/n-type-vs-p-type-solar-panels/.

[37] L. Golsteijn, *Life cycle assessment (lca) explained*, PRé Sustainability, Originally published on July 17, 2022, Mar. 2024. [Online]. Available: https://pre-sustainability.com/articles/life-cycle-assessment-lca-basics/#h-1-goal-and-scope-definition.

[38] Ecochain, *Life cycle assessment (lca) guide*, https://ecochain.com/blog/life-cycle-assessment-lca-guide/, Accessed: 2024-08-16, 2024.

[39] M. Z. Hauschild, "Introduction to lca methodology," in *Life Cycle Assessment: Theory and Practice*, M. Z. Hauschild, R. K. Rosenbaum, and S. I. Olsen, Eds. Cham: Springer International Publishing, 2018, pp. 59–66, ISBN: 978-3-319-56475-3. DOI: 10.1007/978-3-319-56475-3_6. [Online]. Available: https://doi.org/10.1007/978-3-319-56475-3_6.

[40] M. Z. Hauschild, R. K. Rosenbaum, S. I. Olsen, *et al.*, *Life cycle assessment*. Springer, 2018, vol. 2018.

[41] R. K. Rosenbaum, M. Z. Hauschild, A.-M. Boulay, *et al.*, "Life cycle impact assessment," in *Life Cycle Assessment: Theory and Practice*, M. Z. Hauschild, R. K. Rosenbaum, and S. I. Olsen, Eds. Cham: Springer International Publishing, 2018, pp. 167–270, ISBN: 978-3-319-56475-3. DOI: 10.1007/978-3-319-56475-3_10. [Online]. Available: https://doi.org/10.1007/978-3-319-56475-3_10.

[42] M. A. Curran, "Overview of goal and scope definition in life cycle assessment," in *Goal and Scope Definition in Life Cycle Assessment*, M. A. Curran, Ed. Dordrecht: Springer Netherlands, 2017, pp. 1–62, ISBN: 978-94-024-0855-3. DOI: 10.1007/978-94-024-0855-3_1. [Online]. Available: https://doi.org/10.1007/978-94-024-0855-3_1.

[43] M. Oele and R. Dolfing, "Simapro," *Retrieved from SimaPro: https://simapro. com/2019/whats-new-in-simapro-9-0*, 2019.

[44] Sphera, *Sphera (gabi)*, LCA Software, Feb. 2024. [Online]. Available: https://lca-software.org/sphera-gabi/.

[45] openLCA, *Openlca*, openLCA website, 2024. [Online]. Available: https://www.openlca.org/.

[46] ifu Hamburg GmbH, *Umberto lca software*, ifu Hamburg GmbH website, Accessed on: [your access date], 2024. [Online]. Available: https://www.ifu.com/umberto/.

[47] Brightway LCA, *Brightway lca framework documentation*, Brightway LCA documentation, Accessed on: [your access date], 2024. [Online]. Available: https://docs.brightway.dev/en/latest/.

[48] V. Bisinella, T. H. Christensen, and T. F. Astrup, "Future scenarios and life cycle assessment: Systematic review and recommendations," *The International Journal of Life Cycle Assessment*, vol. 26, no. 11, pp. 2143–2170, 2021. DOI: 10.1007/s11367-021-01954-6. [Online]. Available: https://doi.org/10.1007/s11367-021-01954-6.

[49] J. Weyant, "Some contributions of integrated assessment models of global climate change," *Review of Environmental Economics and Policy*, 2017.

[50] E. Stehfest, D. van Vuuren, L. Bouwman, T. Kram, *et al.*, *Integrated assessment of global environmental change with IMAGE 3.0: Model description and policy applications*. Netherlands Environmental Assessment Agency (PBL), 2014.

[51] G. Luderer, M. Leimbach, N. Bauer, *et al.*, "Description of the remind model (version 1.6)," 2015.

[52] L. Jiang and B. C. O'Neill, "Global urbanization projections for the shared socioeconomic pathways," *Global Environmental Change*, vol. 42, pp. 193–199, 2017, ISSN: 0959-3780. DOI: https://doi.org/10.1016/j.gloenvcha.2015.03.008. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0959378015000394.

[53] "The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century," *Global Environmental Change*, vol. 42, pp. 169–180, 2017, ISSN: 0959-3780. DOI: https://doi.org/10.1016/j.gloenvcha.2015.01.004. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0959378015000060.

[54] R. Sacchi, T. Terlouw, K. Siala, *et al.*, "Prospective environmental impact assement (premise): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models," *Renewable and Sustainable Energy Reviews*, vol. 160, p. 112 311, 2022, ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2022.112311. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S136403212200226X.

[55] Rolf Frischknecht and Lydia Krebs, Eds., *Environmental life cycle assessment of electricity from pv systems - fact sheet*, R. Frischknecht and L. Krebs, Eds., PV Power Systems Task 12, International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS), 2021. [Online]. Available: https://iea-pvps.org/wp-content/uploads/2021/11/IEA-PVPS-Task12-LCA-PV-electricity-_-Fact-Sheet.pdf.

[56] International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS), "Environmental life cycle assessment of passivated emitter and rear contact (perc) photovoltaic module technology," International Energy Agency Photovoltaic Power Systems Programme, Report IEA-PVPS T12-26: 2024, 2024. [Online]. Available: https://iea-pvps.org/wp-content/uploads/2024/03/IEA-PVPS-T12-26-Report-LCA-PERC-technology-v21.pdf.

[57] S. I. Kommers, "Life cycle analysis of perc architecture for production in europe," Mentor: M.R. Vogt, Photovoltaic Materials and Devices - EEMCS, Master's thesis, Electrical Engineering, Mathematics and Computer Science, TU Delft, Delft, Netherlands, 2023. [Online]. Available: http://resolver.tudelft.nl/uuid:787d3188-6af9-466f-8889-976bcc5986fb.

[58] A. Barrou, "Life cycle assessment of heterojunction solar cells. from raw materials to final devices," 2022.

[59] A. Louwen, W. Van Sark, R. Schropp, W. Turkenburg, and A. Faaij, "Life-cycle greenhouse gas emissions and energy payback time of current and prospective silicon heterojunction solar cell designs," *Progress in Photovoltaics: Research and Applications*, vol. 23, no. 10, pp. 1406–1428, 2015. DOI: https://doi.org/10.1002/pip.2540. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/pip.2540. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/pip.2540.

[60] M. Roffeis *et al.*, "New insights into the environmental performance of perovskite-on-silicon tandem solar cells – a life cycle assessment of industrially manufactured modules," *Sustainable Energy & Fuels*, vol. 6, no. 12, pp. 2924–2940, 2022.

[61] E. Bellini, *Heterojunction solar cell with 24.18% efficiency via hydrogenated amorphous silicon passivation*, PV Magazine, Sep. 2022. [Online]. Available: https://www.pv-magazine.com/2022/09/16/heterojunction-solar-cell-with-24-18-efficiency-via-hydrogenated-amorphous-silicon-passivation/.

[62] Delft University of Technology, *Solar energy section 12.2*, Delft University of Technology OpenCourseWare. [Online]. Available: https://ocw.tudelft.nl/wp-content/uploads/solar_energy_section_12_2.pdf.

[63] Delft University of Technology, *Solar energy section 12.2*, Delft University of Technology OpenCourseWare. [Online]. Available: https://ocw.tudelft.nl/wp-content/uploads/solar_energy_section_12_2.pdf.

[64] R. Frischknecht, P. Stolz, L. Krebs, M. de Wild-Scholten, and P. Sinha, *Life cycle inventories and life cycle assessments of photovoltaic systems 2020 task 12 pv sustainability*, Dec. 2020. DOI: 10.13140/RG.2.2.17977.19041.

[65] M. Goedkoop, R. Heijungs, M. Huijbregts, A. Schryver, J. Struijs, and R. Zelm, "Recipe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level," Jan. 2008.

[66] J. Bare, P. Hofstetter, D. Pennington, and H. Haes, "Midpoints versus endpoints: The sacrifices and benefits," *Int. J. Life Cycle Ass.*, vol. 5, pp. 319–326, Apr. 2012. DOI: 10.1007/BF02978665.

[67] M. Goedkoop, R. Heijungs, M. Huijbregts, A. Schryver, J. Struijs, and R. Zelm, "Recipe 2008," *A life*, Jan. 2009.

[68] M. Zeman, *Solar cells*, TU Delft OpenCourseWare, Course Part 2 of 3 in the Solar Energy Engineering MicroMasters Program, 2023. [Online]. Available: https://ocw.tudelft.nl/courses/solar-cells/.

[69] N. Jungbluth, M. Tuchschmid, and M. de Wild-Scholten, "Life cycle assessment of photovoltaics: Update of ecoinvent data v2. 0," *ESU-services Ltd*, vol. 50, 2008.

[70] Premise, *Introduction to premise*, 2024. [Online]. Available: https://premise.readthedocs.io/en/latest/introduction.html.

[71] Y. Chen, D. Chen, P. P. Altermatt, *et al.*, "Technology evolution of the photovoltaic industry: Learning from history and recent progress," *Progress in Photovoltaics: Research and Applications*, vol. 31, no. 12, pp. 1194–1204, 2023. DOI: https://doi.org/10.1002/pip.3626. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/pip.3626. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/pip.3626.

A

Invertory Details

A.1. Inventory Data Calculations

In this section, the calculations adopted to obtain the inventory data for Silane are shown.

Following the assumption in 4.2.1, the value used by A. Louwen in [59] was 1.62 g/m^2. This was for a cell area of 156 mm $\times$ 156 mm and a thickness of $180\,\mu$m. In the current study, the cell area is $182,$ mm $\times$ 182 mm and thickness $120\,\mu$m. Since the value used is per m^2, area scaling is not required, but a scaling for the thickness has been performed:

$$\text{Amount of Silane (g/m}^2\text{)} = \frac{1.62}{180} \times 120 = 1.08\,\text{g/m}^2.$$

This value is then converted to kg/m^2 by dividing by 1000, to get 0.00108 kg/m^2. Similar scaling calculations are performed for other chemicals as well.

Towards the end of this study, an LCA was again performed to check how the results would change if this scaling according to the wafer is not performed, and is done according to the amorphous layers. For this, the total amorphous layer thickness was 20nm in this study. This meant that the silane and other chemicals consumption would decrease by a factor of 10 (approximately). (Since A. Louwen had used amourphous layer of 300nm [59]). This was incorporated along with reduction in electricity by same factor, and the results for current scenario for GWP potential were checked. It was seen that the overall emissions did not change by a lot. In fact, for the module manufacturing, the original value was 9.8 g CO_2/kWh and the new value came to be about 9.75 g CO_2/kWh, which is a very small difference and will not make much impact. It was expected so as well. As discussed in the the contribution analysis of results section, the contribution from any of the cell manufacturing steps are very low and thus, such minor changes are not expected to make a significant impact on the results obtained.

This further validates the conclusion that SHJ cell manufacturing steps do not show high impacts for environmental degradation, and thus are higly acceptable globally, if other process steps are made more sustainable.

A.2. Inverter inventory

Data used is for per m^2, [64]

Table A.1: Detailed Data of 2.5 kW Inverter

Name	Location	Unit	Amount
Inverter, 2.5 kW, average, at plant	RER	1 unit	1
Inverter, 5 kW, average, at plant	RER	1 unit	0
Inverter, 10 kW, average, at plant	RER	1 unit	0
Inverter, 20 kW, average, at plant	RER	1 unit	0
Electricity, medium voltage, production ENTSO, at grid	ENTSO	kWh	1.06E+1
Light fuel oil, burned in industrial furnace 1MW, non-modulating	CH	MJ	2.26E-1
Natural gas, burned in power plant	DE	MJ	3.57E+0
Heat, natural gas, at industrial furnace >100kW	RER	MJ	9.21E+0
Aluminium, production mix, cast alloy, at plant	RER	kg	4.77E+0
Aluminium alloy, AlMg3, at plant	RER	kg	2.12E-1
Copper, at regional storage	RER	kg	1.91E+0
Steel, low-alloyed, at plant	RER	kg	9.07E-1
Polypropylene, granulate, at plant	RER	kg	8.82E-1
Polycarbonate, at plant	RER	kg	2.02E-1
Cable, connector for computer, without plugs, at plant	GLO	m	1.31E-1
Inductor, ring core choke type, at plant	GLO	kg	8.71E-1
Inductor, miniature RF chip type, MRFI, at plant	GLO	kg	1.10E-3
Integrated circuit, IC, logic type, at plant	GLO	kg	6.61E-2
Integrated circuit, IC, memory type, at plant	GLO	kg	1.87E-3
Transistor, unspecified, at plant	GLO	kg	1.92E-2
Transistor, SMD type, surface mounting, at plant	GLO	kg	4.17E-2
Diode, glass-, SMD type, surface mounting, at plant	GLO	kg	2.01E-3
Light emitting diode, LED, at plant	GLO	kg	1.44E-5
Capacitor, film, through-hole mounting, at plant	GLO	kg	1.66E-1

Continued on next page

Table A.1 continued from previous page

Name	Location	Unit	Amount
Capacitor, electrolyte type, > 2cm height, at plant	GLO	kg	2.57E-1
Capacitor, electrolyte type, < 2cm height, at plant	GLO	kg	6.71E-3
Capacitor, SMD type, surface-mounting, at plant	GLO	kg	1.33E-2
Resistor, SMD type, surface mounting, at plant	GLO	kg	4.57E-3
Ferrite, at plant	GLO	kg	2.55E-5
Transformer, low voltage use, at plant	GLO	kg	4.01E-2
Plugs, inlet and outlet, for network cable, at plant	GLO	unit	2.79E-1
Glass fibre reinforced plastic, polyamide, injection molding, at plant	RER	kg	2.56E-2
Cable, ribbon cable, 20-pin, with plugs, at plant	GLO	kg	2.40E-4
Sheet rolling, steel	RER	kg	9.07E-1
Wire drawing, copper	RER	kg	1.91E+0
Section bar extrusion, aluminium	RER	kg	4.77E+0
Steel product manufacturing, average metal working	RER	kg	1.92E-2
Metal working factory	RER	unit	1.10E-8
Corrugated board, mixed fibre, single wall, at plant	RER	kg	6.60E-1
Folding boxboard, FBB, at plant	RER	kg	1.16E+0
Packaging film, LDPE, at plant	RER	kg	1.15E-2
Transport, light lorry, fleet average	OCE	tkm	6.76E-1
Transport, freight, rail	OCE	tkm	2.25E+0
Transport, transoceanic freight ship	OCE	tkm	2.03E+1
Tap water, at user	RER	kg	1.99E+1
Water, unspecified natural origin, DE	-	m3	3.78E-2
Treatment, sewage, unpolluted, to wastewater treatment, class 3	CH	m3	1.99E-2
Disposal, packaging cardboard, 19.6% water, to municipal incineration	CH	kg	1.82E+0
Disposal, polyethylene, 0.4% water, to municipal incineration	CH	kg	1.15E-2

Continued on next page

Table A.1 continued from previous page

Name	Location	Unit	Amount
Disposal, treatment of printed wiring boards	GLO	kg	1.22E+0
Disposal, municipal solid waste, 22.9% water, to municipal incineration	CH	kg	2.43E-1
Disposal, hazardous waste, 25% water, to hazardous waste incineration	CH	kg	1.28E-2

A.3. Inventory for mounting structure

Data used is for per m^2, [64]

Table A.2: Mounting structure inventory

Product	Location	Unit	Amount
Aluminium, wrought alloy	GLO	kilogram	2.25
Corrugated board box	RER	kilogram	0.114
Polyethylene, high density, granulate	RER	kilogram	0.0282
Polystyrene, high impact	RER	kilogram	0.00602
Polyurethane, flexible foam	RER	kilogram	0.0184
Synthetic rubber	RER	kilogram	1.24
Steel, low-alloyed	GLO	kilogram	0.2
Section bar extrusion, aluminium	RER	kilogram	2.25
Section bar rolling, steel	RER	kilogram	0.2
Transport, freight train	RER	ton kilometer	0.852
Transport, freight, light commercial vehicle	Europe without Switzerland	ton kilometer	0.375
Waste plaster-cardboard sandwich	CH	kilogram	0.114
Waste polyethylene/polypropylene product	CH	kilogram	1.29
Waste polystyrene isolation, flame-retardant	CH	kilogram	0.00602
Transport, freight, lorry 7.5-16 metric ton, EURO6	RER	ton kilometer	0.207

B
Electricity Production for pLCA

The figures below show the predicted electricity generation from various technologies for the 3 pLCA scenarios, SSP1-Remind, SSP2-Remind and SSP2-Image:

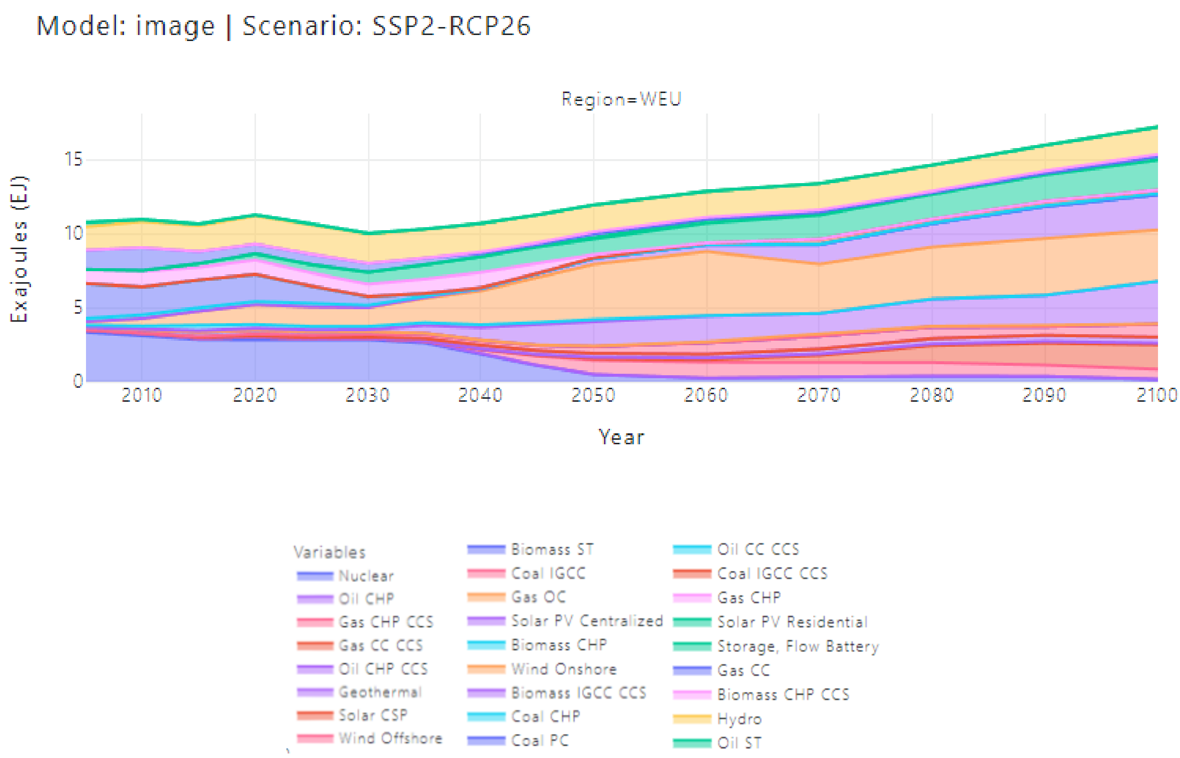

Figure B.1: Electricity production by technology SSP2 Image Model [70]

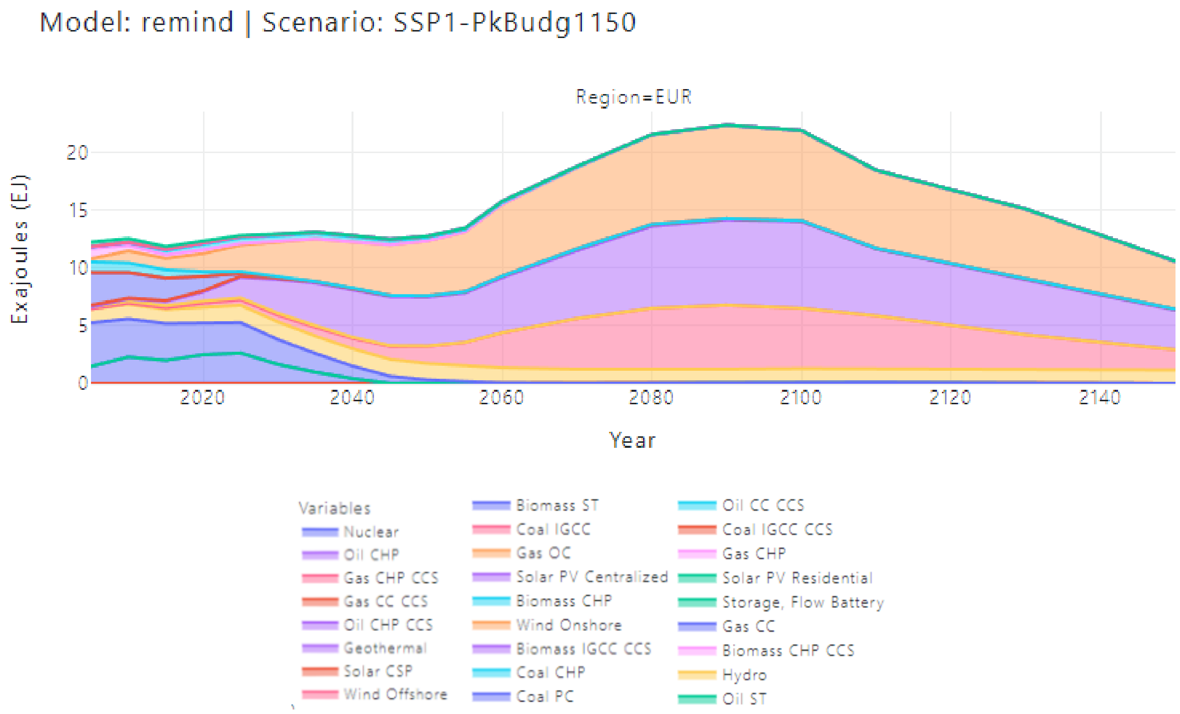

Figure B.2: Electricity production by technology SSP1 Remind Model [70]

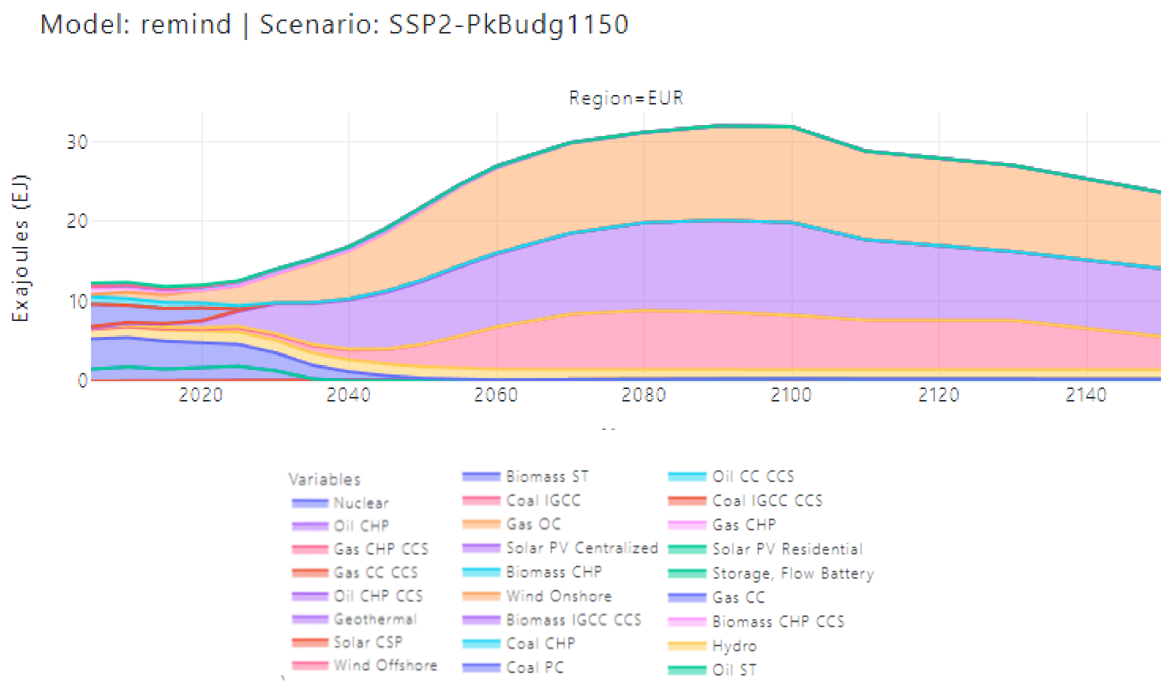

Figure B.3: Electricity production by technology SSP2 Remind Model [70]

The next figures show a more closer look at the same distribution of the electricity for the year 2035 and the learning curves of the years before and after it.

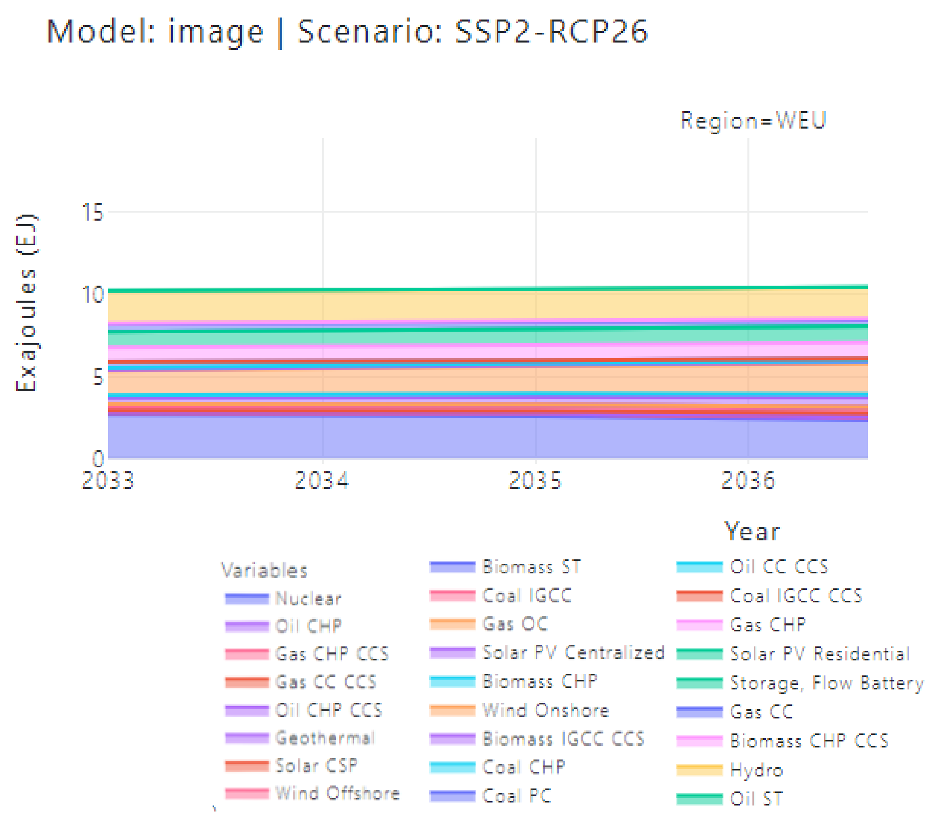

Figure B.4: Electricity production by technology SSP2 Image Model-2035 [70]

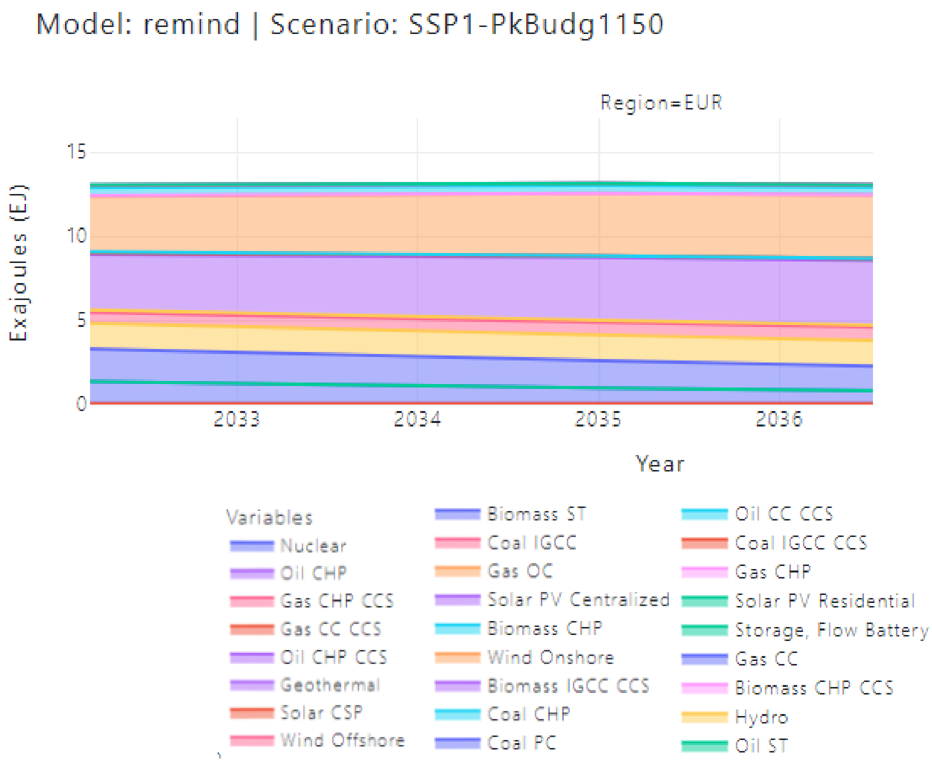

Figure B.5: Electricity production by technology SSP1 Remind Model-2035 [70]

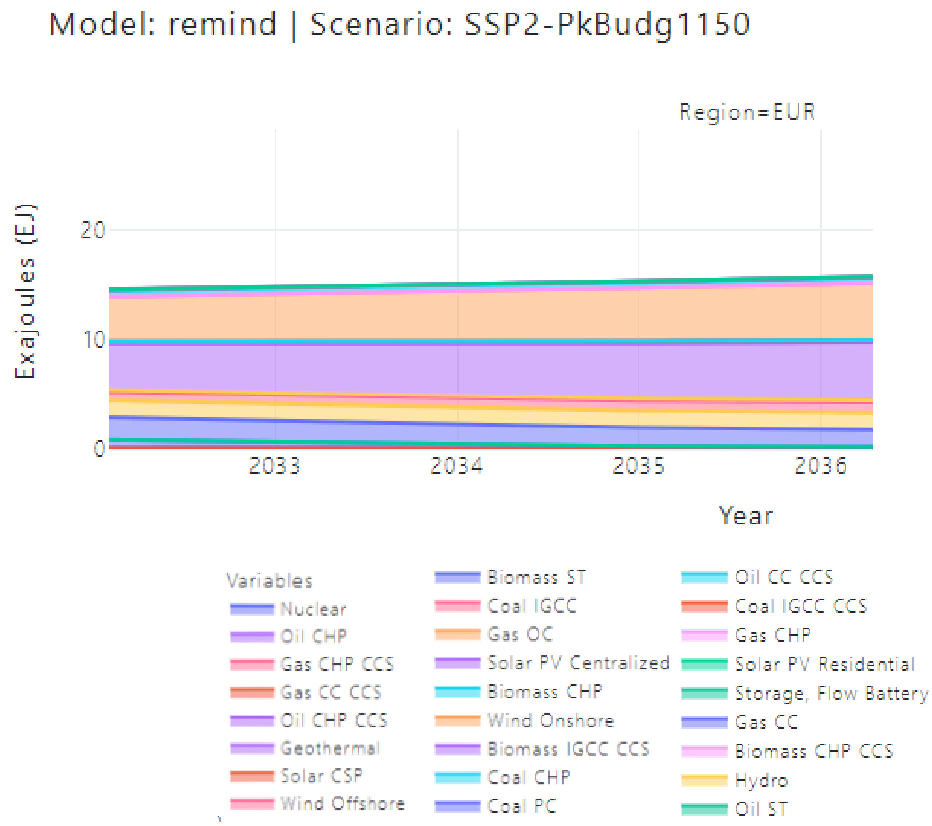

Figure B.6: Electricity production by technology SSP2 Remind Model-2035 [70]

C

Impact Assessment Results

C.1. Results for all the categories

The following table shows the results of complete BoS for all the impact categories, and for all the 4 scenarios.

Table C.1: Environmental Impact Data with Units

Database	Unit	SJH Production	SSP2-image	SSP2-remind	ssp1–remind
Climate change	Kg CO_2-eq	2.20E-02	1.3E-02	6.9E-03	8.8E-03
Terrestrial acidification potential (TAP)	Kg SO_2-eq	9.0E-05	4.6E-05	3.4E-05	3.7E-05
Freshwater eco-toxicity potential (FETP)	kg 1.4-DCB-eq	1.4E-02	9.2E-03	9.2E-03	9.2E-03
Marine ecotoxicity potential (METP)	kg 1.4-DCB-eq	1.7E-02	1.2E-02	1.2E-02	1.2E-02
Terrestrial ecotoxicity potential (TETP)	kg 1.4-DCB-eq	1.1E-01	8.7E-02	9.2E-02	9.2E-02
Fossil fuel potential (FFP)	kg oil-eq	5.6E-03	2.8E-03	1.7E-03	2.1E-03
Freshwater eutrophication potential (FEP)	kg P-eq	2.5E-05	1.4E-05	1.3E-05	1.3E-05
Marine eutrophication potential (MEP)	kg N-eq	1.2E-06	6.6E-07	5.6E-07	5.8E-07
Human toxicity potential (HTPc)	kg 1.4-DCB-eq	3.5E-03	2.3E-03	2.3E-03	2.3E-03
Human toxicity potential (HTPnc)	kg 1.4-DCB-eq	1.7E-01	1.1E-01	1.1E-01	1.1E-01

Continued on next page

Table C.1 – continued from previous page

Database	Unit	SJH Production	SSP2-image	SSP2-remind	ssp1–remind
Ionising radiation potential (IRP)	kg Co-60-eq	2.4E-03	1.5E-03	9.3E-04	8.7E-04
Agricultural land occupation (LOP)	$\mathrm{m^2\ crop-eq}$	1.6E-03	1.1E-03	1.0E-03	1.1E-03
Surplus ore potential (SOP)	kg Cu-eq	1.0E-03	7.1E-04	7.0E-04	7.1E-04
Ozone depletion potential (ODPinfinite)	kg CFC-11-eq	9.5E-09	4.5E-09	3.5E-09	3.8E-09
Particulate matter formation potential (PMFP)	kg PM2.5-eq	4.3E-05	1.7E-05	1.2E-05	1.3E-05
Photochemical oxidant formation: human health (HOFP)	kg NOx-eq	6.8E-05	3.3E-05	2.5E-05	2.7E-05
Photochemical oxidant formation: terrestrial ecosystems (EOFP)	kg NOx-eq	7.1E-05	3.4E-05	2.7E-05	2.9E-05
Water consumption potential (WCP)	$\mathrm{m^3}$	3.5E-04	2.4E-04	2.1E-04	2.2E-04

C.2. pLCA with new layer

In this section, the results for the prospective scenarios are discussed, with the addition of a SiOx layer. For the addition of this layer, the inventory was updated for silane, diborane and hydrogen consumption. Additionally, carbon dioxide was also required for this process but in a very small amount. Electricity and water usage were kept the same as before.

The results for the climate change impact category was evaluated as shown in the table below:

Table C.2: Global Warming Potential with and without SiOx Coating

Scenario	Without SiOx	With SiOx	Unit
SSP2-Image	0.012715	0.012850	Kg CO_2-eq/kWh
SSP1-Remind	0.006906	0.006959	Kg CO_2-eq/kWh
SSP2-Remind	0.008757	0.008764	Kg CO_2-eq/kWh

Although, the inventory used here is based on assumptions for SiOx deposition, it can be seen that there is an increase in impact by the implementation of SiOx layer, but it is so small that it does not make a noticeable difference. Therefore, it can be concluded that even if such a layer is added to enhance the overall cell performance, the environmental impacts of such a PV system would not increase by a lot.