Life Cycle Analysis of EXASUN Module

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LIFE CYCLE ANALYSIS OF EXASUN MODULE

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by

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ABSTRACT

This thesis deals with the Life Cycle Assessment (LCA) of the manufacture of an EXASUN X-Glass photovoltaic (PV) module to understand its true environmental impact. The methodology and general guidelines for conducting an LCA on a Photovoltaic (PV) system are developed, within the scope of this thesis. The LCA follows a standard framework, proposed by International Organization for Standards (ISO) and International Energy Association (IEA). LCA is a technique used to understand the total environmental impact of all the processes involved in the manufacture of a particular product. It takes into account all production process stages, to check the highest impact involved in production.

The results from this LCA study are obtained using the SimaPro software. These results quantify the production impact and aid in understanding where and how to improve the carbon footprint of associated production processes. The environmental impact categories from the ReCiPe 2016 assessment methods were used in this study. All the impact categories such as global warming potential, ozone depletion, photochemical ozone formation, etc. were taken into consideration. This includes all the mid point and end point categories offered by ReCiPe method. Additionally, the cumulative energy demand method was used to calculate the total renewable and non-renewable energies mix, used in the production process. Subsequently, using this information, impact categories such as energy payback time, net energy ratio and GHG emissions rate were obtained.

This study is based on the data obtained from Ecoinvent LCA database, accessed through the SimaPro software. This data was then changed according to the inventory update published by IEA PVPS. PV cell data was obtained from literature. However, the remaining materials used in the X-Glass module's manufacture were noted and their associated data was used to develop an appropriate LCA model. The model incroporated factors including transport, quantity, etc. The functional unit (FU) in this study is 1 m^2 of X-Glass production. For better analysis, all the impacts caused by manufacturing **1** X-Glass module were used to compare the results.

Results clearly show that the contribution of PV cells production to the environmental impact is high when mono-Si is used by the PV module. The energy requirements and geographical influence of these energy mixes that are involved in the PV cell manufacture are clearly explained. The cells for a typical X-Glass manufacture were modeled with a Chinese energy mix as the cells were produced in China. The energy payback time (EPBT) of X-Glass module installed in the Netherlands are 1.3 years with 73 g CO_2/kWh GHG emission rate. The CO_2 offset period was found be 3.9 years. These modules were then compared to a similar model developed for an European energy mix. The differences in results, due to the change in energy mix show that he energy payback time for manufacturing the same X-Glass module was found to be 1.3 years, with GHG emission rate of 32 g CO_2 eq. The CO_2 offset period for these was 1.7 years. The obtained results were cross-validated based on literature, outlining various LCA studies conducted on similar PV technologies. Thus, based on the results, it can be concluded that the environmental performance of X-Glass module was found to improve by 40% when cells from Europe are used as the EPBT of EU based model was found to be 1.3 years with an emission rate of 32 g CO_2 eq.

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's-Gravenhage, September 2020.

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LIST OF ACRONYMS

APAC	Asia Pacific
BIPV	Building Integrated Photovoltaics
CDP	Committee for Development Policy
CED	Cumulative Energy Demand
CN	China
Cz Process	Czocharlski Process
EG-Si	Electronic Grade Silicon
EPBT	Energy Payback Time
FU	Functional Unit
GHG	Green House Gases
GLO	Global
GWP	Global Warming Potential
LCA	Life cycle Assessment or Life cycle Analysis
LCI	Life Cycle Inventories
LCIA	Life Cycle Impact Assessment Analysis
MG-Si	Metallurgical Silicon
mono-Si	Mono-crystalline Silicon
NREPBT	Non-Renewable Energy Payback Time
NYR	Net Energy Ratio
ODP	Ozone Depletion Potential
PV	Photovoltaics
RoW	Rest of the World
SDG	Sustainable Development Goals
UN	United Nations
US	United States

1 INTRODUCTION

The word *Sustainability* or *Sustainable* gained interest as a clear environmental and social aspect in the 1970's [1]. According to Jeremy L. Caradona, the earliest book about sustainability found was in 1976 [2]. Since then sustainability has been used more often in the context of sustainable human life on Earth. Sustainability gained lot more attention after being cited in the definition of sustainable development and sustainability in the United Nations (UN) General Assembly on March 20, 1987. The definition states "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs [3]." Moreover, the UN developed various blueprints called Sustainability Development Goals (SDGs) and urged many countries to follow the goals to create a sustainable future. There are currently 17 goals relating to poverty, inequality, climate change, environmental degradation, peace and justice to be achieved before 2030 [4]. According to a report developed by the Committee for Development Policy (CDP) on SDG scores, *Goal 13* on *Climate change* is given the second most attention after *Goal 17* on *Global Partnerships* [5]. Furthermore, in 1992, the UN established a UN Framework Convention on Climate Change Secretariat (UNFCCC) and effectively work at intergovernmental climate change negotiations and analysis & review of climate change information [6]. In order to fasten up the process on Climate change issue, the UNFCCC made the well-known Paris Agreement in 2015. The major goals of the Paris Agreement are [7],

- to mitigate climate change by bringing down this century's global temperature increase to below 2^oC.
- to improve a country's ability to cope with the climate change.
- to plan steady financial flows with low Greenhouse Gas (GHG) emissions.

The above discussed goals show that global temperature rise and GHG emissions play a major role in the climate change.

Gases like Carbon dioxide, Methane, Nitrous oxide, Flourinated gases (F-Gases) do not allow heat to escape the atmosphere. These are called Greenhouse Gases (GHG). Figure 1.1 shows the annual share of different types of GHG gases emitted(tonnes) in the year 2014 [8]. From the figure, Carbon dioxide gas has major share in the GHG emissions with 65% from fossil fuels(man made emissions) and 11% from forestry(natural emissions from trees). Hence, carbon dioxide is considered to be one of the most important greenhouse gases.

Figure 1.2a shows the graph of annual CO_2 emissions (tonnes) in different regions. From the graph 1.2a, increase in global CO_2 emissions from 6.37 billion tonnes in 1950 to 36.58 billion tonnes in 2018 can be observed. Moreover, the reason for this drastic raise in GHG emissions can be understood from figure 1.2b showing the plot of Annual CO_2 emissions(tonnes) by fuel type. Comparing the above CO_2 emissions value depicts that the fuel type has a major influence on the emissions. Furthermore, figure 1.3 shows the annual CO_2 emission share by different sources. The energy production has a maximum CO_2 emission share of 61%. This maximum share correspond to the type of fuel used in the energy production. The energy generations from non-renewable sources like coal, gas and oil are one of the major reasons for this drastic increase in the CO_2 emissions.

Now, considering the above discussed points, we can conclude that using a sustainable source of fuel to produce energy will help in bringing down the emissions.

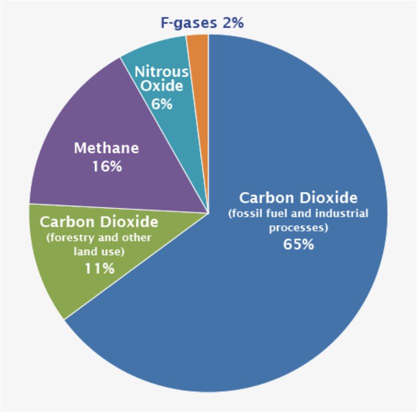
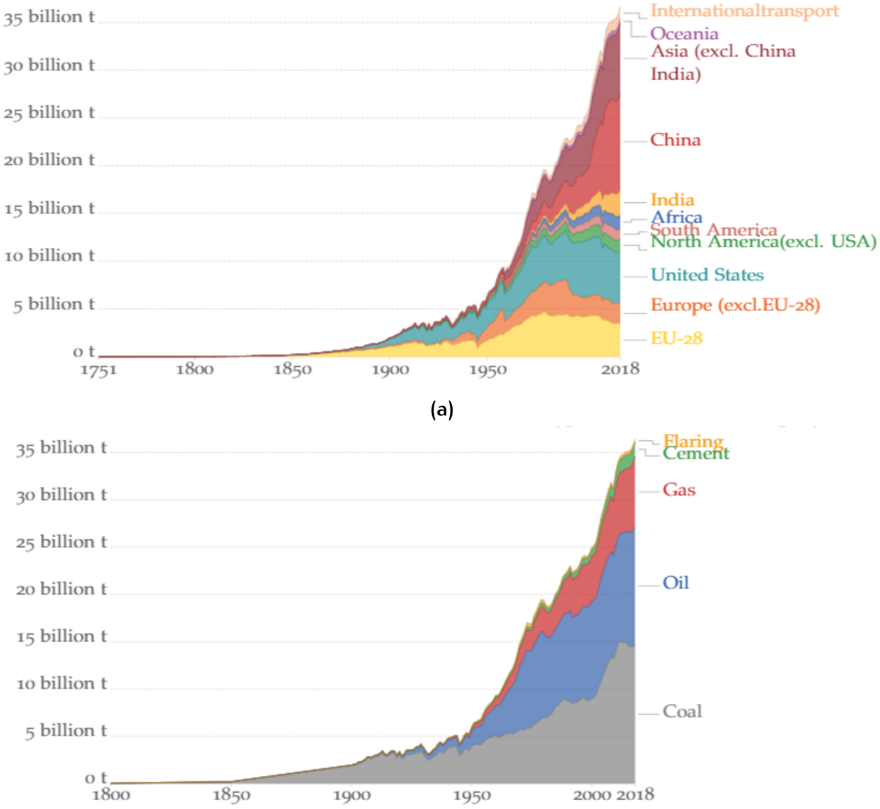


Figure 1.1: Global GHG emissions by gas [8].



(a)

(b)

Figure 1.2: **(a)** Annual Global CO_2 emissions in tonnes *(EU-28 : 28 European Union Countries)* [9], **(b)** Annual Global CO_2 emissions by fuel source [10]

As energy sector has the highest share in CO_2 emissions, changes in the sector will heavily influence the output. Figure 1.4 shows the graph of annual share of renewables in global percentage share of power generating capacity by renewable and non-renewable energy. The capacity to generate power from a renewable source has been gradually raising from 2018. The share of renewable has crossed the half way 50% line in since the late 2011. Moreover, figure 1.5 shows the global power capacity of different renewable energy sources installed annually (2012-2018). The graph depicts the trend of 4 renewable energy sources like solar, wind, hydro, biofuels and geothermal, etc. It also shows the total renewable power generation trend from 2012 to 2018 reaching 181 GW. It can be observed that for the past 3 years (2016-2018) there has been a linear increase in Solar Photovoltaics (PV) production with the highest capacity share of 55% surpassing Wind and Hydropower [12].

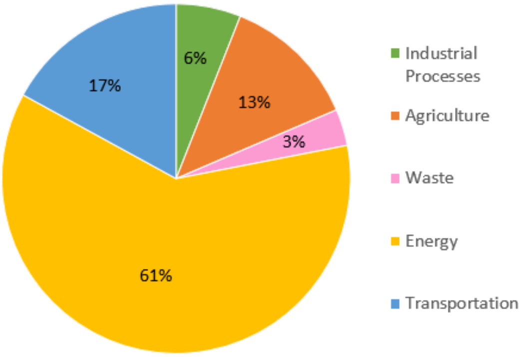


Figure 1.3: Annual CO_2 emission share percentage by different sources [11]

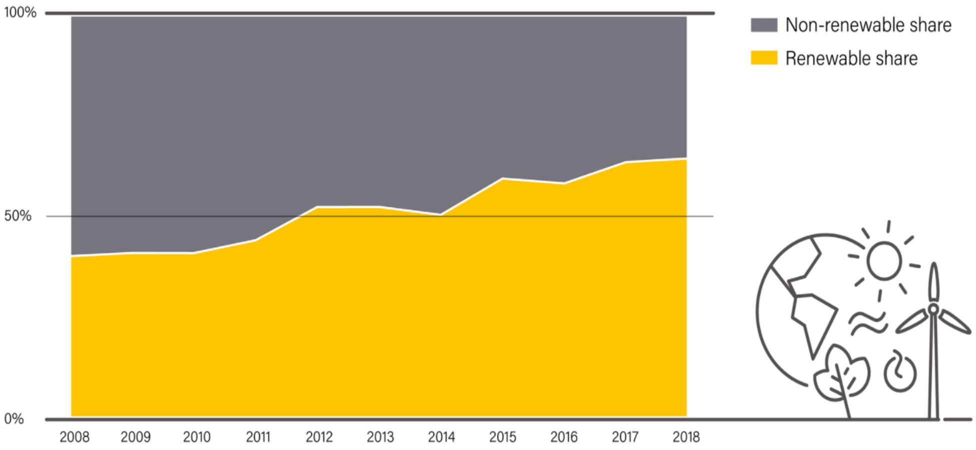


Figure 1.4: Global Percentage share of Power Generating Capacity depending on the type of generation, (2008-2018) [12].

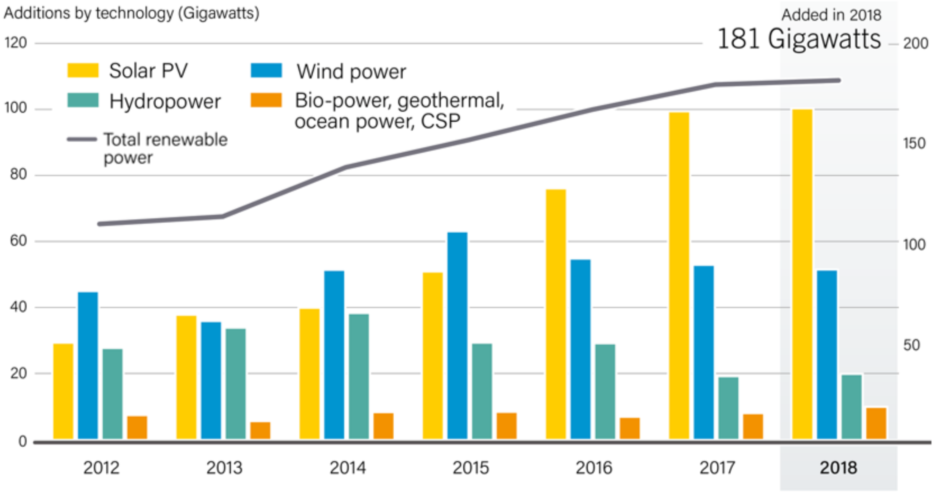


Figure 1.5: Annual Additions of Renewable Power Capacity by technology 2012-2018) [12].

The main reasons for this sudden increase in PV capacity are [12],

- the urge to produce energy in a sustainable manner to reduce the global warming.
- reduced costs of PV modules

- introduction of new pricing, policies and technologies in the PV system

Components of PV systems may be different depending on the type of PV system. The solar cells within the PV modules convert the sunlight to electricity, so the modules are one of the crucial components in the PV system. To provide more sustainable energy, extensive research is being carried out on PV technologies to achieve groundbreaking cell efficiencies, thinner modules, coloured modules, etc. However, most of the major PV module manufacturers fail to consider the environmental impact of manufacturing a particular PV module. Knowing the impact of a PV module's production on environment will give a better idea on how sustainable photovoltaics truly are. Having enough details on the environmental impact of a PV module is useful for the designers and engineers to design a sustainable building.

The environmental impact of manufacturing a product can be found by performing Life Cycle Analysis (LCA) of the product. A brief discussion on basics of LCA is carried out in the next Section 1.1.

1.1 LIFE CYCLE ANALYSIS

1.1.1 What is LCA?

"Life Cycle Analysis is a well-defined method to calculate the environmental burden of a product or service [13]." In other words, Life Cycle Analysis or Life Cycle Assessment (LCA) computes the environmental impact caused in the life cycle of the product considering the manufacture and energy flows. A basic LCA system framework is shown in Figure 1.6.This general framework is described in the **ISO14040** and **ISO14044** [14], [15].

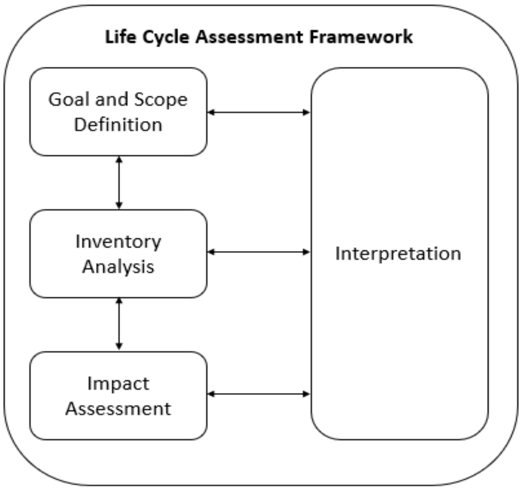


Figure 1.6: The basic LCA Framework[16]

1.1.2 Goal and Scope Definition Phase

The goal and scope phase of an LCA is a key factor that must include the background of the study and must determine how the results are reported considering geographical locations[16]. The following are some of the important technical details that must be included in the goal and scope of the study [17],

- **The Functional Unit (FU)** - must be defined initially. FU is the unit of the system being studied. It helps in setting a reference to easily analyze and relate between the inputs and outputs [18].

- **The system boundary** - must set a boundary on what processes to include and exclude in the analysis of the system [19].
- **Assumptions and limitations** - any assumptions regarding raw materials or energy must be stated clearly
- **Data quality** - the details regarding the quality of the database considering country of study, data range, etc. must be included[20].
- **The impact categories** - must contain details regarding what environmental impact categories are included in the study like Global Warming Potential (GWP), Ozone Depletion Potential (ODP), etc [20].

1.1.3 Life Cycle Inventory (LCI) Phase

This phase includes the collection of data for the LCA calculations. This data must include detailed information regarding raw materials, processing, energy flows, water & heat use and finally emissions to air, water, and soil by each process (unit processes).

1.1.4 Life Cycle Impact Assessment (LCIA) Phase

This phase analyzes the environmental impact caused by the emissions involved in each of the unit processes. It includes detailed explanation of different environmental impacts, process-wise effect (e.g. copper treatment impact) and substance-wise effect (e.g. ammonium, fluorine impact) effect on the environment.

1.1.5 Interpretation Phase

This phase includes the analysis of results from the LCI and LCIA phases with conclusions and recommendations.

1.2 EXASUN

EXASUN is an innovative Dutch Solar PV manufacturing company based in Den Haag, The Netherlands. Glass-Glass solar modules with a high efficiency and a lengthy lifetime are produced at EXASUN. In addition to the Black Glass module (60 cells, 1 × 1.6 m), the company also produces innovative Building Integrated PV (BIPV) modules for a waterproof PV-roof (Black Roof) and for PV facades (Black Facade). EXASUN started its production line with an initial capacity of 150 MW at the current Dutch location in 2017. The main aim of EXASUN is to reduce the cost of solar electricity, by means of local production and local suppliers.

1.3 GOAL AND SCOPE OF THE PROJECT

The main goal of the study is to analyze the environmental impact in the manufacturing of EXASUN produced PV panel particularly **X-Glass PV panel**. X-Glass is a standard 320 Wp PV panel with 60 mono-crystalline silicon (mono c-Si) cells. It is a glass-glass module with a working guarantee of 30 years. More specifications about the X-Glass module is included in the appendix section A.1 and can aslo be accessed via the EXASUN website [21]. In this report, the LCA calculations will follow **Attributional** approach with respect to the methodology guidelines on PV created by the International Energy Association (IEA). The attributional LCA (also called Retrospective LCA) is used to analyze currently installed PV systems and to compare different PV systems or technologies [22]. The assumptions and recommendations regarding this LCA approach will be discussed in the section 2.3. More information regarding different approaches and their recommendations are discussed later in the methodology guide [22]. All the impact assessment categories will be analysed in this study focusing mainly on GHG emissions, Cumulative Energy Demand (CED) and Energy PayBack Time (EPBT). The scope of the study was based on recent LCA literature to use the latest available technology. LCA research published after 2012 was referred and an appropriate model was developed with latest energy update until 2018.

Depending on the goal and scope of the study, there are numerous ways to analyse the effect of environmental impact of a PV Technology. EPBT and CED are the most influential categories that helps to understand the significance of PV's impact [23]. Additionally, GHG emissions are equally important to understand the impact. All these impact categories slightly vary but have similar order of magnitudes when compared between different LCA literature. The reason for this difference could be due to the use of different processes, electricity mixes of manufacturing country, technology, [23] etc. These effects will be discussed in detail later in the results chapter 5.

A gate-to-gate LCA will be conducted on manufacturing process of the EXASUN panel including all the materials, water, energy, heat used in the process. A cradle to gate analysis is calculated since creation of each unit process until the final manufactured product reaches the gate of the factory excluding use and recycle stages. The materials used for the production of an EXASUN panel is purchased from different locations and is transported to The Netherlands. The known details about the country of origin where the materials were manufactured will be modeled appropriately including transportation. The environmental impact of balance of system(BOS) for silicon-based technologies have remained constant [23], so the BOS will not be considered during the LCA model development in this study.

Table 1.1: Parameter Inventory and their respective units

Parameter	**Unit**
Functional Unit	1 m^2 of PV module
CED	MJ per m^2 of PV module
EPBT	years
GHG emissions	kg CO_2 eq.per m^2 of PV module

The results of EXASUN LCA model will not solely be enough to make conclusions on environment impact. So, using previous LCA studies, creating similar models for PV panels with cells manufactured in Europe will be useful to compare the major influences in the production of a PV panel. The comparison will also provide information on how the environmental performance of the EXASUN panel is compared with other panels produced in other locations.

The unit processes that influences modules performing comparatively better in other locations will be analysed and the factors influencing those performance will be noted. Using these factors, a X-Glass EU model will be developed considering all the factors to compare the environment impact. The results of X-Glass EU model will then be compared with the original model to check whether the changes are feasible technologically and economically. Finally, the results of EXASUN panel model will be compared with some of the models from literature and the major differences will be discussed for a better understanding of the EXASUN panel's impact on the environment.

1.3.1 Research Questions

1. What is the environmental impact of manufacturing X-Glass module
   The main aim of this study was to check the environmental impact of manufacturing the X-Glass.

2. Which material has most influence on the environment?
   The materials used in the manufacture of X-Glass module must be analysed and the most influential material must be determined.

3. What is the Energy Payback Time (EPBT), Net Energy Ratio (EYR), GHG emission rate, CO_2 offset period of the X-Glass module?
   The EPBT, NYR, GHG rate and offset period must be determined for the X-Glass module.

4. How do these values compare to other literature and how can the impact be reduced?
   The results will be validated with recent literature and check the factors affecting these result values. Further, possible solutions will be suggested to improve the enviromental performance of the X-Glass module.

1.3.2 Structure of the report

In chapter 1, a basic introduction to sustainability and LCA was covered. The rest of the report is organized as follows. In Chapter 2, discussions about the tools and database analysis used during the course of this project with basic information regarding basic database and impact assessment analysis are covered. In chapter 3, a basic comparison of several LCA studies with assumptions and important factors that affect the results are discussed. The information regarding a the manufacturing steps of PV modules are covered in Chapter 4. Additionally, the details PV cell manufacturing process and data collection to develop a model are also explained in this chapter. The results are analyzed and discussed covering each impact category in Chapter 5 including the results of X-Glass EU panel. This chapter also has the discussions on comparison of all the developed model's results to the PV panel results from research papers. Finally, the conclusions based on the arrived results and some recommendations for better environmental performance were discussed in Chapter 6.

2 TOOLS AND DATABASE ANALYSIS

Extensive research on LCA of different PV technologies has been carried out for the past 30 years [24]. Before discussing about the research on PV LCA, it is important to decide on which LCA tool to use depending on the study. A brief discussion about the software, database, and Life Cycle Impact Assessment analysis is covered in the next sections.

2.1 SOFTWARE ANALYSIS

The general framework for LCA was introduced in the previous chapter, section 1.1. Since the 1990s LCA tools have had a gradual development as the policies on climate change and sustainability developed. There are several LCA tools available depending on the purpose of study[25]. Table 2.1 shows some of the important software tools and their details that are used to perform LCA.

	openLCA	**SimaPro**	**GaBi**
Free version	yes	no	no
Student Pricing	free	yes	yes
Product Footprint	yes	yes	yes
Full LCA Report	no	yes	yes
Developed by	GreenDelta©	PRé consutants©	previously- ThinkStep; now- Sphera

Table 2.1: LCA Softwares and some descriptions [25]

2.1.1 openLCA

openLCA software was developed in 2006 with an idea to develop a life cycle modelling software that is fast and efficient. Additionally, the software was designed to help users create their own modules for framework of the software [26]. openLCA gives access to many databases. The major advantage of using openLCA is that it is an open-source software [25]. However, most of the database offered by openLCA are not free to use.

2.1.2 GaBi

GaBi was developed in the 1990s and it is a powerful LCA tool for the following applications [27],

- Life Cycle Assessment
- Life Cycle Costing
- Life Cycle Reporting
- Life Cycle Working Environment

Even though many industries rely on GaBi LCA calculations extensively, it is mainly used in its country of development, i.e., Germany [25].

2.1.3 SimaPro

SimaPro is used globally as it provides users flexibility to model a system from scratch, which is not possible in GaBi. SimaPro has been widely used LCA software for industrial and academic research in more than 80 countries, for more than 30 years [28]. It is a complex software with many databases and impact assessment methods that helps users analyze the LCA calculations in detail[25].

Any of the aforementioned software tools can be used for LCA calculations depending on the availability of the software, databases, and impact assessment methods. In this thesis, **SimaPro - Student License (Industrieel Ontwerpen - TU Delft)** was used for the LCA calculations. There were 2 main reasons for considering this software:

- Availability through institutional access.
- It is the most widely used software [28]. Many LCA researchers from the committee of International Energy Association (IEA) have used SimaPro to analyze the LCA results on PV in their research work[29, 30].

There are also other software tools like Ecochain, Mobius, oneclicklca, etc. each having their own advantages for a particular field of study. Detailed information regarding these tools is tabulated in A.1 and in the Appendix A.2.

2.2 SYSTEM MODELS

The basic life cycle inventory modelling aspects were discussed in the methodology and guidelines for LCA on PV Electricity developed by Task 12 of the IEA. This guide helps users to develop a consistent and balanced LCA model with quality data to improve the integrity of the obtained result[22]. The methodology guide proposed 3 different approaches depending on the goal of study and they are,

- **Attributional LCA**
  1. Environmental impacts of currently installed PV system
  2. Comparing different PV systems or technologies
  3. Comparing future PV systems or technologies, also known as future attributional LCA or long-term propective LCA.
- **Decisional LCA**
  1. Selecting an appropriate PV supplier
  2. Raw material or energy supplier comparison
- **Consequential LCA**
  1. Large scale of PV electricity analysis
  2. Long term energy supply in grids of nations and regions

As discussed in the section 1.3, LCA calculations were based on **attributional** approach as the goal of the study to analyse the environment impact of EXASUN PV panel. The guide provides basic assumptions and recommendations depending on the type of LCA study. For attributional approach, the following are the two major recommendations proposed [22],

- The current average electricity grid mix must be included depending on the country of manufacture.
- If a PV material is manufactured in a different county, then the country-specific electricity can be selected.

- The level of country-specific electricity used must be clearly interpreted to avoid misunderstandings in the different regions used.

All these proposed recommendations were considered while developing the model for the LCA studies.

2.3 DATABASE ANALYSIS

The student license of SimaPro offers a wide range of databases that are listed with relevant documentation in SimaPro Libraries Manuals [31]. Database is a structured collection of multiple data sets accessed electronically using a software like SimaPro (E.g., Ecoinvent, IDEMAT, etc.). Data sets are collection of data in database corresponding to a particular process or product(E.g, Glass manufacture, Glass tempering process, etc.) [32]. Initially, different databases were considered before the start of the LCA modelling. The selection of a database was based on the literature study. LCA experts of the Task 12 along with the Swiss Federal Offices have also been gathering and compiling PV related Life Cycle Inventory (LCI) data in the **Ecoinvent** database and the latest updated report published in 2015 [33]. These are publicly available and updated data sets that were compiled in *Ecospold v1* format into the Ecoinvent **v2** database. However, these databases are not updated into the latest version of Ecoinvent **v3** [22]. The selection of an appropriate database can be done by analyzing recently published literature on LCA of PV. Table 2.2 shows the different databases and impact assessment methods used in the latest research on PV LCA. More details regarding the ecoinvent versions and impact assessment methods are discussed in the subsequent section 2.3.1.

Table 2.2: Database used by recently published LCA papers on PV

No.	Research Papers	Year	Ecoinvent Version
1.	Rashedi et al.[34]	2020	v3.1
2.	Li T et al.[35]	2020	v3.1
3.	Fthenakis et al.[30]	2017	v2.0
4.	Kabaskian et al.[36]	2015	v2.2
5.	Lamantaou et al.[37]	2015	v3.0
6.	de-wild Scholten et al.[38]	2013	v2.2

2.3.1 Ecoinvent

Table 2.3 shows the different versions of Ecoinvent database over the years. Currently, SimaPro provides users with both v2 & v3 versions of Ecoinvent database for LCA calculations. Ecoinvent database is the most widely used life cycle inventory database worldwide for most LCA based research since 2007 [39]. From table 2.3, it can be observed that Ecoinvent **v3** is the latest version consisting of latest information regarding factors such as energy, transport, etc. However, PV related LCA research is carried out in both **v2** & **v3** (from table 2.2). As discussed earlier(section 2.3), data compiled and updated by Task 12 of IEA was done in ecoinvent v2.2 database with the latest update in 2018. These v2 data sets are maintained in a library called **UVEK 2018** of ecoinvent database.

UVEK 2018

UVEK is an abbreviation for Umwelt, Verkehr, Energie und Kommunikation (UVEK), when translated they are Environment, Transport, Energy and Communications. Jungbluth et al.[40] conducted a study on LCA of PV power plants in

Table 2.3: Ecoinvent versions over the years with general description [39].

Ecoinvent Version	Year	Description
v1.1 to v1.3	1994-2007	Developed by Swiss Fedral offices
v2.0 to v2.2	2007-2013	Extension and revision of v1 contents
v3.0 to v3.6	2013-present	2,200 new and 2,500 updated data sets relating to various fields like building and construction materials, chemicals, electricity, metals, transport and recycling, waste treatment, etc. in various locations.

Switzerland on behalf of the Swiss Federal Office of Energy (SFOE). The data collected during this study from manufactures and researchers were uploaded in the Ecoinvent database. Moreover, the data was continuously updated by IEA Task 12 committee (Frischknecht et al.[33]). This contains about 5147 data sets that are based on ecoinvent v2.2. The public LCI report & the *Ecospold v1* format of the database can be downloaded in the ESU-Services website [24]. The data sets of many different fields in the UVEK 2018 database were updated recently with major changes in [41],

- **Photovoltaic** - 3kWp PV power plant, slanted roof plant, etc.
- **Electricity** - production (EU and other countries), ENTSO-mix, etc.
- **Power Production** - run-of-river hydro-power, nuclear power, etc.

Other fields like aluminium, natural gas, refinery products, etc. were also included in the update. A detailed information regarding the UVEK2018 update is listed in table A.2 of the Appendix (section A.3). In this library, PV related data update was extensive that included various LCA models for different types, capacities and technologies of solar power plants. Some data sets were updated for the year 2016 and some for 2018. As the basis of this database was v2.2, it could not be used in the Student version of SimaPro. The databases and LCIA methods in student version of SimaPro can be accessed only through online institutional server. However, the UVEK database could not be loaded to the online server. So, UVEK data was accessible but was unavailable to in LCA calculations as the database has only inventories without LCIA methods. Moreover, this data set could not be imported into the software through ecoinvent v2.2, i.e., one of the databases offered in SimaPro. Further, manually changing the data in the SimaPro offered ecoinvent 2.2 was not possible as it was outdated without any recent updates. Hence, in this study, **Ecoinvent v3.6** database was used in the LCA calculations.

Ecoinvent v3

The v3 of Ecoinvent database consists of more than 10,000 data sets with 2,200 new and 2,500 updated data sets and 240+ new products [42]. However, datasets related to PV are not as extensive as in UVEK2018 that had datasets for various power plants. In this version of ecoinvent, the cell and panel related data sets were directly taken over from previous Ecoinvent v2.2 database that was developed using the study conducted by Jungluth et al [43]. However, these data sets were not updated by the IEA Task 12 in the currect ecoinvent version with the last updated on 2009. The recent updates on this data were published in 2015 [33]. These published cell and panel data were used in Ecoinvent v3 to develop a model for this LCA study. SimaPro provides the following three different models of ecoinvent v3 database,

1. Consequential [44]:

    - The consequential model is also called Substitution or Long-Term model is used to analyze large scale PV electricity.
    - It is also used to analyze the consequences of small-scale, long term decisions with respect to the time frame of the produce.
    - This model expands the system combining multi-product systems to a single product.

2. Allocation, at cut-off [45]:
    - This model is also called allocation, recycled content system model
    - Simple to use and easy to understand.
    - Used in the previous versions of Ecoinvent v1 and v2.
    - In this model, the benefits of recycling a material will not be considered for a process. If a certain material is recycled, then the credits for recycling the material will not be attributed to the primary producer. For example, recycled paper process considers only waste paper collection and their recycling process without any burdens from the primary paper productions.
3. Allocation, at the point of substitution (APOS) [46]:
    - This model is also called allocation, default system model.
    - It follows attributional approach, i.e, all the burdens are applied to corresponding process including the recycling and waste treatments.
    - Consistent approach avoiding infinite burden-free materials.

More information regarding the system models can be found in the Ecoinvent and SimaPro website [47, 44]. The selection of an appropriate model is based on the goal of the LCA study [22]. Since this LCA study is based on attributional approach as discussed in the section 2.2, the consequential model was not considered. While developing a model for EXASUN, for some processes in the cell production recycling process and waste treatments were added as per the literature. So, **APOS model was preferred in this LCA study**. Now that a suitable inventory database is selected, an appropriate LCIA method must be selected to calculate the environmental impact of a specific material.

The software offers 2 versions, unit and system process for all the above mentioned models. In unit process, many processes are interlinked to one process and also provides more information regarding environmental hot-spots and supply chain analysis [46]. For example, PV cell production and glass production are unit processes that are linked in the PV module production unit process. It also helps users to understand the process conditions and the relationship between data sources [48]. Whereas, system process only include environmental flows of its respective unit process and the sub processes contributing to the main unit process cannot be accessed or changed [46]. **The unit process model is considered for this study** to analyze the impact of various materials that are used in the manufacture.

2.4 LIFE CYCLE IMPACT ASSESSMENT (LCIA) ANALYSIS

The 3^{rd} step in the LCA calculation framework is the LCIA phase (from figure 1.6). There are various LCIA Methods offered by SimaPro with the following as a common structure [49],

1. Characterization - Relative contribution of a substance is showed by multiplying a characterization factor to the substance that affects an impact category. (E.g., 1 kg methane = 25 kg CO_2)

2. Damage Assessment - This helps in combining the many impact categories into a limited number of damage categories. Generally, there are 15-20 impact categories and 3-4 damage categories depending on the LCIA method.

3. Normalization - This helps in comparing the impact category results by using a normal or reference value.

4. Weighting - The impact categories are converted to a total or single score by multiplying a weighting factor.

The structure depends on the impact assessment method used and may vary method to method. There are numerous LCA studies that used different LCIA methods in their calculations (from table 2.2) depending on the goal and scope of the study. In this study, all the major impact categories are analysed and compared focusing mainly on the GHG emissions, CED and EPBT for comparison as proposed in the methodology guide for PV LCA [22]. In order to analyse the impact categories, selection of an appropriate impact assessment method in SimaPro is an essential step. Based on literature, the following are the three most commonly used methods for PV LCA calculations (the method versions vary with respect to the time of study),

- Centrum voor Milieuwetenschappen Leiden - Impact Assessment (CML-IA)
- ReCiPe
- IPCC
- Cumulative Energy Demand (CED)

SimaPro software offers several other impact assessment methods, while some impact assessments like EPBT, EYR (Energy Yield Ratio) are to be manually calculated.

2.4.1 CML-IA

This impact assessment method was developed by CML (Center of Environmental Science of Leiden University) scientists in 2001 with a latest update implemented in August 2016 [49]. This is an European method that is further subdivided into two versions depending on the characterization factor,

1. **baseline version** - 10 impact categories

2. **extended version** - more than 15 impact categories within certain time frame depending on the scope of the study.

2.4.2 ReCiPe 2016

This is a global method and the latest version of this impact assessment was an extended version of ReCiPe 2008. This is the most advanced impact assessment methods with 18 midpoint characterization factors and 3 endpoint level [34]. Midpoint categories are problem oriented, while endpoint are damage oriented categories [49]. The advantages of CML-IA (mid-point based analysis) and Eco-indicator 99(endpoint based analysis) are combined into this one method [34]. These 18 midpoint characterisation factors are aggregated to 3 endpoint categories through the damage pathways. This relation can be calculated using the following equation as discussed by M. Huijbregts et al. in their study on ReCiPe method [50],

$$CF_{end_{x,a}} = CF_{mid_x} X F_{M\rightarrow,E,a} \tag{2.1}$$

where,
CF_{end} - Endpoint Characterization Factor
CF_{mid} - Midpoint Characterization Factor

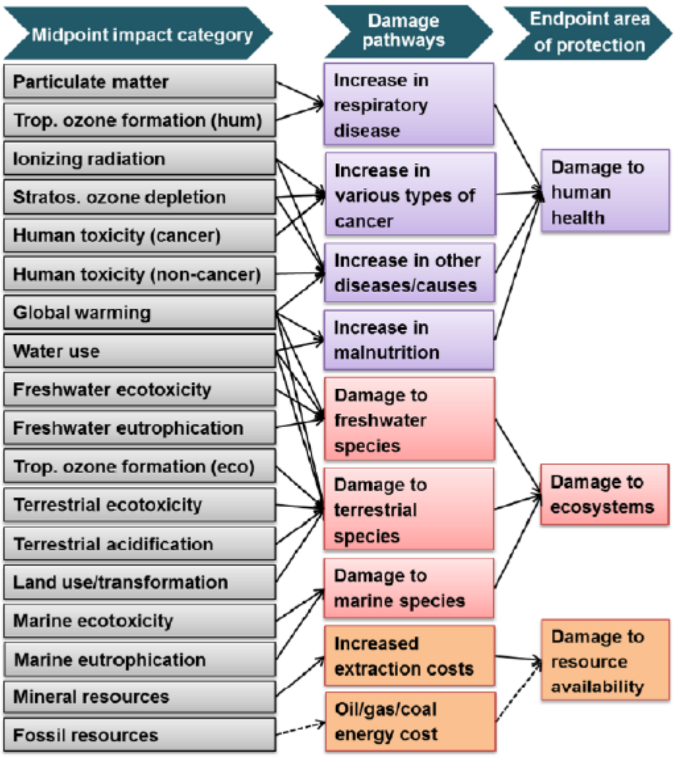


Figure 2.1: Relation between Midpoint and Endpoint level Impact Categories

$F_{M \to ,E}$ - Midpoint to Endpoint conversion Factor
a - area of protection i.e. human health, ecosystems, etc.
x - type of impact
The conversion and characterisation factors vary with respect to the mid point and endpoint categories and the unit changes accordingly. This relation is depicted in the figure 2.1 showing the midpoint categories causing multiple damages in different fields and these are finally aggregated into the 3 endpoint impact categories.

This study mainly focuses on X-Glass production's environmental impact. Therefore, detailed analysis of the categories and their relationship is not the focus of this thesis. Nevertheless, additional information regarding these categories is extensively discussed in the ReCiPe 2016 manual [51]. There are 3 perspectives in this method. These perspectives are groups with similar assumptions sorted and combined together. The perspectives are [50],

- **Individualist**: short time frame, usually 20 years. Optimistic approach in which the technology used can avoid many problems in future.

- **Hierarchist**: consensus model, generally used in scientific research. This is considered to be the default model with time frame of 100 year.

- **Egalitarian**: long term perspective with time frame of 1000 years and it is considered the most precautionary perspective.

The default and most common perspective with respect to time range is **Hierarchist (H)** perspective. The difference between the perspectives is explained in detail in ReCiPe2016 [50]. In this study, the advanced **ReCiPe 2016 method, Hierarchist(H) perspective** method will be used to analyze the results focusing on the the midpoint characterization factors. Additionally, Cumulative Energy Demand method was also used to manually calculate EPBT.

2.4.3 IPCC [49]

This method is a single issue method that gives the climate change factors as calculated by the IPCC. The most recent version was developed in 2013, as an extension to the IPCC 2007 study. Different versions of IPCC method are adopted by various other impact assessment methods, including the above discussed CML-IA and ReCiPe methods to calculate climate change or GWP.

2.4.4 Cumulative Energy Demand (CED)

The direct and indirect energy consumed in the whole life cycle of a product, including extraction, manufacturing, transportation, disposal, and recycling is termed as the CED of the product [52]. This method was developed and updated by Ecoinvent with the following characterization factors,

- Non-Renewable, fossil
- Non-Renewable, nuclear
- Non-Renewable, biomass
- Renewable, biomass
- Renewable, wind, solar, geothermal
- Renewable, water

The information regarding several other impact assessment methods like Ecoindicator 99, Greenhouse Gase Protocol, etc. offered in SimaPro are discussed in detail in the Database Manual- Methods Library created by Pre Consultants [49].

2.4.5 Energy Payback Time (EPBT) & Non-Renewable Energy Payback Time (NREPBT)

The basic definition of energy payback time proposed in the Solar Energy book is the total energy consumed by the product during its entire lifetime over the annual energy yield of the system [53],

$$EnergyPaybackTime = \frac{total\ invested\ energy}{average\ annual\ energy\ yield} \tag{2.2}$$

The EPBT value of a system depends on various factors such as PV array orientation, annual solar irradiance, etc.[53].

Moreover, a similar definition was proposed in the methodology guidelines on LCA of PV by R. Frischknecht et al. stating that the EPBT of a renewable energy system is the time taken by the system to compensate the energy that was used for the production of the system itself [22],

$$EnergyPaybackTime = \frac{E_{mat} + E_{manuf} + E_{trans} + E_{inst} + E_{EOL}}{((E_{agen}/\eta_G) - E_{O\&M}} \tag{2.3}$$

where,
E_{mat} - Primary energy demand to produce materials in PV system (MJ),
E_{manuf} - Primary energy demand to manufacture the PV system (MJ),
E_{trans} - Primary energy demand to transport the materials used in life cycle (MJ),
E_{inst} - Primary energy demand to install the system (MJ),
E_{EOL} - Primary energy demand for end-of-life (MJ),
E_{agen} - Annual Electricity Generation (MJ),
η_G - Grid efficiency (kWh per MJ),
$E_{O\&M}$ - Annual primary energy demand for operation and maintenance (MJ),
Using the above equation (2.3), two further approaches were proposed in the methodology guide [22],

- EPBT - In this approach, both renewable and non-renewable primary energy consumed during the whole lifetime are considered, to calculate the payback time of the PV system. This gives the time period required to compensate all the consumed energy.
- NREPBT - In this approach, only Non-Renewable primary energy consumed during the life cycle of the PV system is considered, as indicated in equation 2.3. This is called non-renewable energy payback time, i.e., the time required to compensate only the non-renewable energy consumed.

Considering both of the aforementioned definitions, Akinyele et al. provide the following simplified equations to calculate the EPBT of a system [54],

$$EPBT = \frac{CED}{AEO}.\eta_G \tag{2.4}$$

where,

$$AEO = S_{irr}.A_{pv}.\eta_{pv}.PR \tag{2.5}$$

CED - Cumulative Energy Demand (MJ),
AEO - Annual Energy Output (kWh),
η_G - primary energy to electrical energy conversion factor,
S_{irr} - annual solar irradiation (kWh/m^2/yr),
A_{pv} - Total surface area of the PV module (m^2),
η_{pv} - module efficiency (%),
PR - performance ration (%) - This gives the relation between the measured energy output and the calculated energy (at Standard Testing Conditions-STC) of a PV module. It is a quality factor that describes the quality of the module [55]. Therefore, in this study, the EPBT and NREPBT are calculated and analyzed using the equations 2.4 and 2.7.

2.4.6 Energy Yield Ratio (EYR)

The ratio of total energy generated by the PV system during its lifetime to the energy consumed over its life cycle is defined as the Energy Yield Ratio [53]. This is also otherwise known as Net Energy Ratio (NER) or Energy Return on Investment (EROI) and expressed as follows [54],

$$EYR = \frac{T_{pv}.AEO}{\eta_G.CED} = \frac{T_{pv}}{EPBT} \tag{2.6}$$

where, T_{pv} - PV system Lifetime (years).

2.4.7 GHG Emission Rate

The GHG emission rate will measure the value of GHG gases emitted by 1 kWh of the PV generated electricity [56].

$$GHG_{e-rate} = \frac{GHG_{e-total}}{E_{output}} \tag{2.7}$$

2.4.8 CO_2 Payback time

The time required to offset the CO_2 emissions over the lifetime of the PV system over the CO_2 reductions obtained from the system is called CO_2 payback time or CO_2 offset period. This CO_2 reductions can be calculated by multiplying the amount of electricity generated annually by the system by the GWPs in the country's energy mic where the PV module is installed. This will give the number of years needed to ofdset the CO_2 emissions [57].

$$CO_2 \ \ Paybacktime \ \ = \frac{total \ \ CO_2 \ \ emissions}{Annual \ \ CO_2 \ \ reduction} \tag{2.8}$$

In this study, the EPBT, NREPBT and EYR are manually calculated using CED obtained from SimaPro, PV module yield, and Solar irradiance data depending on the input location. These 3 impact assessments mainly depends on CED, the efficiency of the module and the solar irradiation. From the equation 2.4 and 2.7, when the efficiency and solar insolation is high, then the EPBT and NREPBT will be low. When there is more Cumulative Energy Demand, the payback time value increase. Even if the module efficiency is high mounted in a high insolation region, the energy used to produce the module must be low for a better EPBT value. Moreover, equation 2.6 depicts that EYR considers the expected lifetime of the PV module including the degradation that gives a clear insight on the PV power gain. The results from these impact assessments helps to compare different PV technologies depending on the manufactured location and their efficiency.

Now that the tools and databases have been compared and selected for LCA calculations, the next step is to analyse the LCA inputs and results of various studies on the LCA of PV calculations. A discussion on life cycle stages, energy influence and technology use, as seen in state-of-the-art literature is carried out in the next chapter.

3 BACKGROUND STUDY

3.1 LIFE CYCLE OF PHOTOVOLTAICS

The general flow of life cycle phases for a PV system is shown in the figure 3.1. The life cycle of PV includes raw material extraction, manufacture, use, decommissioning, disposal and recycling with material and energy as inputs and effluents (waste during manufacture) as output. The life cycle stages of a PV system depends on the PV cell technology used. PV cell technology can be divided into 3 types, based on their generations [58]. The table 3.1 shows description, types and efficiencies of all the 3 generations of PV cell.

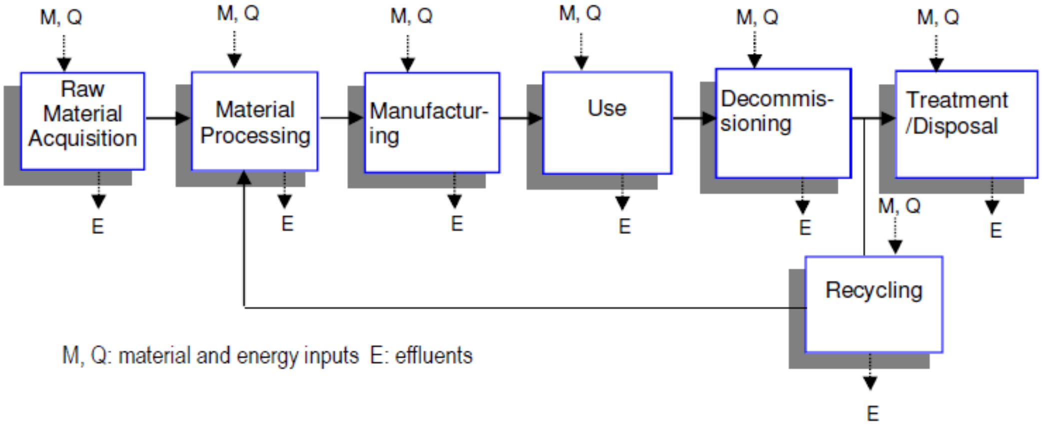


Figure 3.1: The life cycle stages of PV system with energy, materials and effluents [33]

EXASUN uses mono-crystalline silicon(mono c-Si) cells for X-Glass production. Hence, in this study, only silicon based solar cells, especially mono c-Si PV cells were considered. However, due to confidential industry practices, exact information regarding the PV Cell manufacture was not shared by the manufacturer. So, the PV cell data from the Ecoinvent data was used in this study. As discussed in subsection 2.3.1, cell and panel production data sets in Ecoinvent were developed using the study conducted by Jungbluth et al. in 2009 [43]. However, these data were updated to recent values using the data published by the IEA committee [33]. The life cycle stages of mono-silicon based PV electricity is shown in the figure 3.2. The initial production process begins with the mining of quartz sand and impure metal grade silicon (98% pure MG-Si) is extracted from silica sand [34]. Then, electronic grade silicon (EG-Si) is produced by heating trichlorosilane ($SiHCl_3$) and hydrogen (H_2) gases in a reactor chamber to a temperature of 1100-1200^{0}C. This process is called Siemens process and is also used to produce off-grade silicons with upto 99.79% purity [59]. The silicons (EG-SI & off grade-Si) are used in building intergrated circuits [60]. To further increase the purity to 99.99%, silane (SiH_4) and hydrogen (H_2) are added while the temperature is lowered to 800C, making the modified Siemens also more energy efficient [56].

The next step is the solar grade silicon mix that has a share of the off-grade-Si, SoG-Si and EG-Si. These are melted and made into a mould that contributes to the silicon feed stock for the PV industries (SoG-Si Mix). The next step is Czochralski

Table 3.1: Different PV cell technologies and their efficiencies(commercial efficiency with lab efficiency in brackets) [58].

Generation	Description	Solar Cells	Efficiency
First Generation	Silicon Based Solar Cells	mono-crystalline silicon, mono-si	16-22% (25-27%)
		multi-crystalline silicon, multi-si	15-18%
Second Generation	Thin Film Solar Cells	amorphous Silicon, a-Si	4-8% (12%)
		Gallium Arsenide, GaAs	29% (lab efficiency)
		Cadmium Telluride, CdTe	10-15% (21%)
		Copper Indium Gallium Selenide, CIGS	20% (under certain conditions)
		Gallium Indium Selenium, CIS	10-13%
Third Generation	Next Generation Solar Cells	Perovskites Solar Cel,. PSC	19-22%
		Organic PV and Polymer Solar Cells	4-5% (9%)
		Dye-sensized solar cell, DSSC	Around 10%

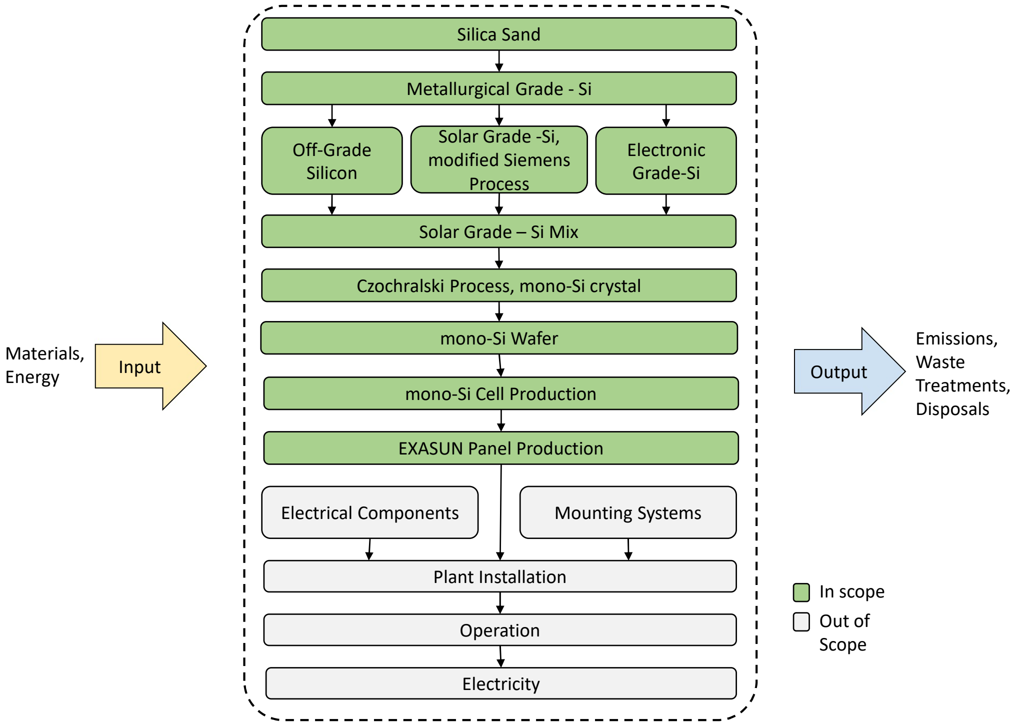


Figure 3.2: The system boundary of Silicon Based PV systems [40]

(CZ) process where the growing mono c-Si crystal is extracted from the molten silicon pot. The mono c-Si wafer is then produced by wafer sawing i.e., cutting the silicon ingots using saws to obtain a wafer of required size and thickness [56].The dimensions of a mono c-Si wafer is usually 156 x 156 mm^2 (M12 cells - 210 x210 mm^2) and has a thickness of 180-260 μm [61][62]. The next stage after obtaining mono-si wafer is the cell production. According to J. Peng et al., following are the important technologies that are incorporated in the PV cell production [56],

- **Etching**: The extra bits in from the sliced parts of the wafers are removed by giving the wafers a chemical bath.
- **Doping**: The photoactive PN junction is developed after etching by adding impurities to the wafer called dopants. Phosphorous is used as dopants to make N-type wafers and p-type dopants like boron are used in PN junction.
- **Screen Printing**: Metallic wires are drawn in the front and back side of the wafer to collect the charges
- **Coating**: Wafers are then coated with anti-reflective coating to increase the efficiency by increasing in path length of the light due to refraction on a textured surface.
- **Testing**: The cell production is complete after testing the cell for electrical qualities such as efficiency.

Then, a PV module is assembled with the cells arranged and connected into strings enclosed within the layers of encapsulant (top and bottom). The encapsulants are electrical insulators and resist moisture ingress, while being transparent. These encapsulants and cell layers are further enclosed either between 2 glass sheets (top and bottom) or between a top glass sheet and a bottom back sheet (usually Tedlar film) [40]. This stack with the glass, encapsulant and PV cells is then laminated under heat and pressure. Furthermore, the junction box that is then attached to the PV laminate. A junction box is an electrical circuit that connects the PV panel to the rest of the system. It includes cables, diodes and copper plates. Finally, fully functional PV module is made by an aluminium frame around is fixed around the laminate for strengthening and easy mounting [56]. The performance of the PV module is checked by conducting various quality tests.

The next life cycle stage is the installation of PV power plant that includes several PV panels arranged using the mounting system. These panels are interconnected along with electrical components like inverters and/or charge controllers, etc. to finally produce electricity. The main scope of this study is to determine the environmental impact of manufacturing a PV panel. Hence, the electrical components and other bill of materials (BOM) of the PV system were not considered in the LCA calculations.

The life cycle stages involved in the PV panel manufacture were discussed. Now, before developing a PV LCA model, it is important to check which life cycle stage in the manufacture affects the environment the most. In the next section, the most influential life cycle stage and the reason for their effect will be analyzed using previously conducted studies. In order to quantify the impact of the entire PV module, the impact of all the aforementioned steps will be individually determined and analyzed.

3.1.1 Energy Requirements

The GHG emissions associated with PV systems is mainly in the PV module manufacturing stage. This is because more energy is used in the PV cell production. 80-90% of the GHG emissions are directly related to the energy used in the manufacture of silicon based cells [63]. Figure 3.3 shows the required energy used per m^2 PV module with different PV cell technologies in China, EU and the US in a study conducted by Liu et al. in 2020 [64]. From figure, it can be observed that the

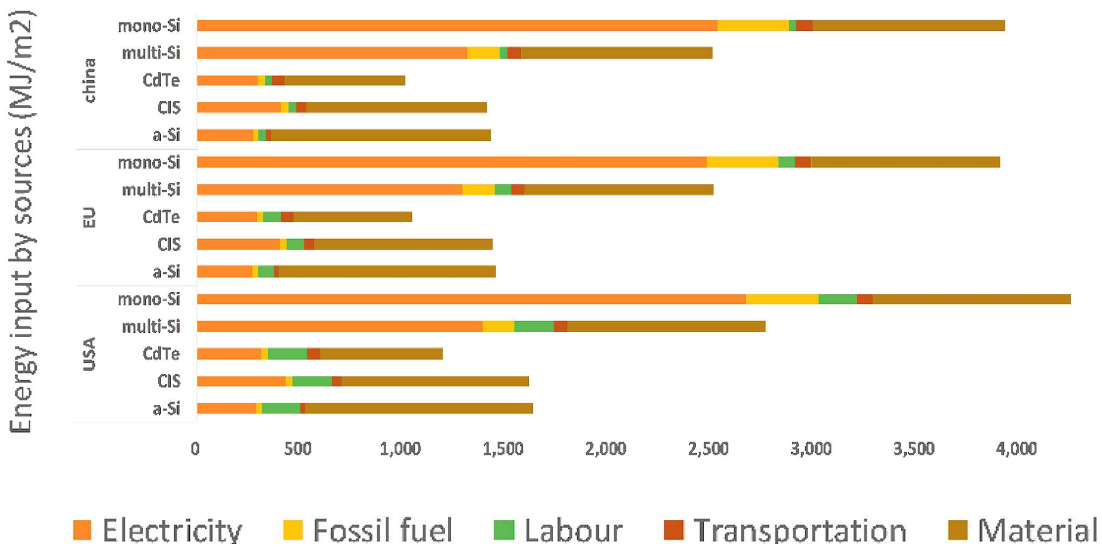


Figure 3.3: Energy requirements in the manufacture of PV systems with different cell technologies and locations [65]

silicon based cells, especially mono-si cells require a large amount of electricity and fossil fuels when compared to the thin film cell technologies. Moreover, extensive production of mono-si that involves silicon heating up to 1200^{o}C for a long period will further increase the energy use. According to Dones et al., when the PV system is manufactured completely using non-renewable source of energy, then the GHG emissions will be twice the actual value. However, when both renewable and non-renewable energies are used in the PV manufacture then the GHG emissions can be reduced depending on the share of renewable energy used. [63]. Hence the LCA results will be more accurate when recent energy values and location are considered.

The following table 3.2 shows the different energy values used in various LCA studies from 1998 to 2014. The energy used in the LCA studies varies depending on the goal of the study. From the table, it can be seen that the initial stages of cell manufacturing tend to use more energy. In particular, MG-Si and CZ process require more energy compared to the other processes.. Furthermore, the total energy used in the module production in LCA research after 2005 was around 3000 MJ/m^2, while in 1998 it was around 11000 MJ/m^2. The reason for this reduced energy use in the manufacture is due to [66],

- Reduction of silicon wafer thickness
- Improved Siemens process
- Recycling and reusing of silicon materials

Despite these technology improvements, the mono-si cell production still uses more energy when compared to other cell technologies (from figure 3.3). Thus, using mono-si cell technology will have relatively high GHG emissions. However, these emissions can differ with respect to the manufacturing location of the PV materials used in the panel production [23]. Also, these high emissions at manufacturing will be compensated in part by the longevity of the modules.

3.1.2 Geographical Influence

The importance of energy requirements in the PV manufacture was discussed in the previous section. Furthermore, electricity mix of the origin country where the

Table 3.2: Energy required by each life cycle process of mono-si module manufacture as per different LCA studies [66]

Authors	Year	MG-Si (MJ/m^2)	CZ Process (MJ/m^2)	Wafer Production (MJ/m^2)	Cell Production (MJ/m^2)	Module Production (MJ/m^2)	Total Energy (MJ/m^2)
Yue et al. [67]	2014	-	1436.8	307	308.8	615.8	3900
Jungbluth et al. [40]	2012	141	1208	562	595	466	3860
Fthenakis et al. [30]	2012	446	1841	581	643	772	4662
Laleman et al. [68]	2011	2397	432	-	-	684	3513
Lu et al. [56]	2010	162	1119	432	-	684	2397
Mariska et al. [69]	2009	728	1266	-	389	477	2860
Alsema et al. [62]	2005	1759	2391	-	473	394	5253
Knapp et al. [70]	2001	3950	4100	-	-	-	8050
Alsema et al. [71]	2000	450	2300	250	550	350	5700
Alsema et al. [72]	1998	500	2400	250	600	350	6000
Kato et al. [73]	1998	298	9808	-	261	509	11,673

Table 3.3: Percentage of generation from each energy resource for different regions in 2018 [74]

Electricity Source	China (%)	Asia Pacific (%)	Europe (%)	US (%)
Coal	58.4	54.7	21.3	24.3
Oil	0.1	2.9	1.4	0.8
Natural Gas	15.0	19.9	19.6	37.5
Hydro	15.0	13.0	16.1	6.8
Nuclear	3.6	2.3	22.0	19.3
Geothermal	0.0	0.8	0.0	0.4
Solar PV	2.2	1.6	3.0	2.1
Wind	4.5	2.3	10.0	7.0

PV materials are manufactured is directly related to GHG emissions [23]. As discussed by Dones et al., when more renewable energy is used in the manufacture of PV materials, the GHG emissions will reduce [63]. Hence, electricity mix with more renewable energy will have relatively less GHG emissions. Table 3.3 shows the energy share of various generation sources for different regions like China, Asia Pacific, Europe and the US for the year 2018. From the table, it can be seen that the energy share from a non-renewable source is more than 60% in China, Asia Pacific and US. Hence, GHG emissions will be relatively high when a PV material is manufactured in those regions. Since different regions have different shares of energy generating sources, it is essential to consider the electricity mix of origin country where the PV materials were manufactured. However, some manufacturers produce their own energy from a renewable source that can be used for the production process. In that case, self-generated energy will further reduce the GHG emissions value as the energy used from the country's electricity grid will be relatively less.

Considering all the points discussed in the previous 2 sections, it can be concluded that GHG emissions in PV LCA calculations depend on the energy use and location where the materials are produced. In this study, most recent energy was used for all the life cycle stages. Additionally, most of the materials used in the EXASUN panel manufacture were modelled with the electricity mix of their respective origin country depending on information availability. The development of a LCA model for EXASUN panel considering the material and energy used, location, transport, etc. are discussed in the next chapter.

4 SYSTEM MODEL

The life cycle stages in the manufacture of X-Glass module are quite similar to the general manufacturing stages that were discussed earlier in the chapter 3. The manufacturing flow follows the life cycle stages depicted in figure 3.2 (from Section 3.1). EXASUN does not manufacture the PV cells. At EXASUN, PV modules are assembled with the PV materials supplied from different parts of the world.

4.1 X-GLASS PRODUCTION

X-Glass is standard 1.62 m^2 mono-crystalline silicon glass-glass module. The X-Glass manufacturing process involves the assembly of the components as shown in figure 4.1. The module is a stack of 60 n-type Metal Wrap Through (MWT) mono c-Si cells with a copper foil interconnection (including black aesthetic insulation layer), all encapsulated with a polyolefin solar encapsulant material between two sheets of 2.0 mm fully tempered and textured glass.

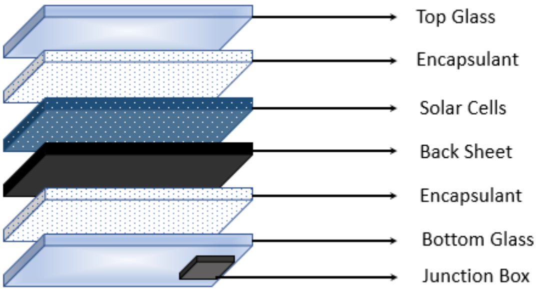


Figure 4.1: X-Glass panel components

The assembly process of X-Glass module is explained below using the figure 4.2. The initial step is to solder copper tabs on top of a copper foil for the junction box connection. The bottom layers are then assembled that consists of bottom glass, encapsulant layer, and insulation foil. The insulation foil consists of Polyethylene Terephthalate (PET) layer and Ethylene Vinyl Acetate (EVA) Layer on top of the copper foil with minute holes to connect the cells. Furthermore, this assembled bottom stack is sent to stencil printing where a conductive adhesive is coated on top of the copper layer (through the minute holes). Then, 60 PV cells are arranged on the bottom stack using a EXASUN developed pick and place machine. The cell contacts are connected to the copper layer by melting the EVA layer with halogen lamps and pressing the cells to fix on to the sticky insulation foil. The top encapsulant and glass are then assembled on top of the bottom layers with cells. The whole assembly is then sent for lamination of the module. The assembled stack undergoes lamination at high pressure and temperature. The pressure forces out all the air and helps the encapsulant to fill all the voids. (also gives a nice bumper) holding the whole setup intact. This assembled stack, post lamination is called a PV laminate. Then, the laminate undergoes curing process at high temperature and then the melted encapsulant is allowed to cool down and solidify. The next step is a quality check

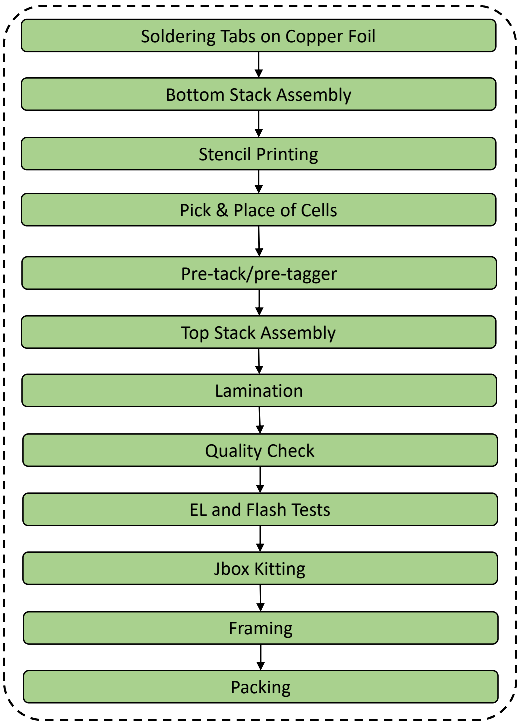


Figure 4.2: EXASUN X-Glass panel assembly steps

to avoid glass or cell damage in the laminate. Several quality checks are done on the manufacture modules. Electroluminescence (EL) and Flash tests are the 2 major tests that are performed check the cell connections and laminate output respectively. ”The electroluminescence test is an experiment typically used to verify the behavior of the photovoltaic cell and to qualitatively check its integrity. It works by operating the photovoltaic cell as a light emitting diode; the cells that light up in a module indicate how many of them work” [75]. Flash test measures the output of the laminate at standard test conditions (radiation of 1000 Wm^{-2}, a cell temperature of 25°C, and no wind) [76]. Then, the junction box is attached at the back of the PV laminate using a silicone adhesive. A junction box is a small circuit that consists of copper plates, diodes and cables. The copper plates in the junction box are soldered to the copper tabs from the laminate. Finally, the PV module is assembled by attaching an aluminium frame around the laminate. The PV modules are then stacked on a wooden pallet with carboard pieces on the sides to avoid damage. This stack is wrapped using plastic wrapping foil and are dispatched to the customer. More details regarding the module specifications are included in the figure A.1 in the appendix section A.1.

4.1.1 Data Collection

Initially, all the materials used in the manufacture were collected and listed in a spreadsheet. Material specifications such as density, dimensions and thickness were noted. The quantity of each material in kg used per module manufacture was noted. Moreover, the quantity of each material was then calculated for kg used per m^2. Finally, each material's country of origin was recorded. Table 4.1 shows the materials used in the manufacture of PV module, including their quantities and countries of origin. These listed materials were then cross-checked in the Ecoinvent database for their respective availability. Some materials have a relatively higher environmental impact than other materials like solar cells (as discussed in the section 3.1.1). Details like electricity mix for the high impact materials were modified with respect to the country of origin. However, these modifications could not be done for

Table 4.1: Material used in the X-Glass manufacture with quantity and origin country details

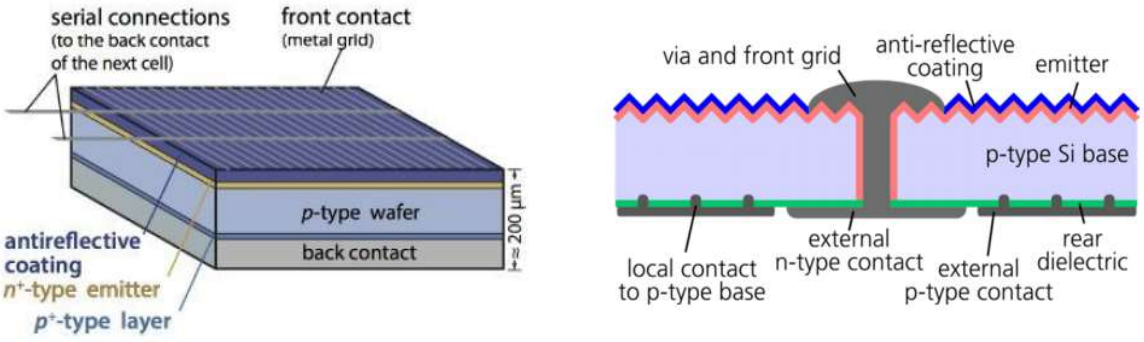
Materials	Quantity used per m^2 of PV module [kg/m2]	Country of Origin	Considered Region from Ecoinvent
PV Cell			
mono-si Cells	2.00E-01	Taiwan	Taiwan (modified)
Laminate Materials			
Conductive Foil - copper layer	1.56E-01	China	GLO
Conductive Foil - isolation layer	6.50E-02	China	GLO
Conductive Adhesive	1.80E-03	USA	GLO
Encapsulant	1.50E+00	UAE	GLO
Copper Tabs	3.40E-03	China	GLO
Junction box with diodes, cables and copper plates	1.20E-01	China	GLO
Potting Material	2.20E-02	Netherlands	GLO
Glass			
Front Glass	5.84E+00	India	India (modified)
Back Glass	5.46E+00	India	India (modified)
Al Framing			
Adhesive for Frame	2.03E-01	Netherlands	GLO
Aluminium Frame	1.44E+00	China	GLO
Packaging Materials			
Cardboard corner pieces	4.23E-02	Netherlands	GLO
Polysterene blocks	3.75E-02	Netherlands	GLO
Plastic wrapping foil	3.75E-02	Netherlands	GLO
Plastic strapping tape, polyester	4.55E-03	Netherlands	GLO
Pallet, wood	6.01E-01	Netherlands	GLO
Warning labels, paper	3.37E-04	Netherlands	GLO
Polyester Film Tape (Green)	4.60E-03	Italy	GLO
Gloves	3.75E-04	unknown	GLO
Isopropyl Alcohol	2.46E-03	unknown	GLO

all the materials. The country of origin specified in table 4.1 is taken from where the supplier is located. Hence, some materials might be manufactured in some country and distributed from another. For such scenarios where the location is uncertain, ecoinvent offers 2 different location based data sets for each materials, global (GLO) and European (RER). The global production of a material in the database has a share from the major producers of that material. Table 4.1 also has the information about the location selected for each of the materials used in the production. Hence, the electricity mixes of the respective countries were considered for solar cells and glass production. As for the rest, global (GLO) manufacture was assumed. The PV cell model was appropriately modeled for its respective location of manufacture. The details about the PV cell manufacture is discussed in the next section.

4.1.2 PV Cells

The life cycle manufacturing stages of a mono-si PV cell was discussed earlier in section 3.1. The updated data in the ecoinvent database consists of all major types of cell productions such as mono-Si, multi-Si, etc. This cell production data was developed for traditional (H-Grid) solar cells where the electricity is collected from the front side of the cell [53]. However, X-Glass uses Metal Wrap Through (MWT) solar cells where the electricity generated from the cell is collected at the rear side.

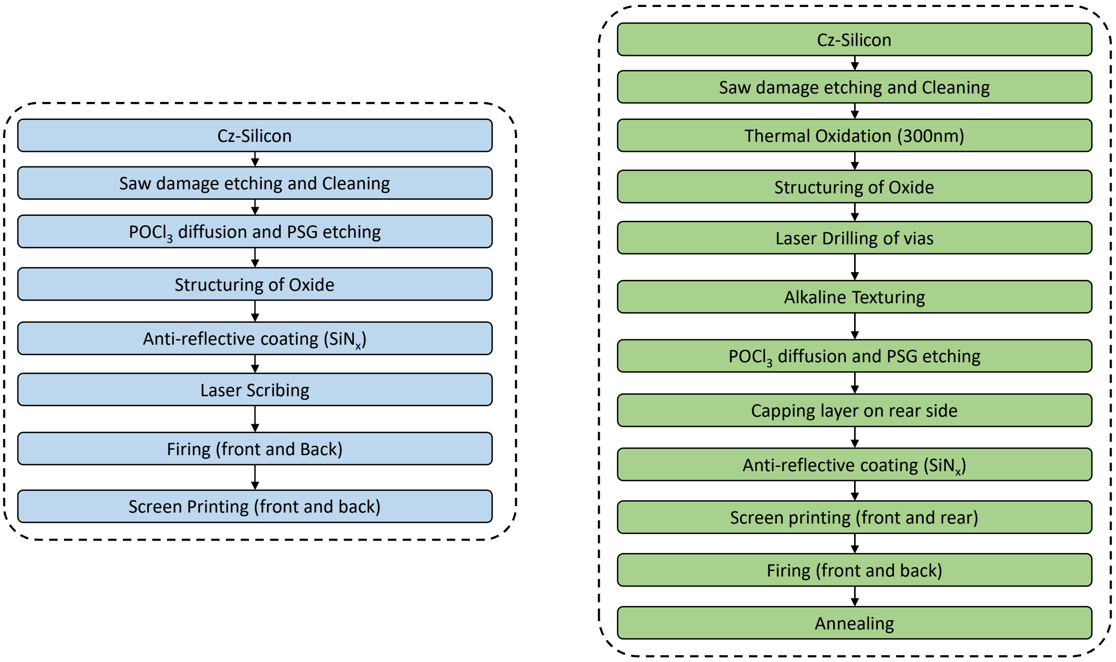
The basic structure of traditional solar cell and MWT solar cell is shown in figure 4.3.



(a) **(b)**

Figure 4.3: Schematic representation of (a) conventional solar cell [53], (b) MWT cells [77]

In an MWT cell, the electrical current from the emitter region is redirected to the back of the cell through holes or "vias". These holes are then filled with silver paste to collect the generated current from the rear side of the cell. The cell efficiency is increased in MWT cells in comparison to the traditional solar cells by avoiding the thick front metal busbars that leads to shading effects (preventing the cell from converting the light to electricity) [78]. MWT solar cells have similar manufacturing steps when compared to the traditional mono-si cells. Figure 4.4 shows the manufacturing sequence of both solar cell types. Detailed information on the production steps for a normal solar cell can be found in [53], and for MWT cells in a study conducted by A. Drews et al. [78]. From the figure, MWT cells have most of the production steps that are involved in producing a traditional solar cell like damage



(a) **(b)**

Figure 4.4: Production sequence of (a) conventional solar cell [53], (b) MWT cells [77]

etching, $POCl_3$ diffusion, structuring of oxide, screen printing, etc. However, there are some additional steps that are required for the MWT cells like alkaline texturing and annealing. The material and energy details required for these extra steps were unknown due to confidential industry practices. Hence, in this study, the model for cell production was developed assuming traditional mono c-Si cell production.

Moreover, these cells are supplied from Taiwan. So, the PV cell production model was developed with Taiwan electricity grid mix assuming all previous life cycle stages (from Silica sand extraction to mono-si wafers production) were done in China. The reason for this assumption was due to the lack of information and also china is the largest exporter of mono-si wafers [33].

4.1.3 Energy, Water and Waste

While developing a suitable model for LCA calculation, inputs like electricity, heat and water used must be included. Additionally, waste disposal or recycling involved in the manufacture must be added. All these inputs were considered as per literature until the cell production stage. For the X-Glass panel model, actual electricity, heat and water data were considered.

Initially, all these inputs were collected for a time range of 1 year. Then, data regarding number of modules manufactured for that year period was recorded. EXASUN manufactures different types of modules like X-Roof, X-compact, X - tile. The energy inputs that were recorded include the production of all the aforementioned EXASUN modules. The X-Roof, X-Compact and X-Tile modules are small modules with less number of cells. So, X-Glass module was considered as 1 Full Size Equivalent (FSE) module and the rest were converted to this FSE scaling up to 60 cells. For example, 1 FSE = 1 X-Glass with 60 cells , 2 X-Compact with 30 cells, 4 X-Roof with 15 cells, 6 X-Tile modules with 10cells. Using the total FSE modules produced in 1 year, the electricity, heat and water of 1 FSE module was calculated. However, these input values may differ with respect to the type of module produced because some manufacturing processes, like flashing, soldering of junction boxes as they do not scale with the same FSE ratio. During the lamination process, 4 X-Glass modules undergoes lamination. Whereas, 16 X-Roof modules are not laminated at the same time. Only 10 X-Roof modules' are laminated at the same time as it has spacing to uniformly laminate all the modules. This is similar to other type of modules produced at EXASUN. Thus, X-Glass uses less energy when compared to the other smaller size modules. Therefore, exact information on the energy used by a particular type of module is difficult to calculate. The energy and water for 1 FSE module in year was taken for this LCA study.

The exact quantity of waste disposal during the manufacture of X-Glass module was not known due to the lack of data. So, basic municipal waste disposal value was taken from the PV panel production data from ecoinvent (developed by Jungbluth et al. [40]). At EXASUN, the modules are not recycled after its total usage. So the details regarding the recycling were not available. Recycling of the materials used was considered only until the Cell production process.

4.1.4 Transport

As discussed earlier, the materials used in the manufacture of X-Glass module are supplied from different parts of the world (shown in figure 4.1). Some materials are shipped by air and some by water. The materials from within Europe are transported by road. The mode of transport from the origin country was noted. The travel distance for each mode was calculated using the websites shown in the table 4.2.

Table 4.2: Websites used to calculate travel disctances

Mode of Transport	Website
Ocean	http://ports.com/sea-route/
Road	https://www.google.com/maps
Air	https://www.greatcirclemapper.net/en/great-circle-mapper.html?route=ZSNJ-EHAM&aircraft=237&speed=

4.1.5 EXASUN model Inventory Data

Considering all the above discussed points in the previous subsections, a model for the manufacture of X-Glass panel was developed. The X-Glass model was divided into several groups to understand the impacts of the each groups. The gropus are PV Cell production, laminate materials, glass production, aluminium framing and packaging materials.

Laminate Materials

The lamination materials are grouped and shown in table 4.3 with the description of each material.

Table 4.3: Ecoinvent unit process data for per m^2 of laminate materials used in the X-Glass module

Laminate Materials	Quantity	Unit	Description
Sheet rolling, copper {GLO}— market for — APOS, U	3.13E-01	kg	Copper foil
Polyethylene terephthalate, granulate, amorphous {GLO}— market for — APOS, U	1.31E-01	kg	Insulation foil
Silver {GLO}— market for — APOS, U	1.86E-04	kg	Conductive Adhesive
Copper {GLO}— market for — APOS, U	7.50E-04	kg	
Epoxy resin, liquid {RoW}— market for epoxy resin, liquid — APOS, U	9.32E-05	kg	
N-olefins {GLO}— market for — APOS, U	1.51E+00	kg	Encapsulants
Copper {GLO}— market for — APOS, U	3.40E-03	kg	Tabs
Solder, paste, Sn95.5Ag3.9Cu0.6, for electronics industry {GLO}— market for — APOS, U	8.76E-03	kg	Junction Box
Polyphenylene sulfide {GLO}— market for — APOS, U	2.19E-02	kg	
Copper {GLO}— market for — APOS, U	1.18E-02	kg	
Diode, glass-, for surface-mounting {GLO}— market for — APOS, U	2.72E-03	kg	
Cable, unspecified {GLO}— market for — APOS, U	8.75E-02	kg	
Silicone product {RER}— market for silicone product — APOS, U	2.10E-02	kg	

Glass Production

Similarly, table 4.4 shows the data used in the glass production group.

Table 4.4: Ecoinvent unit process data for glass production used in the X-Glass module

Materials	Quantity	Unit	Description
Solar glass, low-iron {GLO}— market for — APOS, U	1.09E+01	kg	Solar Glass Production
Tempering, flat glass {GLO}— market for — APOS, U	1.09E+01	kg	Tempering Process

Al Framing

The process details for aluminium framing is listed in the table 4.5

Table 4.5: Ecoinvent unit process data for Aluminium frame used in the X-Glass module

Aluminium Frame	**Amount Used**	**Unit**	**Description**
Silicone product {RER}— market for silicone product — APOS, U	2.03E-01	kg	Adhesive to fix the frame
Aluminium alloy, AlMg3 {CN}— market for — APOS, U	1.44E+00	kg	Frame

Packing Materials

The following table 4.6 has the list of packaging and auxiliary materials used in the panel manufacture.

Table 4.6: Ecoinvent unit process data for packaging materials used in the X-Glass module

Packaging Materials	**Quantity**	**Unit**	**Description**
Solid unbleached board {GLO}— market for — APOS, U	4.20E-02	kg	Cardboard Piece
Packaging film, low density polyethylene {GLO}— market for — APOS, U	3.73E-02	kg	Wrapping foil
Packaging film, low density polyethylene {GLO}— market for — APOS, U	4.53E-03	kg	Strapping tape
EUR-flat pallet {RER}— production — APOS, U	4.00E-02	p	Pallet
Printed paper {GLO}— market for — APOS, U	3.34E-04	kg	Label
Packaging film, low density polyethylene {GLO}— market for — APOS, U	4.57E-03	kg	Plastic Tape
Latex {RoW}— market for latex — APOS, U	3.73E-04	kg	Gloves
Isopropanol {RoW}— market for isopropanol — APOS, U	2.44E-03	kg	Cleaning Solution

Transportation

The quantity and the transport distances of all the above material used in the calculation was used to find the transport distances in tonne kilometers (tkm). These values were calculated for the material's respective mode of transport. Table 4.7 shows the all the transport values used in the model.

Table 4.7: Ecoinvent unit process data for packaging materials used in the X-Glass module

Materials	**Quantity**	**Unit**	**Description**
Transport, freight, lorry, unspecified {RoW}— market for transport, freight, lorry, unspecified — APOS, U	2.79E-01	tkm	To Airport or harbour
Transport, freight, lorry, unspecified {RoW}— market for transport, freight, lorry, unspecified — APOS, U	1.33E-01	tkm	To EXASUN
Transport, freight, sea, transoceanic ship {GLO}— market for — APOS, U	3.03E+00	tkm	Sea Transport
Transport, freight, aircraft {GLO}— market for — APOS, U	1.29E+01	tkm	Air Transport

4.1.6 Others

Table 4.8 shows the unit processes values of PV cell, energy and waste used in the development of X-Glass model.

Now all the materials and processes that are used in the manufacturing of an EXASUN X-Glass module are identified, the environmental impact of the product may be calculated in various ways using the impact assessments, as described in the next chapter.

Table 4.8: Ecoinvent unit process data for PV cell, energy and waste usd in the X-Glass module

Inputs	**Amount**	**Unit**	**Description**
Photovoltaic cell, single-Si wafer {CN}— market for — APOS, U	9.22E-01	m2	PV Cell
Electricity, medium voltage {NL}— market for — APOS, U	1.08E+01	kWh	Electricity and heat
Municipal solid waste {NL}— market for municipal solid waste — APOS, U	3.00E-02	kg	Waste to treatment

5 RESULTS & ANALYSIS

The details regarding the model developed for X-Glass panel manufacture were discussed in the previous chapter, 4. All the materials used in the manufacturing were divided into 5 groups as discussed in the previous chapter, to analyze which one has the worst environmental impact. As discussed earlier in chapter 3, GHG emissions depend on the energy use and the location where the material is manufactured. Hence, before showing the environmental impact results, it is important to validate the energy use data incorporated in the model. Initially, the energy used in the manufacture was verified by comparing it with the literature. Then, top contributors of all the impact categories from ReCiPe method were analyzed. Finally, the European moedel was developed and the results were compared.

5.1 CUMULATIVE ENERGY DEMAND (CED)

The results of the Cumulative Energy Demand from each life cycle stage of the X-Glass module is shown in table 5.1. The table depicts the energy use of each process behind cell production from 6 different sources of energy. The life cycle stage shown in each column is a linear process starting from MG-Si until X-Glass production. The difference between each process gives the energy used a single process. E.g. Energy Used$_{X-Glass}$ = CED$_{X-Glass}$ - CED$_{PVCell}$ Likewise, the energy use for all the processes was calculated.

Table 5.1: Cumulative Energy Demand of each life cycle stages of PV module manufacture in megajoules

Impact category	Unit	MG-Si	CZ process	mono-si Wafer	PV cell	X-Glass
Non renewable, fossil	MJ	131	1773	3210	3520	4043.7
Non-renewable, nuclear	MJ	3.7	57.9	119	172	241.2
Non-renewable, biomass	MJ	0.002	0.013	0.04	0.050	0.24
Renewable, biomass	MJ	10	26.8	48.7	53.6	88.12
Renewable, wind, solar, geothermal	MJ	1.4	21.1	38.2	40.8	41.4
Renewable, water	MJ	7.6	130	232	248	254.4
Total Energy Demand	**MJ**	**153.7**	**2008.81**	**3647.9**	**4034.4**	**4669.2**

As discussed in 2.3.1, the PV cell data were updated using the LCI update published by the IEA Task 12 committee. The materials were updated with transport values, some materials were deleted and some replaced as proposed by byt he IEA [33]. Despite all these changes, the energy used by each life cycle stages in Cell production were not changed. So, the energy used in the initial study [40] to develop these data was used in this X-Glass LCA calculations. Though the data developed by Jungbluth et al. was accessible through ecoinvent v2, the relation between the energy value could not be compared using SimaPro due to differences in the software versions . Table 5.2 shows the comparison between the energy used in the literature[40] and the calculated energy acquired from the CED results. From the table, it can be observed that the energy used in the MG-Si process is similar to the one used in the literature. However, the energy used in other processes differs by at least by 200 MJ. This variation in energy values can be explained due to the update of some sub-process such as transport, mineral production (silver,

Table 5.2: Comparison of energy used in the literture and the energy used in this study.

	MG-Si (MJ)	CZ process (MJ)	mono-si Wafer (MJ)	PV cell (MJ)	Panel Production (MJ)	Total (MJ)
Jungbluth et al.	141	1208	562	595	466	3860
X-Glass Model	154	1855	1639	387	635	4669

copper), etc. in the Ecoinvent database, depending on the technology change. The sub-processes within each stage would have been updated for current energy and heat value. Moreover, in some processes, additional materials like nitrous oxides, flat glass, etc. were included manually as per the IEA update. This published update also had also changes in the heat used in some process. The energy used in the LCA calculations was validated using the recent literature as shown in table 3.2 (section 3.1.1). The energy range in these literatures varies from 3000 MJ to 6000 mJ. The value of energy used in the production of mono-si cell and X-Glass panel were found to be within the range of the values used in various studies. Hence, in this, the afore mentioned energy values (table 5.1) energy used will be used to calculate global warming potential.

5.2 RECIPE 2016

After verifying the energy use, the environmental impact of an X-Glass module's production was calculated using the ReCiPe impact assessment method. Initially, the mid point indicators were analyzed and then the end point indicators were calculated. The midpoint impact category values from the manufacture of one X-Glass module are shown in the table 5.3. The contributors to the total values of midpoint indicators can be analysed through figure 5.1. The graph shows the percentage share of each process in X-Glass production with all the mid point impact categories on the Y-axis and the share percentage in X-Axis.

From the graph, it can be observed that PV cell production has more than 50% impact in all the categories. Additionally, the PV cell contributes for 13 out of 18 mid point categories. However, for human non-carcinogenic toxicity, marine, terrestrial and freshwater ecotoxicity the laminate materials contribute slightly more than PV cells. The major contributors for each of this categories are discussed below. The reason for this contributions are also discussed for each impact categories. However, the calculation procedure and units relations of each contributing processes were not discussed due to the complexity of modeling calculation done by SimaPro. The details regarding the general calculations procedures and unit relations can be found in the ReCiPe manual.[51]

5.2.1 Water Consumption

This impact category quantifies the reduction in the availability of freshwater [51]. Table 5.4 shows top 5 that have the highest impact on water consumption. The Electronic Grade, off-Grade silicon manufacture and CZ processes consume 80% of water when compared to the other processes. This is due to the high temperature involved in all these manufacturing process. More water is used to cool down the product or the heating system [40].

5.2.2 Resource Scarcity

Resource scarcity is defined as a reduction in economic well-being due to a decline in the quality, availability, or productivity of natural resources [51] . ReCiPe

Table 5.3: Total Midpoint indicator results from X-Glass Production

Impact category	**Unit**	**Total**
Global warming	kg CO_2 eq	6.34E+02
Stratospheric ozone depletion	kg CFC eq	1.89E-04
Ionizing radiation	kBq Co-60 eq	2.05E+01
Ozone formation, Human health	kg NO_x eq	1.79E+00
Fine particulate matter formation	kg PM2.5 eq	1.07E+00
Ozone formation, Terrestrial ecosystems	kg NO_x eq	1.81E+00
Terrestrial acidification	kg SO_2 eq	2.43E+00
Freshwater eutrophication	kg P eq	2.12E-01
Marine eutrophication	kg N eq	4.36E-02
Terrestrial ecotoxicity	kg 1,4-DCB	1.93E+03
Freshwater ecotoxicity	kg 1,4-DCB	2.21E+01
Marine ecotoxicity	kg 1,4-DCB	3.30E+01
Human carcinogenic toxicity	kg 1,4-DCB	2.49E+01
Human non-carcinogenic toxicity	kg 1,4-DCB	6.87E+02
Land use	m2a crop eq	1.14E+01
Mineral resource scarcity	kg Cu eq	2.27E+00
Fossil resource scarcity	kg oil eq	1.40E+02
Water consumption	m^3	1.45E+01

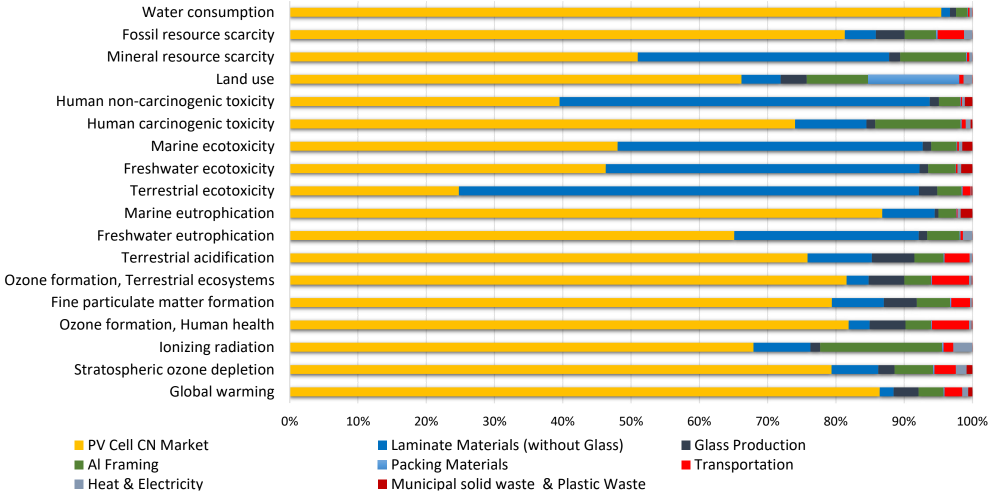


Figure 5.1: Percent relative contribution of characterized midpoint indicator values

Table 5.4: Top 5 process contribution to the Water consumption

Process	**Total Consumption (m^3)**	**Percentage Contributed (%)**
EG-Si	6.70E+00	46.25
CZ-Process	4.47E+00	30.90
Remaining Processes	8.45E-01	5.85
Total Deionised Water used	8.17E-01	5.65
off-grade Si	6.37E-01	5.00
Production	3.97E-01	2.75

method provides 2 types of resource scarcity results, Fossil resource scarcity and Mineral resource scarcity.

Fossil Resource Scarcity

This impact category shows the quantity of fossil resources used in the X-Glass production. Table 5.5 shows the top 5 processes that contribute to this type of resource scarcity. In this study, the PV cell production is based in China. So the Chinese energy mix was considered while developing the model. Since China's major electricity source is from coal, it has the highest share in the fossil resource scarcity. These impacts of fossil resource scarcity can be reduced by replacing fossil fuel energy with renewable energy.

Table 5.5: Top 5 fuel resources that contribute to the scarcity

Process	**Total Scarcity (m^3)**	**Percentage Contributed (%)**
Hard coal {CN}	8.55E+01	61.10
Remaining Process	3.55E+01	25.39
Natural gas, high pressure	4.87E+00	3.50
Petroleum {RoW}	4.22E+00	3.00
Petroleum {RME}	3.96E+00	2.83
Hard coal {AU}	3.01E+00	2.15

Mineral Resource Scarcity

This category calculates the use of major mineral resources in the manufacture of a certain material. Table 5.6 shows the scarcity of top 5 mineral resources involved in the X-Glass manufacture. Silver has the highest contribution, with a share of 30%. Copper concentrate used in sulfide ore extraction is the second highest contributor, with a share of 16%. Furthermore, iron, copper and ferronickel provide a 6% share each. The remaining processes include several other processes that has a share less than 6.32%. The reason for these mineral scarcities can be understood from the table 5.7. The table shows the percentage share of mineral scarcity in each X-Glass manufacturing process. TIn the PV cell production, minerals like silver, copper and nickel are used in the metallization process. This is the process involving printing of a metal grid on the front and back surface of the solar cell for the collection of converted electric current[79]. The PV laminate was found to have second highest share of 36%. This is due to the extensive use of copper in the panel production. Copper foil is used along with back sheet, along with copper tabs that connect the foil and copper plates in the junction box. However, copper is not the only mineral used in the production. Some amount of silver are also used in the adhesive material that help connecting the cell to the copper foil. Moreover, aluminium framing process also contributes 9% to the mineral scarcity as the frame is composed of aluminium and magnesium.

Table 5.6: Top 5 mineral resources that contribute to the scarcity

Process	**Total Scarcity (kg Cu eq)**	**Percentage Contributed (%)**
Silver production	6.87E-01	30.21
Remaining processes	6.11E-01	26.87
Copper concentrate used in sulfide ore	3.68E-01	16.20
Iron production	1.91E-01	6.64
Copper production	1.51E-01	6.60
Ferronickel production	1.50E-01	6.32

Table 5.7: Percentage share of Mineral recourse scarcity in each X-Glass manufacturing process

Process	**Total Share (%)**
PV Cell CN	50.98
Laminate Materials (without Glass)	36.84
Al Framing	9.71
Glass Production	1.61
Heat & Electricity	0.42
Transportation	0.35
Waste	0.02
Packing Materials	0.08

5.2.3 Land Use

This impact category calculates the loss of relative flora and fauna due to local land use. This category covers the process of land transformation, land relaxation and land occupation. In this study, information regarding the the land use of all PV manufacturing processes except lamination is known. However, this missing information about lamination does not significantly affect the final results. This is because it negligible for EXASUN, in comparison to larger scale glass or cell manufacturers. However, the top 5 processes that contribute to this impact were analyzed. Table 5.8 shows the most influential process that has an impact on this category. The major impact is due to depletion of forest to use several products of wood. Forest depletion for wood (including timber) has a maximum share 33.5% in the total land use due as wood chips are used in some silicon manufacturing process. Furthermore, wooden pallets are used to intra-factory movements. The land used in the coal mining process has the 2nd most impact share of 23%. The road and railway has a share of 2% each as more land is used in their construction.

Table 5.8: Top 5 processes that contribute to the land use impact category

Process	**Total Contribution (m^2a) crop eq.)**	**Percentage Share (%)**
Remaining Process	4.50E+00	39.60
Forest depletion for hard and soft wood	3.48E+00	30.60
Land used in the Hard Coal Mine	2.60E+00	22.68
Forest depletion for cleft timber	3.29E-01	2.90
Road Construction	2.39E-01	2.12
Railway Track Construction	2.41E-01	2.10

5.2.4 Toxicity

This impact category calculates the degree of damage caused by using a chemical substance. These are divided into the following midpoint categories,

- Human non-carcinogenic toxicity

- Human carcinogenic toxicity
- Marine ecotoxicity
- Freshwater ecotoxicity
- Terrestrial ecotoxicity

Human Non-Carcinogenic Toxicity

This impact category gives health effects on human beings caused by taking in toxic substances through air, food, water or through the skin that are not caused by respiratory inorganic matter (particulate matter) or ionising radiation [80]. The top 5 processes causing this toxicity in the production of X-Glass module are tabulated in 5.9. From the table, it can be analyzed that sulfidic tailing has the highest impact with a share of 74%. Sulfidic tailings are waste rocks or other materials over an ore, especially in the mining of sulfurous minerals rejected from ores of copper, nickel and coal etc. [81]. The production of copper has a comparable impact of 3% on this category. These materials are used in the cell and back sheet production. This can be validated using the table 5.10 showing the percentage share of each unit processes impact on this type of toxicity.

Table 5.9: Top 5 processes that causes human non-carcinogenic toxicity

Process	**Total Contribution (kg 1,4-DCB)**	**Percentage Share (%)**
Sulfidic tailing from mineral extraction	507.39	73.85
Spoil from hard coal mining	74.57	10.85
Remaining Process	52	7.51
Copper Production	22.85	3.33
Coal slurry	15.45	2.25
Spoil from lignite mining	15.16	2.21

It can be seen that laminate material and PV cell production has the maximum share of 54% and 39% respectively. Other unit processes have much less impact when compared to the aforementioned 2 processes. The reason for these high values are use of several minerals like copper, siver, nickel, etc. in the panel and cell production. Additionally, the spoils or waste associated with coal production also has an impact with a share of 15%. This can be attributed to impact of using coal based energy sources, i.e., Chinese energy for PV cells.

Table 5.10: Percentage share of Human non-carcinogenic toxicity in each X-Glass manufacturing process

Process	Total Share (%)
Laminate Materials (without Glass)	54.25
PV Cell CN	39.53
Al Framing	3.12
Glass Production	1.33
Waste	1.10
Heat & Electricity	0.40
Transportation	0.22
Packing Materials	0.07

Marine & Freshwater Ecotoxicity

Ecotoxicity is the impact on the ecosystem caused by emissions of toxic substance into the air, water and soil [82]. The impacts of toxic substance on marine and freshwater ecosystems are referred to marine and freshwater ecotoxicity respectively. Similar to the previous impact category (non-carcinogenic toxicity), the use of several minerals in the cell and panel production contribute to this impact. The sulfidic tailing and scrap from mineral extractions has the maximum impact (around 65%) on these ecosystems due to the tainted cooling released from the process. Moreover, effluents from the coal mining used in the energy production to manufacture PV cells have an impact of 15% and 18% on marine and freshwater ecosystems, respectively .

Table 5.11: Top 5 processes that causes marine & freshwater ecotoxicity

Marine Ecotoxicity			Freshwater Ecotoxicity		
Process	Total Contribution (kg 1,4-DCB)	Total Share (%)	Process	Total Contribution (kg 1,4-DCB)	Total Share (%)
Sulfidic tailing from mineral extraction	20.43	61.82	Sulfidic tailing from mineral extraction	14.67	66.40
Spoil from hard coal mining	3.42	10.35	Spoil from hard coal mining	2.48	11.21
Silver	1.74	5.26	Scrap from copper treatment	1.19	5.40
Hard coal ash	1.43	4.32	Hard coal ash	1.01	4.58
Scrap from copper treatment	1.42	4.30	Spoil from lignite mining	0.52	2.36
Remaining Process	2.76	8.37	Remaining Process	1.35	6.10

Human Carcinogenic Toxicity

This definition of this impact category is similar to the non-carcinogenic toxicity but are related to cancer causing toxic substances. Table 5.12 shows the impact contributions of top 5 processes. Similar to the previous impact categories, most of the contributions to this are the processes associated with coal mining (46.50%) and mineral extraction (30%) process as long-term exposure to coal dust generated during coal mining can lead to lung damage.

Table 5.12: Top 5 processes that causes human carcinogenic toxicity

Process	Total Contribution (kg 1,4-DCB)	Total Share (%)
Hard coal ash	6.79	27.23
Spoil from hard coal mining	4.81	19.31
Slag from steel treatment	3.14	12.58
Sulfidic tailing from mineral extraction	2.73	10.94
Remaining Process	1.94	7.78
Redmud from bauxite digestion	1.65	6.61

Terrestrial Ecotoxicity

This category calculates the impacts of toxic substances on terrestrial ecosystems. Table 5.13 shows the top 5 processes that affects the terrestrial ecosystems. From the table, copper production has the highest impact share of 73%. The remaining impact shares are comparatively small and are caused due to the use toxic substance used in the PV cell production, transport and electricity production.

Table 5.13: Top 5 processes that causes terrestrial ecotoxicity

Process	Total Contribution (kg 1,4-DCB)	Percentage Share (%)
Copper production	1413.77	73.27
Remaining Process	298.22	15.46
PV Cell CN	78.27	4.06
Brake wear emissions, lorry	60.00	3.11
Ferronickel, 25% Ni	26.79	1.39
Electricity, high voltage	20.94	1.09

Since copper production has the highest impact in this category, the impact share of laminate materials unit process in the production of X-Glass is maximum (67.50%). This can be observed from the table 5.14 showing the impact shares caused by each unit process in the X-Glass manufacture. PV cell production has the second highest impact share with (25%) due to the use of some minerals like silver, copper in the metallization process (as discussed in 5.2.2).

Table 5.14: Percentage share of terrestrial ecotoxicity in each X-Glass manufacturing process

Process	Total Share (%)
Laminate Materials (without Glass)	67.42
PV Cell CN	24.77
Al Framing	3.62
Glass Production	2.68
Transportation	1.17
Heat & Electricity	0.12
Packing Materials	0.10

5.2.5 Marine & Freshwater Eutrophication

The excessive increase in the growth of algae in water due to higher content of minerals and nutrients, thereby reducing the oxygen level is called eutrophication [83]. This impact is calculated for freshwater and marine ecosystems. The top 5 process that contribute to both of these impact categories are listed in table 5.15. In marine eutrophication, the impact Cz process has the maximum share of 48% . This is due to the emissions of nitrous oxides and Nitrates to water. The water treatment in PV cell production has the second highest impact share of 20%. The spoils from coal mining that used to generate electricity and treatment process in Aluminium extraction (5.50%) also contribute to these impacts. Similarly, in freshwater eutrophication, the major impact is caused due to the use of coal based electricity. The spoils and ash from coal mining have the highest impact share of 59%. The next highest impact is the treatment of sulfidic tailing from the mineral extraction contributing 32% to freshwater eutrophication.

Table 5.15: Top 5 processes that causes marine & freshwater eutrophication

Marine Eutrophication			**Freshwater Eurtrophication**		
Process	**Total Contribution (kg N eq)**	**Percentage Share (%)**	**Process**	**Total Contribution (kg P eq)**	**Percentage Share (%)**
CZ-Process CN	2.11E-02	48.36	Spoil from hard coal mining	9.63E-02	45.34
Treatment of wastewater in PV cell Production	8.89E-03	20.38	Sulfidic tailing treatment	8.09E-02	38.08
Spoil from hard coal mining	5.87E-03	13.46	Spoil from lignite mining	2.34E-02	11.03
Treatment of dross from Al electrolysis	2.42E-03	5.55	Hard coal ash	6.00E-03	2.83
Remaining Process	2.35E-03	5.38	Treatment of wastewater in PV cell Production	3.14E-03	1.48
Spoil from lignite mining	1.43E-03	3.27	Remaining Process	2.12E-01	1.25

5.2.6 Terrestrial Acidification

Terrestrial Acidification is the deposition of nutrients (namely, nitrogen and sulfur) in acidic forms, thereby changing the chemical properties of the soil [84]. Table 5.16 shows the top 5 process that contributes to this impact category. Coal based electricity used in the PV cell production has the highest impact share of 59%. The other processes like flat glass, copper productions and oceanic transport emissions have negligible share compared to the electricity production.

Table 5.16: Top 5 processes that causes terrestrial acidification

Process	**Total Contribution (kg SO2 eq)**	**Percentage Share (%)**
Electricity production from hard coal	1.45E+00	59.57
Remaining processes	5.32E-01	21.92
Copper	1.41E-01	5.83
Flat glass, uncoated	1.03E-01	4.24
Transport, transoceanic ship	7.98E-02	3.29
Silicon, metallurgical grade	3.35E-02	1.38

5.2.7 Ozone Formation

This impact category is also known as Photochemical Ozone formation. Terrestrial ecosystems and human health are the two types of Ozone formations categories. This calculates the formation of ozone in the presence of nitrogen oxides (NO_x) and sunlight caused by photochemical oxidation of Volatile Organic Compounds (VOCs) and carbon monoxide (CO) [85] at ground level atmosphere. Similar to the previous processes, the electricity produced using coal has the highest impact share of around 65% in both these categories. Emissions from Transport and flatglass production have the next highest contribution to this category. Blasting rocks to produce mineral and burning diesel also have minor effects on the ozone formation.

Table 5.17: Top 5 processes that causes ozone formation, terrestrial ecosystem & human health

	Terrestrial Ecosystem		**Human Health**	
Process	**Total Contribution (kg NOx eq)**	**Percentage Share (%)**	**Total Contribution (kg NOx eq)**	**Percentage Share (%)**
Electricity production hard coal	1.16E+00	63.79	1.17E+00	65.25
Remaining processes	3.12E-01	19.91	3.30E-01	18.40
Transport	1.29E-01	7.11	1.28E-01	7.14
Flat glass, uncoated	6.47E-02	3.57	6.46E-02	3.60
Blasting	6.50E-02	3.58	6.38E-02	3.55
Diesel	3.72E-02	2.05	3.68E-02	2.05

5.2.8 Fine Particulate Matter

Particulate matter is a mixture of solid particles like dust, dirt, smoke, etc. in the air [86]. This impact category is caused due to the formation of dust or dirt during the manufacturing process. The electricity production from coal can be seen to contribute over 65% to this impact category as shown in table 5.18. This is because the coal mining and smoke produced after heating coal involves a lot of particulate matter formation. Other processes like flat glass, copper production and transport contribute to around 10% to the particulate matter emission.

Table 5.18: Top 5 processes that causes fine particulate matter

Process	**Total Contribution (kg PM2.5 eq)**	**Percentage Share (%)**
Electricity production hard coal	6.89E-01	64.50
Remaining processes	2.64E-01	25.65
Flat glass, uncoated	3.38E-02	3.17
Copper	7.47E-01	3.10
Transport	2.50E-02	2.34
Heat production, at hard coal industrial furnace	1.33E-02	1.24

5.2.9 Ionizing Radiation

The energy released by atoms (gamma or X-rays) as electromagnetic waves or particles (neutrons, beta or alpha) is called ionizing radiation. The processes associated with nuclear based electricity generation mainly cause ionizing radiation, as seen from the table 5.19. The uranium extraction process and nuclear energy generation used in the panel production process are the main contributors.

Table 5.19: Top 5 processes that causes ionization radiation

Process	**Total Contribution (kBq Co-60 eq)**	**Percentage Share (%)**
Tailing from uranium milling	1.86E+01	90.76
Remaining processes	5.96E-01	2.91
Low level radioactive waste	4.44E-01	2.17
Uranium ore	4.21E-01	2.05
Spent nuclear fuel	2.77E-01	1.35
Electricity production, nuclear	1.56E-01	0.76

5.2.10 Stratospheric Ozone Depletion

Emission of compounds like chlorofluorocarbons (CFCs), carbon tetrachloride, methyl chloroform, etc. deplete the stratospheric ozone layer. These compounds are used as aerosol propellants, solvents and refrigerants. Other factors like large volcanic eruptions, climate change and greenhouse gases, methane and nitrous oxide also cause ozone depletion [87]. Table 5.20 shows the top 5 contributors for this impact category. Electricity used in the PV cell production has the highest impact share of 45%. The second highest impact of 17% is caused during nitric acid production that is used in CZ process. Other processes like petroleum, copper production and transportation also has some minor contributions of around 7% to this category.

Table 5.20: Top 5 processes that causes ozone depletion

Process	**Total Contribution (kg CFC11 eq)**	**Percentage Share (%)**
Electricity	8.56E-05	45.39
Remaining processes	5.5E-05	30.12
Nitric acid production	3.24E-05	17.20
Petroleum	8.1E-06	4.29
Copper	3.04E-06	1.61
Transport, natural gas	2.61E-06	1.39

5.2.11 Global Warming Potential

The global warming impacts of different gases is compared using the Global Warming Potential (GWP). GWP can be defined as ”a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO2).” [88]. The heat and electricity production using coal has the maximum share of around 80% in the total GWP. This proves the fact stated by Donnes et al. [63] that usage of more non-renewable energy will increase the GHG emissions, thereby increasing the GWP. MG-Si process has minor contribution to this impact category.

Table 5.21: Top 5 processes that causes global warming potential

Process	**Total Contribution (kg CO2 eq)**	**Percentage Share (%)**
Electricity production, hard coal	367.01	57.86
Remaining processes	137.72	21.71
Hard coal	88.98	14.03
Heat production	19.37	3.05
Flat Glass, uncoated	13.66	2.15
Silicon, metallurgical grade	7.62	1.20

The summary of each process contributing to all the midpoint impact categories are shown in the table 5.22 The PV cell has the maximum contribution to all the midpoint impact assessments due to the extensive use of non-renewable source of energy i.e., coal. However, the contribution of laminate materials is high in toxicity and the reason for this impact is the use of minerals like copper, silver, etc.

5.2.12 Damage Assessment (End point category)

The end point categories for the manufacture of 1 X-Glass module is shown in the table 5.23 and the percentage of share of damage assessment in each unit process is shown in the figure 5.2. The characterization factors of midpoint categories that were used to calculate end point damage assessments can be found in the study conducted by Huibregts et al. [51].

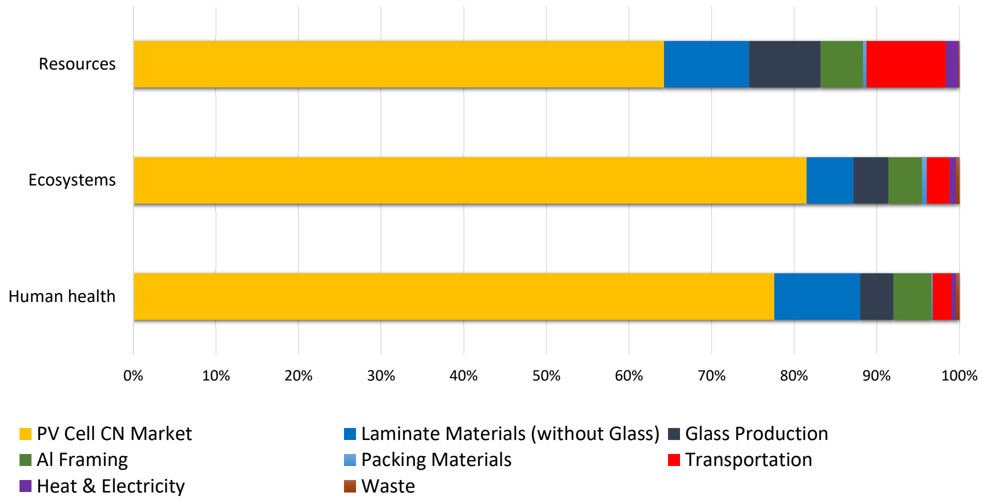


Figure 5.2: Percentage share of damage assessment in the X-Glass Production

From the graph and the table, it can be clearly seen that PV Cell has the highest impact raising above 60% in all the endpoint damage assessments. This is due to the fact that more non-renewable energy is used in the production of mono-si PV cells. However, these high values can be reduced when the PV cells are manufactured using renewable energy sources. From the table 3.3, it can be observed that Europe uses less energy from non-renewable source. Only 21% of total energy is generated using coal. Therefore, PV cell manufacture in Europe will drastically reduce the

Table 5.22: Summary of each process contributing to all the midpoint impact categories

Impact category	Unit	Major Contributing Process - %	Top 2 Unit Process - %	
Global warming	kg CO2 eq	Heat & Electricity - 80	PV Cell - 86.3	Glass - 3.77
Stratospheric ozone depletion	kg CFC11 eq	Electricity - 45	PV Cell - 79.2	Laminate - 6.83
Ionizing radiation	kBq Co-60 eq	Tailing from Uranium - 91	PV Cell - 83.3	Al Framing - 17.9
Ozone formation, Human health	kg NOx eq	Electricity (Coal) - 65	PV Cell - 81.8	Glass - 5.28
Fine particulate matter formation	kg PM2.5 eq	Electricity & Heat (Coal) -64	PV Cell - 79.1	Laminate - 7.58
Ozone formation, Terrestrial ecosystems	kg NOx eq	Electricity (Coal) - 64	PV Cell - 81.5	Glass - 5.27
Terrestrial acidification	kg SO2 eq	Electricity (Coal) - 60	PV Cell - 75.8	Laminate -9.42
Freshwater eutrophication	kg P eq	CZ-Process -59	PV Cell - 64.8	Laminate- 26.9
Marine eutrophication	kg N eq	Spoil & ash from Coal - 48	PV Cell - 86.7	Laminate- 7.67
Terrestrial ecotoxicity	kg 1,4-DCB	Copper Production (Laminate Materials) -73	PV Cell- 24.8	Laminate- 67.4
Freshwater ecotoxicity	kg 1,4-DCB	Sulfidic Tailing (Mineral Extraction) - 66	PV Cell- 46.2	Laminate- 45.9
Marine ecotoxicity	kg 1,4-DCB	Sulfidic Tailing (Mineral Extraction) - 61	PV Cell - 48	Laminate - 44.6
Human carcinogenic toxicity	kg 1,4-DCB	Hard Coal Mining -46	PV Cell - 73.8	Al Framing- 12.5
Human non-carcinogenic toxicity	kg 1,4-DCB	Sulfidic Tailing (Mineral Extraction) - 74	PV Cell - 39.5	Laminate- 54.2
Land use	m2a crop eq	Hard Coal Mine - 23	PV Cell - 66.1	Packing - 13.3
Mineral resource scarcity	kg Cu eq	Silver Production - 30	PV Cell - 51	Laminate- 36.8
Fossil resource scarcity	kg oil eq	Hard Coal -63	PV Cell - 81.1	Laminate- 4.53
Water consumption	m3	EG-Si -46	PV Cell - 95.4	Al Framing - 1.67

Table 5.23: The end point categories of each unit process of X-Glass production

Damage category	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Total	1.52E-03	2.86E-06	2.47E+01
PV Cell CN Market	1.18E-03	2.33E-06	1.59E+01
Laminate Materials (without Glass)	1.57E-04	1.62E-07	2.55E+00
Glass Production	6.12E-05	1.21E-07	2.14E+00
Al Framing	7.05E-05	1.16E-07	1.27E+00
Packing Materials	1.58E-06	1.63E-08	1.04E-01
Transportation	3.47E-05	7.95E-08	2.38E+00
Heat & Electricity	8.30E-06	2.21E-08	3.92E-01
Waste	5.84E-06	1.14E-08	1.16E-02

enviromental impact as coal based energy production is the main contributor for most of the impact categories (from the table 5.22). This was verified by building a PV cell manufacture model using European energy mix.

5.3 GEOGRAPHICAL INFLUENCE

With the total impacts known from the X-Glass model, the impacts of a hypothetical models completely made in Europe can be modelled and compared. The LCA model for X-Glass produced completely in Europe was developed by changing the following,

- The same data were used as listed in table 4.1. The location of PV cell and glass production were assumed to be Europe, i.e. the European (ENTSO-E - European Network of Transmission System Operators for Electricity) electricity grid mix was used to produce these materials.
- The life cycle stages in the manufacture of PV cells were taken from the published inventory data update by IEA. According to this study, the metal grade silicon (MG-Si) was considered to be manufactured in Norway as it is the largest producer of MG-Si in Europe. Moreover, Germany was considered for the electronic and solar grade silicon production [33]. The rest of the PV cell production were modelled with European energy mix (ENTSO-E).
- The same electricity mix, ENTSO-E was assumed for the manufacture of solar glass used in the production.
- All the materials that were transported from other parts of world were assumed to be shipped from Europe. A standard distance of 500km by truck/lorry was assumed while developing this European model as transport has negligible effect when compared to PV cells and laminate materials. The transport details were not changed for the materials that were shipped within Europe.

With all the above changes, the mid point impact results of X-Glass EU production is shown in table 5.24 and the percentage share of each unit process is shown in 5.3.

Table 5.24: Total Midpoint indicator results from X-Glass Produced in Europe

Impact category	**Unit**	**Total**
Global warming	kg CO2 eq	2.78E+02
Stratospheric ozone depletion	kg CFC11 eq	1.65E-04
Ionizing radiation	kBq Co-60 eq	6.89E+01
Ozone formation, Human health	kg NOx eq	6.19E-01
Fine particulate matter formation	kg PM2.5 eq	4.84E-01
Ozone formation, Terrestrial ecosystems	kg NOx eq	6.37E-01
Terrestrial acidification	kg SO2 eq	1.19E+00
Freshwater eutrophication	kg P eq	2.61E-01
Marine eutrophication	kg N eq	4.78E-02
Terrestrial ecotoxicity	kg 1,4-DCB	1.78E+03
Freshwater ecotoxicity	kg 1,4-DCB	2.18E+01
Marine ecotoxicity	kg 1,4-DCB	3.26E+01
Human carcinogenic toxicity	kg 1,4-DCB	1.95E+01
Human non-carcinogenic toxicity	kg 1,4-DCB	6.97E+02
Land use	m2a crop eq	1.18E+01
Mineral resource scarcity	kg Cu eq	2.32E+00
Fossil resource scarcity	kg oil eq	7.70E+01
Water consumption	m3	2.05E+01

This percentage share of each unit process of X-Glass produced in Europe is similar to that of the actual X-Glass production model (figure 5.1) with visible difference observed only in the transportation stage. The changes were made in the PV cell,

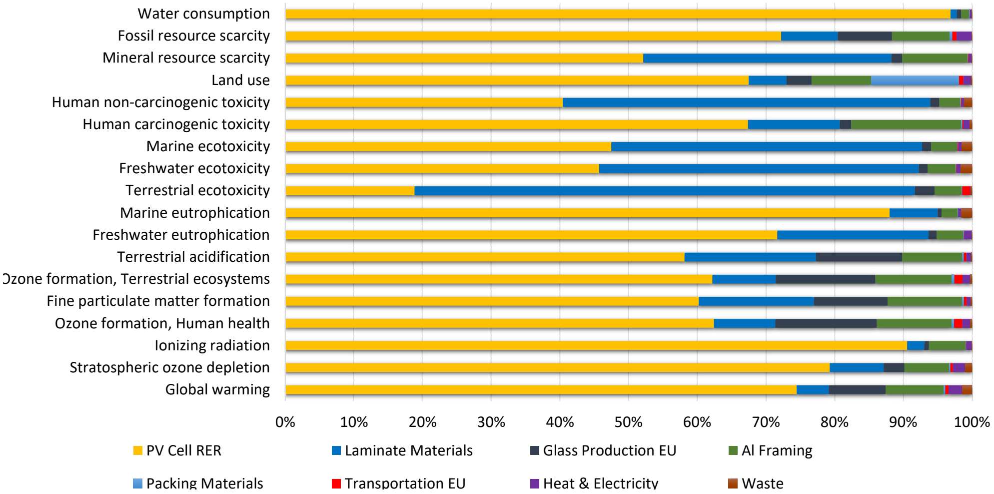


Figure 5.3: Percent relative contribution of characterized midpoint indicator values in X-Glass produced in EU

glass production and transportation unit processes. Each of these unit processes can be compared to check the deviation in the mid point results.

5.3.1 PV Cells

The comparison of PV cells manufactured in China and Europe are shown in the figure 5.4. It can be observed from the graph that most of the impact categories are drastically reduce when the cells are manufactured in the Europe. The impact categories like GWP, ozone depletion, particulate matter formation, etc. have better impacts in Europe as more renewable sources are used to generate electricity, in comparison to China. However, some impact categories like water consumption, mineral scarcity, land use and non-carcinogenic toxicity are better in China due to the vast availability of land, water and minerals.

5.3.2 Glass Production

The figure 5.5 shows the percentage variation in the production of solar glass in 2 different locations i.e., India and Europe. The changes are drastic only in the eutrophication and marine ecotoxicity categories with 15-20% less when manufactured in Europe. All the other impacts are similar when produced with 10% - 15% variation in both the locations.

5.3.3 Transport

Transporting all the materials from Europe that are used in the X-Glass manufacture will greatly reduce the impact caused due to the transport. When the materials are transported within Europe, the travelling distance reduces when compared to shipping from other continents. This mainly reduces the transoceanic and air transport that are the major causes of most of the impacts in transportation. This can be easily identified from the figure 5.6. However, this value will increase when the transport distance increases. In this study, a standard distance of 500km was assumed for the transport within Europe. Even if the distance increases, the effect on the environment will be significant when compared to PV cells. It can be see that except from the 5 impact categories (land use, non-carcinogenic toxicity and the 3 types ecotoxicities), every other impact has at least 60% difference when materials are transported within Europe.

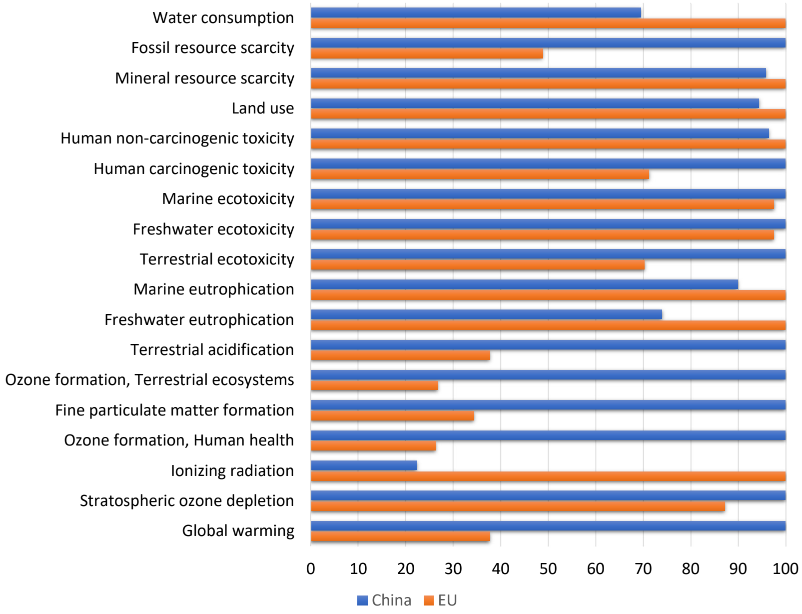


Figure 5.4: Comparison of PV cell manufactured in China and EU

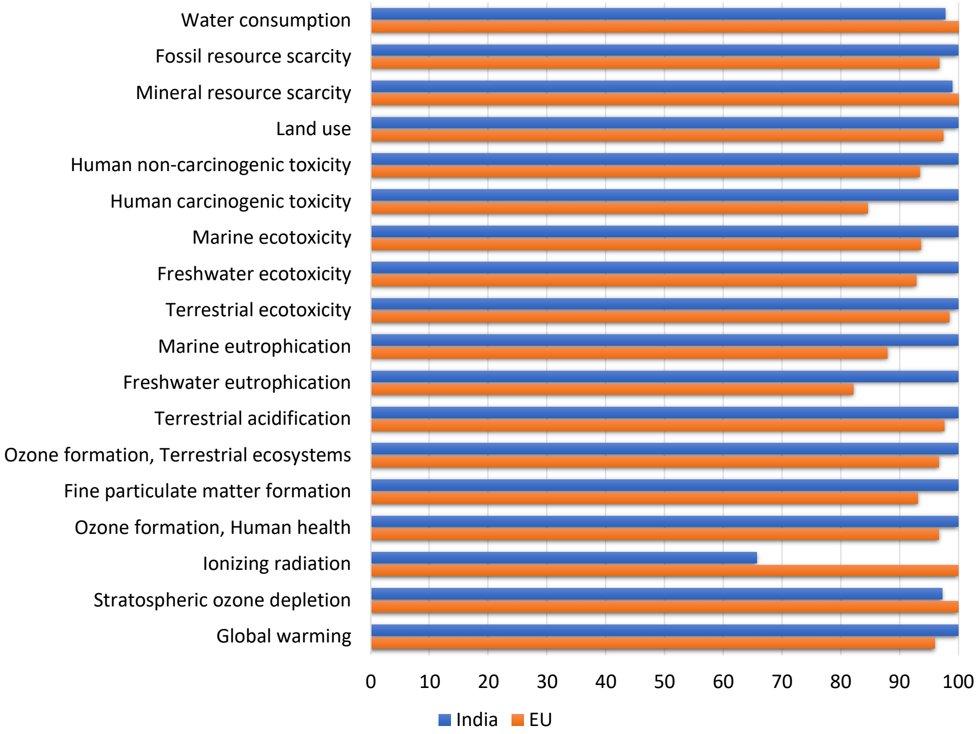


Figure 5.5: Comparison of Glass manufactured in India and EU

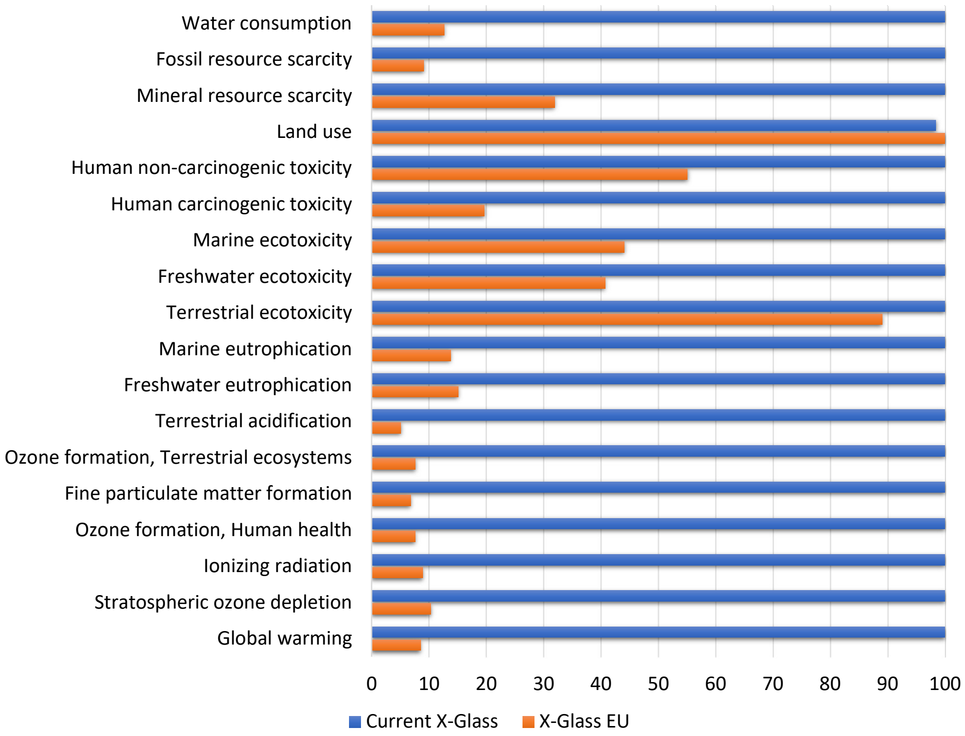


Figure 5.6: Comparison of material transport in current X-Glass and X-Glass EU

Considering all the aforementioned comparisons, it is clearly evident that when PV cells are produced and transported within Europe, the environmental impact of X-Glass manufacture can be immensely reduced. The location of glass manufacture does not affect these impacts as it has minor changes when compared to PV cells and transportation. Additionally, transport of this heavy glasses have less significant impact on the environment. However, manufacturing glass in Europe will further reduce the inter-continent transportation. This can be understood from the table 5.25 and figure 5.7 showing the comparison of current X-Glass production (materials from other countries) and X-Glass EU when materials are manufactured in Europe.

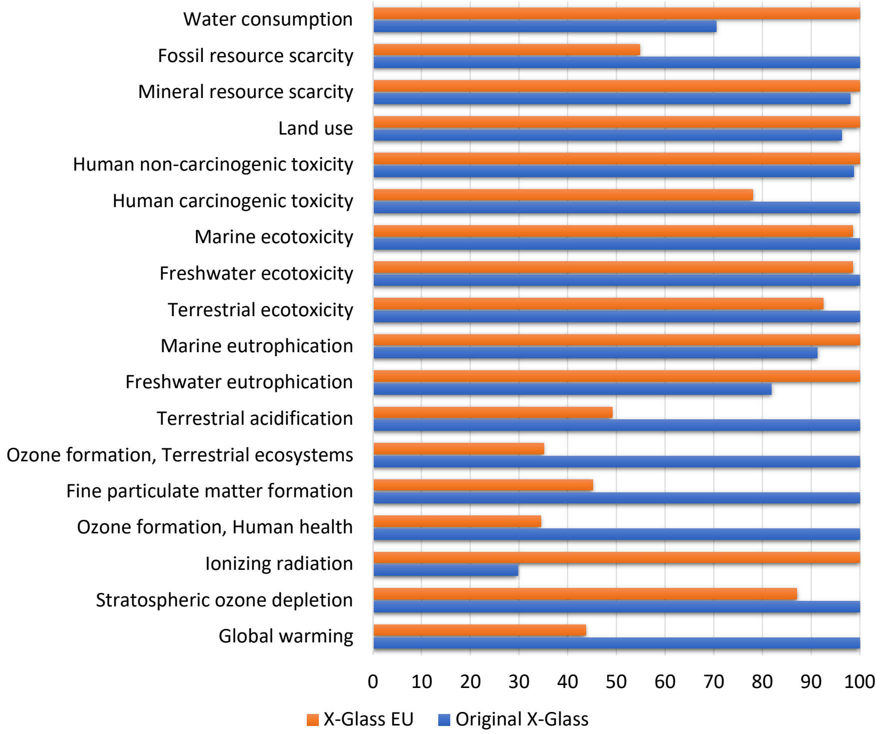


Figure 5.7: Comparison of Current X-Glass production and X-Glass EU (materials from EU)

Table 5.25: The mid point category results for current X-Glass and X-Glass EU modules

Impact category	Unit	Current X-Glass	X-Glass EU
Global warming	kg CO2 eq	6.35E+02	2.78E+02
Stratospheric ozone depletion	kg CFC11 eq	1.89E-04	1.65E-04
Ionizing radiation	kBq Co-60 eq	2.05E+01	6.89E+01
Ozone formation, Human health	kg NOx eq	1.80E+00	6.19E-01
Fine particulate matter formation	kg PM2.5 eq	1.07E+00	4.84E-01
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.82E+00	6.37E-01
Terrestrial acidification	kg SO2 eq	2.43E+00	1.19E+00
Freshwater eutrophication	kg P eq	2.13E-01	2.61E-01
Marine eutrophication	kg N eq	4.37E-02	4.78E-02
Terrestrial ecotoxicity	kg 1,4-DCB	1.93E+03	1.78E+03
Freshwater ecotoxicity	kg 1,4-DCB	2.21E+01	2.18E+01
Marine ecotoxicity	kg 1,4-DCB	3.31E+01	3.26E+01
Human carcinogenic toxicity	kg 1,4-DCB	2.50E+01	1.95E+01
Human non-carcinogenic toxicity	kg 1,4-DCB	6.88E+02	6.97E+02
Land use	m2a crop eq	1.14E+01	1.18E+01
Mineral resource scarcity	kg Cu eq	2.27E+00	2.32E+00
Fossil resource scarcity	kg oil eq	1.40E+02	7.70E+01
Water consumption	m3	1.45E+01	2.05E+01

Table 5.26: LCA result review of current X-Glass module and X-Glass EU

	Current X-Glass	**X-Glass EU**
CED (MJ/ m^2 module)	4670	3862
Irradiation (Slope 30) (kWh/m2/yr)	1198	1198
Location	Netherlands	Netherlands
Module Efficiency (%)	19.76	19.76
Performance Ratio	0.75	0.75
Annual Energy Output	284.54	284.54
EPBT (yr)	1.6	1.3
NREPBT (yr)	5.2	3.6
Lifetime (yr)	30	30
NER	19.1	23.1
GHG Emission (kg CO2 eq./m^2 module)	396	174
GHG Emission Rate (g CO2 eq/kWh)	73	32
CO_2 off-set period (yr)	3.9	1.7

5.4 OTHER IMPACT ASSESSMENT CATEGORIES

The impact categories from ReCiPe 2016 were analysed and compared in the previous section. The impact categories that includes the performance of the PV module will be discussed in this section. As discussed in section 2.4, the impact categories like Energy Payback time (EPBT), Energy yield ratio and the GHG emission rate were manually using cumulative Energy Demand (CED) and Global Warming Potential (GWP) from SimaPro. These are essential impact categories that takes module performance and lifetime of the module. Table 5.26 shows the results of all the impact categories that were manually calculated. The cumulative energy demand was taken from the SimapPro results. The average solar irradiance for 30^0 tilted rooftop X-Glass module dacing south in The Netherlands was calculated to be 1198.45 $kWh/m^2/yr$. The module surface area and efficiency are 1.6 m^2 and 19.76%. The performance ratio for slanted rooftop was taken as 0.75 as proposed in the LCA methodology guide [22]. The energy conversion factor (η_G) was assumed to be 35% as proposed by Akinyele et al. [54]. With all these values the annual energy output was calculated. The, the EPBT and NREPBT was calculated using the equation 2.4. **The EPBT and NREPBT for X-Glass was thus found to be 1.6 and 5.2 years, respectively**.

All the above calculations were done for X-Glass EU model when materials are manufactured within EU assuming the cell efficiency to be the same as the Chinese cells. From the table, it can be seen that relatively less energy is used in this module manufacture. This is due to the reduction of several transoceanic and air transport for the material shipment as truck transport is less polluting than. The EPBT and NREPBT with this CED value for X-Glass EU was found to be 1.3 years and 3.6 years. The NREPBT of this module proves that the renewable share of energy source is comparatively higher than China with a difference of 1.6 years.

The Net Energy Ratio (NER) takes lifetime of the PV module into account (from equation 2.7) compared to the EPBT that takes only annual yield. The lifetime of an X-Glass module is 30 years [89]. The module degradation was assumed to be 1% for the first year and 0.5% from the 2nd year until the rest of its lifetime. The NER for original X-Glass module was calculated to be 19.1 signifying that the net energy produced by the module during its lifetime is larger than the electricity consumed. The NER for X-Glass EU model has a higher value of 23.1 comparatively. GHG emission rate was calculated using the equation 2.8. The manufacture of X-Glass module was found to emit 73 g CO_2 eq./kwh GHG gases. Finally, the CO_2 offset period was calculated for both the modules using the equation 2.8. The GHG emission rate for dutch electricity grid is in between the range of 0.48-0.63 kg CO_2 eq/kWh. Average value of 0.55kg CO_2 eq/kWh was used in this study. The time take by the X-Glass pannel to off-set the CO_2 emissions is 3.9 years. The X-Glass EU takes even lesser CO_2 off-set period of 1.7 years All these values can be validated by comparing the results of various studies conducted on different type of modules.

Table 5.27: LCA Results review from various studies

Author	Year	Location	Mounting Type	Irradiation (kWh/m2/yr)	PR	Efficiency (%)	Lifetime (yr)	EPBT (yr)	GHG emission rate (g CO2 eq./kwh)
Kim et al. [57]	2014	South Korea	Ground Mounted	1301.35	0.80	15.96	30	4.65	41.8
Fthernakis et al. [30]	**2012**	**United States**	**Ground Mounted**	**1800**	**0.8**	**20.1**	**30**	**1.4**	**64.2**
Ito et al. [90]	2010	China	Ground Mounted	1702	0.78	N/A	30	2.5	50
Kannan et al. [91]	2006	Singapore	Roof Mounted	1635	N/A	11.86	25	5.87	217
Muneer et al. [92]	2006	United Kingdom	N/A	800	N/A	11.5	30	8	44
Jungbluth et al. [40]	2005	Switzerland	Roof Mounted	1117	N/A	16.5	30	3-6	79
This Study	**2020**	**Netherlands**	**Roof Mounted**	**1200**	**0.75**	**19.76**	**30**	**4.1**	**305.5**

Table 5.27 shows the LCA results from recent LCA studies including the X-Glass production results. The results of EPBT and GHG emission rate varies in all these literature. Generally, the EPBT varies from 1.4 to 12.1 years and GHG emission rate varies from 30 to 280 g CO_2 eq as stated by Wong et al. [66]. The results of X-Glass production fall between these range. The variations in these values are due to different reasons like solar irradiation, CED used in the production, manufacturing technology and types of installations. Since all these study used different inputs for the LCA calculations, it is not possible to compare X-Glass LCA calculations with these studies. However, the study conducted by Fthenakis et al. on Sunpower PV module is comparable to X-Glass LCA study as the total energy used to produce the module was taken to be 4662 MJ/m^2. The energy used in this study was 4669 MJ/m^2. Even though original X-Glass module was calculated with a similar module efficiency of 20.1%, the irradiance was taken for the United States i.e., 1800 kwh/m^2. So, for an irradiance of 1800kwh/m^2, EPBT was calculated for an X-Glass panel, and found to be 1.1 years. These values slightly differ due to the difference in CED values. In the literature, the EPBT of 1 MW of ground-mount installations of Sunpower was calculated. This includes CED values of several number of PV modules with electrical components. Additionally, EPBT for these different irradiances and performance ratios were calculated for X-Glass EU model. These EPBT values are tabulated in the table 5.28.

The EPBT values increase with decrease in irradiance as seen from the table 5.28. Similarly, the EPBT values also vary with respect performance ratio. The increase in the performance ratio decreases the EPBT drastically. In the study conducted by Mann et al., the EPBT of different BOS components were found to be in the range of

Table 5.28: EPBT of X-Glass for different irradiance and PR values

Solar Irradiance kwh/m2	**PR = 0.75**		**PR = 0.80**	
	Current X-Glass (yr)	**X-Glass EU (yr)**	**Current X-Glass (yr)**	**X-Glass EU (yr)**
1200	1.6	1.3	1.5	1.2
1300	1.5	1.2	1.4	1.15
1400	1.4	1.1	1.3	1.1
1500	1.3	1.05	1.2	1.0
1600	1.2	1.0	1.1	0.9
1700	1.1	0.9	1.05	0.9
1800	1.1	0.9	1	0.8

0.7-0.9 years for rooftop systems [93]. The EPBT of original X-Glass module ranges from 2-2.5 years for roof-top applications, i.e., performance ratios of 0.75. The conclusions based on these discussed impact categories that were manually calculated and also the results from ReCiPe2016 will be discussed in the next chapter.

6 CONCLUSION & RECOMMENDATIONS

6.1 KEY FINDINGS

The main objective of this study was to find the environmental impact of manufacturing an X-Glass module. To this end, an LCA was conducted on the X-Glass production to calculate several impact categories such as GHG emissions, energy payback time, net energy ratio and GHG emission rate. The **GHG emission** for the manufacture of **1 X-Glass module** was found to be **634 kg CO_2 eq**. The **payback time** for this module was found to be **1.6 years** with **73 g CO_2 eq** GHG emission rate per kWh of electricity generated. The GHG emission impact of just the module without the cells was found to be **80 kg CO_2 eq**. Furthermore, the CO_2 offset period for X-Glass panel was found to be **3.9 years**. These calculated values were then cross-validated using different LCA studies of mono-Si PV modules. As per different LCA studies, the EPBT for a mono-Si PV varies from anywhere between 1.5 to 9 years, depending on various factors such as solar irradiance, module efficiency and type of technology used [66]. Similarly, the GHG emission rate was found to be in the range of 30 to 280 g CO_2 eq. [66]. Both the EPBT and GHG emission rate of X-Glass module lie within this range. However, a PV module that is manufactured completely in Europe has less environmental impact, in comparison to current X-Glass module manufacturing. The reason for this can be attributed to the source of energy used for the production of the PV cell itself.

6.1.1 Energy Influence

The results from this LCA study show that the manufacture of PV cells has a major impact on the environment. PV cell manufacturing is majorly associated with 16 out of 18 impact categories of the ReCiPe method due to the high energy requirements of its sub-processes such as solar grade silicon production, Cz process, etc. The energy used in the cell production directly contributes to the GHG emissions and other impact categories. The severity of the impact depends on the type of fuel source used for the generation of electricity, subsequently used for manufacturing the panel. The use of non-renewable energy based electricity has a high impact on the environment. The source of energy, in turn depends on the country where the electricity is generated. Therefore, when the PV cells are manufactured in a country with more non-renewable energy share, the environmental impact is very high. Currently, X-Glass uses PV cells that are manufactured in China. The non-renewable share of energy produced in China is around 70%. Hence, the impact of X-Glass module on the environment is high and quite negative. Nevertheless, this high impact can significantly be reduced by using PV cells manufactured locally in Europe. The non-renewable energy share of Europe is drastically low, in comparison to China. Hence, GHG emissions can be **reduced by 40% when the PV cells are manufactured in Europe.** Therefore, using PV cells manufactured in Europe for X-Glass production leads to improved environmental performance. Moreover, **the EPBT can be improved by 3.6 months with 40 g CO_2 eq lesser GHG emission rate** for 1 module when installed in The Netherlands. If X-Glass were to be installed in a different region with higher insolation, the environmental performance of the module can be further improved. In the X-Glass module, other than PV cells, some other materials used for manufacturing are shipped from different parts of the world. However, the energy used for the production of these materials is very low, in comparison to the PV cells. Using the cells from Europe will reduce the impact drastically that will allow certain freedom towards buying and shipping materials from other countries. Even though procuring cells from Europe has an effect on the capital investment, it drastically reduces the environmental impact of the total module.

6.1.2 Energy self-production

EXASUN uses 10 kWh of energy from the Netherlands electricity grid to produce one X-Glass module. The Netherlands electricity mix is mainly based on non-renewable energy sources with more than 70% share from coal, oil and natural gas [74]. So using the energy from the grid will further increase the environmental impact of the X-Glass production. Therefore, self-generating electricity from a renewable source to manufacture these modules can bolster its environmental performance.

6.1.3 Mineral Usage

Other than PV cells, the laminate materials and aluminium framing were found to have a major impact on mineral scarcity and ecotoxicity. This is due to the use of minerals such as copper, silver, etc. Copper is majorly used in X-Glass module as part of the conduction foil. Additionally, copper tabs and plates are used to connect the junction box. The improvements in these impact categories can be reduced by cutting down the use of copper. One such option could be using aluminium tabs instead of copper. However, aluminium extraction for framing the module partly contribute to these impacts. Therefore, replacing the minerals will also have some minor effects on toxicity and scarcity of the material. These impact reduction depends mainly on the material that are replaced. The process of finding a replacement material is time consuming as it needs additional testing to analyze the net electrical performance of the module. However, if the sole purpose is to reduce the environmental impact, then finding a replacement of copper should be a top priority.

6.2 RECOMMENDATIONS

Replacement of PV cells

As X-Glass uses mono-Si, this study was mainly based on this type of cell manufacture. However, there are other cell technologies that can be incorporated in the X-Glass module. Multi crystalline silicon is one option that can be considered as the manufacturing process uses lesser energy when compared to mono-Si (figure 3.3). A similar model for multi-silicon can be developed using SimaPro and compared with the current model to check the environmental performance in replacing the cell. Moreover, when these cells are manufactured within Europe, the impact of the cells can be reduced even more. However, replacing the cells will have a major impact on the electrical performance of the module due to its lower efficiency.

Energy Uncertainties

In this study, for all LCA calculations, the energy for PV cell production were obtained from literature. This was due to the unavailability of data from the cell manufacturers. The environmental impact of silicon based PV modules mainly depends on cell production. Therefore, while developing cell production model, using appropriate data from cell manufacturers will give an even more accurate environmental impact result. Additionally, traditional mono-Si PV cells were considered for this study. However, for X-Glass manufacture, MWT solar cells are used. The

6.3 FUTURE WORK

6.3.1 Sensitivity Analysis

The energy used to produce various types of silicon (MG-Si, EG-Si, SoG-Si, wafer, etc.) varies from 3000 MJ to 6000 MJ for recently conducted LCA studies. If the energy data for cell production is unknown due to corporate confidentiality purposes, then trying different energy values for each process will give a proper range of environmental impacts caused in each of the silicon production processes.

6.3.2 Geographical Analysis

In this study, models for PV cells were based on China and Europe. However, the cells are also manufactured in some other parts of Asia and the United States. Consequently, there are slight variations in some sub-processes for the PV cell production, depending on location. For example, MG-Si produced within Asia is typically manufactured in South Korea [33]. Thus, LCA calculations based on different regions can provide clear idea on the effect of location based manufacture.

6.3.3 Cost Analysis

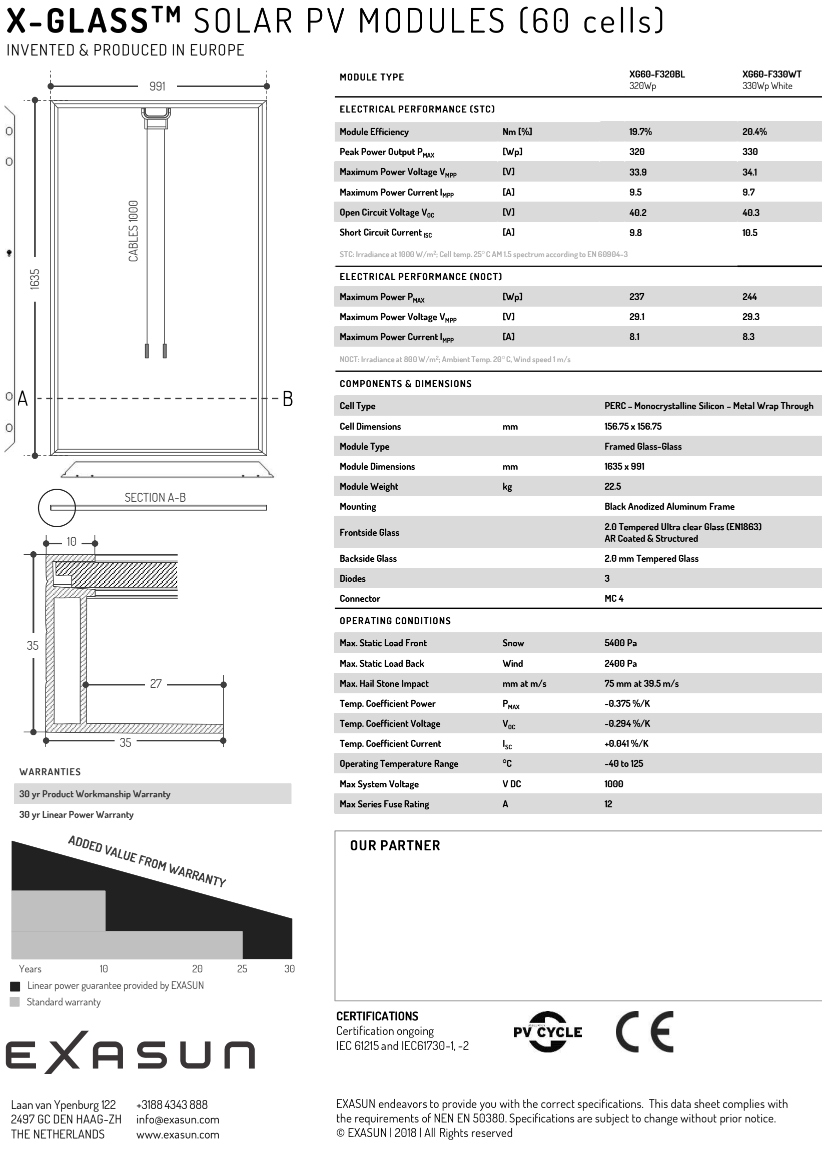
The major conclusion of this study was to use mono c-Si PV cells that are manufactured in Europe. Though European manufactured cells reduce the environmental impact, procuring cells from Europe is not economically feasible. When cells from Europe are used, the cost of the entire PV module increases due to the higher cell costs [94]. Hence, PV module manufacturers usually prefer PV cells from China due to their lower cost. Therefore, to check the economic feasibility of using European modules, performing a cost analysis including different cell manufacturers from several locations can give a better idea on the PV cell costs.

6.3.4 Recycling or Reusing of materials

At EXASUN, the degraded module after is lifetime is disposed. However, not all material used in the manufacture are disposable. 90% of glass and 95% of solar cells from a PV module can be reused [95]. The glasses can be shredded and recycled to produce glass products depending on the application. The solar cells can be removed from the PV module by a high temperature process called pyrolysis [96]. These cells can be reused to silicon wafers again. Therefore, re-using more of these items discarded from the cell will increase the environmental performance. This increase again depends on the energy that is used to recycle. An LCA model for recycling of X-Glass module can be developed to analyze the impacts of different recycling processes.

A | APPENDIX 1

A.1 X-GLASS SPECIFICATION DATASHEET



X-GLASS™ SOLAR PV MODULES (60 cells)

INVENTED & PRODUCED IN EUROPE

MODULE TYPE		XG60-F320BL 320Wp	XG60-F330WT 330Wp White
ELECTRICAL PERFORMANCE (STC)			
Module Efficiency	Nm [%]	19.7%	20.4%
Peak Power Output P_{MAX}	[Wp]	320	330
Maximum Power Voltage V_{MPP}	[V]	33.9	34.1
Maximum Power Current I_{MPP}	[A]	9.5	9.7
Open Circuit Voltage V_{OC}	[V]	40.2	40.3
Short Circuit Current $_{ISC}$	[A]	9.8	10.5

STC: Irradiance at 1000 W/m²; Cell temp. 25° C AM 1.5 spectrum according to EN 60904-3

ELECTRICAL PERFORMANCE (NOCT)			
Maximum Power P_{MAX}	[Wp]	237	244
Maximum Power Voltage V_{MPP}	[V]	29.1	29.3
Maximum Power Current I_{MPP}	[A]	8.1	8.3

NOCT: Irradiance at 800 W/m²; Ambient Temp. 20° C, Wind speed 1 m/s

COMPONENTS & DIMENSIONS		
Cell Type		PERC – Monocrystalline Silicon – Metal Wrap Through
Cell Dimensions	mm	156.75 x 156.75
Module Type		Framed Glass-Glass
Module Dimensions	mm	1635 x 991
Module Weight	kg	22.5
Mounting		Black Anodized Aluminum Frame
Frontside Glass		2.0 Tempered Ultra clear Glass (EN1863) AR Coated & Structured
Backside Glass		2.0 mm Tempered Glass
Diodes		3
Connector		MC 4

OPERATING CONDITIONS		
Max. Static Load Front	Snow	5400 Pa
Max. Static Load Back	Wind	2400 Pa
Max. Hail Stone Impact	mm at m/s	75 mm at 39.5 m/s
Temp. Coefficient Power	P_{MAX}	-0.375 %/K
Temp. Coefficient Voltage	V_{OC}	-0.294 %/K
Temp. Coefficient Current	I_{SC}	+0.041 %/K
Operating Temperature Range	°C	-40 to 125
Max System Voltage	V DC	1000
Max Series Fuse Rating	A	12

WARRANTIES

30 yr Product Workmanship Warranty

30 yr Linear Power Warranty

■ Linear power guarantee provided by EXASUN
▨ Standard warranty

OUR PARTNER

CERTIFICATIONS
Certification ongoing
IEC 61215 and IEC61730-1, -2

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EXASUN endeavors to provide you with the correct specifications. This data sheet complies with the requirements of NEN EN 50380. Specifications are subject to change without prior notice.

Figure A.1: X-Glass panel assembly steps

A.2 DETAILS OF MOST WIDELY USED LCA SOFTWARE

	Ecochain	**Mobius**	**openLCA**	**SimaPro**	**GaBi**
Collaborative	yes	yes	yes	no	no
Free version	yes	free trial	yes	no	no
Company	EcoChain	EcoChain	GreenDelta	Pre Consultants	Sphera
Price Rating (out of 5)	4	2	1	5	5
Student Pricing	yes	yes	free	yes	yes
Product Footprint	yes	yes	yes	yes	yes
Activity-based Footprinting	yes	no	no	no	no
EPD Generator	yes	no	yes	yes	yes
Full LCA Report	yes	no	no	yes	yes
Supplier Dashboard	yes	no	no	no	no
Offers consultancy	yes	yes	yes	yes	yes
Software or Online?	Online	Online	Software	Download	Download
User Focus	Sustainability Professional	Product Developer	LCA Consultant	LCA Consultant	LCA Consultant
Model alternative products	no	yes	yes	yes	yes

Table A.1: LCA softwares and details [25].

A.3 ECOINVENT-UVEK 2018 LCI DATABASE UPDATE INFORMATION

No.	Updated background data	Scope of the update
1.	Natural gas	Supply mix
		LPG supply chain from production
		Russia Regional distribution network
2.	Photovoltaics	Polysilicon manufacturing
		Saw gap and wafer-thick cadmium-telluride technology
		Module efficiency Disposal
		Specific energy yield and degradation rate of photovoltaic plants
3.	Nuclear power	Uranium extraction and treatment
		Fuel chain
		Operation of nuclear power plants
		Geological deep storage
4.	Hydropower	Running water storage power
		Small hydropower Pump storage
5.	Electricity production, transmission and distribution	Electricity production (Europe and rest of the world)
		European electricity mix (ENTSO-E)
		Electricity losses and distribution of electricity grid infrastructure
6.	Electricity mix Switzerland	Electricity mixes for 2011
		Electricity mixes for 2014
7.	Corrections of errors	Various
8.	Kva	updated material and energy flows
9.	Petroleum products (e.g. petrol, diesel, heating oil EL) - Reference year 2014 & 2016	Mix of raw materials of crude oil
		Share of Swiss and European refineries in the supply of petroleum products in Switzerland
		Transport distances of crude oil and imported petroleum products
10.	Wood	Forest management Production of wood products
11.	Aluminum	Production of primary and secondary aluminium aluminium production mixes
12.	Transport services Road	Passenger and freight transport, incl. construction machinery and tram
13.	Transport services Rail	Passenger and freight transport
14.	Transport services Ships	Passenger and freight transport
15.	Transport services Aircraft	Passenger and freight transport, incl. cable cars

Table A.2: Data Update information in UVEK 2018 database[97]

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