ENVIRONMENTAL SUSTAINABILITY ANALYSIS OF RENEWABLE ENERGY GENERATION WITH PHOTOVOLTAIC SOLAR PANELS IN TURKEY

by

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ABSTRACT

ENVIRONMENTAL SUSTAINABILITY ANALYSIS OF RENEWABLE ENERGY GENERATION WITH PHOTOVOLTAIC SOLAR PANELS IN TURKEY

Life Cycle Assessment is a method that scrutinizes in detail the toxic environmental effects of products and services over their entire life span. The aim of this study is to reveal the environmental effects of solar panels, which are accepted as the cleanest method of obtaining energy, throughout their life cycle and to present a more sustainable solar energy generation roadmap. For this reason, multi-Si PV solar panel type, which is the most widely used type and dominates the world market, has been studied. Environmental impact categories were assessed using GaBi 9.5 Software, EcoInvent Database and CML Assessment Methodology. While evaluating the life cycle of the multi-Si PV panel, metallurgical silicon smelting, solar grade multi-Si purification, wafer slicing, ingot casting, cell processing, panel assembly, transportations and recycling stages were studied. In addition, three different recycling scenarios, which diverge according to delamination methods, were also examined in terms of their environmental effects. Thus, a framework has been put forward on how the toxic effects of solar panels at the end of their life can be minimized. In this research, both real sector data and literature data were used. The multisilicon production process, which consists of the stages of metallurgical silicon smelting and solar grade multi-Si purification, and module assembly stage emerged as the two processes that cause the most environmental impact. In recycling scenarios, the FRELP2 process, which is a combination of thermal and chemical delamination processes, provided the best results in terms of environmental impact.

ÖZET

FOTOVOLTAİK GÜNEŞ PANELLERİ İLE TÜRKİYE'DEKİ YENİLENEBİLİR ENERJİ ÜRETİMİNİN ÇEVRESEL SÜRDÜRÜLEBİLİRLİK ANALİZİ

Yaşam Döngüsü Değerlendirmesi, ürün ve hizmetlerin tüm yaşam süreleri boyunca toksik çevresel etkilerini ayrıntılı olarak inceleyen bir yöntemdir. Bu çalışmanın amacı, en temiz enerji elde etme yöntemlerinden birisi olarak kabul edilen güneş panellerinin yaşam döngüleri boyunca neden oldukları çevresel etkileri ortaya koymak ve daha sürdürülebilir bir güneş enerjisi üretim yol haritası sunmaktır. Bu nedenle en yaygın kullanılan tip olan ve dünya pazarına hakim olan multi-Si PV güneş paneli tipi üzerinde çalışılmıştır. Çevresel etki kategorileri; GaBi 9.5 Yazılımı, EcoInvent Veritabanı ve CML Değerlendirme Metodolojisi kullanılarak değerlendirildirilmiştir. Multi-Si PV panelin yaşam döngüsü değerlendirilirken; metalurjik silikon eritme, güneş dereceli multi-Si saflaştırma, gofret dilimleme, ingot döküm, hücre işleme, panel montajı, nakliye ve geri dönüşüm aşamaları incelenmiştir. Ayrıca delaminasyon yöntemlerine göre farklılık gösteren üç farklı geri dönüşüm senaryosu da çevresel etkileri açısından incelenmiştir. Böylece güneş panellerinin ömrünün sonundaki toksik etkilerinin nasıl en aza indirilebileceğine dair bir çerçeve ortaya konmuştur. Bu araştırmada hem reel sektör hem de literatür verileri kullanılmıştır. Metalurjik silikon ergitme ve solar dereceli multi-Si saflaştırma aşamalarından oluşan multisilikon üretim süreci ve modül montaj aşaması, en fazla çevresel etkiye neden olan iki süreç olarak ortaya çıktı. Geri dönüşüm senaryolarında ise, termal ve kimyasal delaminasyon süreçlerinin bir kombinasyonu olan FRELP2 yöntemi çevresel etki açısından en iyi sonuçları sağladı.

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LIST OF SYMBOLS/ABBREVIATIONS

a-Si	Amorphous Silicon
Ag	Silver
AP	Acidification Potential
BOD	Biochemical Oxygen Demand
BOS	Balance of System
C_2H_4	Ethene or Ethylene
CdTe	Cadmium Telluride
CFCs	Chlorofluorocarbons
CFC-11	Trichlorofluoromethane
CH_4	Methane
CI(G)S	Copper Indium Gallium Selenide
CO	Carbon monoxide
CO_2	Carbon dioxide
COD	Chemical Oxygen Demand
DCB	Dichlorobenzene
EP	Euthropication Potential
EPBT	Energy Payback Time
EoL	End-of-Life
EU	European Union
EVA	Ethylene Vinyl Acetate
FAETP	Freshwater Aquatic Ecotoxicity Potential
FRELP	Full Recovery End-of-Life Photovoltaic
FU	Functional Unit
GHG	Greenhouse Gases
GWP	Global Warming Potential
HCl	Hydrochloric acid
HCFCs	Hydro chlorofluorocarbons
HF	Hydrofluoric acid
HNO_3	Nitric Acid
HTP	Human Toxicity Potential
ISO	International Organization for

	Standardization
kg	Kilogram
kWh	Kilowatt-hour
kWp	Kilowatts peak
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LGRF	Laminated Glass Recycling Facility
Mg-silicon	Metallurgical Grade Silicone
multi-Si	Multicrystalline Silicon
mono-Si	Monocrystalline Silicon
NMVOC	Non-methane volatile organic compound
NH_4	Ammonium
NO	Nitrogen monoxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
ODP	Ozone Layer Depletion Potential
PET	Polyethylene Terephthalate
PO_4	Phosphate
POCP	Photochemical Ozone Creation Potential
PV	Photovoltaic
PVC	Polyvinyl Chloride
PVF	Polyvinyl Fluoride Film
SETAC	Society of Environmental Toxicology and Chemistry
SO_2	Sulfur dioxide
SoG-silicon	Spin-on-Glass Silicon
SO_x	Sulfur oxides
TETP	Terrestrial Ecotoxicity Potential
UNEP	United Nations Environment Programme
UV	Ultraviolet

WEEE	Waste from Electrical and Electronic Equipment

1. INTRODUCTION

The production and consumption patterns of humanity have changed rapidly since the first industrial revolution that started in the late 1700s. Economic development and population growth which are the result of this change have constantly increased and continue to increase the energy needs of humankind. Although there are many different energy production methods today, most of the energy needed is provided through fossil fuels. However, this intense use of fossil fuels causes various environmental problems such as air pollution, acid rains, global warming and climate change. As a result of this fact, there has been growing interest in renewable energy production technologies. Wind, solar, geothermal, hydroelectric and biofuel energy applications have been applied worldwide.

When renewable energy sources are reviewed, solar energy is the most abundant and inexhaustible natural resource in the world. Solar power is usable energy generated from the sun in the form of electric or thermal energy. Solar energy is captured in a variety of ways, the most common of which is with photovoltaic (PV) solar panels that convert the sunlights into usable electricity. As it has many features such as being easily exploitable, clean, inexhaustible, long-lasting and reliable, solar energy plays a key role in the increasing problems of energy demand in today's world.

The objective of this study is to carry out a life cycle assessment (LCA) of electricity production through multicrystalline photovoltaic panels, most common type of solar panels, taking into account the recycling processes. From its initial production until today, the end-of-life scenario for solar panels was landfilling or incineration. However, due to the fact that solar panel waste contains toxic chemicals, it is necessary to switch to effective recycling methods, considering the damage it will cause to the environment at the end of their life time. In this study, it is aimed to reveal potential environmental impacts throughout the entire life cycle stages of multi-Si PV solar panels and to provide a comprehensive perspective on how different EoL scenarios can be effective on global warming potential.

2. LITERATURE REVIEW

2.1. Photovoltaic Solar Panels

The rapidly increasing world population and the consumption habits of modern world societies are increasing expeditiously every year. However, we have to part ways with fossil fuels, which we have been dependent on for many decades, because this type of energy consumption causes great environmental and climatic destruction. At this point, renewable energy sources look very promising and solar energy is one of the most prominent.

Although the emergence of the modern version of solar panels was in the middle of the last century, the photovoltaic industry took its real leap forward in a dramatic way around the world after 2000. Global installed solar photovoltaic power reached 310 GW in 2016 and almost 700 GW in 2020. Looking at the projections for 2050, there are strong predictions that this amount will reach 4500 GW (Sica et al., 2018).

The global solar PV technologies market has been showing impressive growth rates in recent years. According to the Snapshot of Global Photovoltaic Markets 2018 Report of the International Energy Agency (IEA), by the end of 2017, the photovoltaic solar panel system capacity reached 402.5 GW, including grid-connected and grid-independent installations worldwide as reported in Figure 2.1. Solar energy has experienced steady growth of around 37% per year since the 1990s and is now ranked as the fastest growing renewable energy source (Deng et. al., 2019). The global PV market has been observed to expand continuously from 2005 to 2017, which naturally led to a positive trend in the PV system usage.

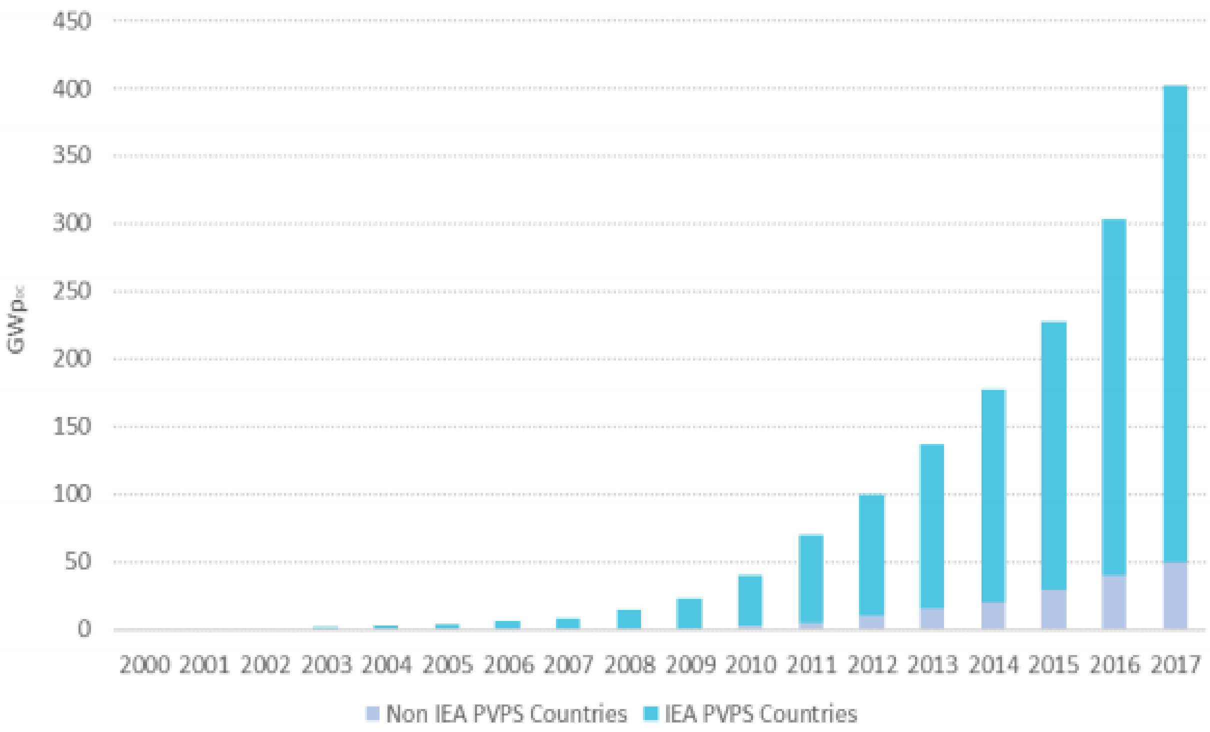

Figure 2.1. Total PV installations for IEA PVPS countries and non IEA PVPS countries from 2002 until 2017 (Snapshot of Global Photovoltaic Markets, 2018)

Silicon-based panels are the most widely used method for generating electricity from solar energy in the world market. According to Photovoltaic Report (2018) of Fraunhofer Institute for Solar Energy Systems, silicon solar cells have occupied 90% of global PV market with highest conversion and efficiency for monocrystalline silicon (mono-Si) and multicrystalline silicon (multi-Si) are 41.7% and 22.3% respectively. Discovered in the first quarter of the 1800s, silicon, which is the most abundant semiconductor on the planet, occupies maximal place in the production of photovoltaic solar panel technologies due to its stable structure.

While producing silicon-based solar panels, silicon goes through numerous stages. During the extraction of silicon raw material, multi-row delayed blasting technique, downhole drilling and detonatings are mostly used. After exraction stage, silica needs to be reduced to silicon, and during this process a type of carbon from coal, coke or wood scrap is used. Then, silicon dioxide is degraded to metallurgical grade silicon in an arc furnace. The silicon is then purified to solar grade silicon, using numerous methods such as typical Czochralski, Siemens or modified processes (Ludin et. al., 2018).

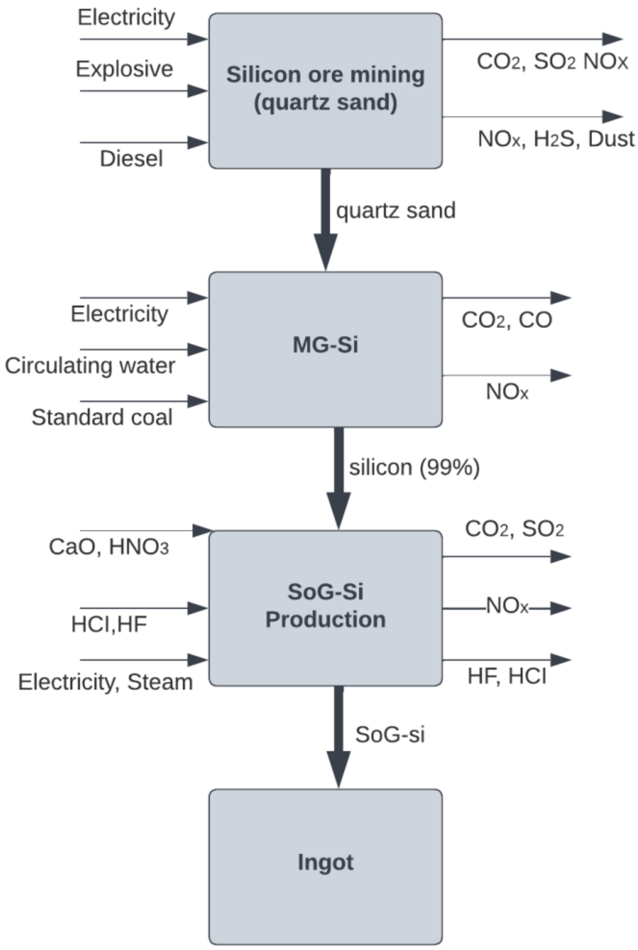

Figure 2.2. Scheme of converting silica ore to solar grade silicon.

Production of silicon PV panels is growing rapidly, and it is important to assess their development in this growth process and to evaluate their current and future environmental effects and energy performance at the end. Within this respect, life cycle assessment (LCA) is one of the most reliable decision making tools to interpret their environmental performance. Many studies have been done on Life Cycle Analysis of multicrystalline PV panels in the literature, but few of them have focused on the recycling process of multi-Si solar panels. Solar panels are considered to be a quite clean and sustainable energy source compared to fossil energy sources. However, considering the heavy metals and chemicals they contain, the damage these panels will cause to the environment at the End-of-Life (EoL) phase and the greenhouse gas emissions they will cause should be carefully examined. According to the End-of-Life Management: Solar Photovoltaic Panels report of the International Renewable Energy Agency, the amount of photovoltaic solar panel waste will reach 60-78 million tons worldwide by 2050 (IRENA, 2016). Considering the amount of panel waste that will be generated in the middle of the twenty-first century, the criticality of the panel recycling process is increasing considerably.

Due to its geographical location, Turkey is a country with a high solar energy production potential. Despite this potential, Turkey has not made a serious leap in energy production with photovoltaic panels. However, the RES Support Scheme established within the scope of the Law on the Use of Renewable Energy Resources for the Purpose of Electricity Generation, which was put into effect in 2005 in order to evaluate the renewable energy potential, has still been an important turning point. Since this date, thanks to the incentives given to energy production from renewable sources, the share of renewable energy sources other than hydraulic energy has started to increase in Turkey's energy production. The development of solar energy (PV) installed power in Turkey and the change in the share of solar energy in electricity generation over the years are presented in Figure 2.3 (Oral, 2020).

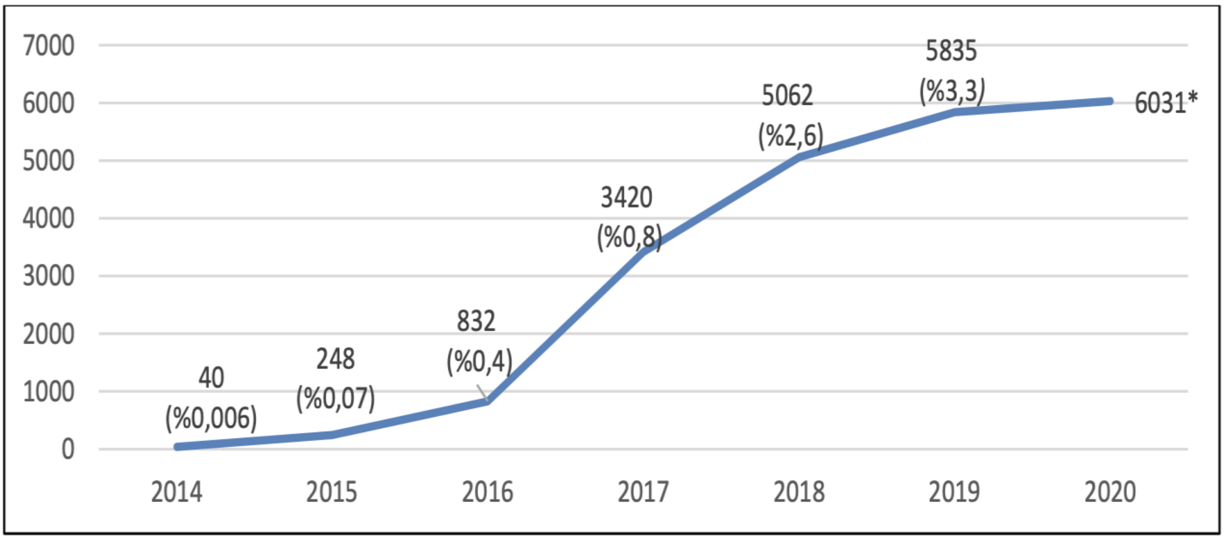

Figure 2.3. Development of solar energy (PV) installed power in Turkey and the share of solar energy in electricity production (Oral, 2020).

Since the emergence of solar energy as an electricity generation technology, Turkey has not been producing its own solar panels, but recently, domestic panel production studies have started on a quite small scale. Solar cells have been imported from China, Canada and some European countries for a long time. The production of photovoltaic solar panels for the first time in Turkey started in August 2020 by a small number of companies. Due to both the rapid increase in the share of solar energy in electricity production and the start of domestic solar panels production, Turkey needs to determine strong policies regarding the sustainability of solar energy systems and their fate at the end of their life cycles.

The interest in solar energy, which is a relatively cleaner method, is increasing around the world, after the understanding of how much of a danger the climate crisis created by energy production based on fossil fuels poses for the future of humanity and the entire planet. Solar energy, along with many other types of renewable energy such as wind, hydroelectric, nuclear, geothermal, biomass, wave, has shown a much better environmental performance compared to fossil fuels, according to research to date. Silicone based photovoltaic solar panels do not release any pollutants during the usage process (Tao and Yu, 2014), but still, the panel can give many toxic emissions to the soil, water and air, especially at some production stages and at the end of its life. Since the first significant amount of photovoltaic solar panel installations took place in the early 1990s, panels with a lifetime of around 25-30 years will reach the end of their life with increasing momentum in the coming years. Currently, all solar panels that have reached the end of their life are not subjected to processes such as recovery and recycling all over the world. There are some recycling processes, mostly at local and experimental levels. However, due to the rapid increase in the number of solar modules approaching the end of their life, efforts are currently being made to develop solutions for recycling processes.

The Waste Electrical and Electronic Equipment Directive, launched in 2003, mainly regulates the treatment of electrical and electronic waste at the end of its life cycle. The Waste Electrical and Electronic Equipment Directive (WEEE), which has been amended since 2012, provides a legal framework for expanded producer responsibility of photovoltaic solar panels on a European scale. The WEEE Directive sets minimum collection and recovery targets for solar panels and defines the basic legal rules and obligations for photovoltaic panels within the EU. According to the latest version of WEEE published in 2019, the recovery rate in electronic waste should be 85%, and the reuse or recycling rate should be 80%. Moreover, within the scope of this directive, since 2014, the collection, transportation and recycling of solar panels are regulated in each European Union country.

Turkey observed compliance with this regulation in the process of adaptation with European Union laws, and in this context, in parallel with the EU directives, the Waste Electrical and Electronic Equipment Control Regulation was published in 2012. Similarly, this regulation obliges manufacturers to collect, recover and recycle waste electronic products with the principle of "polluter pays". This task assigned to companies can be fulfilled through organizations authorized by the Ministry of Environment, Urbanization and Climate Change. There is no mandatory minimum rate for recovery and recycling processes in the electronic waste regulation in Turkey, but while the average recycling rate of electronic waste is 12% worldwide, this rate is around 5% in Turkey. Turkey, which is rapidly increasing its solar energy investments, will also need to determine a sustainable roadmap for the collection and appropriate recycling of PV panels that fall under the scope of electronic waste.

On the other hand, the European Green Deal, details announced in 2019, aims for the European Union to achieve at least 55% of greenhouse gas reductions by 2030 and includes several guidelines to accelerate the decarbonisation of energy production processes (Kougias et. al., 2021). The European Green Deal offers a set of actions to reduce greenhouse gas emissions in sectors such as energy, transport, industry, finance, trade. In order to reach these carbon reduction rates, it will be necessary to quickly turn to clean and renewable energy sources. As part of the Deal, solar energy, the lowest cost and most easily deployed clean energy, will play a leading role in Europe's goal of being climate neutral by 2050.

The European Green Deal sets out 3 key principles for the clean energy transition that will reduce carbon emissions:

1. Ensuring a secure and cost-effective energy supply
2. Creating a fully integrated, interconnected and digitized energy market for EU countries
3. Prioritizing energy efficiency, developing the energy performance of buildings and creating an energy sector based mainly on renewable resources

Figure 2.4. Elements of the European Green Deal (Factsheet: Financing Sustainable Growth)

Although the European Green Deal reveals a new commercial system and energy production roadmap for EU countries, this will not be limited to the member states of the union. Within the scope of this new roadmap, the European Commission expects the countries with which it trades to comply with these new standards, and otherwise plans to impose sanctions by imposing various taxes. In the context of these regulations, Turkey, whose biggest trade partner is the European Union, is expected to be highly affected by both these new regulations and the developments in energy transformation. For this reason, Turkey has to adapt to the Deal in order to keep its relations with the EU, which plans to carry out all its import and export activities within a new international trade system in a short time, strong and sustainable.

Within the scope of the adaptation process with the European Green Deal, the "Green Deal Action Plan of Turkiye" prepared by the Turkish Ministry of Trade was published on 16 July 2021. The Green Deal Action Plan mainly sets out the following objectives; to enable green investment through green financing, to allocate 1 GW of capacity per year for solar and wind power-based generation until 2027, to use a cleaner energy supply model, transition to an internationally competitive, sustainable, efficient and technological agricultural policy and to comply with EU environmental regulations. Within the framework of this action plan, transformation is inevitable for all stakeholders, especially in the production, consumption, industry and energy sectors.

One of the most important issues in the European Green Deal is The Carbon Border Adjustment Mechanism. This regulation refers to pricing, in other words taxation, of carbon in products exported to the EU in order to reduce greenhouse gas emissions. With this regulation, the EU transfers its responsibility for reducing carbon emissions to its commercial stakeholders and tries to ensure that they adopt it. Turkey, whose energy and industrial production mostly depends on fossil fuels, needs to invest rapidly and at high rates in renewable energy sources in order not to be heavily affected by these taxation.

One of the most crucial components of the European Green Deal, which is accepted as the new economic roadmap of the EU, is the circular economy. The regulations that will shape the EU Circular Economy Action Plan envisaged by the Green Deal will be implemented by taking into consideration the cyclical approach principles such as waste reduction, durability, recycling, reuse and repair. These comprehensive changes in the commercial roadmap of the European Union, Turkey's largest trade and investment partner, undoubtedly mean new regulations for the countries they partner with. These regulations, on the other hand, will strongly affect areas such as energy production, recycling and recovery. In this context, solar energy systems are one of the areas that need to determine a stronger roadmap.

2.2. Photovoltaic Solar Panels Types

There are various types of solar panels such as monocrystalline (mono-Si), multicrystalline (multi-Si), amorphous (a-Si), cadmium telluride (CdTe) thin film and CIS thin film, heterogeneous solar cells and dye sensitive solar cells. The most extensively used type today are monocrystalline and multicrystalline solar panels, also called silicon-based or crystalline silicon.

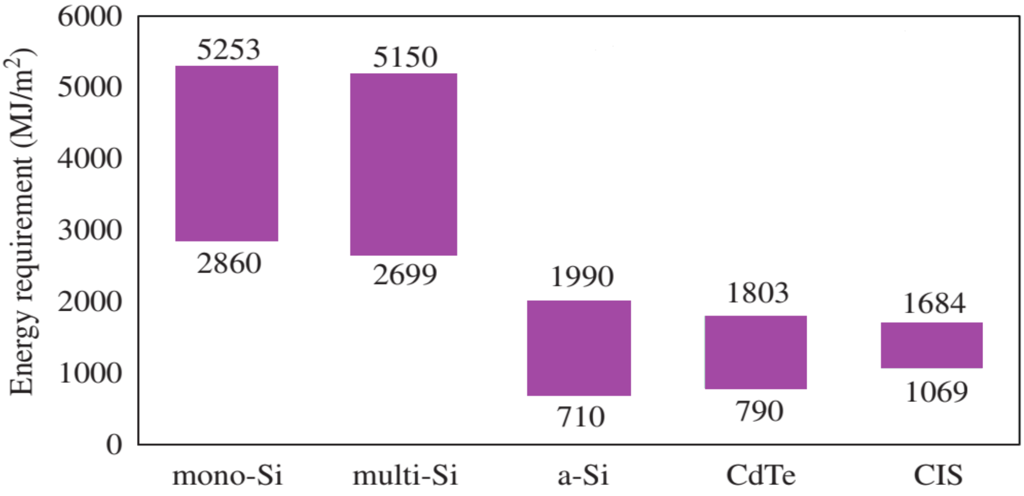

Figure 2.5. Energy requirements for the manufacturing of photovoltaic solar panels (Peng et.al., 2013).

As Figure 2.5 shows, the energy requirements for the production of thin-film photovoltaic solar panels are much less than that of crystalline silicon photovoltaic panels (Peng et.al., 2013). The two most common environmental parameters, Energy Payback Time (EPBT) and Greenhouse Gas emission rate, are used to assess the sustainability and environmental performance of PV solar panels. EPBT can be defined as the number of years required to compensate for the amount of energy consumed by a photovoltaic solar panel system throughout its entire life cycle, such as raw material extraction, panel production, transportations, panel assembly and recycling. For mono-Si PV systems, the life cycle energy requirement EPBT ranges from 1.7 to 2.7 years, for multi-Si panels it is 1.5-2.6 years. The life cycle EPBTs for a-Si, CdTe and CIS, which are thin film PV systems, are 1.8-3.5, 0.75-2.1, and 1.45-2.2 years, respectively (Peng et.al., 2013).

2.2.1. CdTe (Cadmium Telluride) Thin Film Solar Panels

Cadmium Telluride solar cells were created in the early seventies and are now the second most common PV technology worldwide after crystalline silicon cells. CdTe Thin Film solar panels are shown as an alternative to traditional silicon-based technologies because they can be produced quickly and inexpensively. The most common are CdTe solar cells, types consisting of a p-n heterojunction structure containing a p-doped CdTe layer paired with an n-doped cadmium sulfide (CdS) or magnesium zinc oxide window layer. When CdTe solar cells were first designed in the 1970s, they had an efficiency rate of around 6%. Thanks to the redesign of the CdTe solar device and a series of changes in the production line, its efficiency has been enhanced to more than 22% in the last 5 years (Romeo & Artegiani, 2021). In addition, according to numerous scientific studies in the literature, one of the crucial advantages of this thin film technology is that its life cycle has an extremely low environmental impact.

2.2.2. CI(G)S Thin Films Solar Panels

Copper indium diselenide is a multicrystalline thin film material with chalcopyrite structure characterized by high sunlight absorption rate. CIS type solar panels are considered as one of the most innovative technologies in the solar energy market in recent years due to the advantages they provide in terms of energy efficiency and minimal environmental impact. In the productions made in recent years, the photoconversion efficiency for CIS has been calculated between 27% and 32%, and this rate is quite close to other types used in solar panels (Sawant et al., 2020).

2.2.3. Amorphous (a-Si) Thin Films Solar Panels

Such thin-film solar cells have been able to reach an efficiency of 27% in theoretical studies, but efficiency rates of around ten percent have been observed in real processes where they are used to generate energy. The overall structure of an a-Si thin film solar cell is generally composed of Ag substrate, back electrode, active site (a-Si:H), and front electrode. Although amorphous thin film solar panels have rich material resources, strong absorption coefficient, ultra-thickness and scalable production flexibility, they occupy less than the ratio of CIGS and CdTe solar cells in the solar panel market. The two main reasons for this are the wide band gap and relatively poor absorption efficiency of a-Si thin film solar cells (Li et al., 2021).

Thin-film solar panels are the least expensive on the market, but have much lower efficiency ratings compared to mono-Si and multi-Si PV panels. When all types are examined, thin film panels have efficiencies in the range of approximately 10% to 13%. Considering that silicon-based modules often have efficiencies above 20%, the aforementioned low efficiency rates are a disadvantage for thin-film type panels.

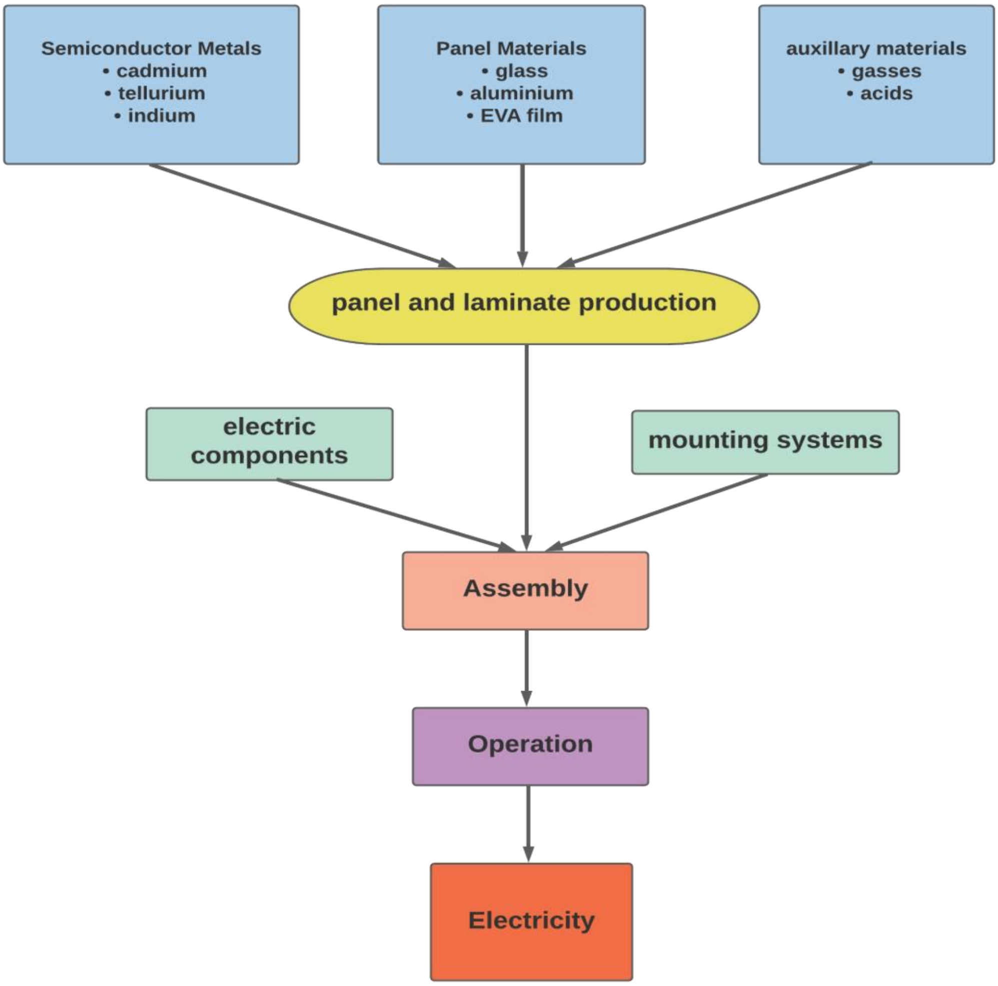

Figure 2.6. The production schema of thin film PV panels.

2.2.4. Mono-Si PV Solar Panels

Monocrystalline (mono-Si) photovoltaic solar cells are the oldest solar cell technology, yet they are ranked as one of the most expensive solar panels. Mono-Si solar cells are made from a single crystal of high purity silicon in the same way as a semiconductor. The name monocrystalline is given because the wafer is made of single crystal silicon. Monocrystalline photovoltaic solar panels are called the most efficient solar panel type because their efficiency rates can reach up to 22%. During the production of mono-Si photovoltaic panels, processes are carried out at quite high temperatures and the generally used method is known as the "Czochralski Method" (Fischer et al., 2015). The structures of these solar cells, consisting of a single silicon crystal, make it easier for electrons to flow through the cell, and this is the main factor that makes the efficiency this high. The production processes of monocrystalline solar panels are more complex and consume more energy. Therefore, they are more expensive compared to multi-Si PV panels. Mono-Si solar panels have a higher environmental toxic effect compared to multi-Si, since more energy is consumed in the production processes and this energy is mostly sourced from fossil fuels.

2.2.5. Multi-Si PV Solar Panels

Multicrystalline solar panels have cells grown from versatile crystalline material. Multi-Si solar cells have slightly lower efficiency rates compared to mono-Si PV panels due to the versatile crystal in which the cells are grown. However, they are not cut in a round shape like monocrystalline panels, but in a square shape, and this square shape also allows more solar panel space to be used to generate solar energy as the available solar panel space is used more efficiently. In addition, multi-Si panels are cheaper to manufacture compared to monocrystalline PV cells.

Although multi-Si and mono-Si solar panels have almost the same efficiency on average, the multi-crystalline type consumes less energy throughout its life cycle. When comparing the two in this context, multi-Si solar systems have a shorter EPBT and lower GHG emission rate than mono-Si type solar panels, meaning that multi-crystalline panels cause less environmental damage.

The diagram of the LCA of multi-Si PV panels is shown in Figure 2.7 (Peng et al., 2013). The journey of a polycrystalline (multi-Si) silicon PV module begins with the extraction of the raw material, silica. The silica is then reduced using carbon followed by a purification step. The created high purity silicon is melted and converted into polycrystalline square blocks. The blocks are then cut into ingots and sliced into wafers in the next step (Koroneos et al., 2006). Then the soldering process starts and the multi-Si cells are connected to each other in series or parallel to achieve the expected current and voltage values.

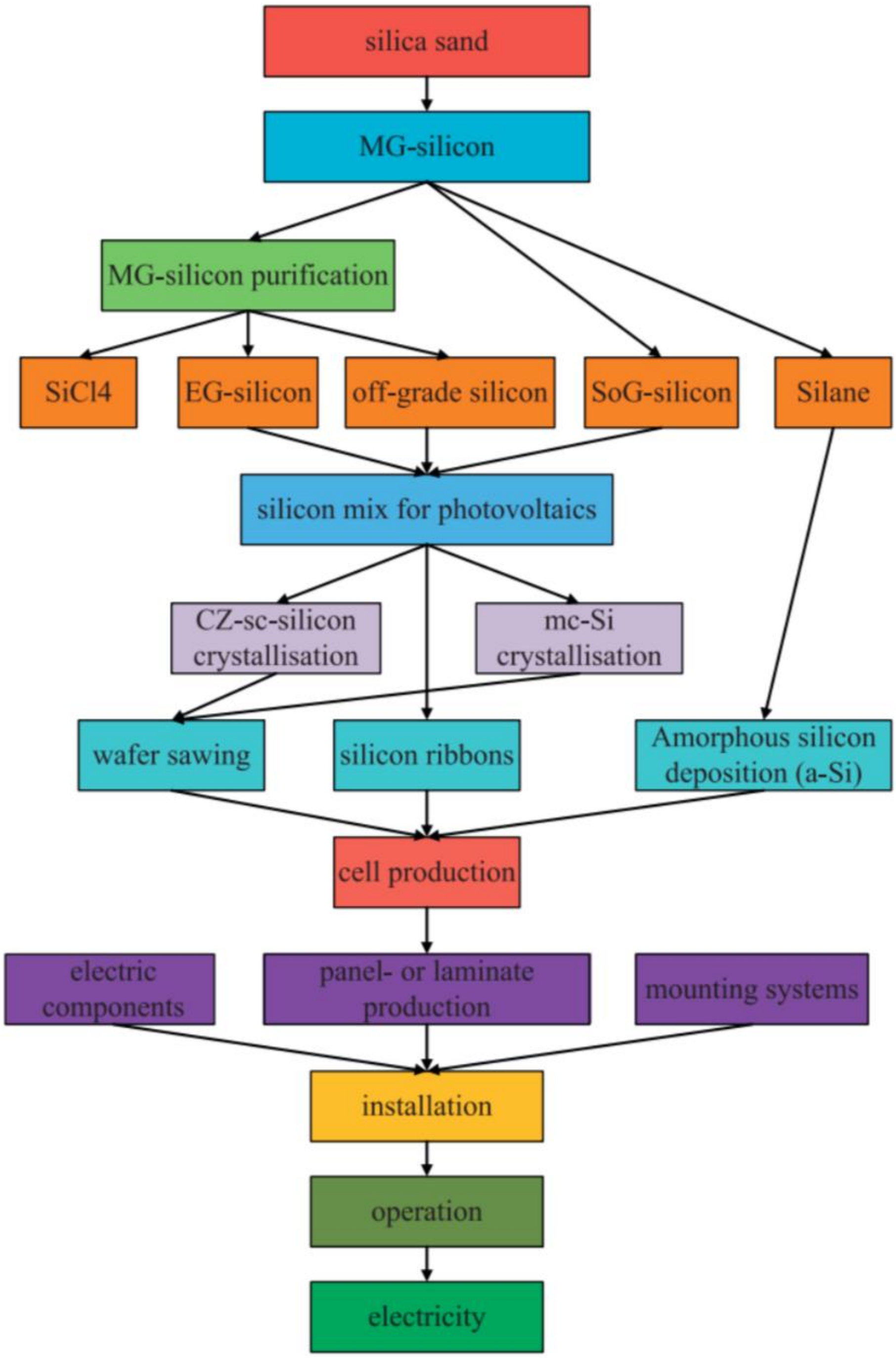

Figure 2.7. The LCA diagram of multi-Si PV panels (Peng et al., 2013).

After soldering, the cells are placed on Ethylene Vinyl Acetate (EVA) laid on the tempered glass, and then the bonding process is applied. EVA is a polymer cover that covers solar panels on both the front and back, protecting them against environmental damage. Since both sides of the panel are coated, this process made with EVA is called sandwich coating. Finally, the back cover called TEDLAR is laid, which protects the panel against many external factors such as UV rays, high temperature and humidity, and ensures that it functions for various years (Girgin, 2011). Cells kept in laminators under high temperature and pressure conditions are thus tightly wrapped with protective

EVA and TEDLAR. The life cycle of multi-Si PV panel production is shown in Figure 2.8. below (Fu et al., 2015).

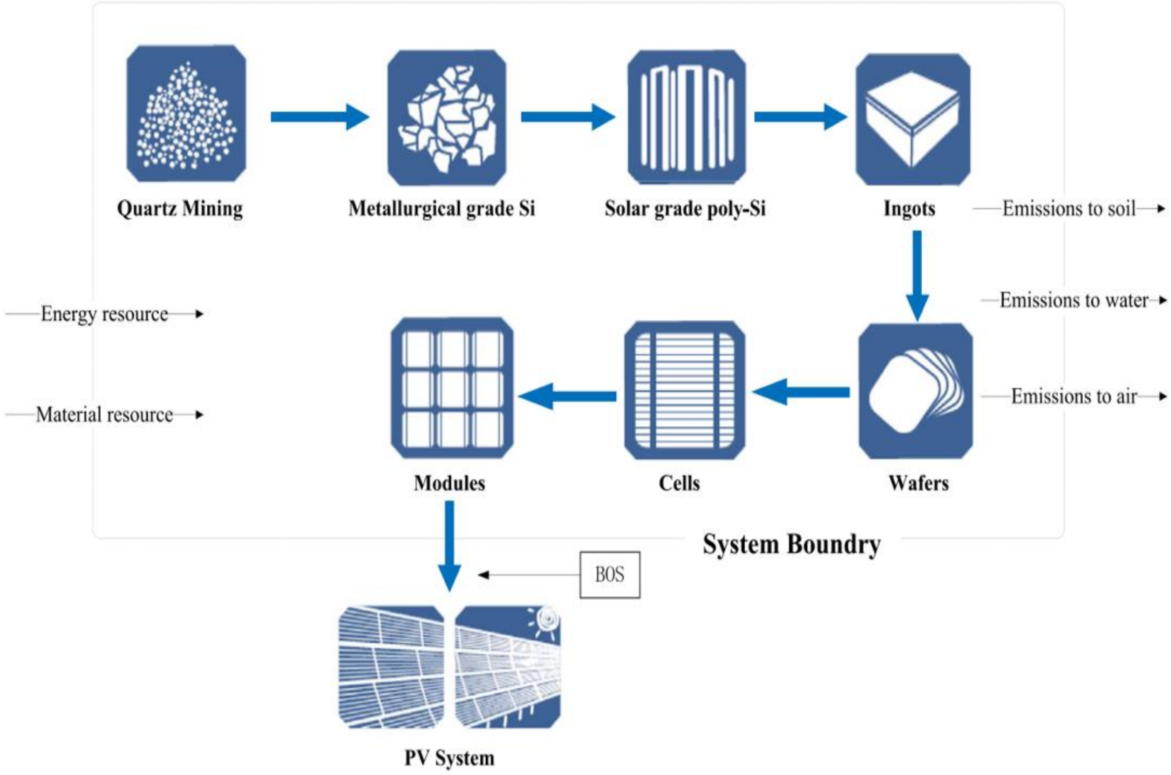

Figure 2.8. Life cycle of a multi-Si PV panel production stage (Fu et al., 2015).

The most critical stages in the life cycle assessment of multicrystalline PV solar panels are the conversion of metal to solar silicon and panel assembly. Nearly more than 50% of the pollutants causing the impact of climate change come from the multi silicon production process, which consists of industrial silicon smelting and solar grade multi-Si production steps. The reason why the conversion from metal to solar silicon is the process that makes the biggest contribution to the Global Warming Potential is due to the enormous use of electricity obtained by fossil fuels.

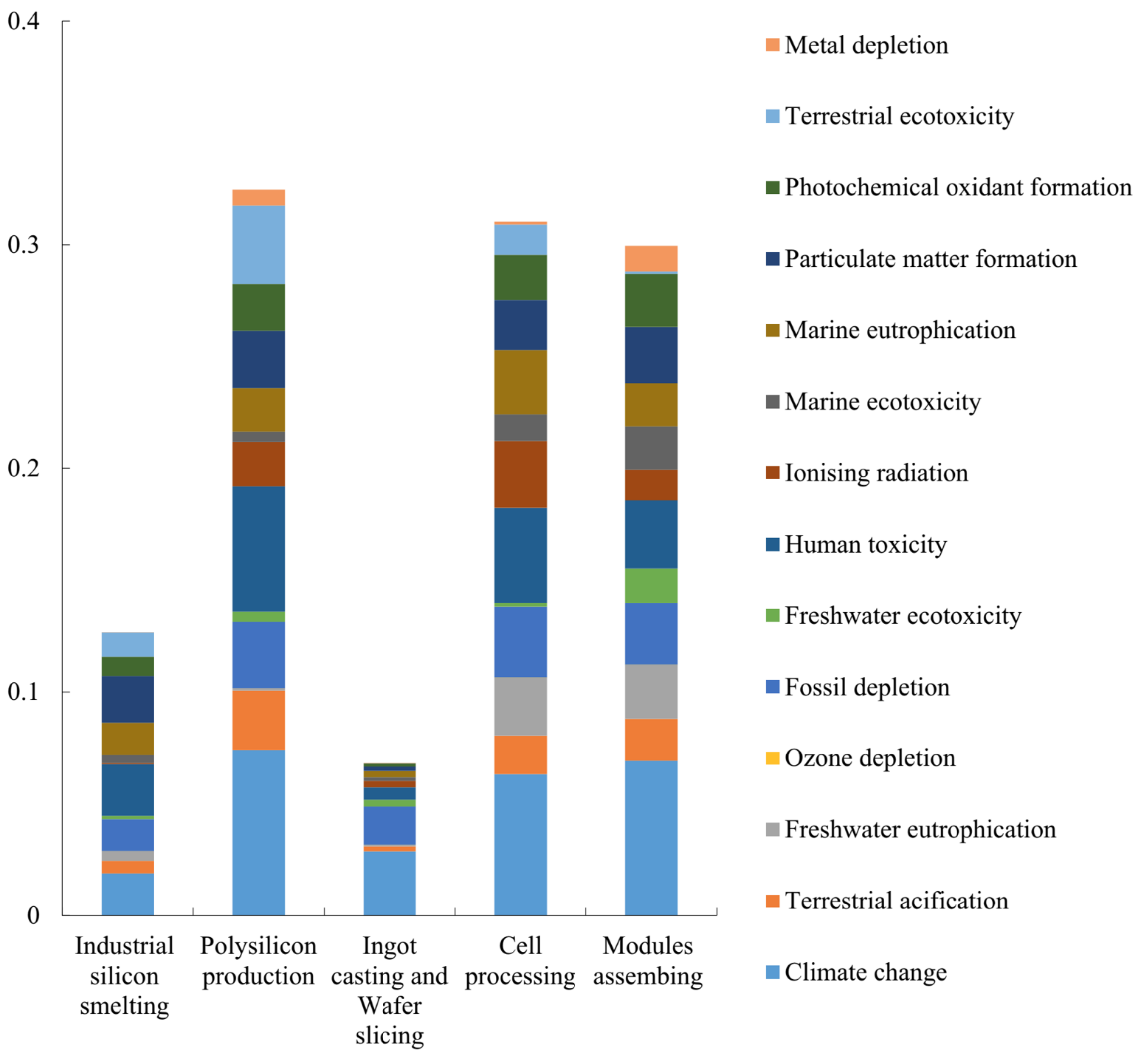

Figure 2.9. Environmental effects of multicrystalline solar panels (Huang et al., 2017).

Considering all the environmental impact categories in the LCA of the multicrystalline solar panel, the most critical environmental factors are:

1) Climate Change caused by carbon dioxide released during the solar silicon production phase and cell processing.

2) Human Toxicity induced by heavy metals released during the cell processing step and panel installation phase.

3) Fossil resource depletion caused by the consumption of coal and oil used during electricity generation (Huang et al., 2017).

The reason for the greenhouse gas emissions during the assembly of the panels is due to the material consumption occurring at this stage, rather than the electricity produced from fossil fuels. Almost three quarters of the greenhouse gas contribution at this stage is due to the manufacturing processes of materials such as glass and plastic (Huang et al., 2017). The main pollutants such as heavy metals such as As, Cr and carbon monoxide and hydrogen sulfide that cause human toxicity mainly originate from multi silicon production (combination of metallurgical silicon melting and solar grade silicon production). When these two important steps in terms of environmental impact are reviewed, the overall environmental burden can be diminished by almost 25% by enhancementing energy efficiency, choosing secondary aluminum for multi-Si production, and reducing the consumption of wafer for photovoltaic solar panel manufacturing (Hong et al., 2016).

For many years, the lifespan of solar panels ended with incineration or landfilling. However, it does not seem possible to continue with these methods due to the amount of waste and greenhouse gas emissions it creates. Therefore, effective recycling processes seem to be the most efficient scenario in terms of end-of-life of multi-Si solar panels. All of the materials used in silicon-based solar panels are highly recyclable and recoverable. This recovery rate can reach 96% for silicon, glass, aluminum and other metal components with the latest developed methods (Celik, 2018). Although the recycling process, which may include processes such as dismantling, remelting, heat treatment and chemical treatment, contributes to environmental pollution and emissions, its overall impact is much lower than the landfilling in comparison (Huang et al., 2017).

After the acceptance of fossil fuels as the main factor that aggravated the climate crisis, the demands for renewable energy and especially solar energy started to increase rapidly. In this case, the number of photovoltaic panels reaching the end of their life is increasing exponentially. It is predicted that the rate of solar panel waste will increase by more than 3% annually and reach 60-78 million tons of photovoltaic waste by 2050 (Weckend et al., 2016). As seen in Figure 2.5., this difference between the estimated amounts is due to the fact that two different scenarios, regular-loss and early-loss, have been studied. Under the regular loss scenario, an increasing trend emerges where PV panel waste will rise to 1.7 million tons in 2030 and will reach approximately 60 million tons by 2050. The early loss scenario predicts a much higher total waste solar panel, pointing to a total of 8 million tons in 2030 and 78 million tons in 2050 (IRENA, 2016). The main reason for this is that the early-loss scenario has a higher percentage of early solar panel failures compared to the normal-loss scenario.

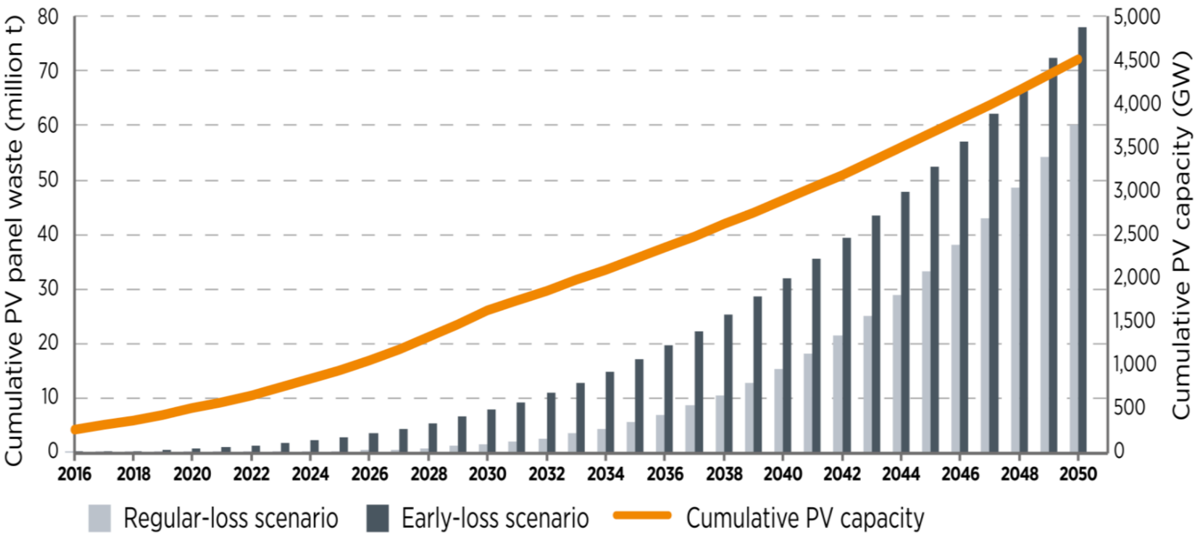

Figure 2.10. Estimated cumulative global photovoltaic solar panel waste volume (IRENA, 2016).

Cumulative estimates of global photovoltaic solar panel waste volume are shown in Figure 2.10. (IRENA, 2016). According to estimations, panels that entered production in the early 2000s will reach the end of their life between 2025 and 2030. The increasing trend of the number of solar power plants is that the global panel waste rates are expected to reach around 4-14% in 2030 and over 80% in 2050.

The fact that the amount of panel waste that will occur in the future is so large has brought along discussions on how to carry out the most efficient recycling processes at the end of the life of solar panels. Compared with landfill, the recycling process effectively prevents toxic and hazardous substances from photovoltaic panels from entering the soil and groundwater, conserving precious and scarce metals through recovery, and reducing the negative effects of panel waste on the lives of living things. In addition, recycling end-of-life solar panels can significantly reduce energy consumption, carbon emissions and resource consumption (Deng et. al., 2019).

Table 2.1. Mass composition of multi-Si photovoltaic solar panel waste.

Component	**Mass (kg)**
Glass	686
Copper (internal, cables)	6.2
Aluminum	184
Silicon	36
Silver	0.53
EVA sheet	51

Table 2.1. Mass composition of multi-Si solar panel waste (continued).

PVC	14
PVF (backsheet)	15
Tin	0.25
Lead	0.25
Total	1000

Since solar panels that have reached the end of their life are included in the scope of electronic waste, their recovery and recycling is very important in the perspective of circular economy. Circular economy is an economic model that aims to minimize waste and emission production as well as resource use by using methods such as recycling, reduction, repair, recovery and reuse. E-waste mainly consists of materials, such as polymers, metals and ceramics, whose separation processes are complex. While some of these materials are precious and critical to recover, some of them are toxic and pose a danger to both human health and the environment. Metals in electronic waste can be found in two forms, in their natural metallic forms or as alloys embedded in non-metallic parts. Metals found in e-waste are often categorized as precious metals, base metals, and toxic metals.

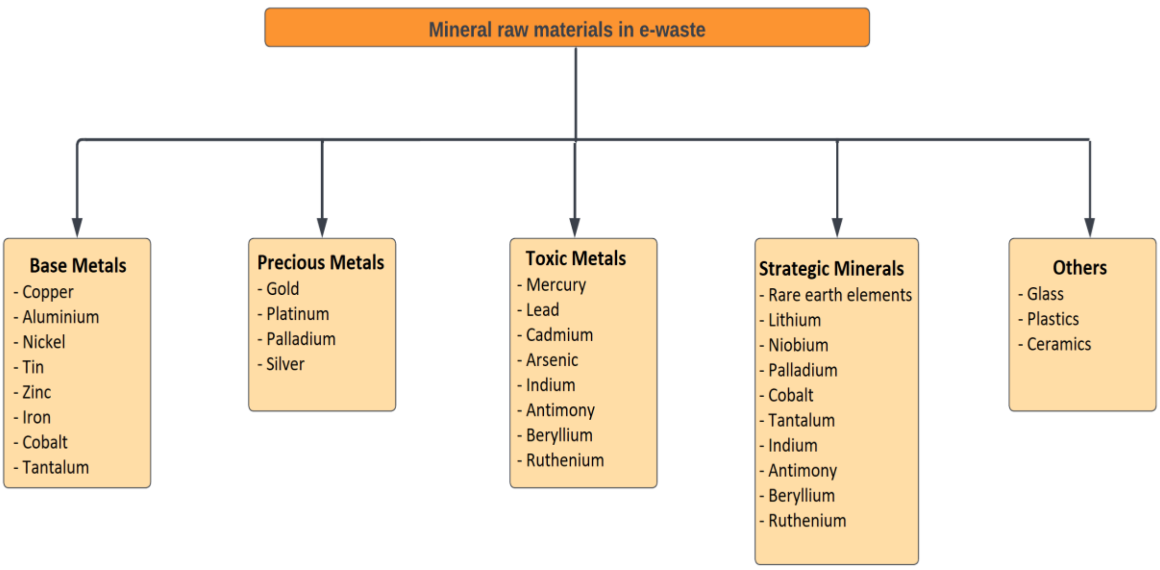

Figure 2.11. Classification of raw materials in e-waste.

Some metals are categorized as 'strategic' because of their rare geological existence, their supply being much lower than demand, no substitutes, and their use for specific applications such as hightech products only. Precious and strategic minerals may comprise up to 80% of the actual value of the electronic device and still not even make up 1% of the total material weight (Xavier et. Al., 2021).

Silver in the structure of solar panels is an example of these precious metals, albeit at a very low rate. E-waste also contains toxic metals such as mercury, beryllium, lead, arsenic, cadmium, and antimony. Although the multi-Si PV solar panel is at a quite low level of 0.25 kg, it contains lead metal. Aluminum and copper are also included in the solar panel as base metals in higher masses compared to other metals and minerals. Recycling these strategic, base, precious and toxic elements will contribute to reducing the consumption of natural resources, reducing environmental damage and managing PV waste in a Circular Economy perspective.

Disparate processes have been developed for the recycling of multicrystalline photovoltaic panels, and satisfactory results can be obtained with alternative or combined recycling approaches in this process. Often the first step is to mechanically remove the aluminum frame and junction box from the rest of the module. The next step is to delaminate the encapsulating material, called the EVA layer, by various methods, including mechanical, thermal and chemical processes. Recycling methods differ greatly from each other according to the type of process applied at this stage (Lunardi et. al., 2018). Delamination of EVA is the most vital phase for the recycling of silicon-based solar panels because, as long as appropriate process is applied, it will be possible to recover module parts undamaged, diminishing recycling expenses and carbon emissions (Lisperguer et. al., 2020).

The mechanical technique is the common practice currently used for recycling multi-Si panels. However, it should be noted that the maximum amount of recovered material obtained from this process can reach approximately 80%. This rate is not considered effective because in terms of new regulations on electronic waste and the value of the recovered resources is lower than the original raw materials. By combining several methods used for the delamination of the EVA layer, much higher results can be obtained (Lunardi et. al., 2018).

In *mechanical delamination*, panel waste is mechanically treated for size reduction. In a two-bladed rotor crusher, single or three consecutive crushes are carried out without any control sieve. When a controlled sieving process is applied, fine fraction formation occurs and control sieving can be avoided to reduce this. After size reduction, a sievening process takes place to evaluate size and product distribution. All samples are sieved and the different fractions are separated from each other using a shaker with different pore sizes and then all the pieces are weighed (Pagnanelli et. al., 2017).

In the *thermal delamination* process, the EVA layer, which is the polymeric encapsulation layer, is thermally separated and the solar panel parts are separated from each other. Thermal treatment is the controlled burning of the EVA layer to recover the glass without breaking it and reuse it directly as a panel component. EVA can be pyrolyzed in a gaseous environment with combustible materials such as methane, acetic acid, propane, propene, ethane, or alternatively, it can be burned in an oxygen setting. In the first method mentioned, EVA is decomposed in a tube furnace at approximately 520°C in an inert atmosphere, thereby recovering silicon wafers and solar cells from expired panels. Just before the evaporation of the EVA, the backsheet of the panel is manually removed. The method of supplying energy to the furnace in the oxygen method is not gas pyrolysis, but burning the EVA layer in an oxygen environment (Deng et. al., 2019).

Due to the separation of the EVA layer in the solar panel from the thermal treatment, gaseous dangerous metals such as Cd, Al, Zn, Pb will be released. If the flue gas processing section is not adequately equipped with an electrostatic precipitator or fabric filter in the facility where the recycling takes place, these toxic gasses cannot be captured and rise into the atmosphere. The ashes that emerge after the thermal process should also be handled with the most appropriate method. If the ashes contain hazardous metals such as lead and precious metals such as silver, some recovery or disposal may be required, depending on the amount of residues present in them (Tammaro et. al., 2015).

The EVA layer in the solar panel can also be dissolved in inorganic or organic solvents and this is called *chemical delamination*. The EVA layer can be separated from the entire solar panel by soaking the panel in nitric acid for 24 hours or ten days in trichloroethylene at 80 °C. (Deng et. al., 2019). The EVA layer soaking in an acic step is called ‘acid leaching’, and acid leaching allows to recover up to almost 95% of the silicon in the waste panel as metallurgical silicon metal. Some experimental studies have shown that when ultrasonic radiation is added to the process of delaminating EVA from the panel, it dissolves in toluene in less than 60 minutes. Thus, predictions were made that ultrasonic radiation could further accelerate the chemical delamination process. (Azeumo et. al., 2019). Figure 2.12 demonstrates the delamination pathways to recycle of multi-Si PV panels (Deng et. al., 2019).

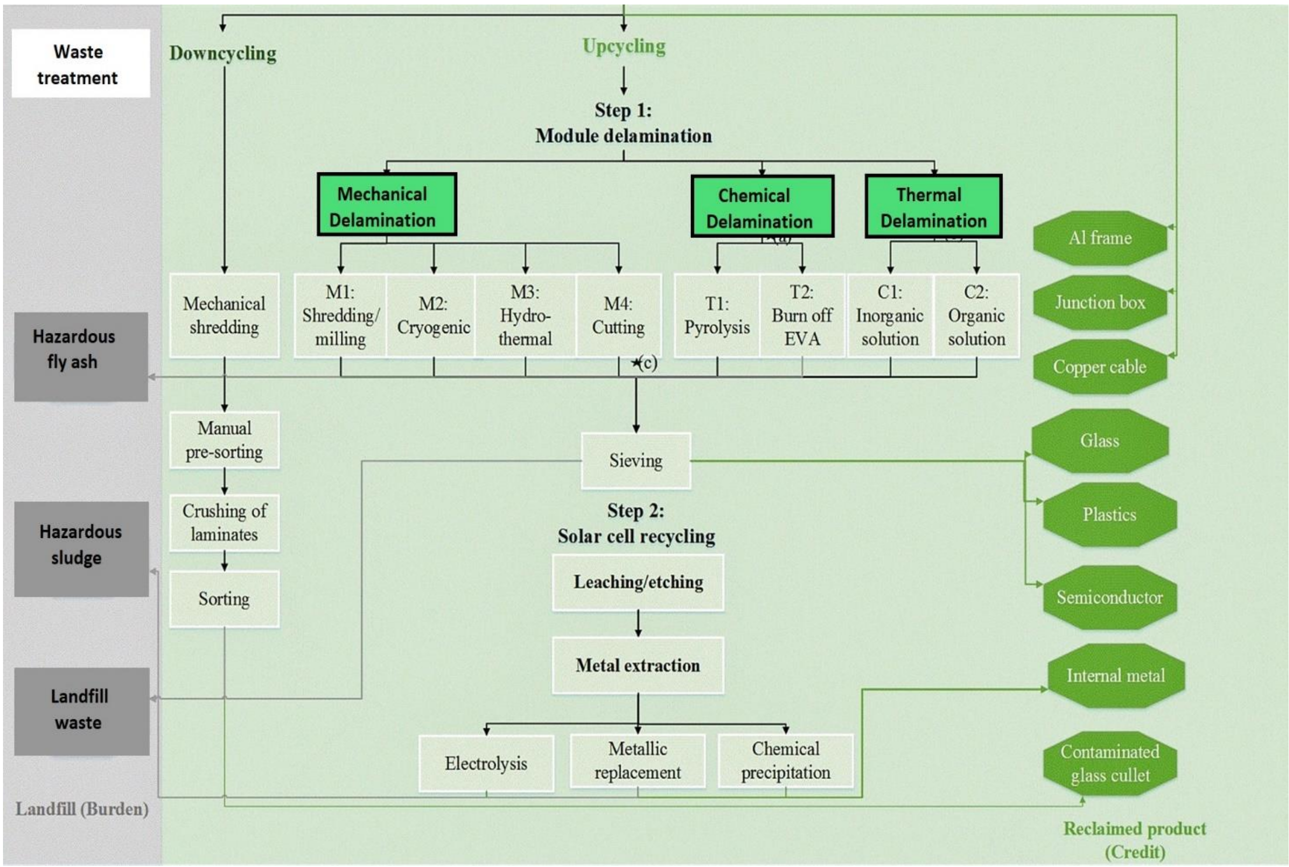

Figure 2.12. Delamination pathways to recycle multi-Si PV panels (Deng et. al., 2019).

Waste from Electrical and Electronic Equipment Directive is a comprehensive manufacturer's responsibility directive that outlines the framework under which manufacturers are responsible for the costs of collection, transportation, processing and management of electronic waste. The Full Recovery End-of-Life Photovoltaic (FRELP) method was developed in 2014 with the EU procedures for recycling specified by the WEEE Directive to create new technologies that will enable the recycling of photovoltaic solar panels both economically cost-effectively and environmentally highly efficiently. The focus is on the analysis of toxic and energy-intensive processes, based on methodologies for the collection and recycling of materials committed by the European Commission.

According to the WEEE Directive, as of 2018, the recycling rate of solar panel waste should be 85%, and the reuse or recycling rate should be 80%, as in all other electronic wastes (Daljit et. al., 2021). The FRELP procedure was created to achieve these high recycling and recovery rates and consists of a combination of several mechanical, chemical and thermal delamination methods. FRELP aims to make the recovered glass high quality and transparent enough to be reused, saving the energy spent in a second glass melting process and reducing the CO2 emissions released during this period. This procedure covers disassembly of frames and cables, glass separation, cutting cells, incineration, sieving of fly ash, acid leaching, filtration, electrolysis, neutralization (Latunussa et. al., 2016).

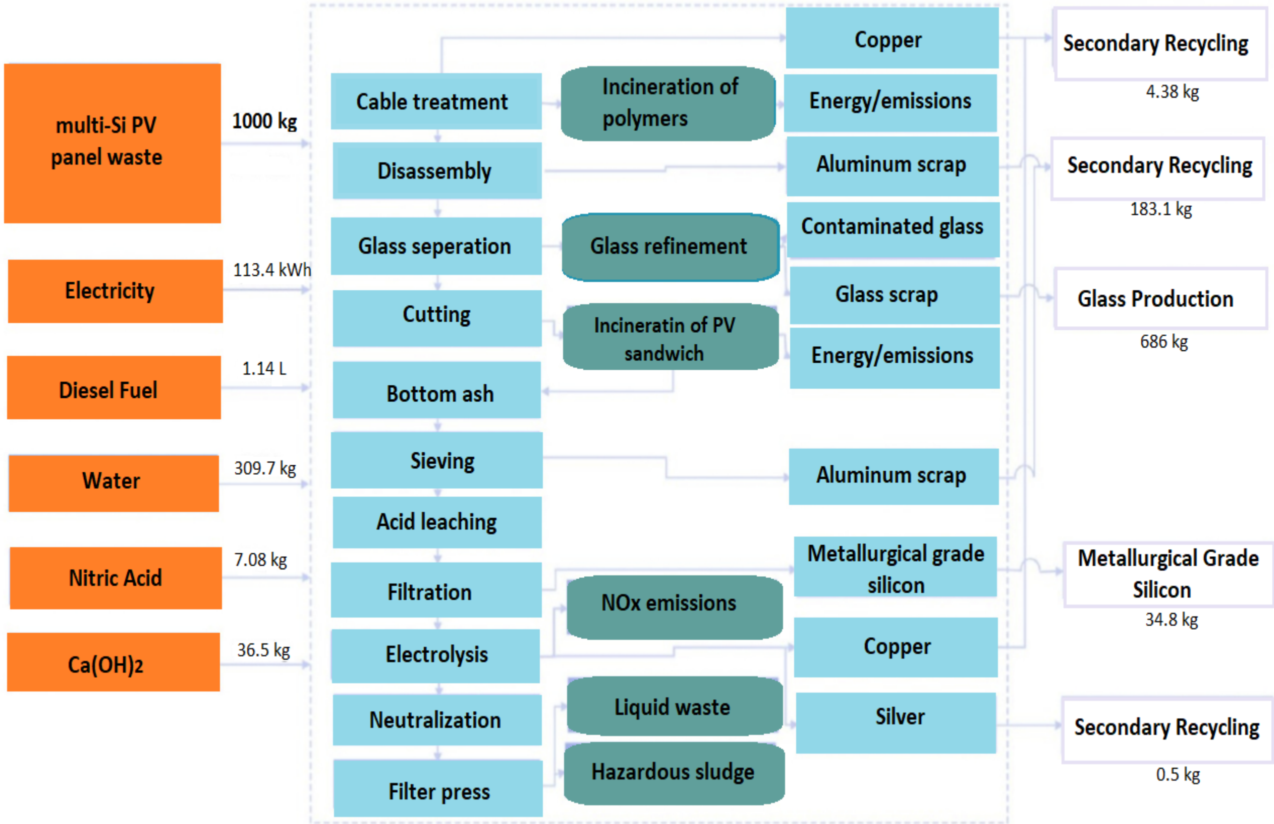

Figure 2.13. Process diagram for the FRELP process of multi-Si PV waste (mechanical and chemical combined version).

Contrast to FRELP, which requires a specially designed solar panel recycling facility, there is no need to build a special facility for Laminated Glass Recycling Facility (LGRF) processing; processing can also take place in other recycling facilities. This process does not require any supplementary investment for the recycling phase as the demanded equipment is already available in the facilities. In LGRF, aluminum frame and junction boxes can be removed manually or the complete solar panel can be disassembled. This sounds like a good option, but LGRF type of recycling is functional for small amounts of photovoltaic waste rather than a regular string of panel waste. To elaborate a little further, the recovery of materials in such a process is restricted and may only recover the glass, aluminum frame and copper in the cables. Such a low recovery rate poses the risk of polluting the soil and groundwater of hazardous materials in the high-volume waste sent to the landfill.

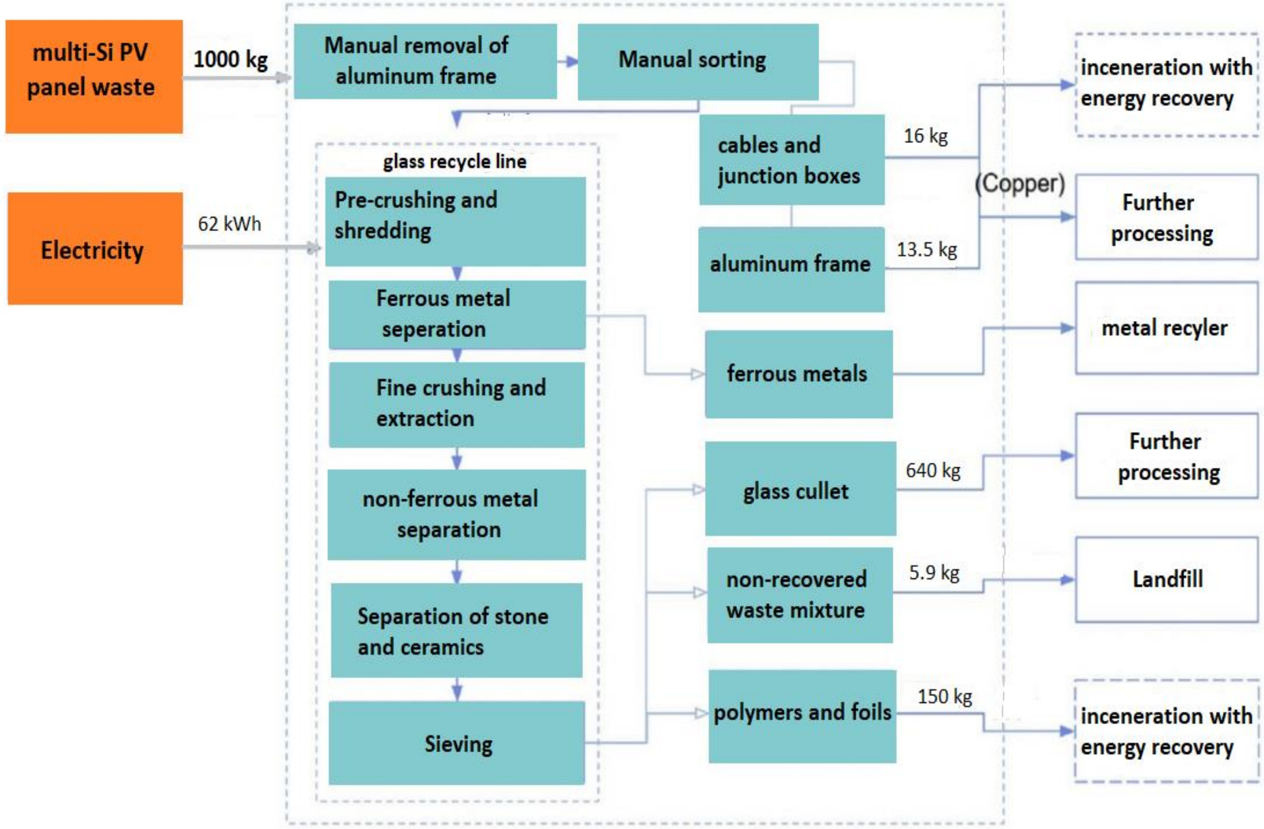

Figure 2.14. Process diagram for the LGRF process of multi-Si PV waste.

When the recycling scenarios are applied appropriately, total recovery rates of 77% and 91% can be achieved in LGRF and FRELP scenarios, respectively. In LGRF recycling scenarios, copper and aluminum recovery rates are 41% and 74%, respectively, while in FRELP scenarios these rates can go up to 99%. While the recovery of silicon and silver is not possible in LGRF methodology, these valuable materials can be recovered by accident in the FRELP method at a rate of 95%. Especially during chemical delamination in FRELP, a step can be applied where components such as copper, silver and aluminum filtered by acid solution are recovered from solar cells (Faircloth et. Al.,).

While the LGRF scenario contributes to the prevention of resource depletion by reducing metal consumption by almost 17%, this rate can reach up to 30% in the FRELP scenario. The FRELP recycling scenario is a more complex process compared to LGRF and may consume more electricity and materials to process photovoltaic solar panel waste. However, in the FRELP recycling process, it may still be in a more advantageous position as resource consumption and toxic effects will be reduced thanks to the increase in silicon, silver, aluminum, copper and glass recovery rates. Thanks to these recycling methods, it is possible to achieve enormous recovery rates in glass as well as toxic, base, precious and strategic metals. It will not be functional to exclude solar panels, which is an important e-waste, from this recycling process if the requirements of the circular economy are to be met.

2.3. Life Cycle Assessment

Conventional environmental impact analysis generally focuses on a small number of life-cycle steps that can analyze the constrained environmental performance of products. In contrast, Life Cycle Assessment is a methodology that can analyze every direct and indirect impact throughout the life steps of products or services (Sumper et al., 2011). Life Cycle Assessment is a systems analysis method created to examine the emergence of multidisciplinary, the existence of complex systems, the consideration of a systems model, and the existence of case studies (Tillman, 2000). LCA is the most popular policy support tool that analyzes in detail the environmental impacts of products and services throughout their lifecycle (production, distribution, transportation, use, and end-of-life periods).

This tool performs environmental impact analysis by measuring the release of resources from raw material extraction and consumption to air, water and soil. It makes this holistic assessment to implement opportunities for improving environmental impacts and to describe how the system's environmental exchanges may change as a result of positive changes in the system. These environmental impacts comprise processes such as acidification, eutrophication. climate change, resource depletion, toxicity and photochemical ozone depletion. The results of an LCA study allow us to learn more about things such as comparing the performances of different system technologies, understanding the highest impacts to identify system components or sub-processes, and improving process performance by reducing environmental impacts.

2.3.1. Framework of Life Cycle Assessment

The International Organization for Standardization regulated practical guidelines and requirements for performing a Life Cycle Assessment according to ISO 14040 and 14044. LCA is structured in four main steps; goal and scope definition, inventory analysis, impact assessment and interpretation (Jungbluth et al., 2008).

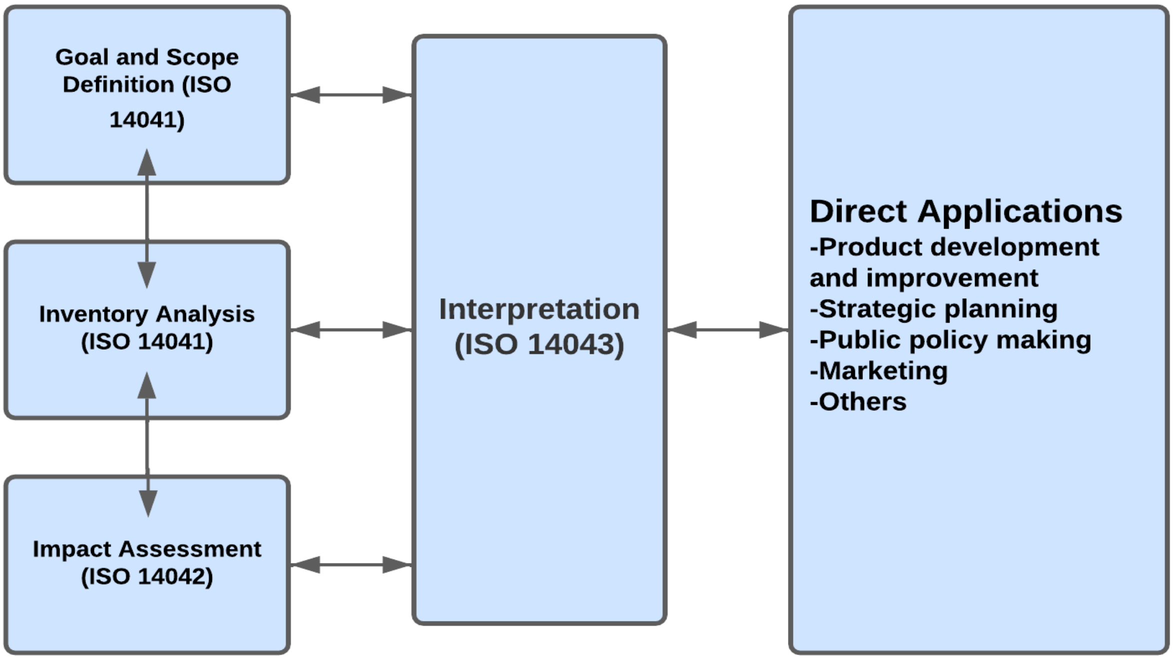

Figure 2.15. Framework of Life Cycle Assessment Methodology.

The definition of the goal and scope reveals the purpose of the research and the boundaries of the system. Inventory analysis concentrates on analyzing and documenting flows of pollutants, materials and resources throughout their life cycle. The presentation and categorization of resource-energy consumption and numerous pollution emissions for different environmental problems such as ecotoxicity, global warming potential, acidification, ozone depletion takes place during the impact assessment process. Scenarios that will reduce the negative effects of the process on the environment, natural resources and human health are presented in the interpretation section (Peng et al., 2013).

Life Cycle Impact Assessment methods can be divided into two main groups: conventional methods that identify impact category indicators at a mid-position of impact pathways, such as 'ozone depletion potential', and damage-focused methods that target 'human health damage' with more easily interpretable results. UNEP and SETAC's joint project Lifecycle Initiative provides a broader LCA framework to unify these methods. The LCI aims to create a common basis for further development of impact assessment methods, with a more certain and extensively accepted version of the main framework elements. In the UNEP/SETAC Life Cycle Impact Assessment Midpoint-Damage Framework, resource consumption and emissions in the LCI analysis are associated to categories such as 'climate change, photochemical ozone depletion, resource depletion, human toxic effects, eutrophication and biodiversity loss'. The damage category can be listed as human health, ecosystem quality and resource depletion (Jolliet et al., 2004).

2.3.2. Life Cycle Assessment of multi-Si PV Solar Panels

Considering the power generation process, photovoltaic solar energy is almost completely called clean. However, the fact that emissions and pollutants into the environment are present during phases such as raw material consumption, silica mining, assembly of the system, dismantling, recovery, and disposal of has long been ignored. There is a steady increase in PV solar capacity worldwide, as it is considered quite clean compared to the effects of fossil fuels. Considering the frequency of use of silicon photovoltaic panels, they occupy the largest place in the solar energy sector with a usage rate of more than ninety percent.

Multicrystalline PV solar panels, on the other hand, cover almost 50% of global PV panel production. This will also increase the production of multi-Si solar panels, which play an important role in the PV panel market. Since the production method of multi-Si cells does not require as much precision as monocrystalline cells, they are cheaper, but when compared in terms of efficiency, they have lower yield values with a quite small difference. Considering the energy and environmental impacts of silicon-based solar panels throughout their life cycle, mono-Si modules show the worst environmental performance due to the intensity of the energy used in their production processes (Peng et al., 2013). In this study, the life cycle of multi-Si PV solar panels will be examined, as they have less harmful effects on the environment, are more affordable in terms of price and have the highest usage rate worldwide.

In multi-Si cells with a multicrystalline structure, the reflection of light causes breakage. Anti-reflective coating is used to prevent this reflection, and the multi-Si cells coated with the effect of this coating are blue in color. High energy consumption is experienced in the production process of solar grade silicon, which is the basic material of silicon-based solar panels, and this process gives a lot of pollutants to the environment. The upstream stage of the life cycle of my multicrystalline solar panels includes the raw materials, and the middle stage contains the silica extraction includes industrial silicon production and ingot casting, cell and module manufacturing, installation, transportation, application and decommissioning (Fu et al., 2015).

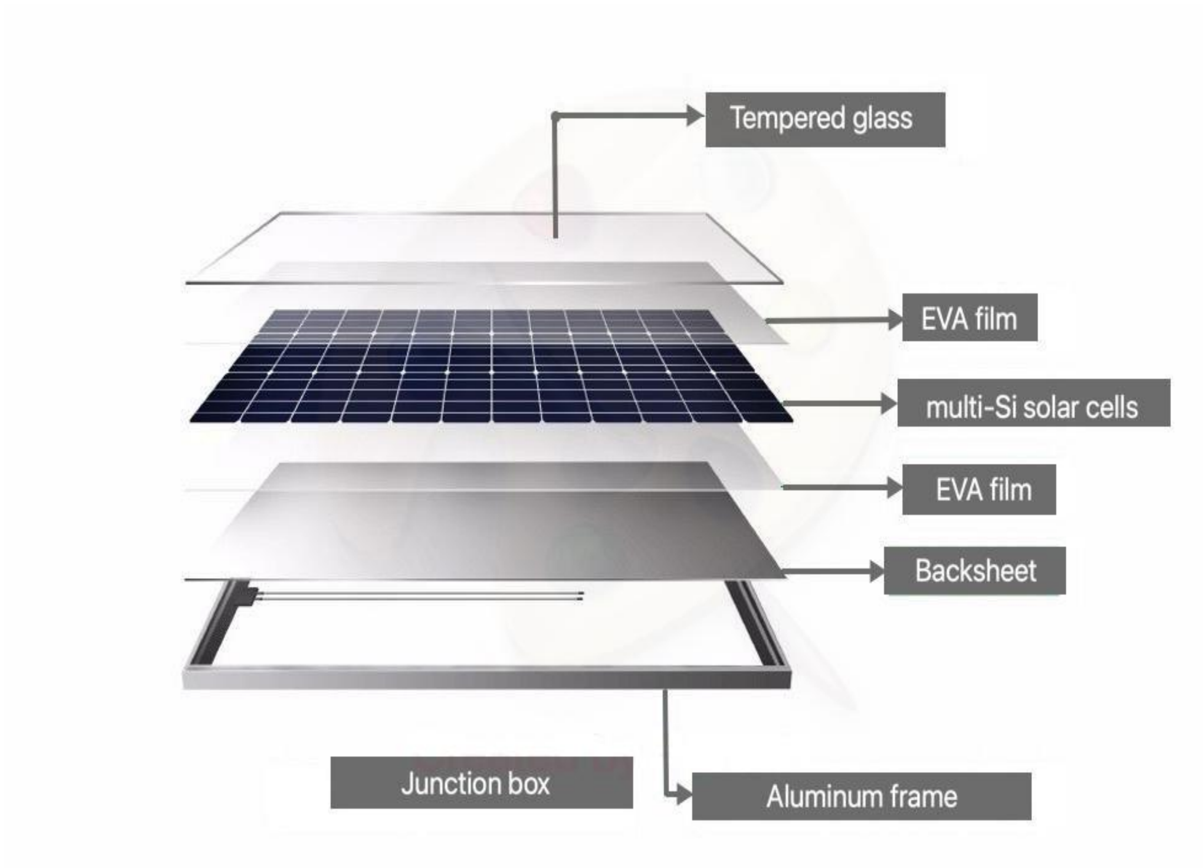

Figure 2.16. Structure of multicrystalline solar panel.

According to the studies in the literature, the most critical steps in the Life Cycle Analysis of multi-Si PV panels are the conversion of metallic silicon to solar grade silicon and module assembly. The primary energy demand for the production and assembly stages of the Multi-Si solar panel constitutes 50% and 25% of the total, respectively. During the production of multicrystalline solar cells, the primary energy requirement is high and a lot of electricity is consumed during this time. The process of providing the high heat required in the production processes is mainly obtained from fossil fuels such as coal, oil and natural gas. Crude oil and natural gas are mainly used in the module assembly stage, where EVA, polyethylene terephthalate (PET) film and polyvinyl fluoride (PVF) films are manufactured (Fu et al., 2015). When evaluating the LCA of multi-Si panels, the most important impacts in the environmental category are: Climate Change Impact caused by carbon dioxide in multi-silicon production and cell processing, Human Toxicity caused by heavy metals in cell processing and module assembly, and Fossil Resources Depletion for electricity generation (Huang et al., 2017).

Since the first advent of solar panel technology, panels have traditionally ended their lives in landfills or incineration, but the profound environmental impacts that have emerged in recent years now make the recycling of panels essential. When the end-of-life scenarios are examined, the environmental impacts of the recycling scenario are less than those of landfill and incineration. Despite the recycling process having environmentally polluting steps such as delamination, dismantling, heat treatment and chemical treatment, it still has a lower overall environmental impact than landfilling of solar panels.

3. MATERIALS AND METHODS

LCA is an assessment tool developed to analyze the environmental performances of a product or service throughout its life cycle. LCA is the most widely used program to evaluate the environmental impact of products and services because it provides more realistic and data-based results for making new policies thanks to the scenarios created within the software. In this study, the environmental impacts of different scenarios of multi-Si PV solar panels were analyzed and compared with each other using GaBi LCA software, EcoInvent database and CML evaluation method.

Ecoinvent is an LCI database of internationally used and industrial data containing more than 16,000 datasets. This database is regularly updated at certain periods and therefore results in high quality results. CML is an impact assessment method that limits quantitative modeling to early stages in the cause-effect chain to reduce uncertainties. Results are grouped into common mechanisms, such as climate change, or in widely accepted midpoint categories, such as ecotoxicity. The CML was developed by the Institute of Environmental Sciences at Leiden University in the Netherlands in 2001 and a table of characterization factors for more than 1700 different flows is available on its website (Vinodh et al., 2012).

3.1. Goal and Scope Definition

The goal and scope definition is the LCA step where the aim of the study, assumptions, limitations and system boundaries are included. The goal of this study is to analyze the environmental performance of multi-Si PV panels, which is the most widely used solar module type currently, with the data provided by a solar energy company in Turkey, including different recycling scenarios. Moreover, the different recycling methods will be analyzed in detail and the best EoL scenario will be presented in terms of environmental impacts. Throughout the study, the entire life cycle of multi-Si solar panels will be evaluated from a cradle-to-cradle perspective, including raw material extraction, cell production, assembly and recycling.

The most important factor creating climate change is the intensive use of fossil fuels, which has been going on for more than a century. The devastating effects of the climate crisis have become undeniable in recent years, and at this point, it is clear that it is necessary to use cleaner and more sustainable energy sources instead of fossil fuels. At this critical point, solar energy emerges as an alternative to fossil fuels and is a highly sustainable energy source. However, although the process of generating electricity from solar energy is quite clean, the production and assembly processes of the panels, as well as the presence of non-recycled panels, have a very harmful effect on the environment.

Especially in today's world where solar energy technology is rapidly increasing, solar panels that are not recycled properly will cause serious environmental pollution and greenhouse gas emissions since these panel wastes contain metals and chemicals. Different delamination scenarios in recycling processes of multicrystalline solar panels; global warming, acidification, eutrophication, ozone depletion, human toxicity, and photochemical ozone generation potentials were compared in the LCA study.

Table 3.1. Different scenarios in the recycling process of multi-Si PV solar panel

Scenario 1	Alternative scenario for recycling phase: FRELP1 recycling process (mechanical treatment and chemical treatment combined)
Scenario 2	Alternative scenario for recycling phase: FRELP2 recycling process (thermal treatment and chemical treatment combined)
Scenario 3	Alternative scenario for recycling phase: LGRF recycling process

The recycling phase of solar panels differ from each other in the context of the applied delamination processes and recovery rate. Mechanical, chemical or thermal delamination processes can be applied alone, as well as hybrid delamination processes consisting of a combination of several of these. In order to find the best recycling practices, three different delamination scenarios will be examined with GaBi software.

3.2. Functional Unit

When we consider LCA studies, all relevant inputs and outputs in the Life Cycle Inventory (LCI) stage and the final impact scores in the Life Cycle Impact Assessment (LCIA) stage are expressed by a reference flow called the Functional Unit. Since the results obtained are used as a decision-making tool, the effect of the functional unit on the selected environmental impact results is quite crucial. In this study, the functional unit is defined as the production of 1 kWp multi-Si PV solar cell consisting of five panels with 200 Wp. The entire life cycle of a solar panel, starting from raw material extraction, production, installation, energy consumption, transportation, and recycling processes are based on this functional unit.

3.3. Data Sources and Key Assumptions

Environmental emissions data for phases such as solar grade silicon production, wafer slicing, ingot casting, cell production, module assembly and recycle were obtained from research written on companies producing existing multi-Si PV technologies in China and industry data in Turkey. Since multi-Si PV modules do not cause any toxic environmental effects during the operating process, the operation (usage) stage is not included in the life cycle assessment (Tao and Yu, 2014). The key assumptions for the input data are in Table 3.1 below. The characteristics and electrical specifications of the multicrystalline photovoltaic solar panel, whose LCA will be performed in this study, are also shown in Table 3.3.

Table 3.2. Key assumptions for the input data.

Input Data	**Selected Process from GaBi 9.5**
Electricity	Electricity from hard coal [System-dependent]
Water	Tap water, at user
Fuel	Diesel, at refinery
Natural Gas	Natural gas China [Natural gas, at production]
Steam	Electrolytic steam
Compressed air	Compressed air, 14 bar, average efficiency

Table 3.3. Characteristics and electrical specifications of PV panel in this study.

Items	Parameters
Module size	1957 x 997 x 42 mm
Mass	24 kg
Frame	Aluminium alloy
Front glass	3.2 mm
Thickness of EVA sheet	0.5 mm
Thickness of wafer	200 mm ± 20 mm
Number of cells per module	6 x 12 = 72
Cell area	156.75 mm x 156.75 mm = 24570.56 mm^2
Efficiency of modules	17.94 %
Operation life	30 years
Annual solar radiation	4680 MJ m2 a1
Optimum operating voltage (Vmp)	40.19 V
Open circuit voltage (Voc)	47.44 V
Short circuit current (Isc)	9.41 A
Rated maximum power (Pmax)	200 Wp
Operating temperature	-40 C to 80 C
Maximum system voltage	1500V DC
Maximum series fuse rating	15 A
Output power tolerance	±5 %

3.4. System Boundaries

The aim of this study is to quantitatively assess the life cycle of multi-Si PV solar panel systems, which are the most common type today, by including recycling scenarios, and to provide a scientific basis by using a cradle-to-cradle approach for creating more sustainable policies in this sector.

The system boundaries of the study are included: upstream phase which contains silica (raw material) extraction, midstream processes which involve solar grade multisilicon production, ingot casting, wafer sciling, cell production, assembling, transportations (Fu et al., 2015). Since multi-Si

PV solar panels do not emit any pollutants or greenhouse gasses during the operation process, the environmental impact assessment of the using stage will not be included in the analysis (Huang et al., 2017). Roughly, the life cycle of a solar panel refers to the time from its manufacture, operation and maintenance to its recycling, but the use and maintenance of PV systems will not be considered because data on these phases already have a quite low environmental impact. In addition, while assessing the end of life of the panels, the transportation phase between the solar panel operation field and the recycling facility is not included in the calculations.

Despite numerous LCA studies on multi-Si PV solar technologies in the literature, the End-of-Life stage is usually excluded from the system boundary or approximately estimated. Few researches to date have also focused specifically on the recycling of multi-Si silicon PV panels. In addition, detailed information about the recycling of multicrystalline PV panels seems to be missing in the LCA databases as well. Scenarios that examine the impact of material recycling are of paramount importance, as implementing the best option at the end of a solar panel's life can result in a significant reduction in environmental impact. This study will reveal a more holistic assessment by focusing on recycling technologies that are often missing in the LCA processes of multi-Si panel technologies.

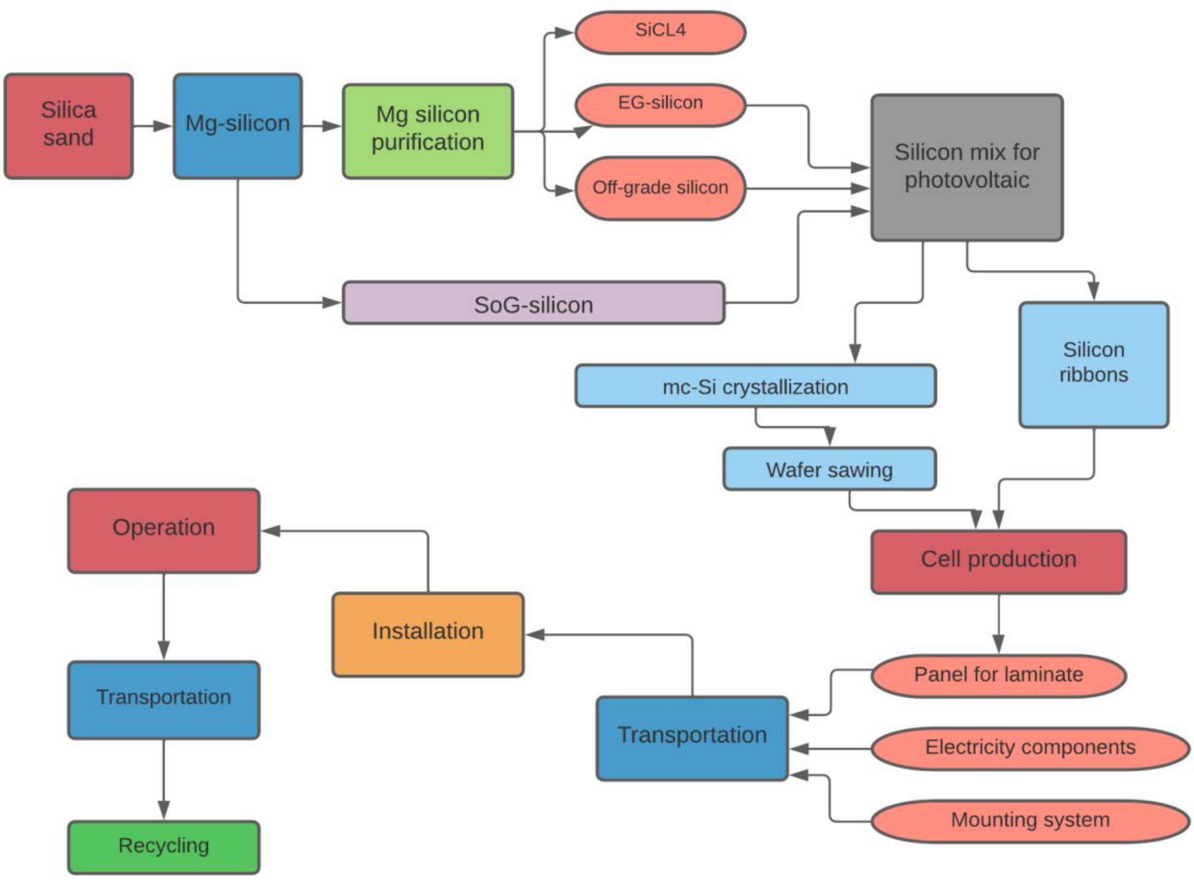

Figure 3.1. System boundaries of multi-Si PV panel.

4. RESULTS AND DISCUSSION

Life Cycle Impact Assessment (LCIA) is the phase of the LCA where the assessment of potential environmental impacts from fundamental flows occur. This section is quite instructive for producers and decision makers to make sense of the environmental damage caused by flows and emissions. The LCA method will be of great benefit in understanding the environmental damage caused by solar energy systems, which are considered to cause almost no greenhouse gas emissions throughout their lifetime, and to develop reduction methods.

4.1. Life Cycle Impact Assessment for Multicrystalline Solar Panel

This part has been carried out by using GaBi 8.0 Software program and EcoInvent database. In the software, flow diagrams of production, transportation, assembly, use and recycling phases were created. Environmental impacts were evaluated by taking into account the results of product inventories. In order to evaluate the environmental impact within the scope of this study; characterization, classification and normalization procedures were taken into account.

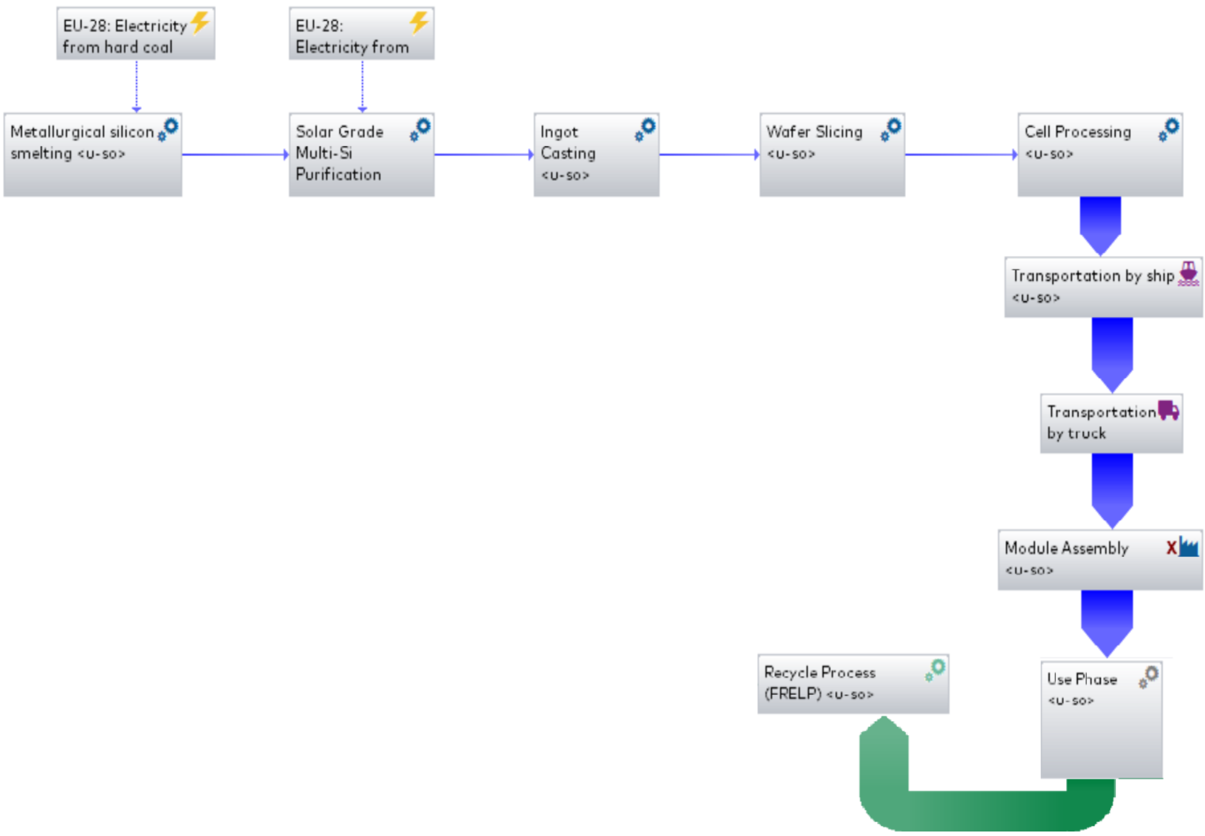

Figure 4.1. Gabi 9.5 Software screenshot for LCA of multi-Si solar panel

4.1.1. Classification

Inventory results should be divided into different impact categories depending on the types of impacts on the environment. In the table below, the classification of emission and impact factors is provided as part of this LCA study. Several LCIA methodologies have been created and include tools for life cycle environmental impact assessment, assessment and mitigation of chemical and ecological impacts. In this study, potential environmental effects of Acidification, Eutrophication, Global Warming, Ozone Layer Depletion Potential, Photochemical Ozone Creation Potential, Terrestrial Ecotoxicity Potential, and Freshwater Aquatic Ecotoxicity Potential were evaluated by using CML Methodology.

Table 4.1. Selected LCI data and impact categories.

Impact Categories	**Selected LCI Data**	**Unit**
Global Warming Potential (GWP)	CO_2, N_2O, CH_4, NMVOC	kg CO_2 eq.
Acidification Potential (AP)	SO_2, NH_3, NO_x, H2SO_4	kg SO_2 eq.
Eutrophication Potential (EP)	NH3, NOx, N_2O, PO_4, P	kg PO_4 eq.
Photochemical Ozone Creation Potential (POCP)	CO, NO_x, SO_2, NMVOC, CH_4, VOC	kg Ethane eq.
Terrestrial Ecotoxicity Potential (TETP) inf.	Highly concentrated chemicals that fatally toxic to rodents	kg DBC eq.
Ozone Layer Depletion Potential (ODP)	Halon 1211, Halon 1301, R11, R114, R12, CH_4	kg R11 eq.
Freshwater Aquatic Ecotoxicity Potential	Highly concentrated chemicals that fatally toxic to freshwater	kg DBC eq.

4.1.2. Characterization

The characterization distribution allows direct comparison of LCI results within the required impact categories. With the GaBi Software, the contribution of emissions from the lifetime of the multi-Si solar panel to each impact category was calculated and the emissions were classified in the relevant categories for recycling scenarios. When the results are examined, metallurgical silicon smelting, cell processing and module assembly stages are noticed as prominent stages in the context of impact categories.

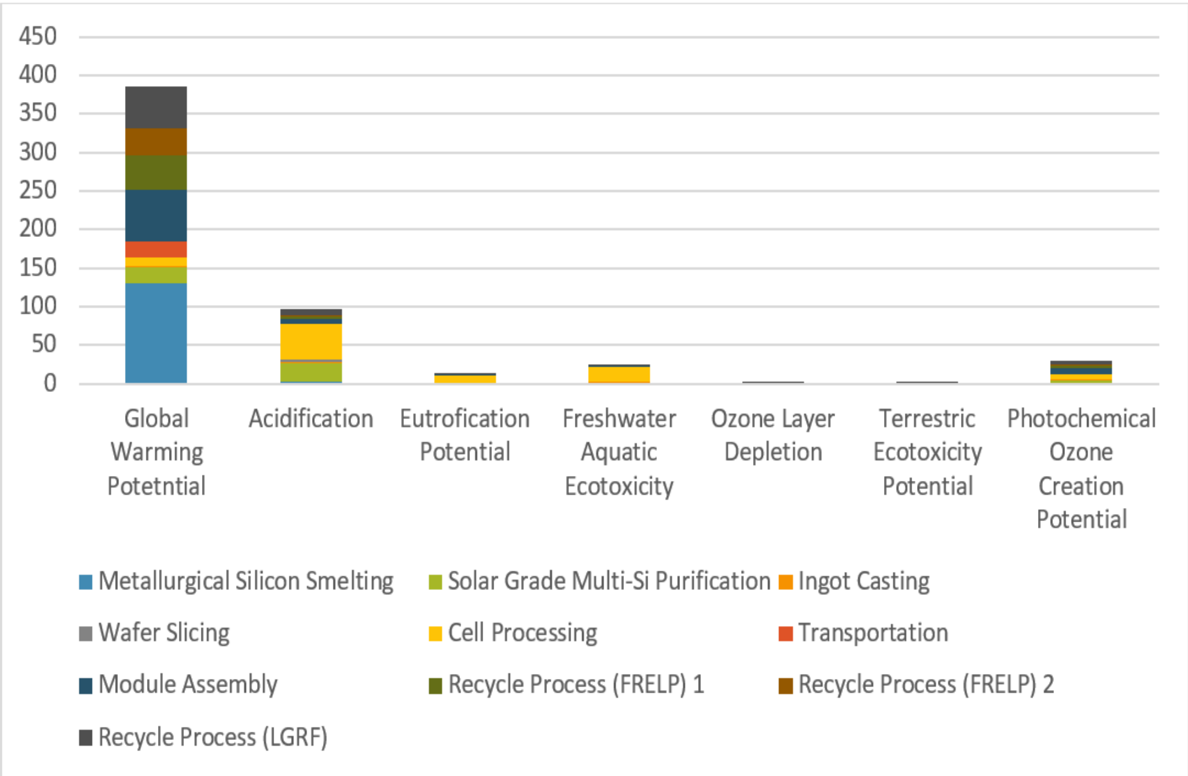

Figure 4.2. Characterization of environmental impact categories in multi-Si solar panel life cycle [kg].

4.1.3. Normalization

The normalization is the demonstration of different types of environmental impact according to the different processes of the photovoltaic panel system. The environmental impact categories specified in Figure 4.2 were compared with the normalization process. According to the results, Global Warming Potential, Acidification Potential and Photochemical Ozone Creation Potential are the three main impact categories and the highest environmental pollution load comes from metallurgical silicon smelting, cell processing and panel assembly stages. The metallurgical silicon melting and module assembly stages have the two highest values in the GWP category, with values of 130 kg CO_2 and 66 kg CO_2, respectively. Therefore, their share in total emissions is also quite large. Another high stage in terms of total emissions is cell processing. However, it is the AP impact category with 46.8 kg SO_2-equivalent that increases the total emission value of this stage.

In recycling scenarios, these three impact categories come to the fore, and LGRF is the scenario with the worst result. LGRF recycling scenario gave values of 54 kg CO_2, 7.09 kg SO_2, 3.82 kg PO_4 in GWP, AP and POCP categories, respectively, and had the highest value in terms of emissions during its life cycle.

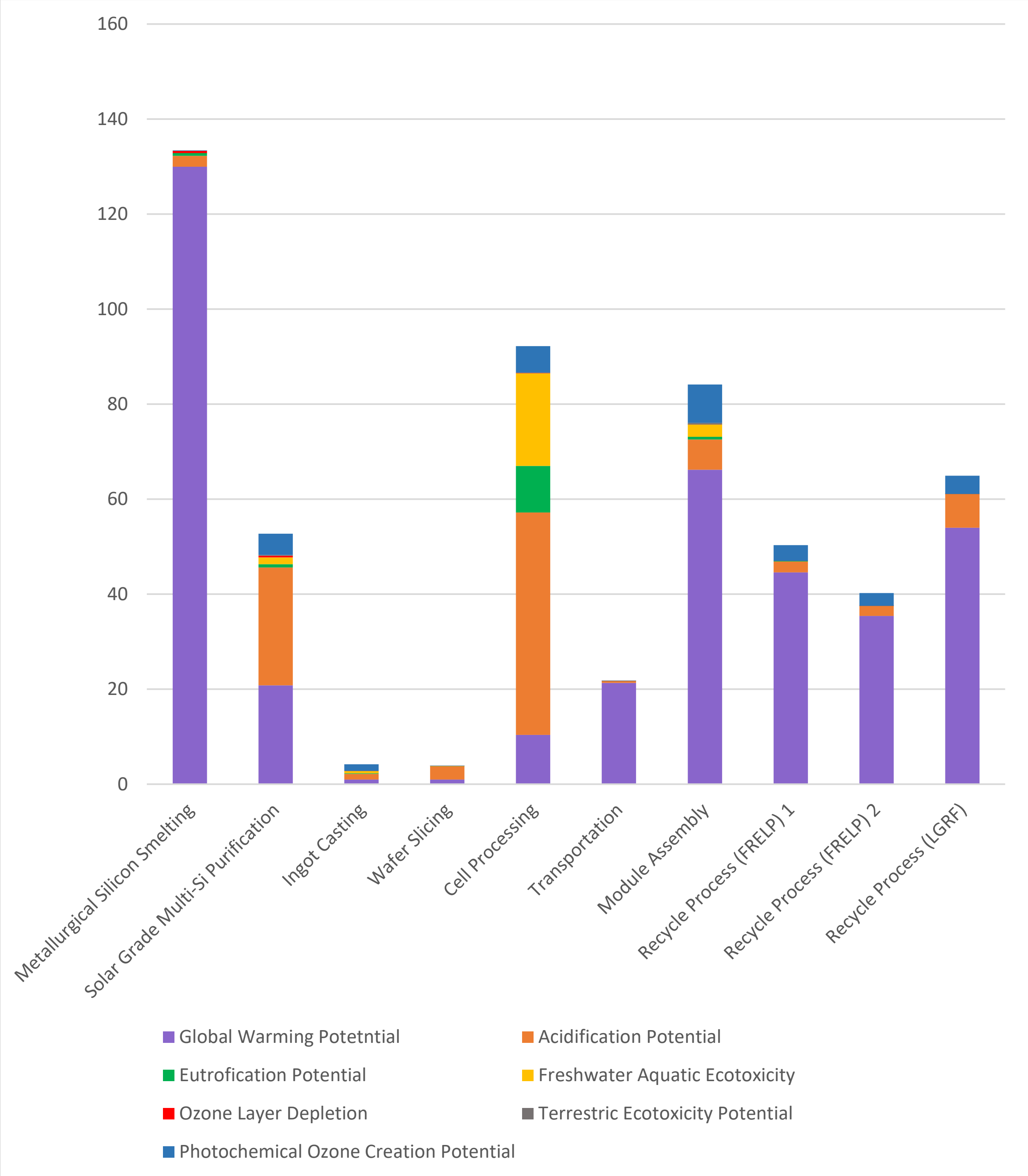

Figure 4.3. Normalization of environmental impact categories in multi-Si solar panel life cycle [kg].

4.1.3.1. Global Warming Potential (GWP)

Global Warming Potential is the merit that allows comparing the effect of different GHGs in the atmosphere by comparing how much energy another gas will absorb compared to carbon dioxide, which is the greenhouse gas that is most present there in volume terms. Greenhouse gasses such as carbon dioxide, methane, nitrous oxide, fluorinated gasses, and water vapor accumulate in the atmosphere of the world and increase the temperature of the world. This increase in temperature causes a change in the climate and threatens the living life and ecosystems in the world. Global warming potential is measured in terms of equivalent carbon dioxide emissions over a 100-year time period.

When each stage in the life cycle of the multicrystalline solar panel and three different recycling scenarios were examined, metallurgical silicon melting and module (panel) assembly emerged as the phases with the highest value in terms of GWP.

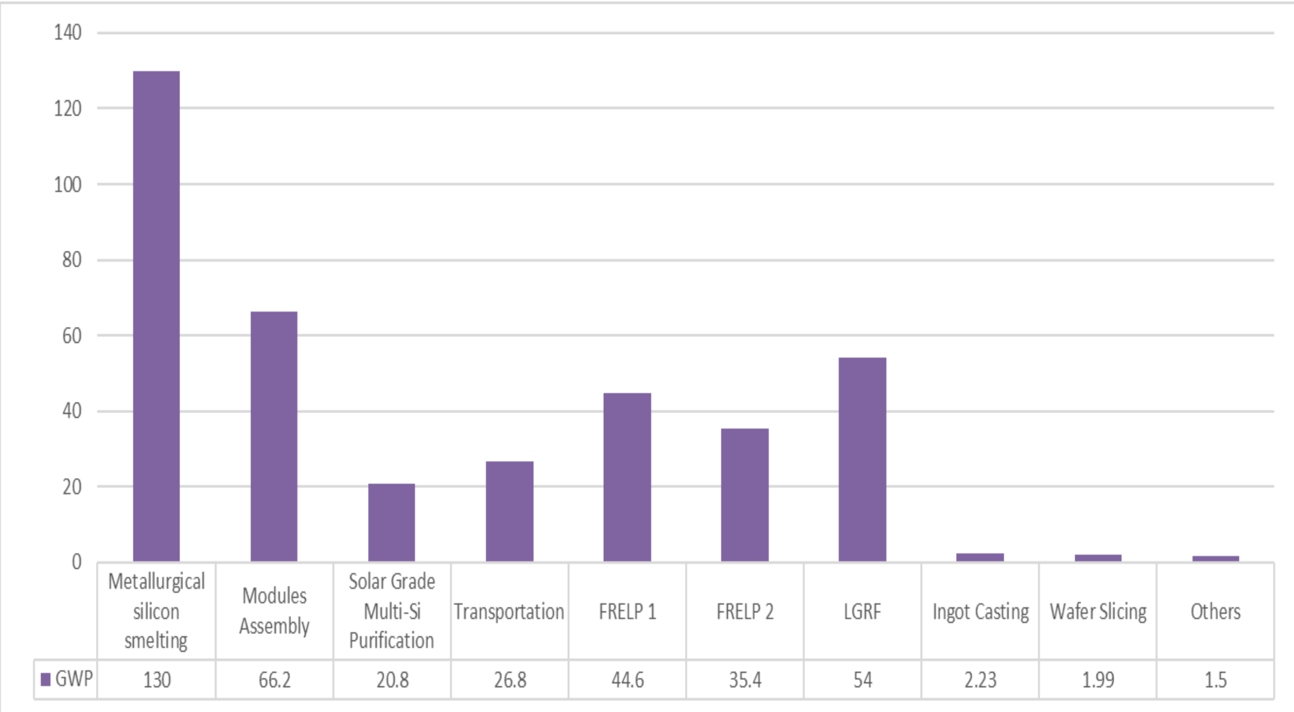

Figure 4.4. Global warming potential (GWP 100 years) [kg CO_2-equivalent].

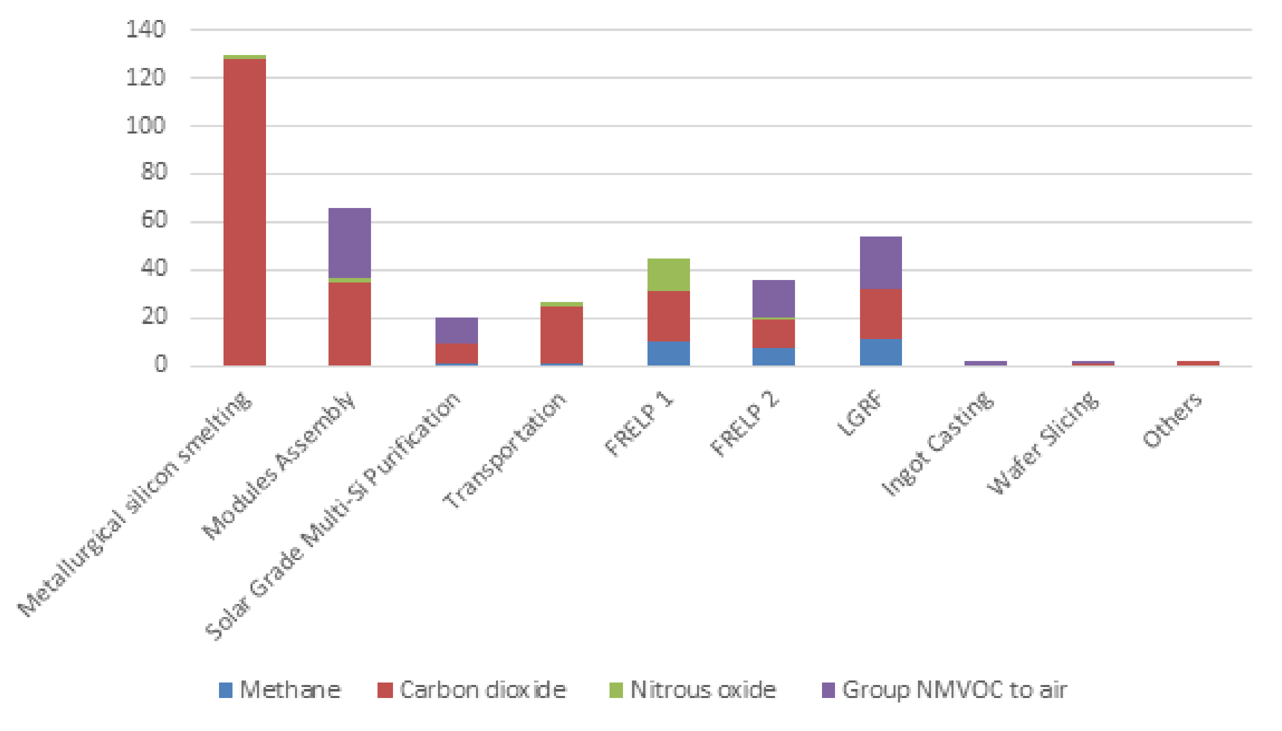

Figure 4.5. Decomposition of substances affecting global warming potential.

Regarding the life cycle scenario of a multicrystalline PV solar panel, for GWP the dominant gas in most phases is CO_2. After CO_2, group NMVOC and methane are the two gasses that contribute the most to global warming potential, respectively. Intensive use of electricity and steam consumption, especially in the metallurgical silicon smelting phase, increases carbon dioxide emissions because the solar panel analyzed in this study was produced in China and the main source of electricity generation is coal-fired power plants. Coal is the type that causes the most greenhouse gas emissions in the energy production process among fossil fuels. For this reason, the use of electricity produced from coal will increase the CO_2 emission rates from the processes.

In the module assembly phase, which contributed the second highest to the GWP, material consumption had a larger impact than electricity consumption. The aluminum frame and PVC production processes resulted in copious CO_2 and NMVOC emissions.

4.1.3.2. Acidification Potential

Acidification potential is the calculation of the toxic effect of acidifying pollutants such as SO_2, NO_x, NH_x on soil, water, organisms, ecosystems and materials as 1 kg sulfur dioxide equivalent. According to the results of the analysis, the stage that contributes the most to the acidification potential is cell processing.

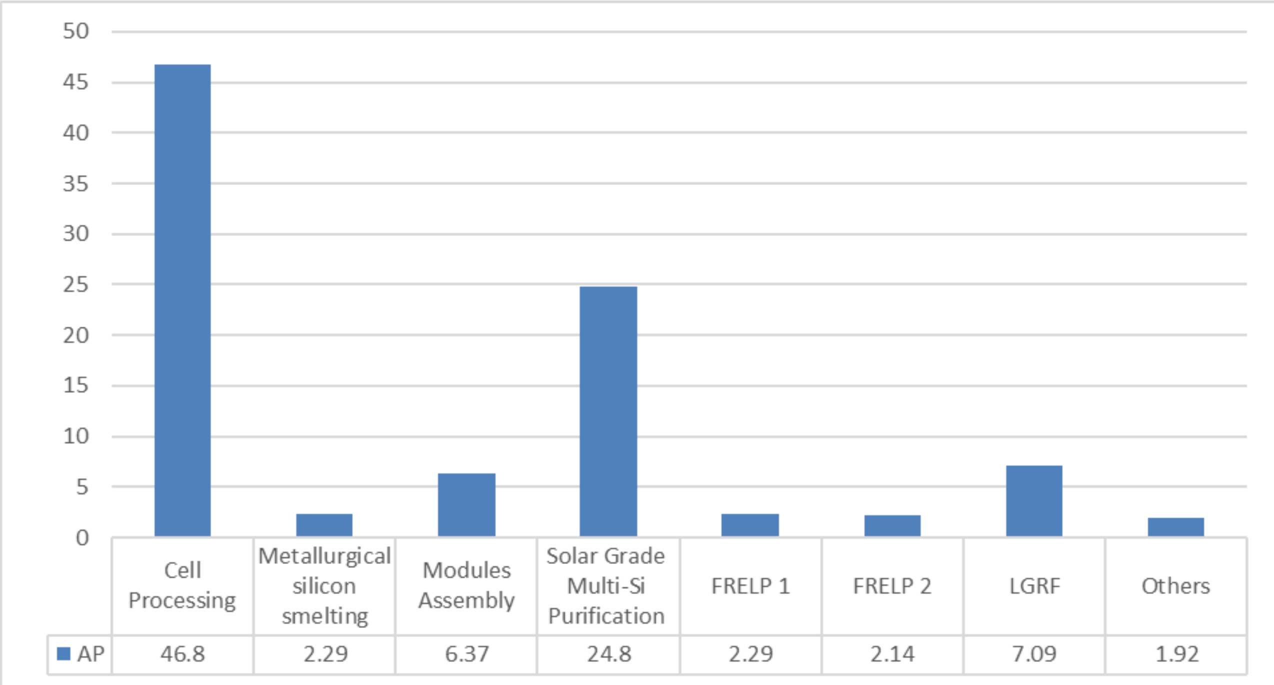

Figure 4.6. Acidification potential [kg SO_2-equivalent].

Nitrogen oxide and sulfur dioxide contributed the most to acidification, as a lot of electricity is used at nearly every stage of the solar panel's life cycle. This is again because China's electricity is largely produced by coal-fired power plants that emit large amounts of nitrogen oxides and sulfur dioxide.

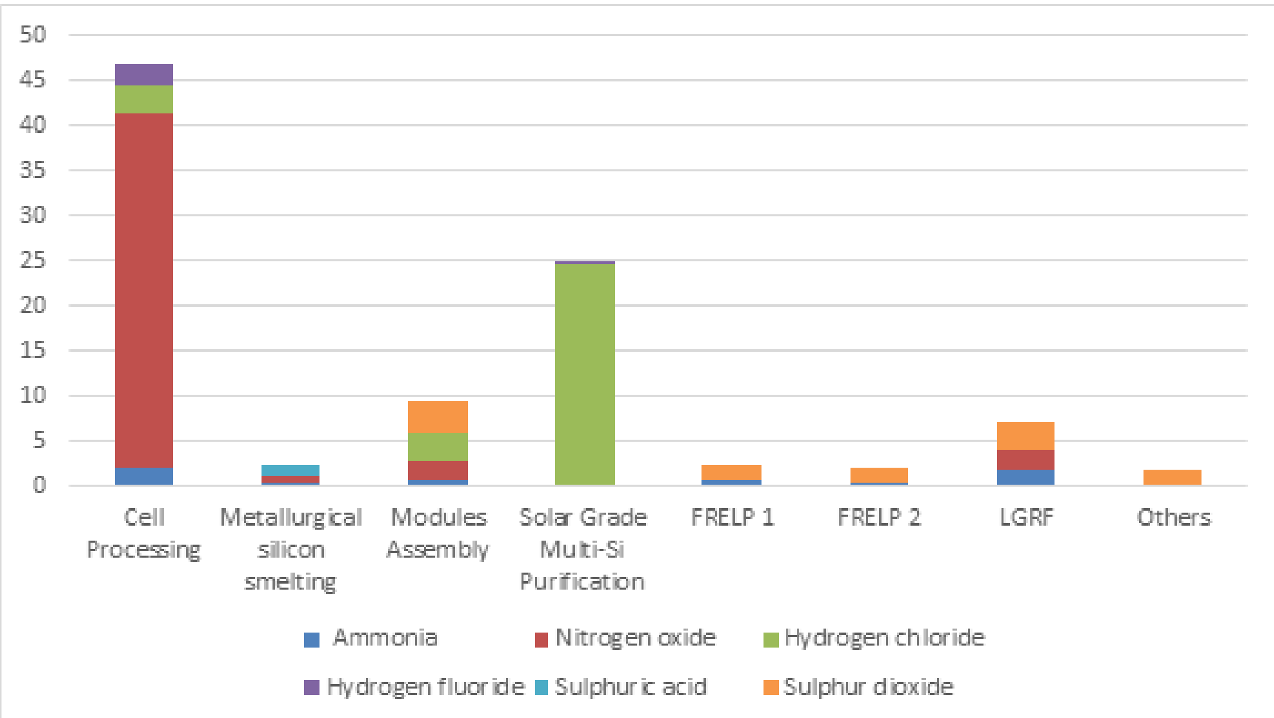

Figure 4.7. Decomposition of substances affecting acidification potential [kg SO_2-equivalent].

4.1.3.3. Eutrophication Potential

The eutrophication potential encompasses the high effects of macronutrient levels such as phosphorus and nitrogen. It often causes high biomass production in ecosystems, leading to disruption of the balance between species. EP is measured in kg of phosphate equivalent.

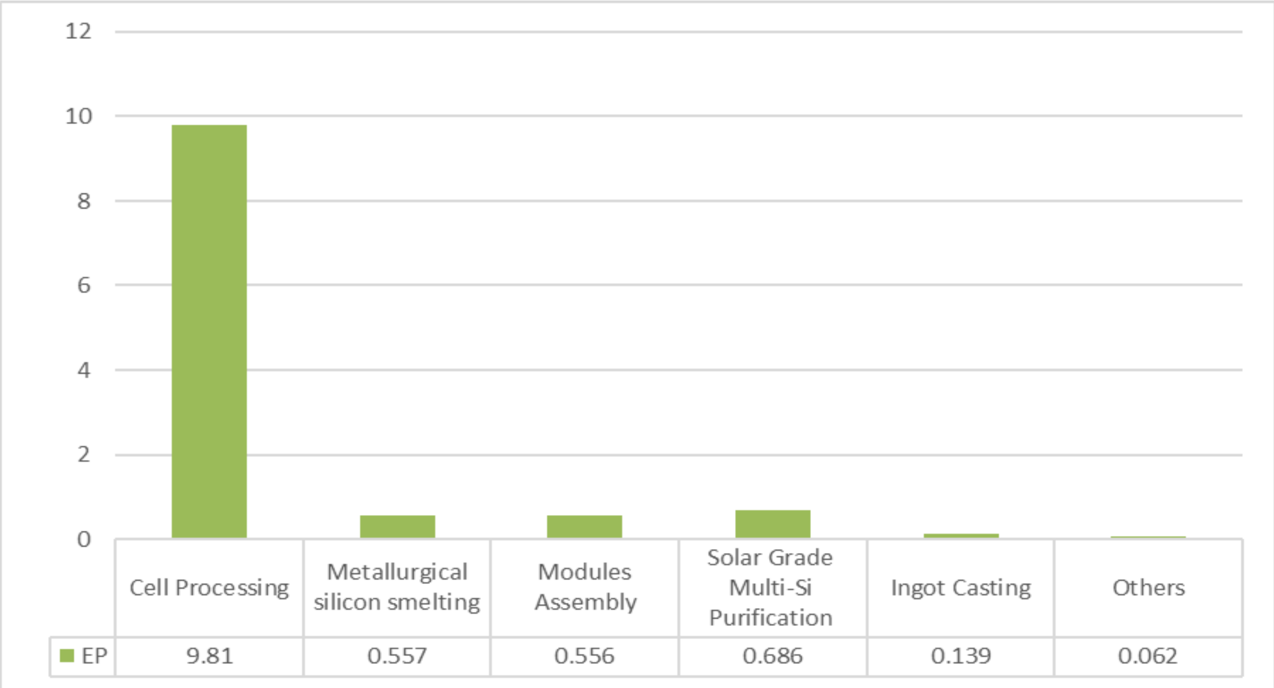

Figure 4.8. Eutrophication potential [kg PO_4-equivalent].

The eutrophication potential for in the lifetime of a multicrystalline solar panel includes emissions to air and fresh water, with a predominance of nitrogen oxides, ammonia and COD.

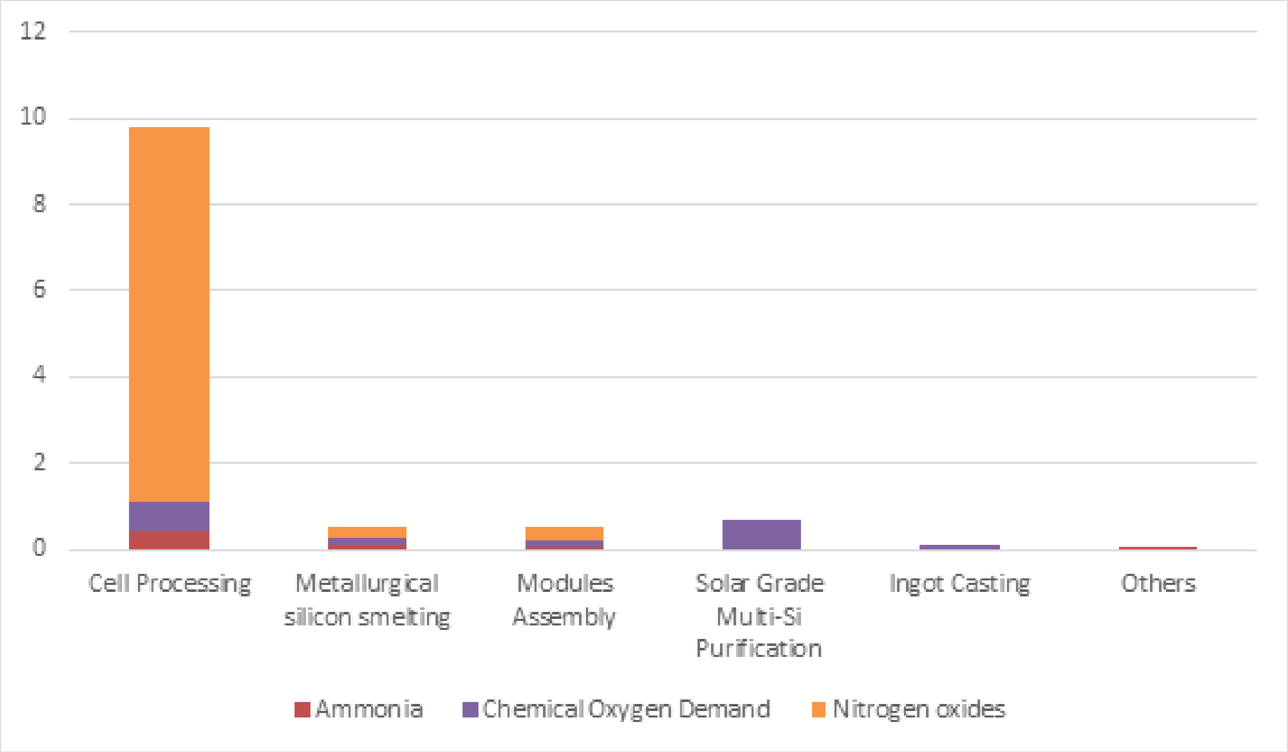

Figure 4.9. Decomposition of substances affecting eutrophication [kg PO_4- equivalent].

4.1.3.4. Ozone Layer Depletion Potential (ODP)

Ozone Layer Depletion Potential is the effect that causes a decrease in the amount of ozone in the stratosphere and thinning of the ozone layer with the effect of gasses such as CFC, carbon tetrachloride, halon, HCFC, and NMVOC group. According to Figure 4.8. module assembly is a hotspot for ODP.

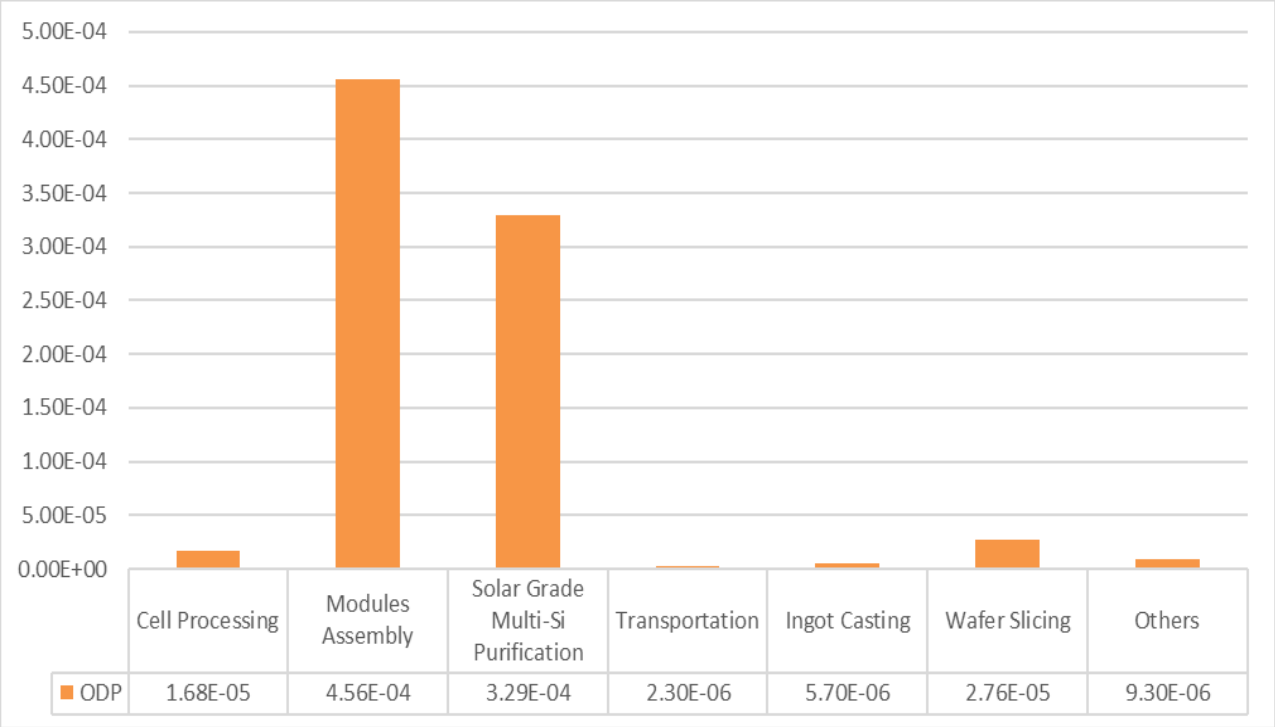

Figure 4.10. Ozone layer depletion potential [kg R11-equivalent].

In the life cycle of the solar panel, the main gasses that cause ozone depletion potential are Halon (1301), carbon tetrachloride and group NMVOC. Halon (1301) contributed the most to the impact on ODP due to the production of the aluminum frame and electricity consumption in the module assembly and solar grade multi-Si purification phases. In terms of Ozone Depletion Potential, the solar grade multi-Si purification step is responsible for most of the carbon tetrachloride.

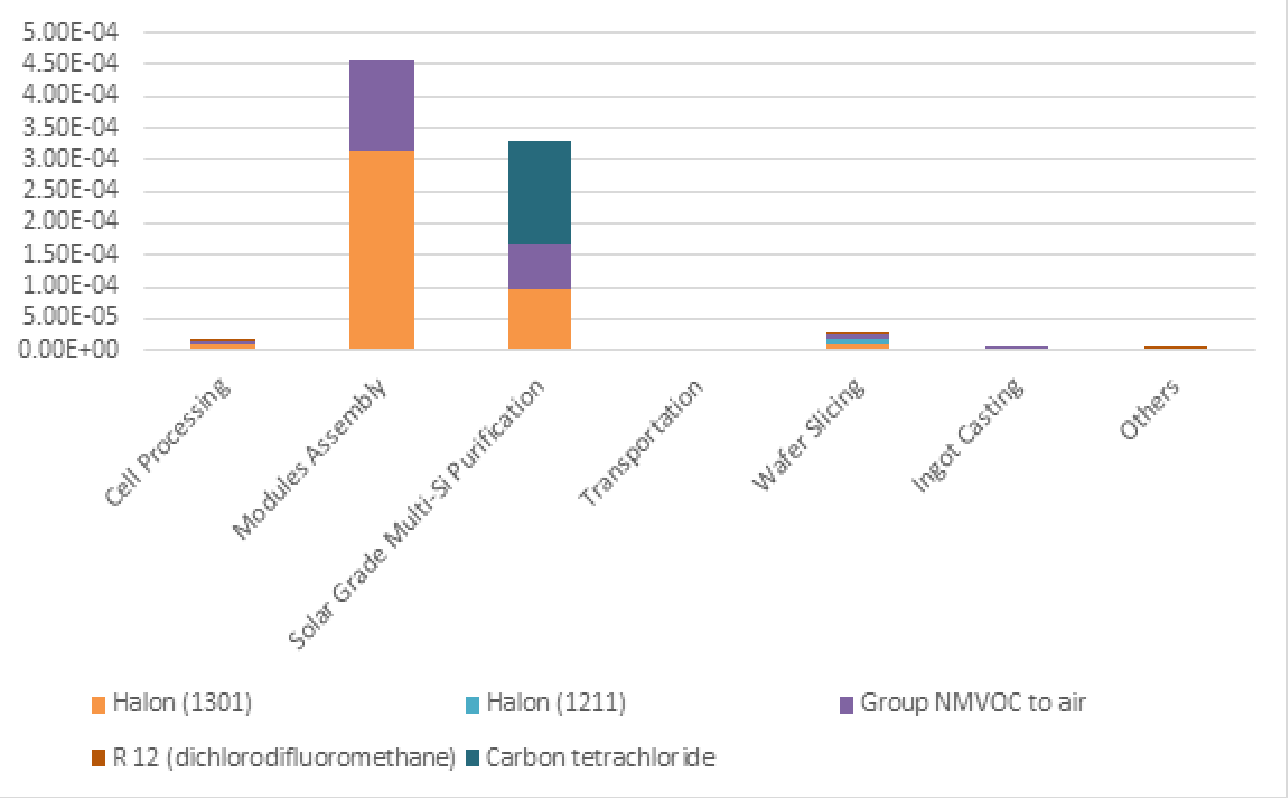

Figure 4.11. Decomposition of substances affecting ozone layer depletion potential.

4.1.3.5. Photochemical Ozone Creation Potential (POCP)

Photochemical Ozone Creation Potential, known as summer smog, describes the capacity of volatile organic compounds to generate ozone at ground level. The oxidizing effect of solar radiation leads to the reaction of oxidizing photochemical compounds with hydroxyl radicals. POCP is calculated by a kilogram of Ethane equivalent. The toxic properties of the Photochemical Ozone directly affect human health and can cause eye irritation, respiratory tract and lung damage. It can also cause degradation of ecosystems.

According to Figure 4.12. module assembly and cell processing stages are the highest in terms of POCP with values of 8.12 kg and 5.53 kg Ethene-eq, respectively.

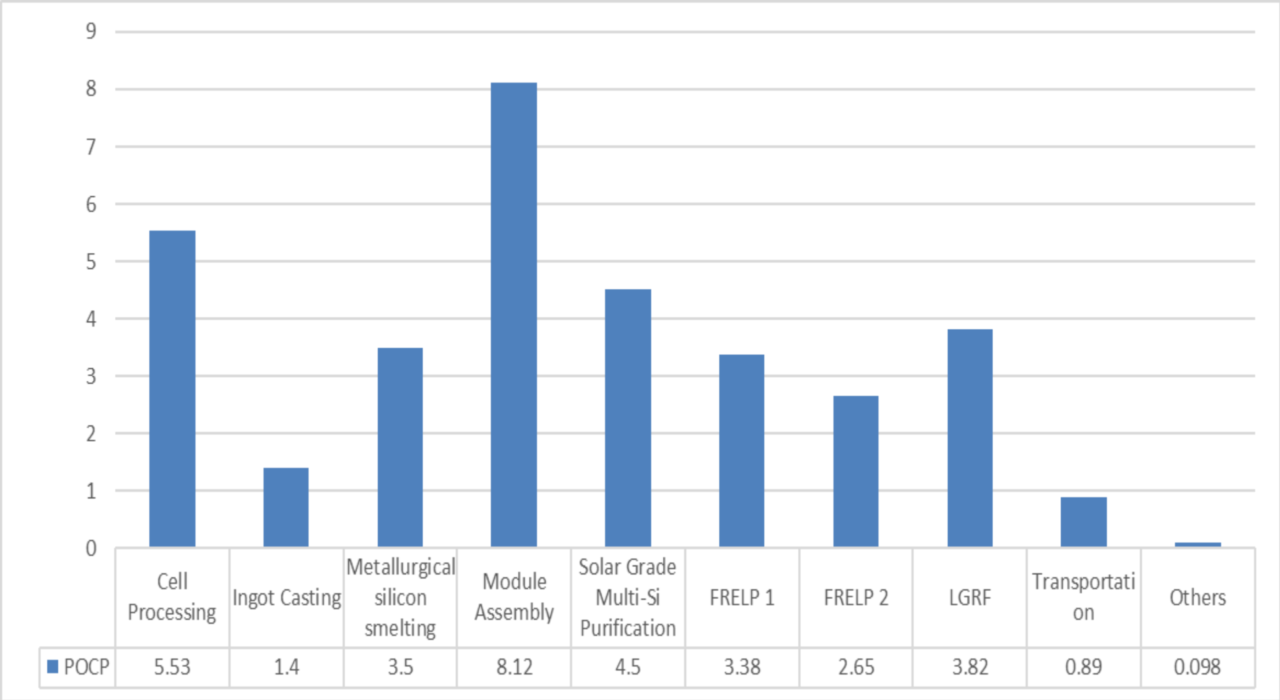

Figure 4.12. Photochemical ozone creation potential [kg Ethene-equivalent].

Figure 4.10. shows the total amount of POCP in detail according to each life cycle phase. According to the analysis results, sulfur dioxide is the dominant emission for POCP. Sulfur dioxide had the biggest impact, due to the large amount of steam and electricity used in the production processes of multicrystalline solar panels, as well as the manufacturing processes of cells, ingots, sheets, aluminum frame and PVF film. NMVOC was the second greater contributor, as aluminum frame, EVA and PVF were used in the panel production. The electricity and steam used in the cell production phase also contributed to NMVOC (non- methane volatile organic compounds) emissions. Nitrogen dioxide, on the other hand, contributed to POCP due to the use of coal in the electricity production process, which is used just like sulfur dioxide.

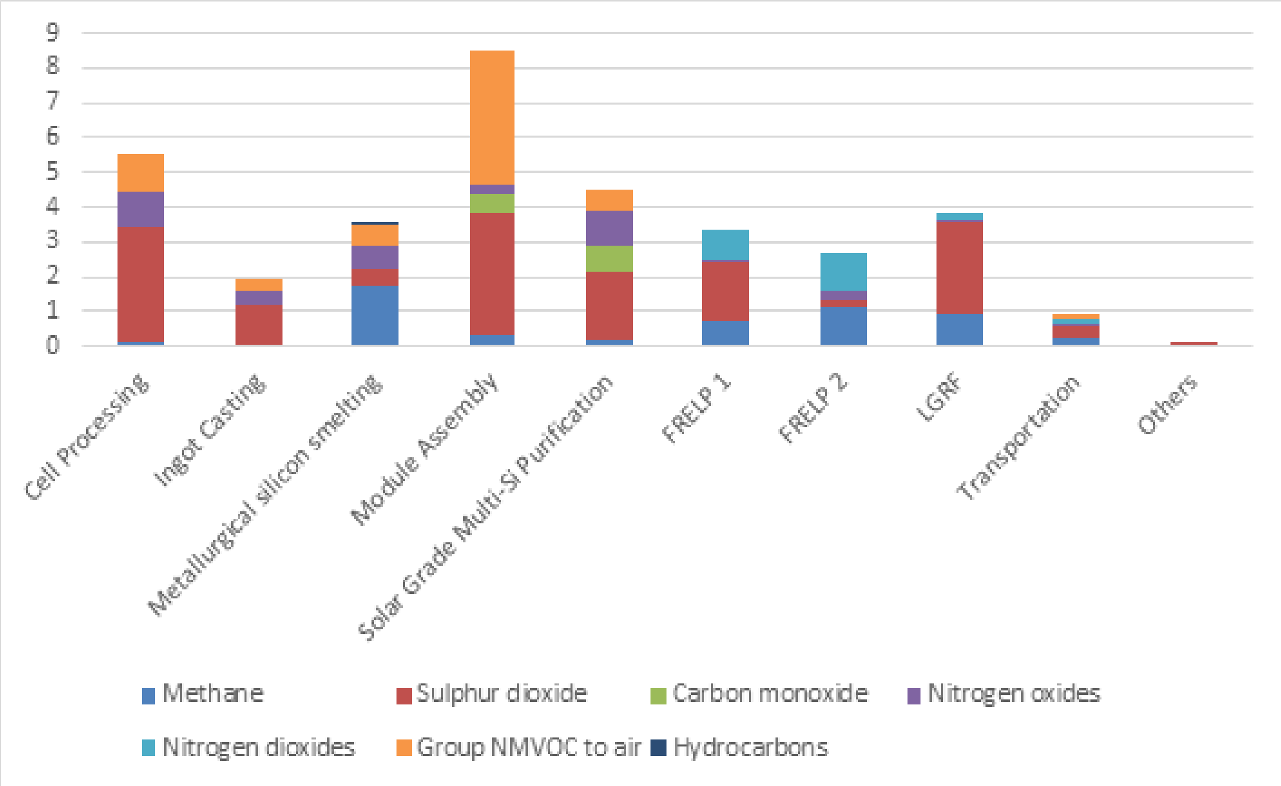

Figure 4.13. Decomposition of substances affecting photochemical ozone creation potential.

4.1.3.6. Freshwater Ecotoxicity Potential (FAETP)

It refers to the damage to the freshwater ecosystem as a result of emissions from toxic substances mixed into the air, water or soil, and according to the analysis results, it has a much higher value in the cell processing stage compared to other impact categories.

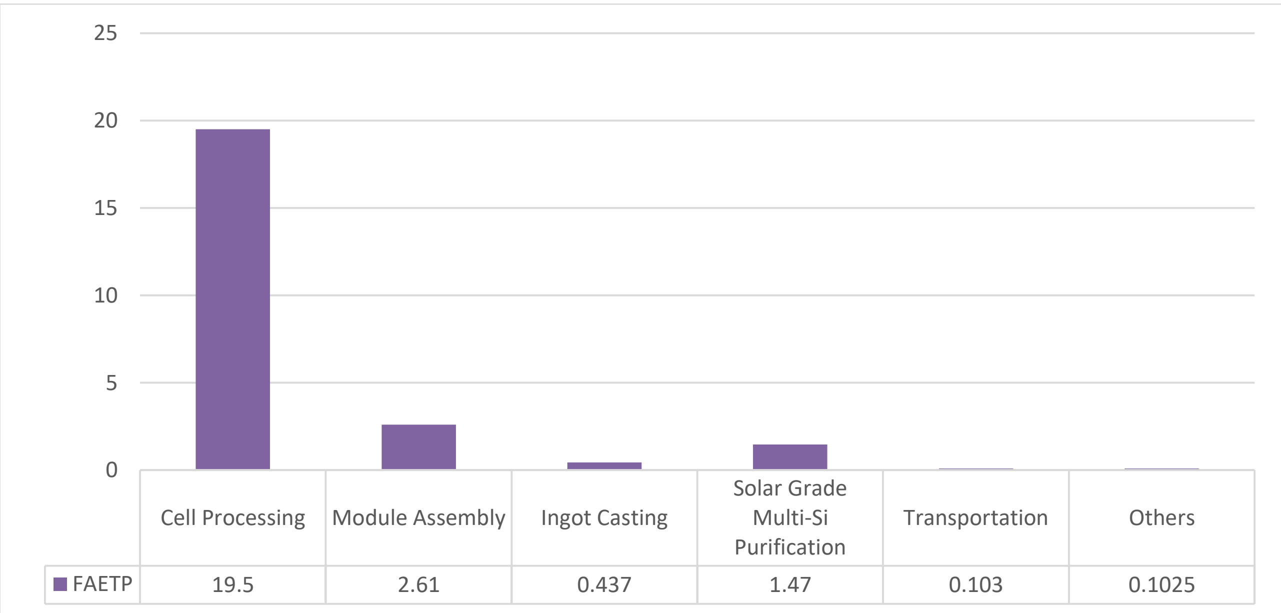

Figure 4.14. Freshwater aquatic ecotoxicity potential [kg DCB-equivalent].

4.1.3.7. Terrestrial Ecotoxicity Potential (TETP)

The concept of terrestrial ecotoxicology can be explained as how environmental pollutants affect soil-dependent organisms and their environment, where there are three components that require a source, a receptor and an exposure route. Terrestrial ecotoxicity measurements often include species such as earthworms, soil microorganisms, plants, birds, and bees. Terrestrial ecotoxicity has effects such as mortality, reduced growth, reproductive failure, occupational disruption, changes in species numbers, and bioaccumulation of residues in terrestrial organisms. In this study, terrestrial ecotoxicity is dominated by sulfuric acid due to steam and electricity used during module assembly, cell processing and solar grade multi-Si purification processes. Since sulfuric acid is very corrosive, it can cause burning of plants, birds or microorganisms exposed to it in the terrestrial ecosystem.

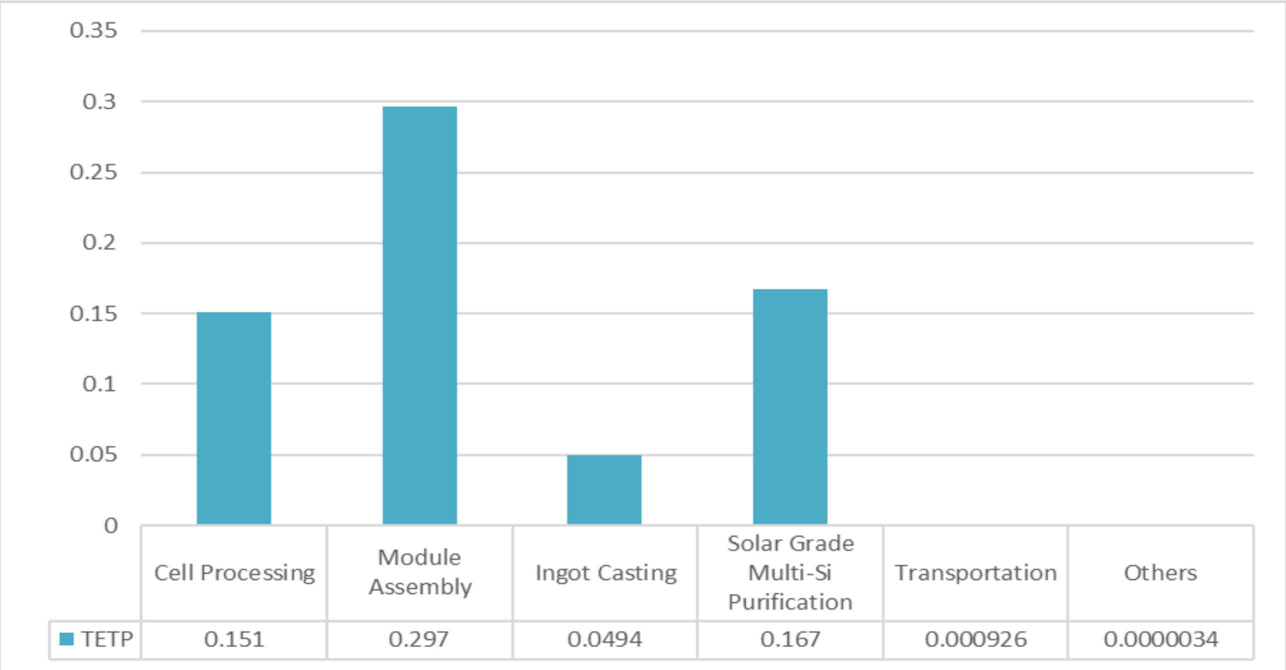

Figure 4.15. Terrestrial Ecotoxicity Potential [kg DCB-equivalent].

4.2. Comparison of Different Recycling Scenarios of Multicrystalline Solar Panels

Recycling end-of-life solar panels reduces both the toxic effects of the PV panels and the resources consumption. The Ethylene-Vinyl-Acetate delamination scenario is the main determining factor for the recycling of silicon-based solar panels in terms of ensuring the least damage recovery of panel parts and reducing the cost and greenhouse gas emissions from recycling. In this study, three different recycling methods consisting of different combinations of mechanical, chemical and thermal delamination processes were analyzed in order to determine the best recycling scenario for multi-Si panels.

In the LGRF scenario, the aluminum frame and junction boxes can be removed mechanically and the solar panel can be disassembled. The recovery of materials in this kind of process is limited and LGRF can only recover glass, aluminum frame and copper in cables. The Full Recovery End of Life Photovoltaic FRELP procedure includes scenarios where mechanical, thermal and chemical delamination methods are combined and aims to achieve much higher recovery amounts in this way. FRELP aims to recover glass undamaged, thus saving energy spent during glass melting and reducing greenhouse gas emissions from the melting process. FRELP 1 includes a combination of mechanical and chemical delamination methods. In FRELP 2, this combination is in the form of chemical and thermal delaminations.

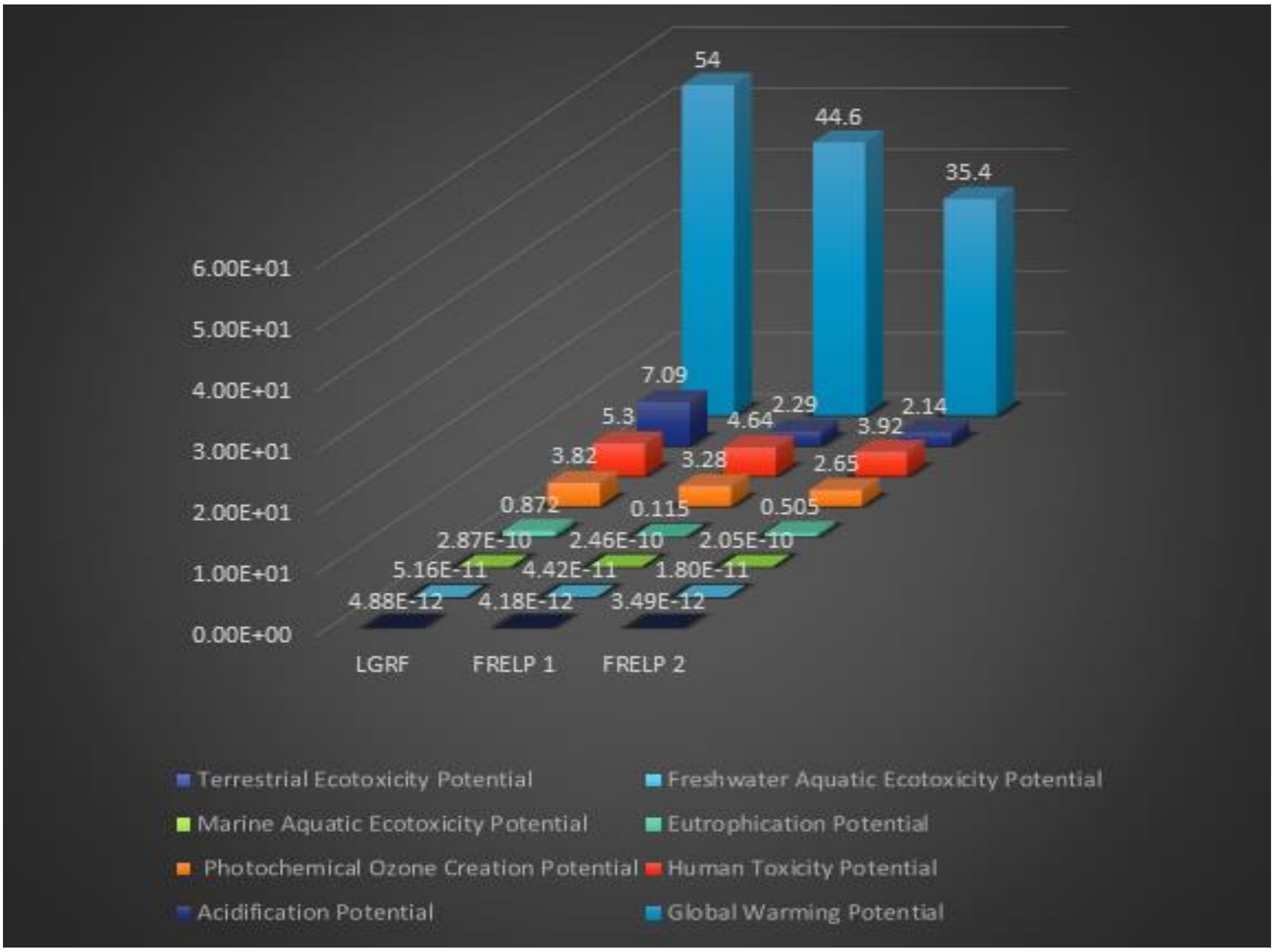

Figure 4.16. Normalization of environmental impact categories in multi-Si solar panel's end-of-life scenarios [kg].

The GWP value is a hotspot for all three scenarios FREL 1, FRELP 2, and LGRF. FRELP1 and FRELP2 scenarios gave quite close values for acidification, human toxicity and photochemical ozone creation potential, but both the grand total and these values were much higher in the LGRF scenario. One of the main causes of human toxicity and freshwater ecotoxicity is emissions from electronic waste from the incineration of plastics. Silicon, silver and other metals in the photovoltaic solar panel cannot be recovered in the LGRF method and are buried in the landfill. This situation increases the risk of toxic substances in the landfill to leak into the soil and watersheds. Therefore, the LGRF method has the highest value for almost all environmental impacts.

4.2.1. Global Warming Potential Comparison of Different Recycling Scenarios

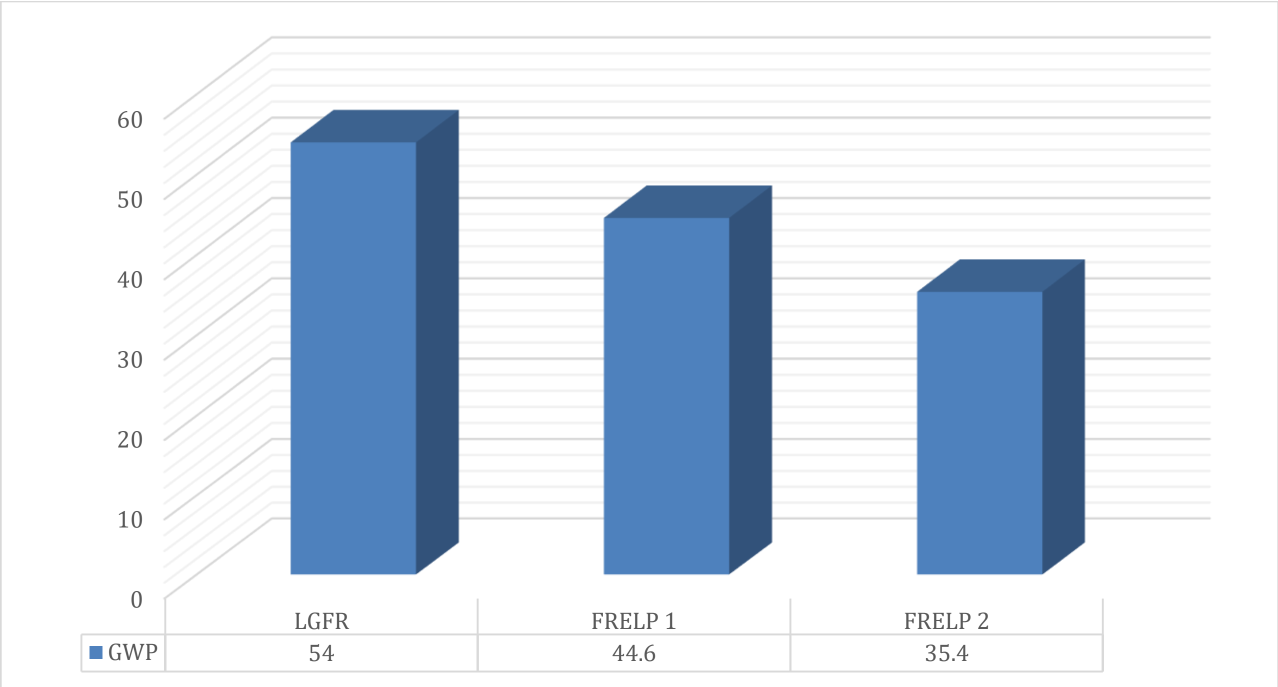

Figure 4.17. Global warming potential of recycling scenarios (GWP 100 years) [kg CO_2-equivalent].

Global Warming Potentials and the amount of CO2 produced in the different EoL scenarios were evaluated, as shown in Figure 4.13. FRELP 2 and FRELP 1 scenarios performed better than the LGRF scenario. The CO_2 emission amounts for the FRELP 1, FRELP 2, and LGRF scenarios were 44.6, 35.4, and 54 kg per kWh, respectively. According to the results, the best option in terms of GWP seems to be FRELP 2, a combination of thermal and chemical delamination scenarios.

4.2.2. Acidification Potential Comparison of Different Recycling Scenarios

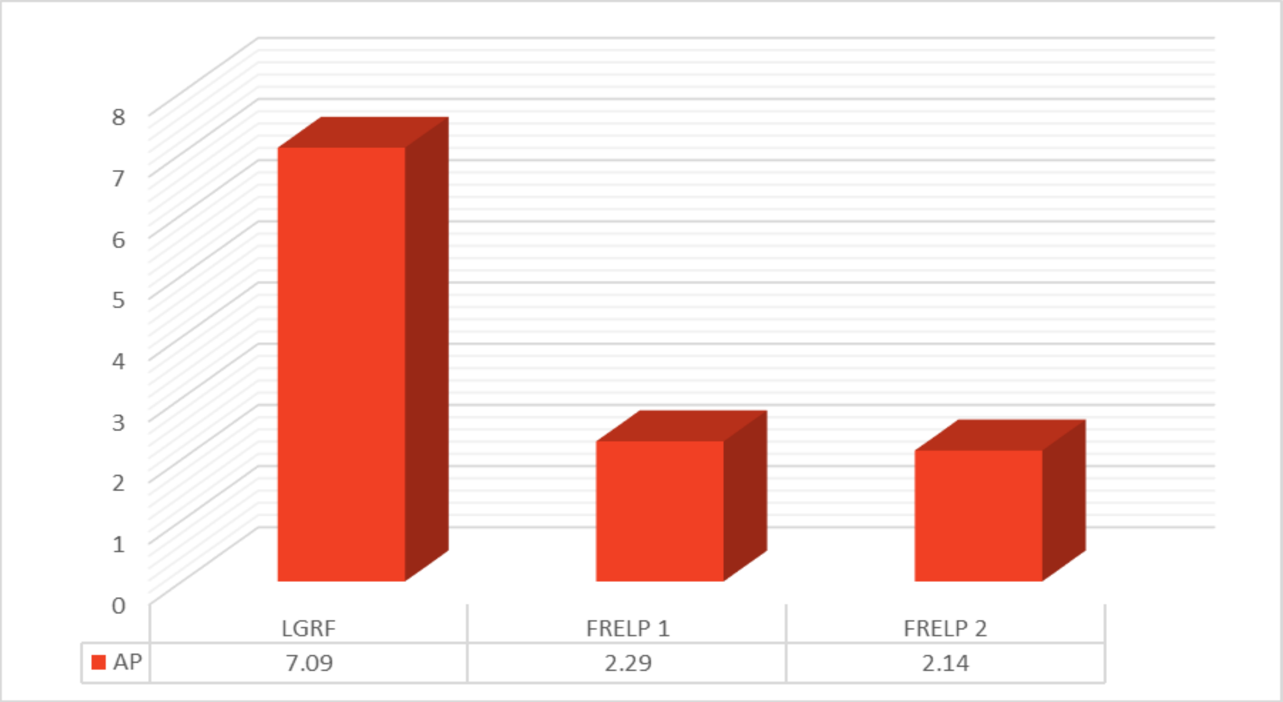

Figure 4.18. Acidification potential of recycling scenarios [kg SO_2-equivalent].

Although FRELP 1 and FRELP 2 scenarios give quite close results in terms of Acidification Potential, LGRF has more than three times their value in this impact category. In terms of AP, LGRF method can be said to be a hotspot.

4.2.3. Eutrophication Potential Comparison of Different Recycling Scenarios

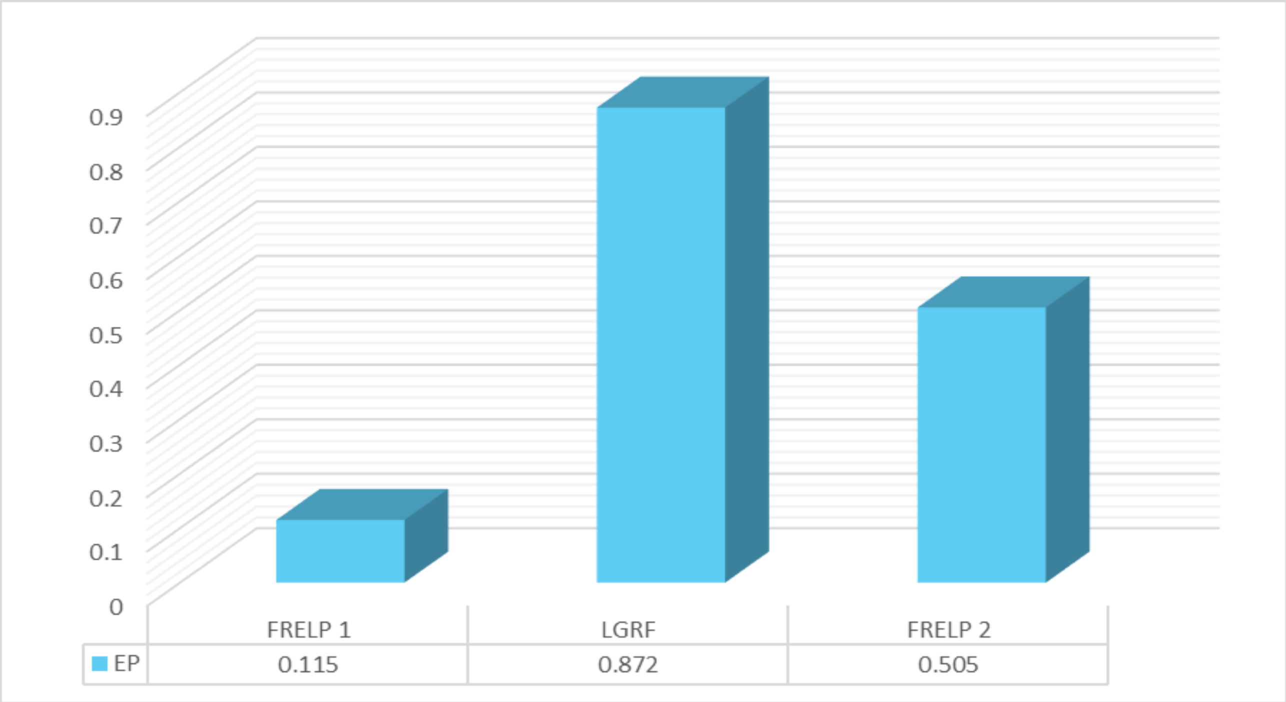

Figure 4.19. Eutrophication Potential [kg PO_4-equivalent].

When the three different methods were compared in terms of Eutrophication Potential results, FRELP 1 gave the best minimum value. While FRELP 1 gave the best result in the EP impact category, the LGRF scenario gave the worst result. The vast majority of terrestrial eutrophication results from sieving, acid leaching, electrolysis and acid neutralization phases.

4.2.4. Freshwater Aquatic Ecotoxicity Potential Comparison of Different Recycling Scenarios

This category of impact refers to the damage done to the freshwater ecosystem by the mixing of toxic emissions to air, water or soil. The reason for this is the emissions that occur during the production of electrical and thermal energy used in recycling processes. LGRF method, which includes only mechanical delamination, has the highest value in this effect. Also, embedding of sludge and fly ash from the thermochemical process of solar panel waste in landfills has an important role in freshwater ecotoxicity.

Figure 4.20. Freshwater Aquatic Ecotoxicity Potential [kg DCB-equivalent].

4.2.5. Human Toxicity Potential Comparison of Different Recycling Scenarios

It is the category that defines the toxic effect on human health caused by the release of several toxic chemicals into the environment. HNO_3 compounds used in acid leaching, electricity used in thermal processes and other processes, and manual separation of the LGRF type aluminum frame were the most important processes that increased human toxicity.

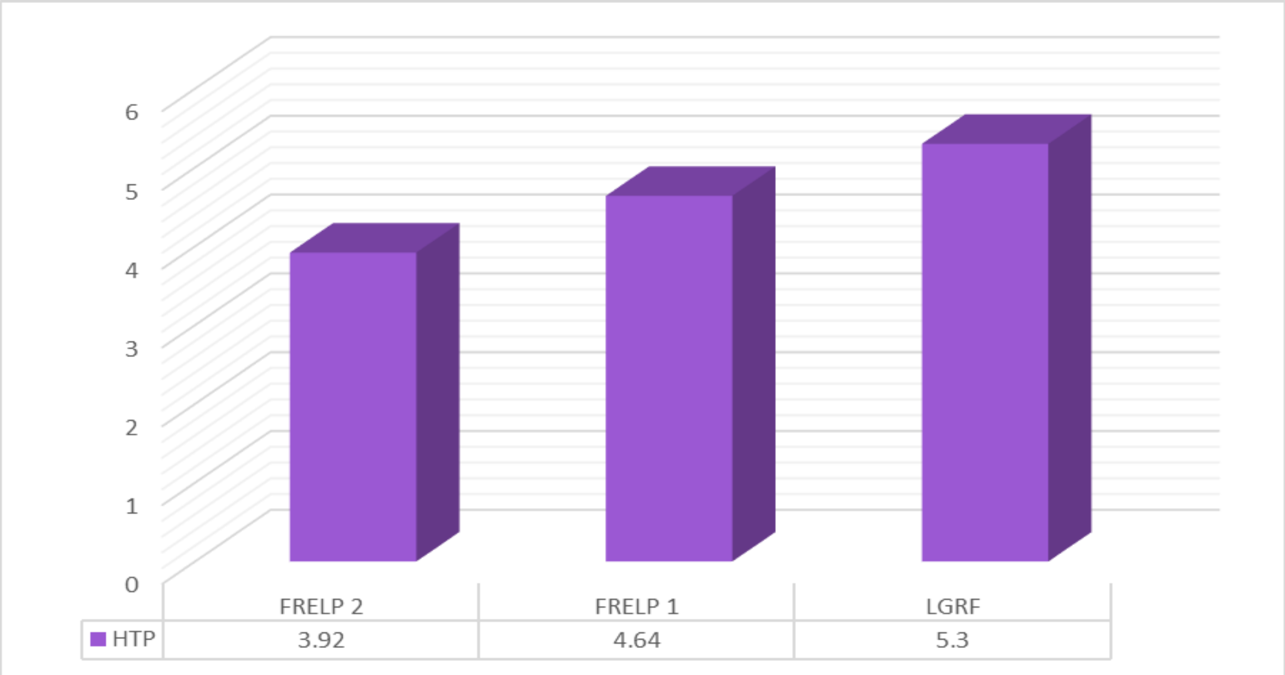

Figure 4.21. Human Toxicity Potential [kg DCB-equivalent].

4.2.6. Marine Aquatic Ecotoxicity Potential Comparison of Different Recycling Scenarios

Marine ecotoxicity comes from the use of hazardous chemicals to recover Si and the burning of EVA and plastics. Shredding and hammer grinding processes in the mechanical delamination process cause significant environmental burdens for marine ecotoxicity due to ash and toxic substances released into the air and water. For this reason, the LGRF method, which has mechanical processes, has the most prominent values for this effect category.

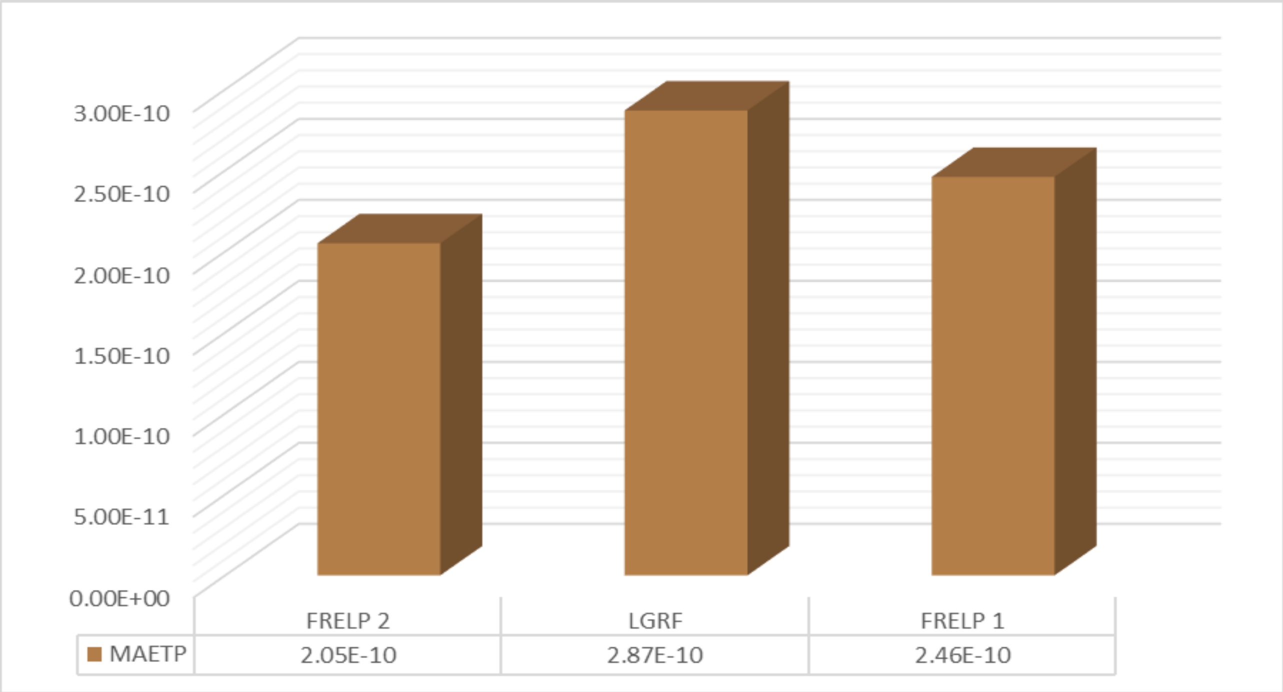

Figure 4.22. Marine Aquatic Ecotoxicity Potential [kg DCB-equivalent].

4.2.7. Photochemical Ozone Creation Potential Comparison of Different Recycling Scenarios

Processes for the recovery of metals from bottom ash are a major contributor to photochemical ozone creation. Also, NO_x released during electrolysis is responsible for significant POCP.

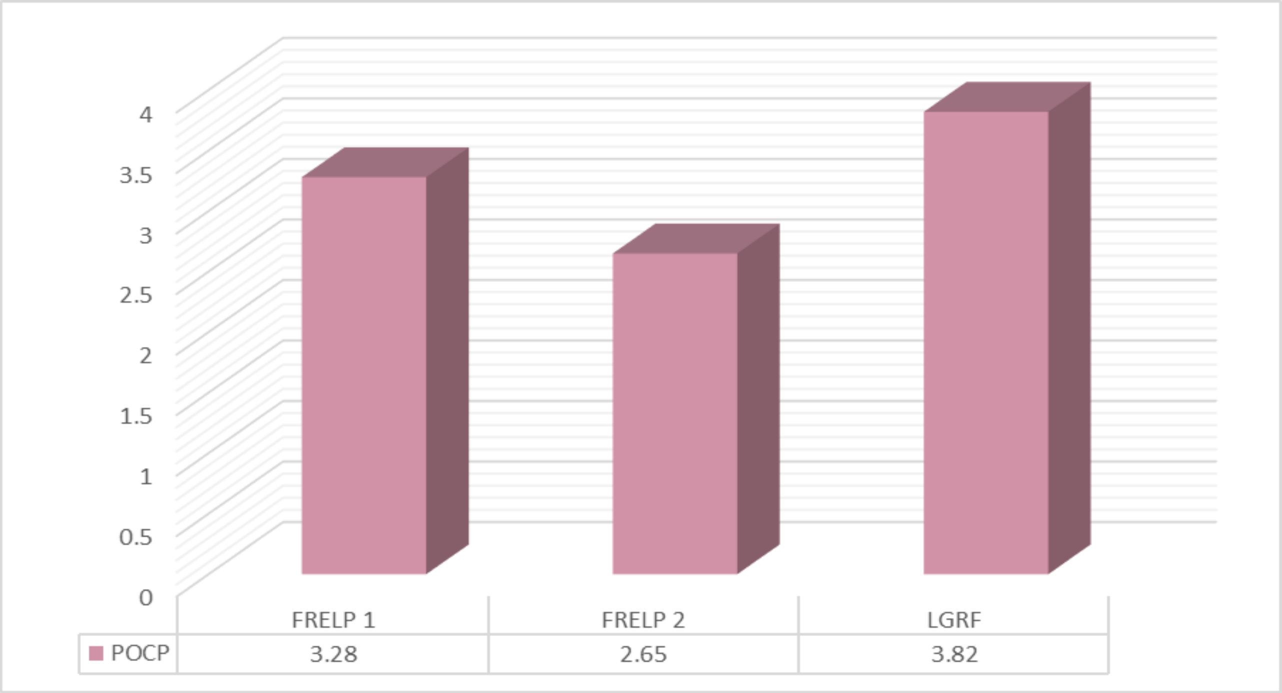

Figure 4.23. Photochemical Ozone Creation Potential [kg Ethene-equivalent].

4.2.8. Terrestrial Ecotoxicity Potential Comparison of Different Recycling Scenarios

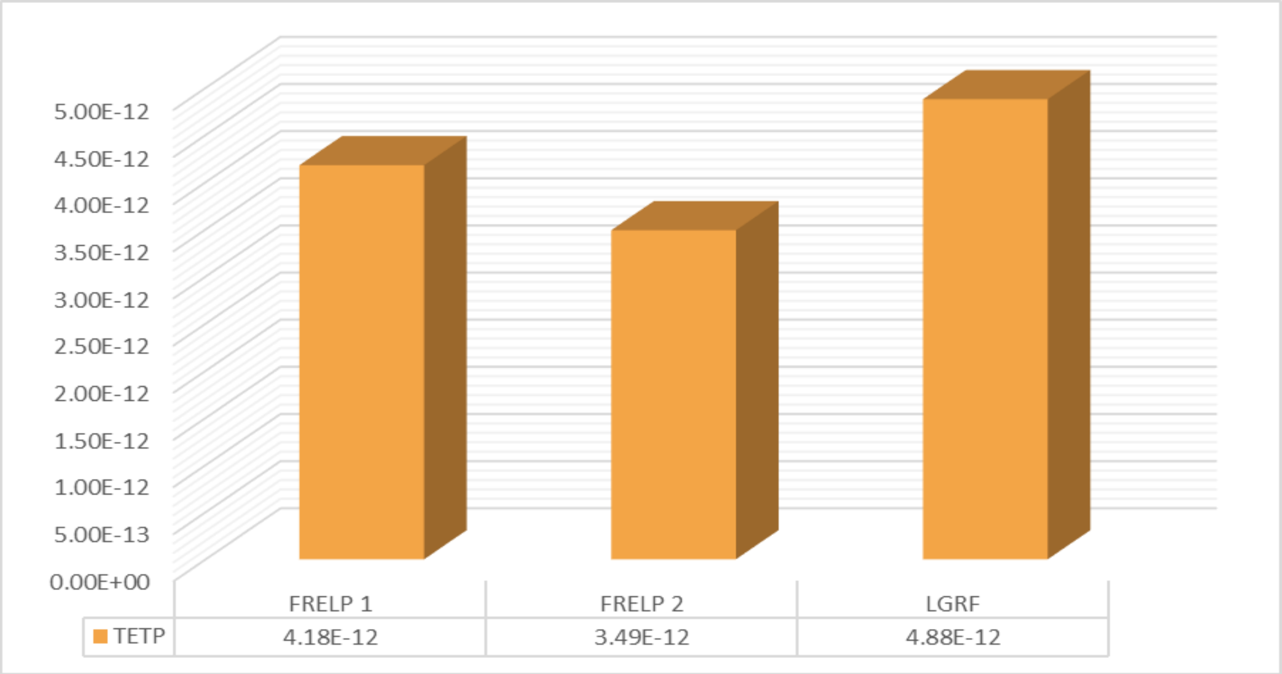

Figure 4.24. Terrestrial Ecotoxicity Potential [kg DCB-equivalent].

5. CONCLUSIONS

The target of this study is to create a roadmap for more sustainable and less environmental impact solar energy production scenarios for the world and Turkey by making the LCA of the most used type of multi-Si solar panels with the CML 2001 evaluation methodology. In this analysis, it is aimed to present a more holistic and inclusive perspective for the analysis of photovoltaic solar panels, with particular emphasis on recycling scenarios. The environmental parameters considered in this analysis are global warming, acidification, eutrophication, ozone layer depletion potential, photochemical ozone creation potential, freshwater ecotoxicity potential, terrestrial ecotoxicity potential, human toxicity potential, and marine aquatic ecotoxicity potential. The results are also interpreted for the selected normalized environmental effects.

Metallurgical silicon smelting, solar grade multi-Si purification, ingot casting, wafer slicing, transportations, cell processing, panel assembly, and recycling phases were included in this analysis. All effects are calculated on the basis of 1 kWh electricity production of multicrystalline photovoltaic solar panels with a lifetime of 25 years.

The metallurgical silicon smelting and solar grade multi-Si purification processes can also be referred to as the multisilicon (polysilicon) production step. 60% of the pollutants that cause global warming are caused by the production of polysilicon. According to the results in GaBi Software, the main pollutants causing climate change are carbon dioxide and must be caused by the high electricity and steam consumption in multisilicon production. The reason for this is that electricity and steam production is done with fossil fuels. Another hotspot is the module assembly phase with a value of 60.2 kg CO_2. The amount of CO_2 resulting from the life cycle of a multi-Si PV panel is 250.68 kg, not taking into account the recycling scenarios.

LGRF, FRELP 1 and FRELP 2 recycling scenarios cause 54, 44.6 and 35.4 kg of CO_2 emissions, respectively.

Figure 5.1. Comparison of three different recycling scenarios in terms of GWP over the entire life cycle of a multi-Si PV panel.

When the results are examined, the best performance according to the GWP effect emerges as FRELP2, that is, the scenario where chemical and thermal methods are combined in the delamination process. The FRELP2 method achieved a CO2 reduction of 34.4% compared to the LGRF scenario with the most GWP.

In terms of acidification potential, the values of LGRF, FRELP1 and FRELP2 methods are 7.09, 2.29 and 2.14 kg SO_2-equivalent, respectively. When we examine all life cycles in terms of AP, the total acidification potentials of the panels in which the FRELP1, FRELP2 and LGRF scenarios are applied are 86.91, 86.76 and 91.71 kg SO_2, respectively. FRELP2 has been shown to perform best, albeit by a very small margin. Looking at the other stages of the life cycle, apart from recycling, it is seen that the highest AP values are the cell processing phase with 46.8 kg SO_2-equivalent. Sulfur dioxide contributes the most to acidification and this is due to fossil fuel-derived electrical energy, which is used extensively in cell processing and some other stages. Since solar panels are mostly processed with the electricity source produced in coal-fired power plants, intense sulfur dioxide and nitrogen oxides are emitted in these phases. Using renewable energy sourced electricity in the production and assembly stages of photovoltaic panels will greatly reduce the environmental toxic effects in their life cycle.

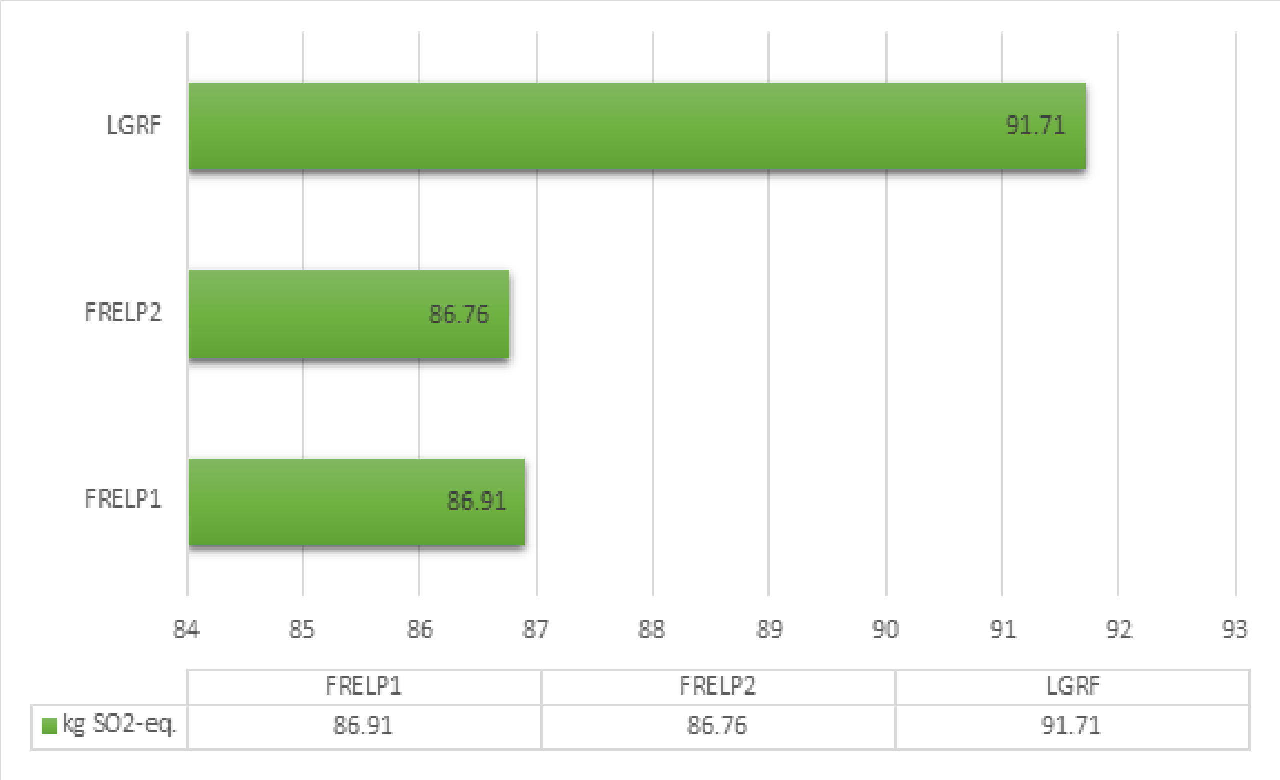

Figure 5.2. Comparison of three different recycling scenarios in terms of AP over the entire life cycle of a multi-Si PV panel.

The stages with the highest values in terms of eutrophication potential are metallurgical silicon melting, solar grade multi-Si purification silicon and module assembly. When we compare the recycling scenarios for eutrophication potential, FRELP1, FRELP2 and LGRF have 0.115, 0.505, 0.872 kg PO_4-equivalent, respectively. When the POCP environmental impact category is examined, module assembly is the process with the highest value with 8.12 kg Ethene-equivalent. In recycling processes, on the other hand, FRELP2 was the scenario that gave the best result with a value of 2.65 kg Ethene-equivalent. Human Toxic Potential (HTP) values are 4.62, 3.92 and 5.3 kg DCB eq. for FRELP1, FRELP2 and LGRF recycling processes, respectively. High electricity consumption, mostly from coal-fired power plants in the multi-Si production stages, contributed the most to environmental impacts and pollution dominant categories, such as AP, EP, GWP, HTP and POCP (Fu et. al., 2015).

Domestic panel production in Turkey started in a quite short time and on a small scale. The parts of the solar panels in the country are mostly purchased from countries such as China and Malaysia, and the module assembly is done in Turkey. Since the electricity production of the aforementioned countries is mostly provided by coal-fired power plants, the environmental impacts arising from the production stages of solar panels are higher. According to the 2022 Presidential Annual Program data, Turkey met 16.6% of its electricity production from renewable sources in 2020. When Turkey, which has a higher use of renewable resources in electricity production, produces its own domestic photovoltaic panels, the harmful environmental impacts arising from the life cycle of multi-Si solar modules will be reduced much less. The environmental impact of transportation was slightly higher in some categories such as GWP and POCP. The reason for this is that the panel parts are imported from distant countries such as China and Malaysia by shipping and then transported to the installation locations of the panels within the country. The use of domestically produced panels will also minimize these harmful environmental effects caused by the transportation phases.

The prominent stages in the Ozone Layer Depletion Potential impact category are module assembly and solar grade multi-Si purification, with values of 4.56E-04 and 3.29E-04 kg R11-equivalent. The ozone layer depletion potential is dominated by Halon (1301) and carbon tetrachloride. Halon (1301) contributed to ODP during the panel assembly and production stages of solar grade multi-Si, where mostly the aluminum frame is made and electricity is consumed. Carbon tetrachloride contributes to ODP due to emissions from the solar grade multi-Si production (metallurgical silicon smelting and solar grade multi-Si purification) process. In the Freshwater Aquatic Ecotoxicity category, the hotspot is the cell processing stage with a value of 19.5 kg DCB-equivalent. The FRELP2 method, which is called Scenario 2, gave the least value with 3.69E-011 kg DCB-equivalent among the recycling scenarios.

The FRELP 2 scenario also gave the best results in the Marine Aquatic Ecotoxicity Potential and Terrestrial Ecotoxicity Potential categories, with values of 2.05E-10 kg DCB-equivalent and 3.49E-12 kg DCB-equivalent, respectively. According to the results, Scenario 2 (FRELP2) gave the lowest emission values in all other categories except for the EP impact category.

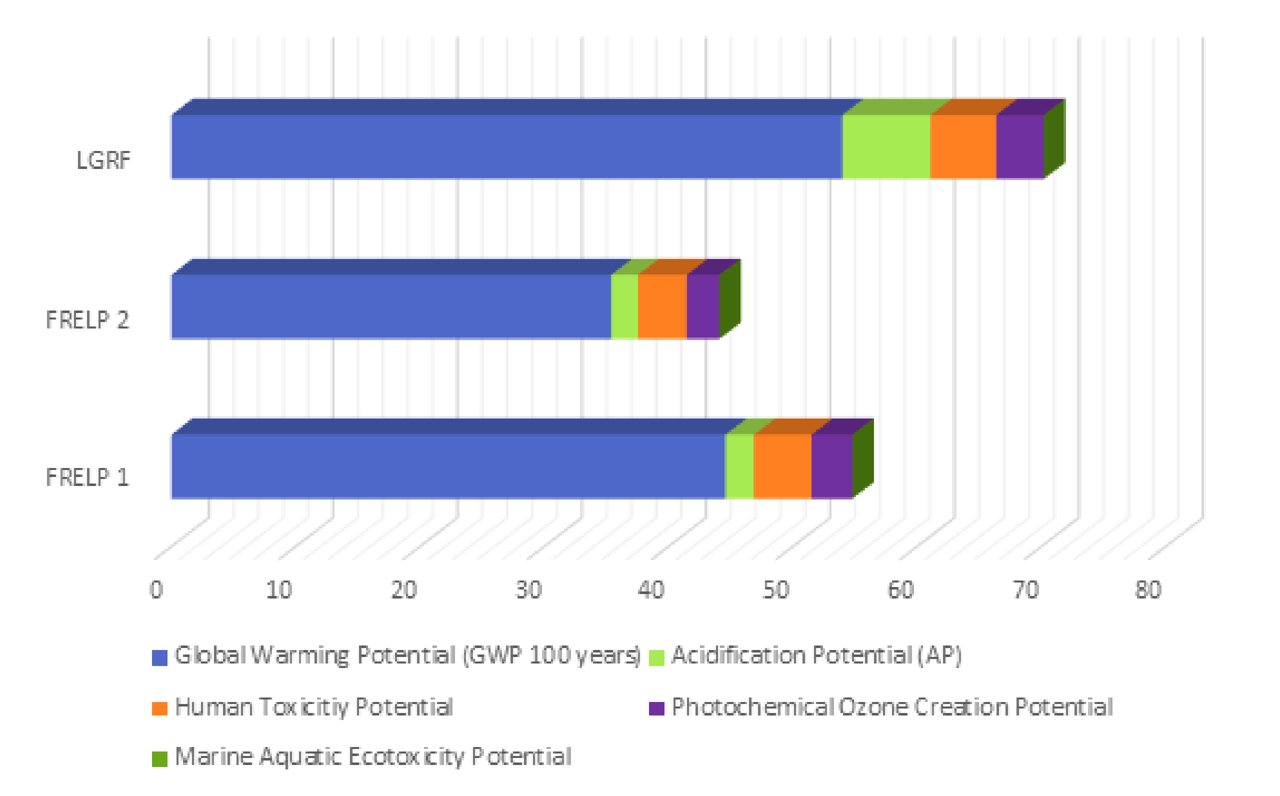

Figure 5.3. Comparison of three different recycling scenarios in terms of impact categories

Comparing the landfill scenario with the recycling scenarios, the LGRF and FRELP1 processes provide environmental impacts reduction of 7% and 26%, respectively (Daljit Singh et. al., 2021). When these reduction ratio comparisons are carefully analyzed, it can be predicted that the FRELP2 method, which gives the best results, reduces much more than the landfill scenario. As of 2018, the WEEE Directive has revealed that the recovery rate in electronic waste is 85%, and the reuse or recycling rate is 80%. Achieving these recycling and recovery rates will not only reduce toxic emissions to the environment and resource depletion, but also significantly reduce the amount of 78 million tons of photovoltaic panel waste expected to emerge worldwide by 2050.

This study was carried out based on the data of PV solar panels, whose import and part production processes were made in China and the module assembly was made in Turkey. Every step during the life cycle of multicrystalline PV solar panels has been examined by the GaBi Software and has revealed the hotspots that cause the most environmental impact. In addition, suggestions have been presented for Turkey, which has started solar panel production at quite new and minor scales and has never given any place to recycling processes, to achieve the new standards of the Green New Deal and to produce a cleaner and more sustainable solar energy.

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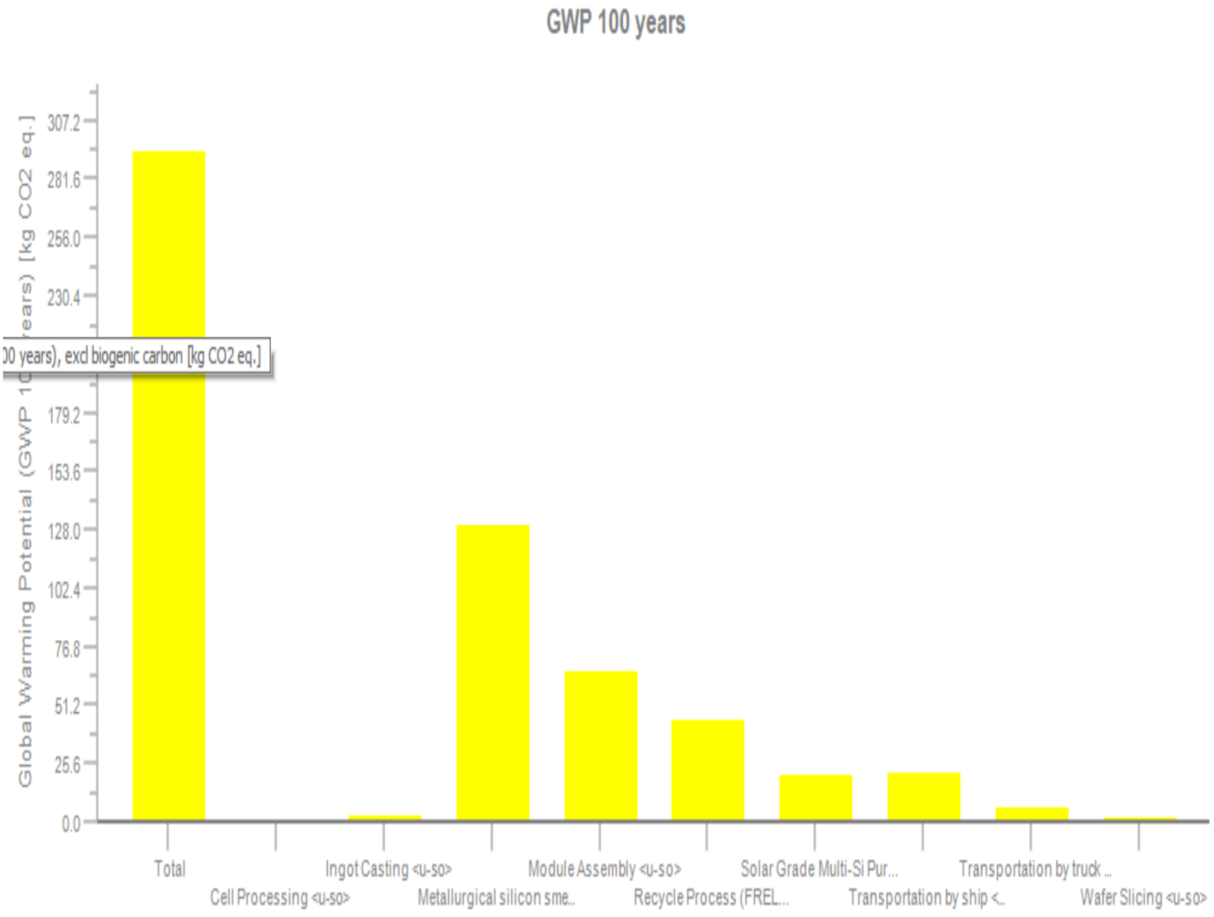
APPENDIX A: GABI SCREENSHOTS OF THE MULTI-SI PV PANEL

GaBi Diagram:GWP_multi-Si Solar Panel - Inputs



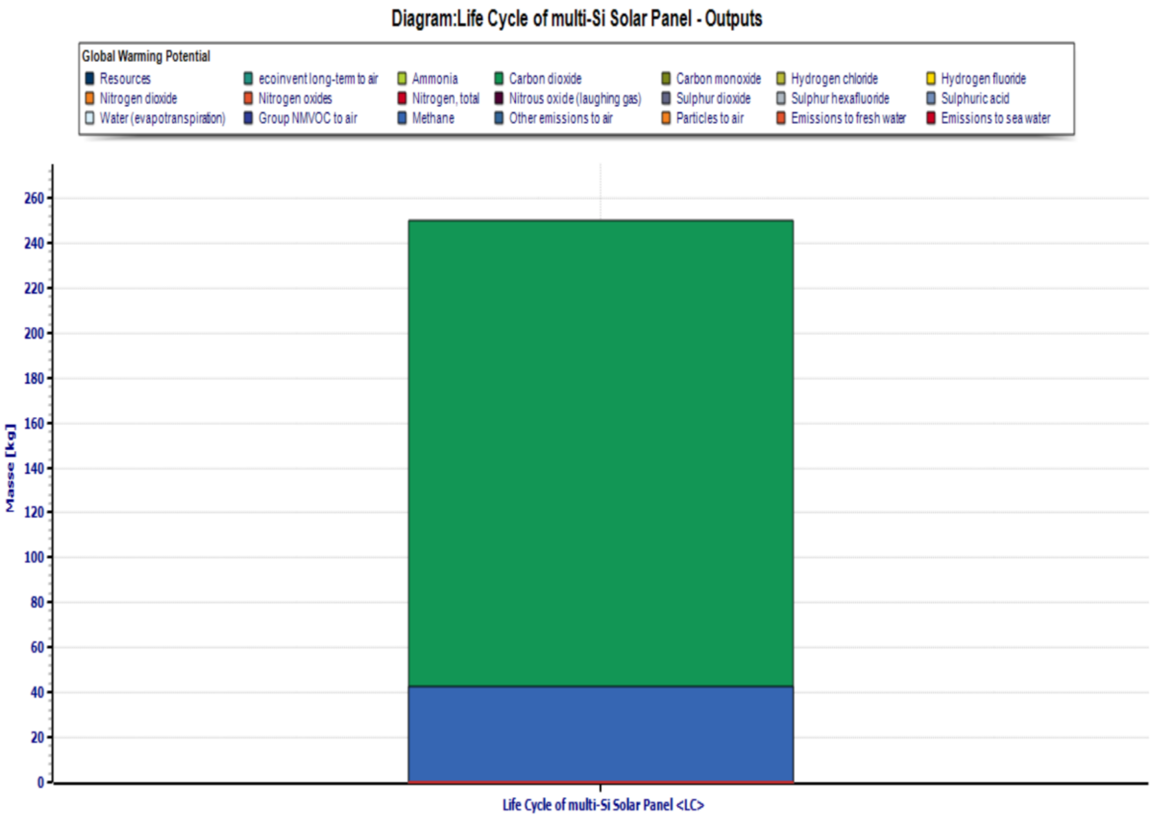


Diagram:Life Cycle of multi-Si Solar Panel - Outputs
Global Warming Potential
Resources
ecoinvent long-term to air
Ammonia
Carbon dioxide
Carbon monoxide
Hydrogen chloride
Hydrogen fluoride
Nitrogen dioxide
Nitrogen oxides
Nitrogen, total
Nitrous oxide (laughing gas)
Sulphur dioxide
Sulphur hexafluoride
Sulphuric acid
Water (evapotranspiration)
Group NMVOC to air
Methane
Other emissions to air
Particles to air
Emissions to fresh water
Emissions to sea water
Masse [kg]
0
20
40
60
80
100
120
140
160
180
200
220
240
260
Life Cycle of multi-Si Solar Panel <LC>

GaBi Diagram:Acidification potential LCA of multi-Si Solar Panel - Inputs

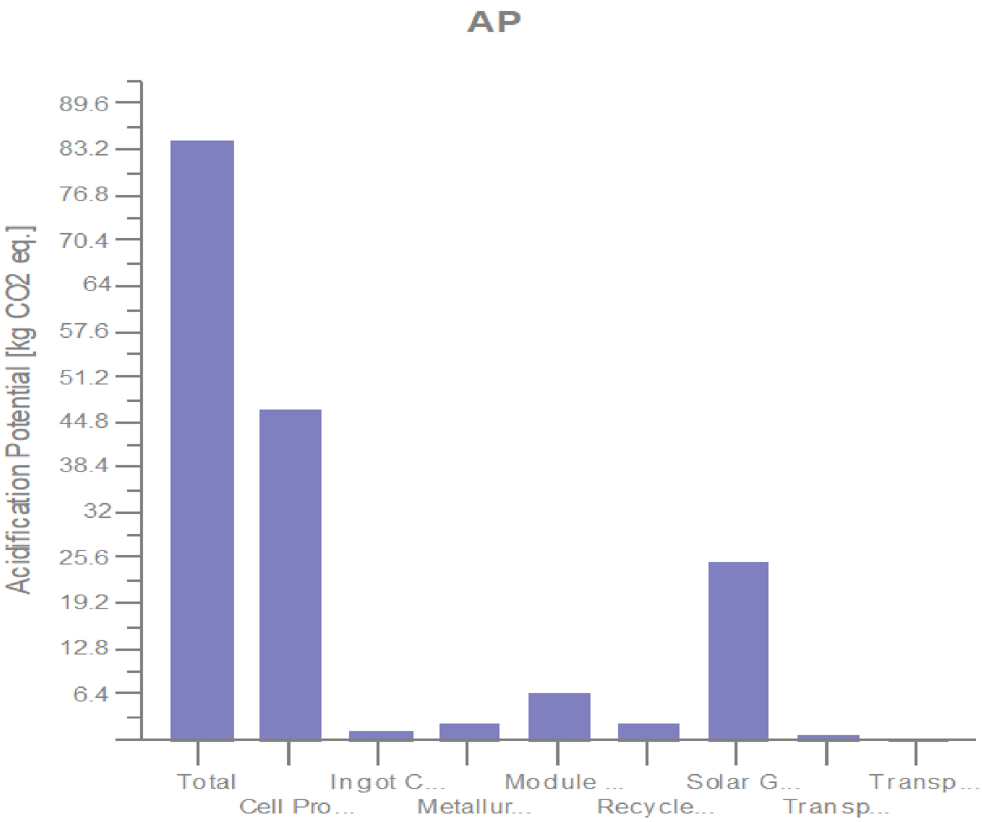
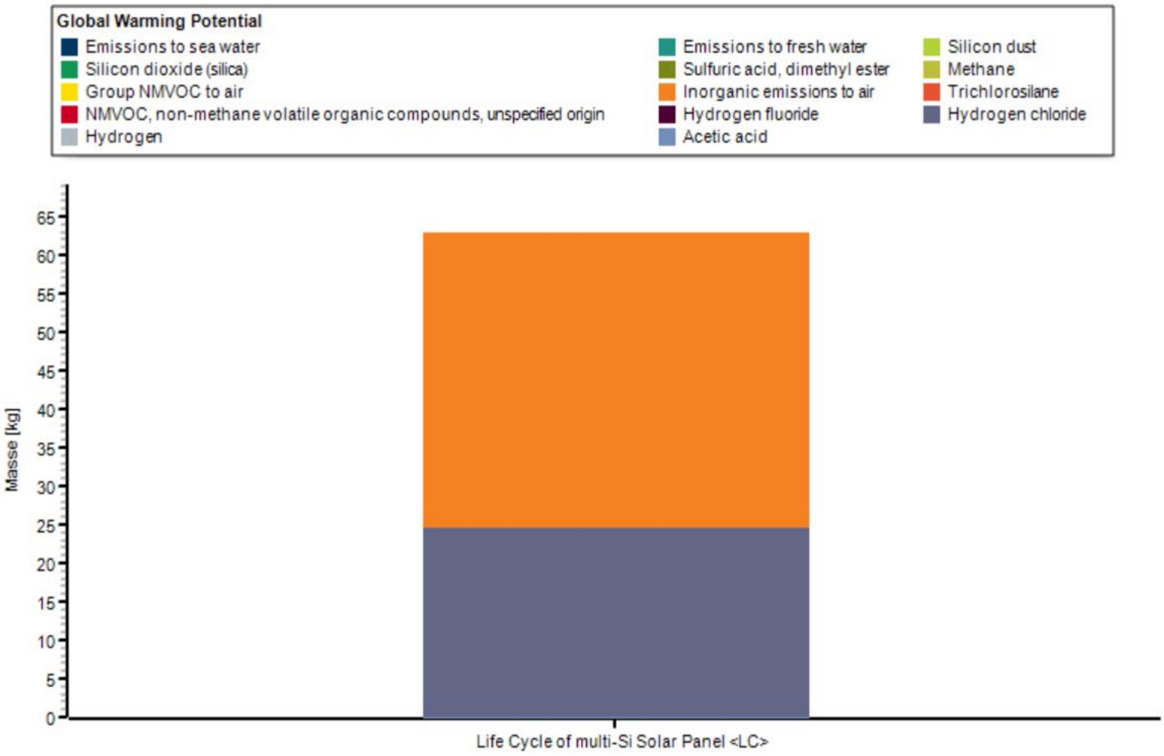
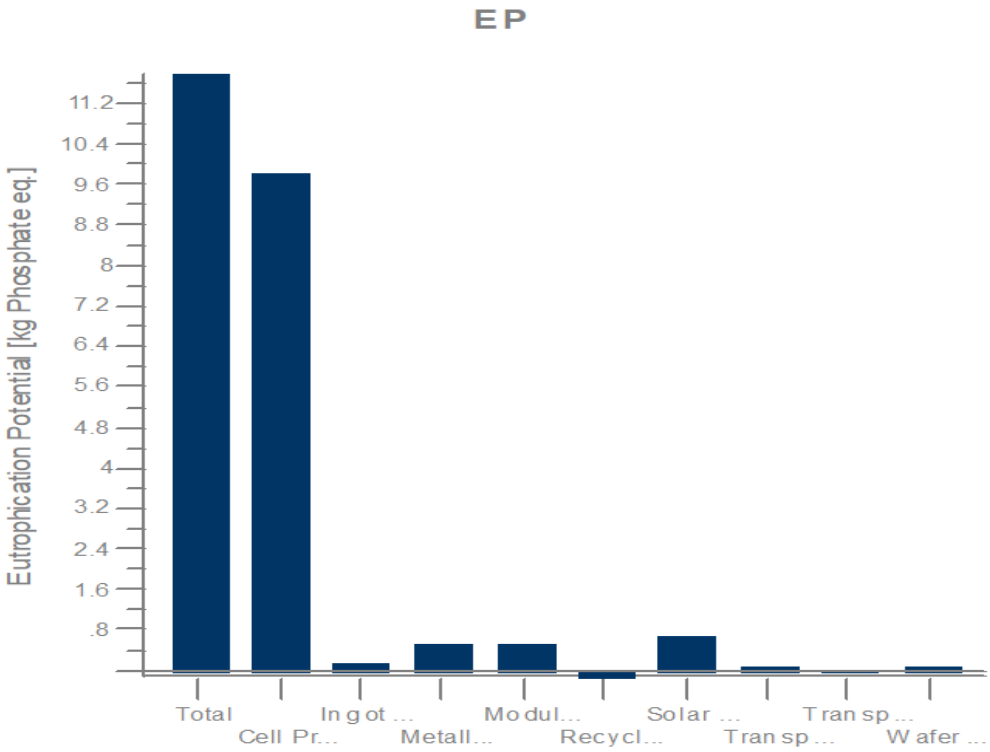
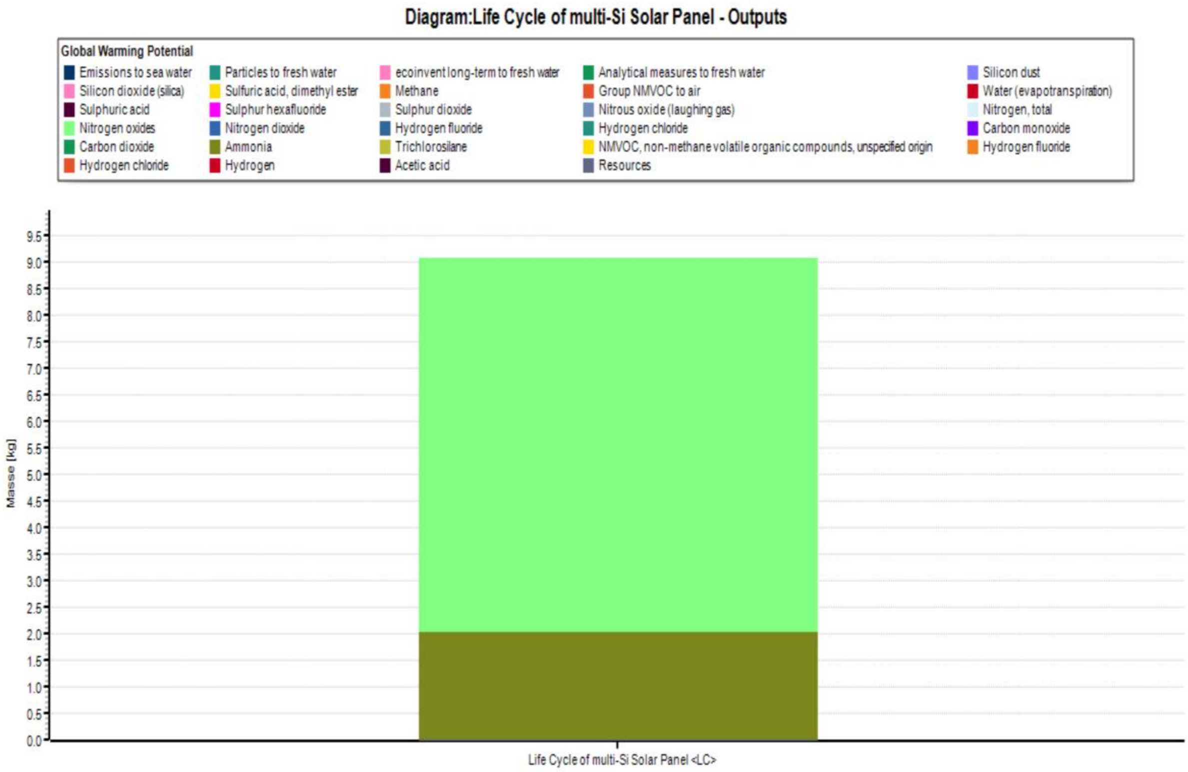


Diagram:Life Cycle of multi-Si Solar Panel - Outputs



GaBi Diagram:Eutrophication pot_LCA of multi-Si Solar Panel - Inputs





GaBi Diagram:Ozone layer dep_ of multi-Si Solar Panel - Inputs

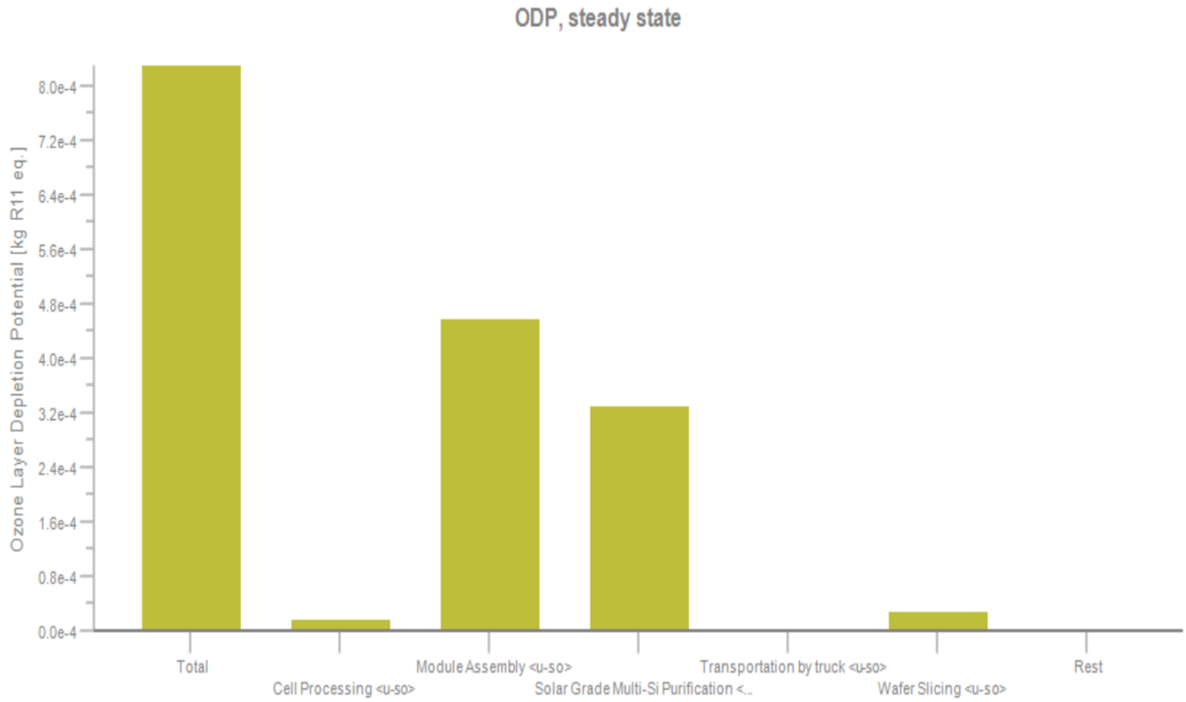
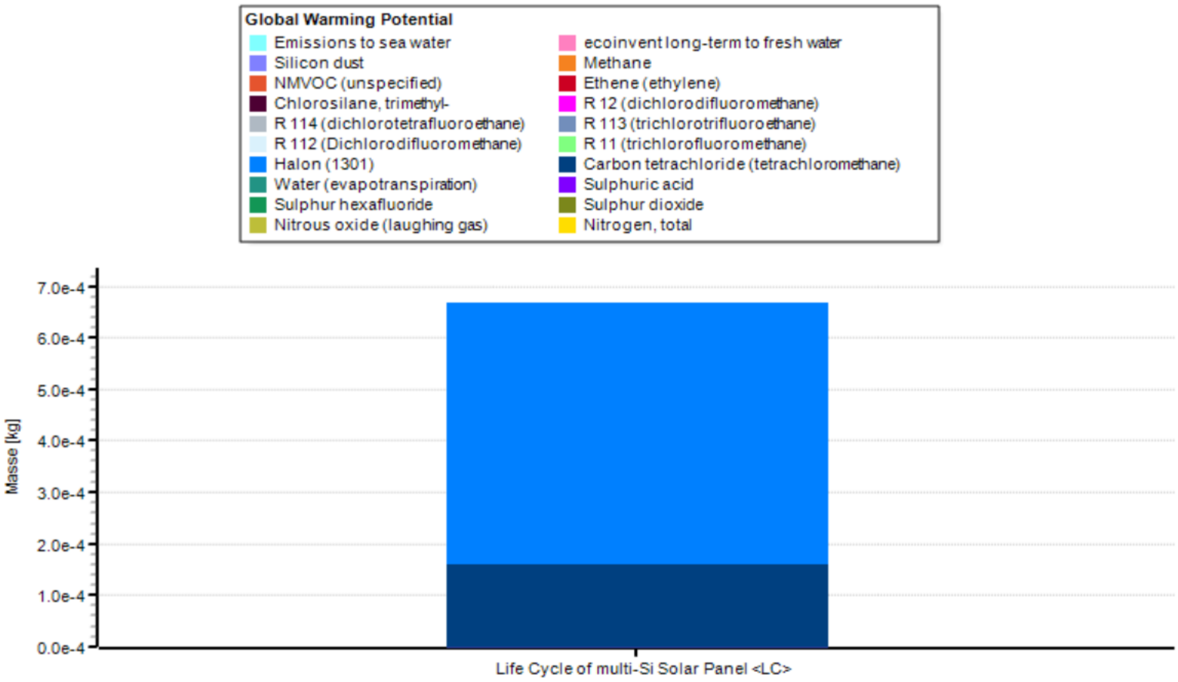


Diagram:Life Cycle of multi-Si Solar Panel - Outputs



GaBi diagram:Photochemical ozone_LCA of multi-Si Solar Panel - Inputs

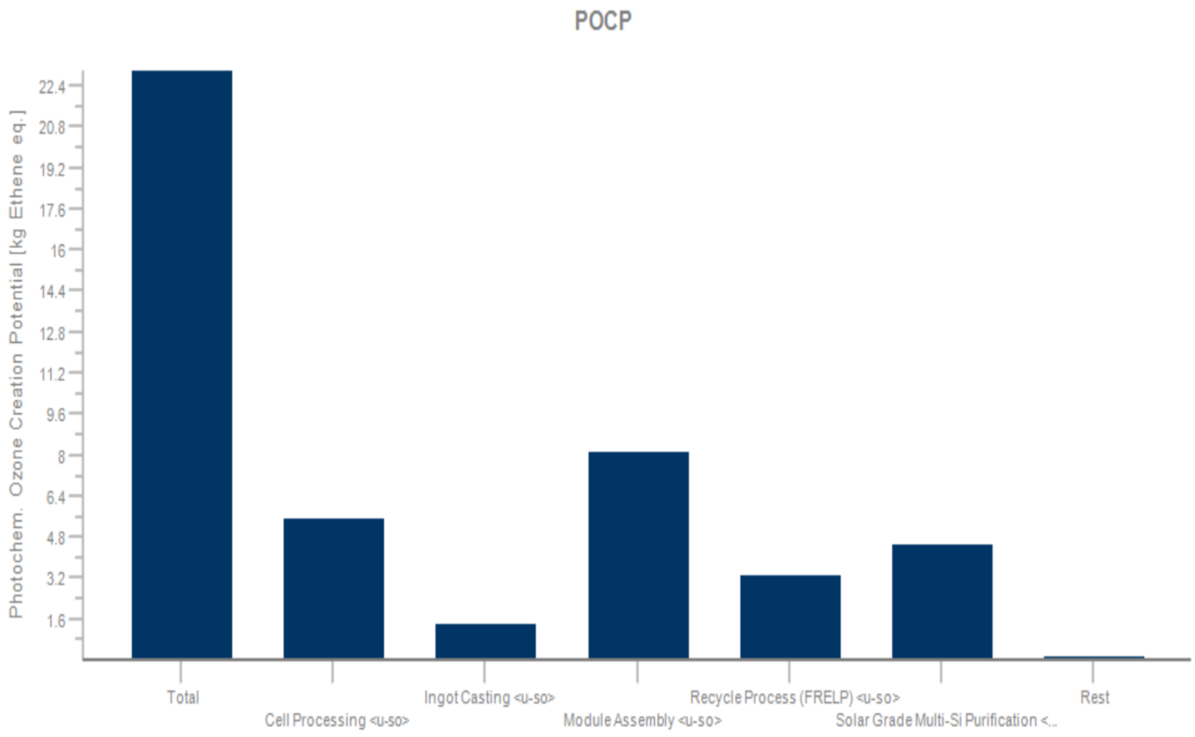
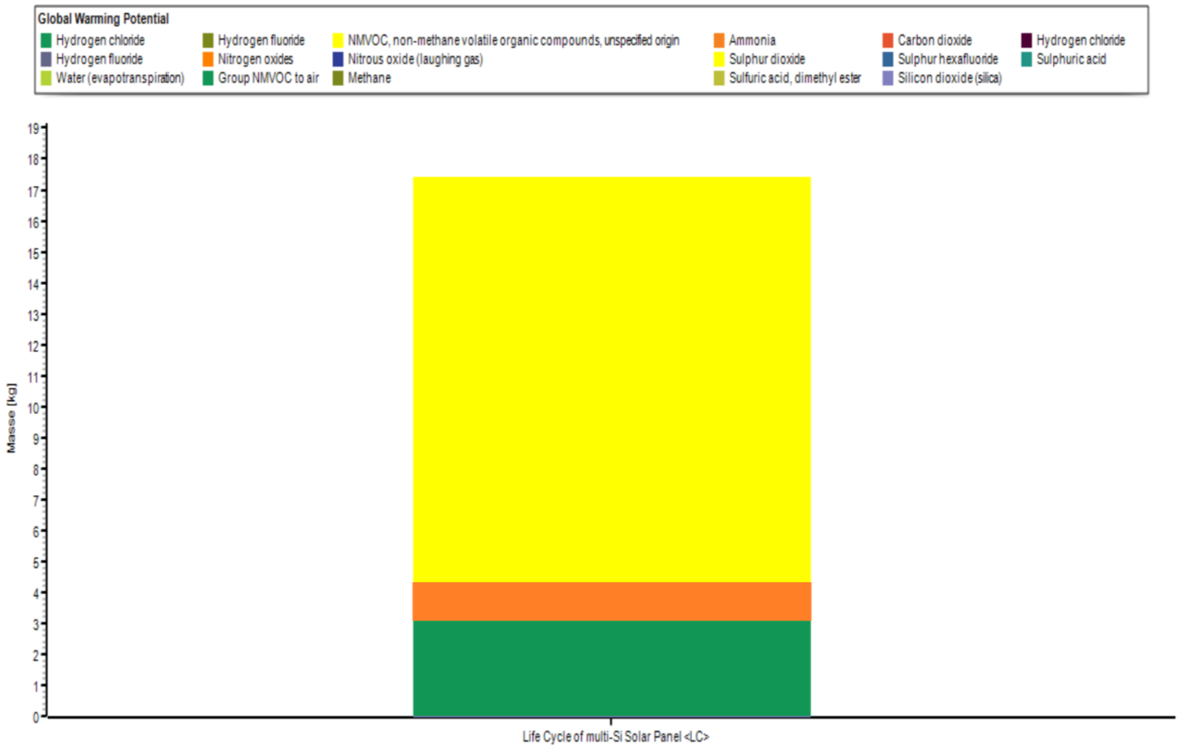
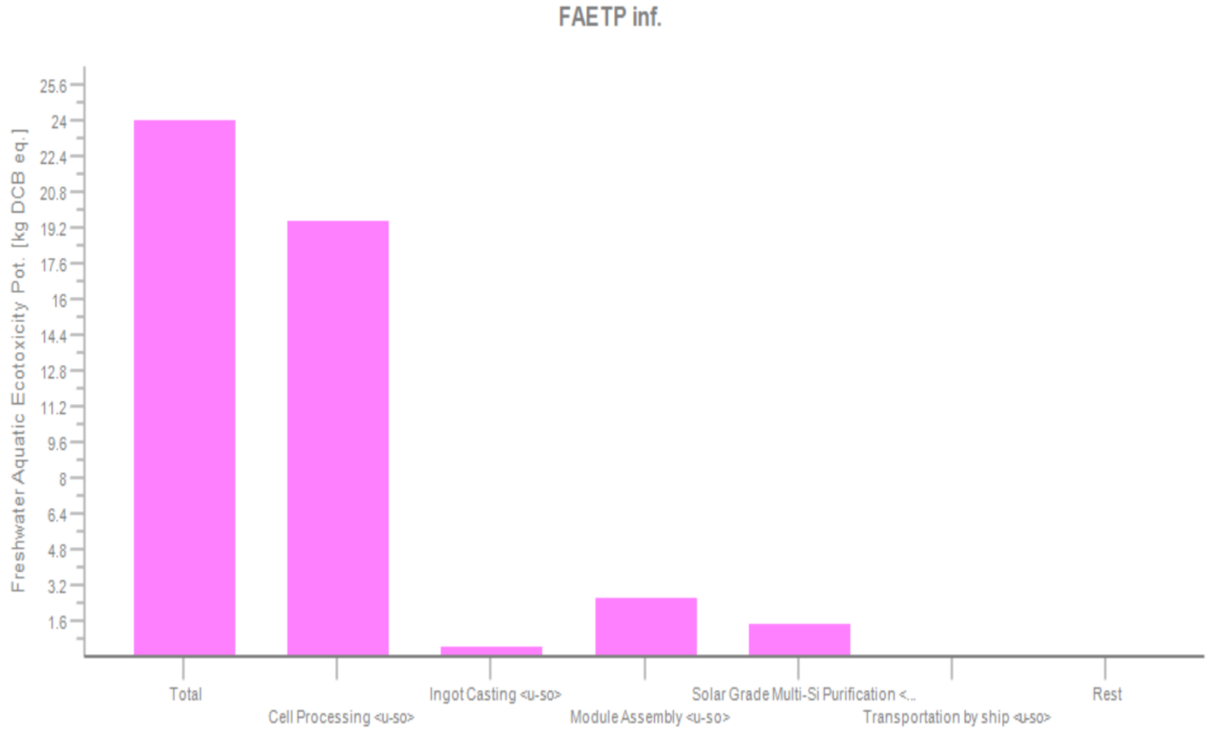
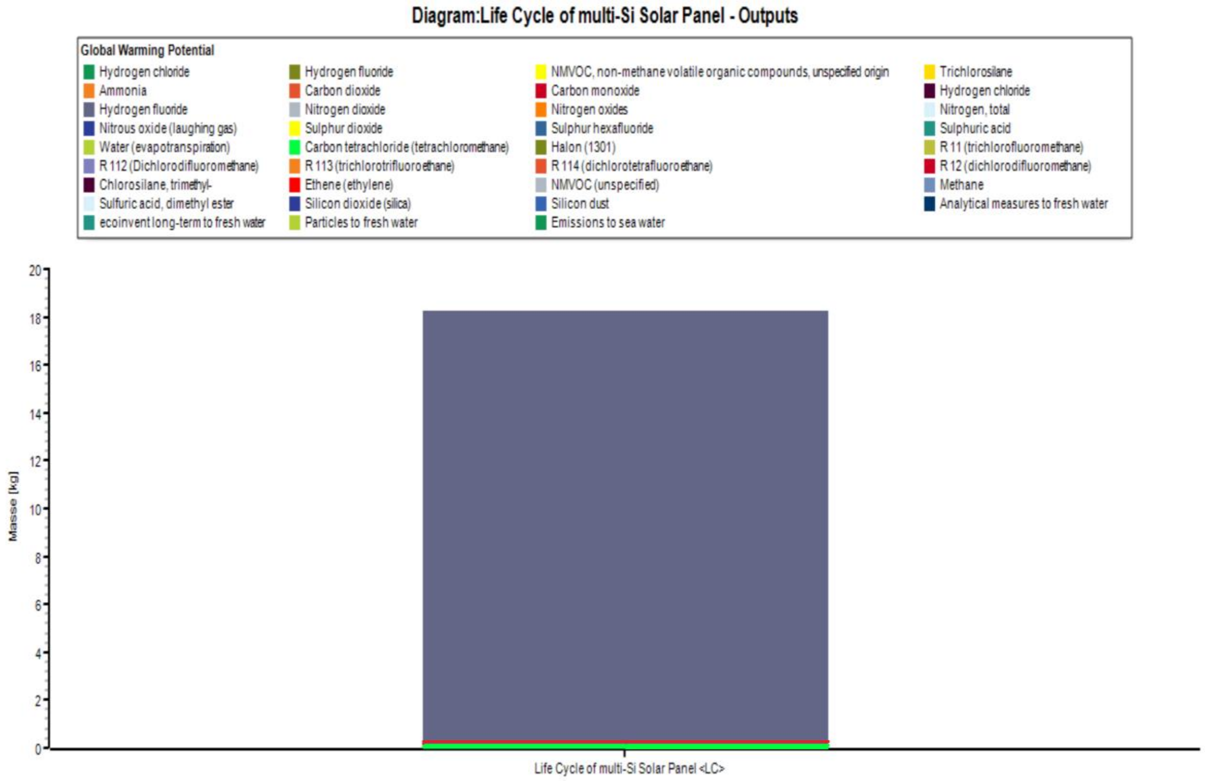


Diagram:Life Cycle of multi-Si Solar Panel - Outputs

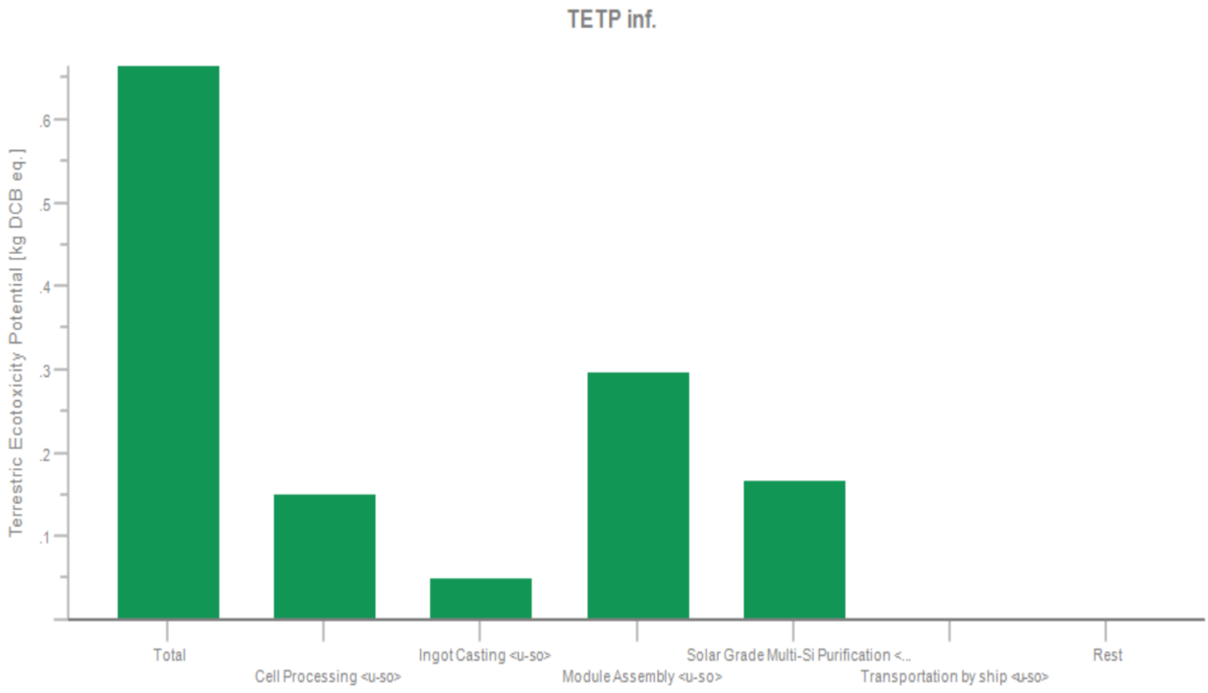


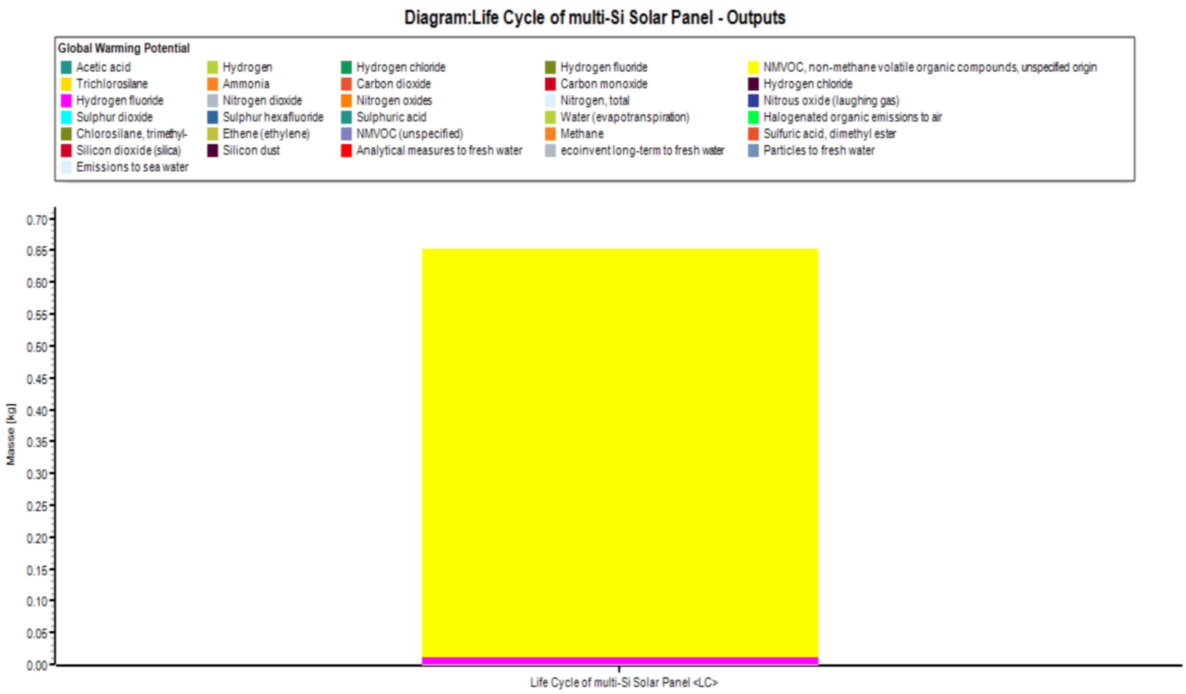
GaBi diagram:freshwater aquatic ecotox_LCA of multi-Si Solar Panel - Inputs



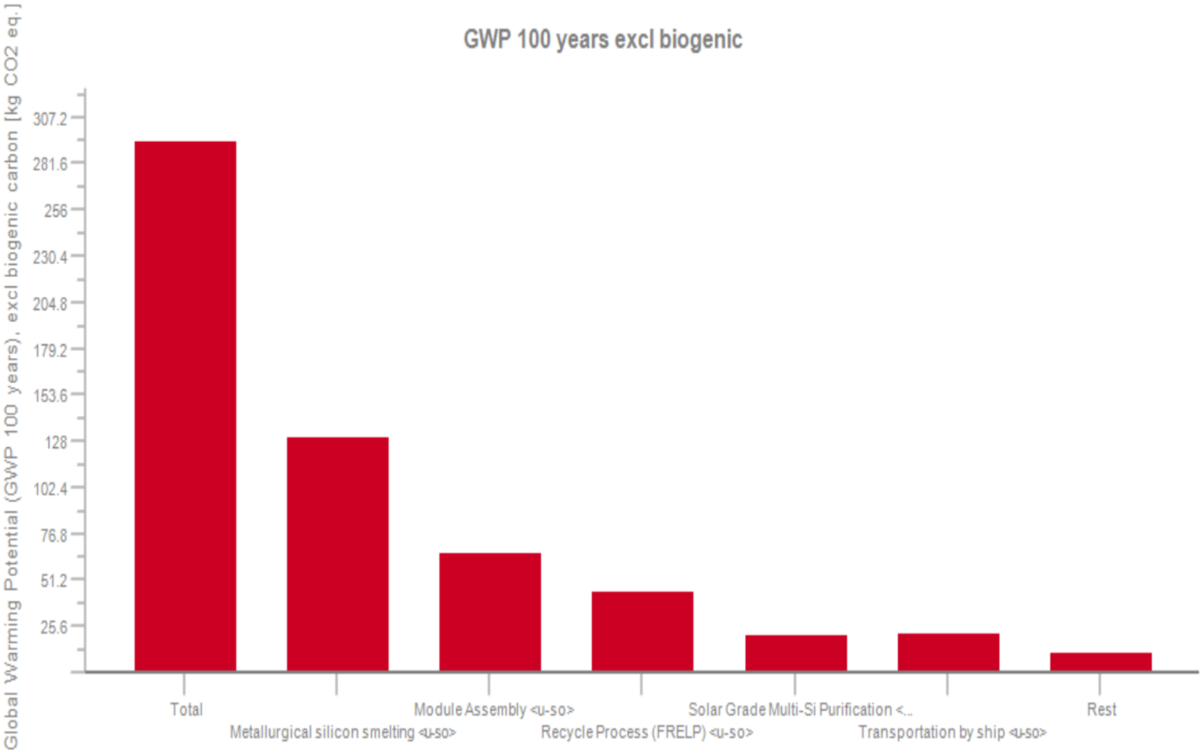


GaBi diagram:Terrestrial ecotox_LCA of multi-Si Solar Panel - Inputs



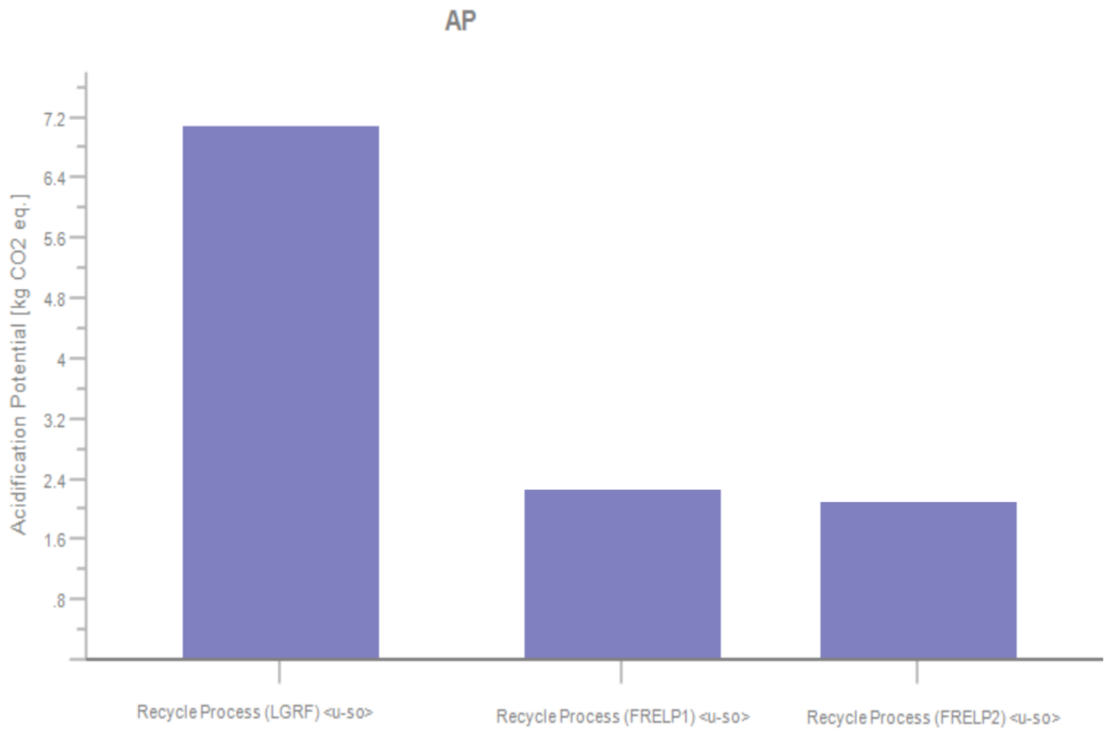


GaBi Diagram:GWP excl_multi-Si Solar Panel - Inputs

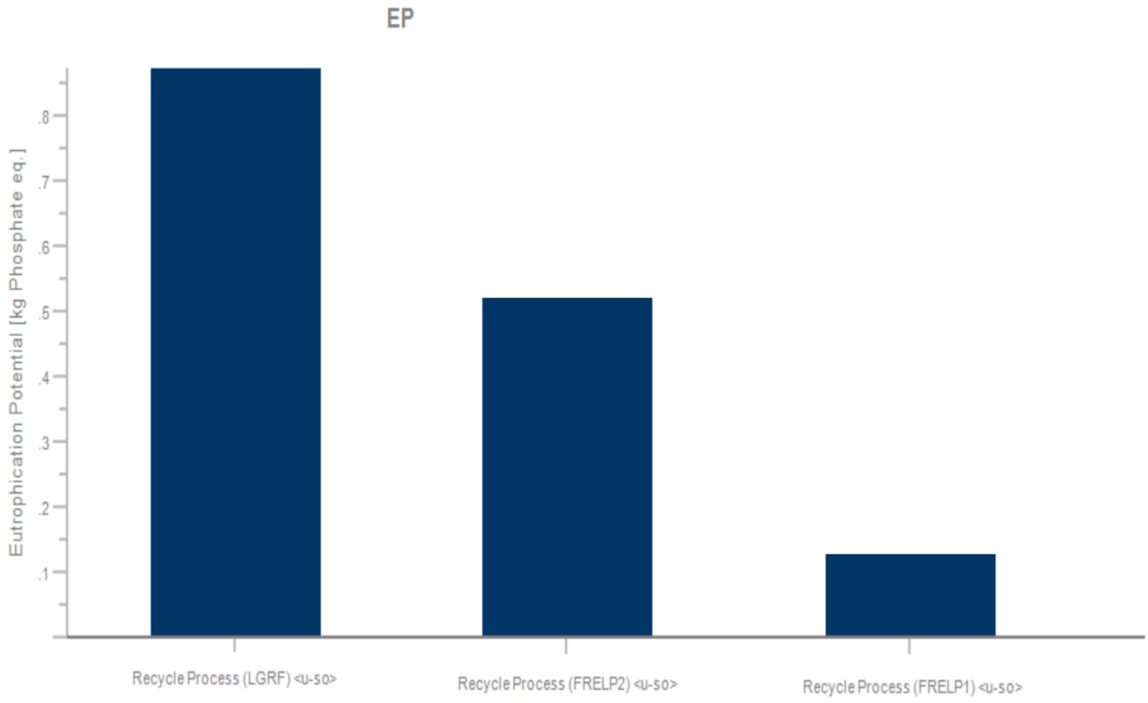


APPENDIX B: GABI SCREENSHOTS OF THE MULTI-SI PV PANEL'S RECYCLE SCENARIOS

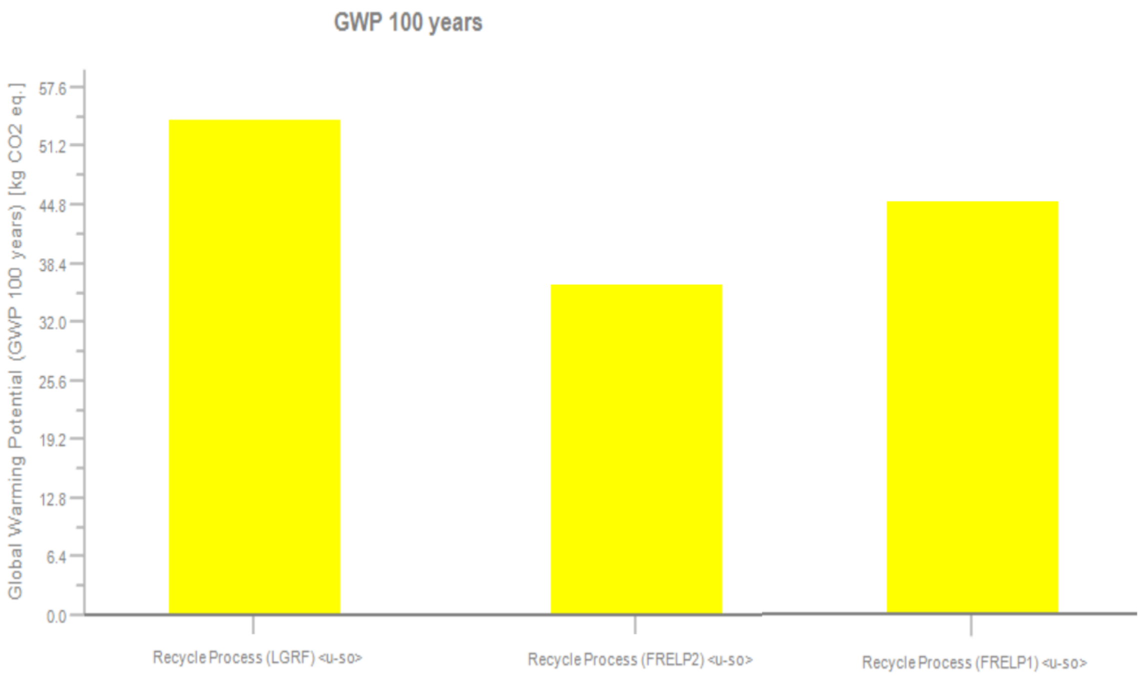
GaBi Diagram:Acidification pot_LCA of multi-Si Solar Panel Recycle - Inputs



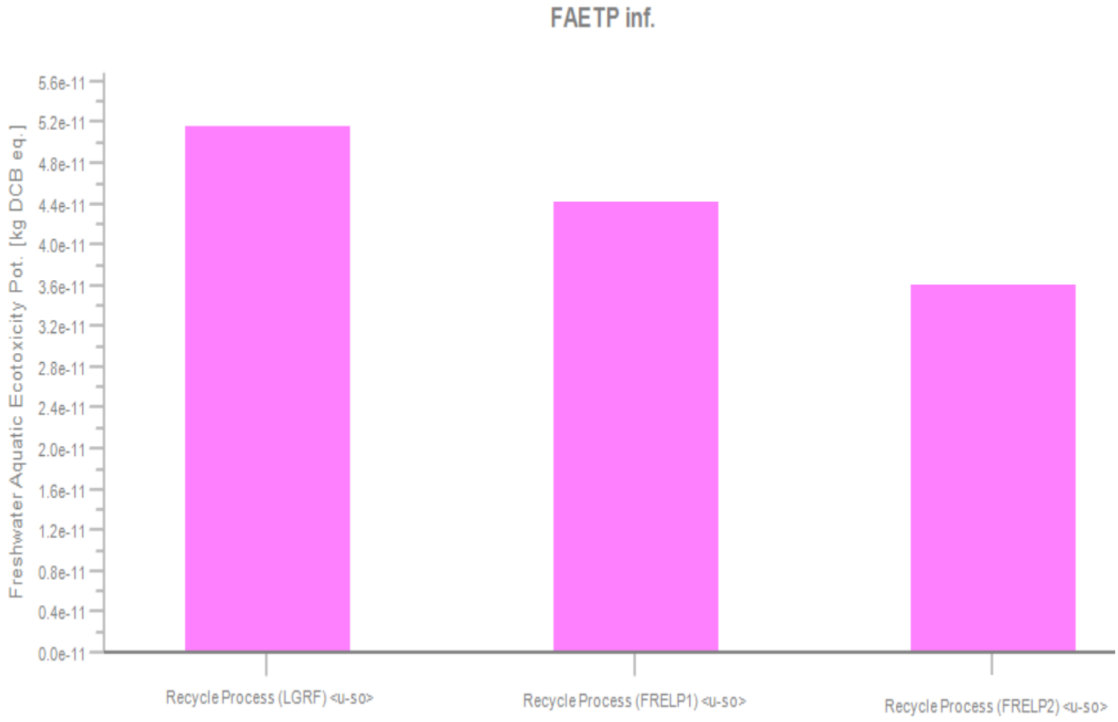
GaBi Diagram:Eutrophication pot_LCA of multi-Si Solar Panel Recycle - Inputs



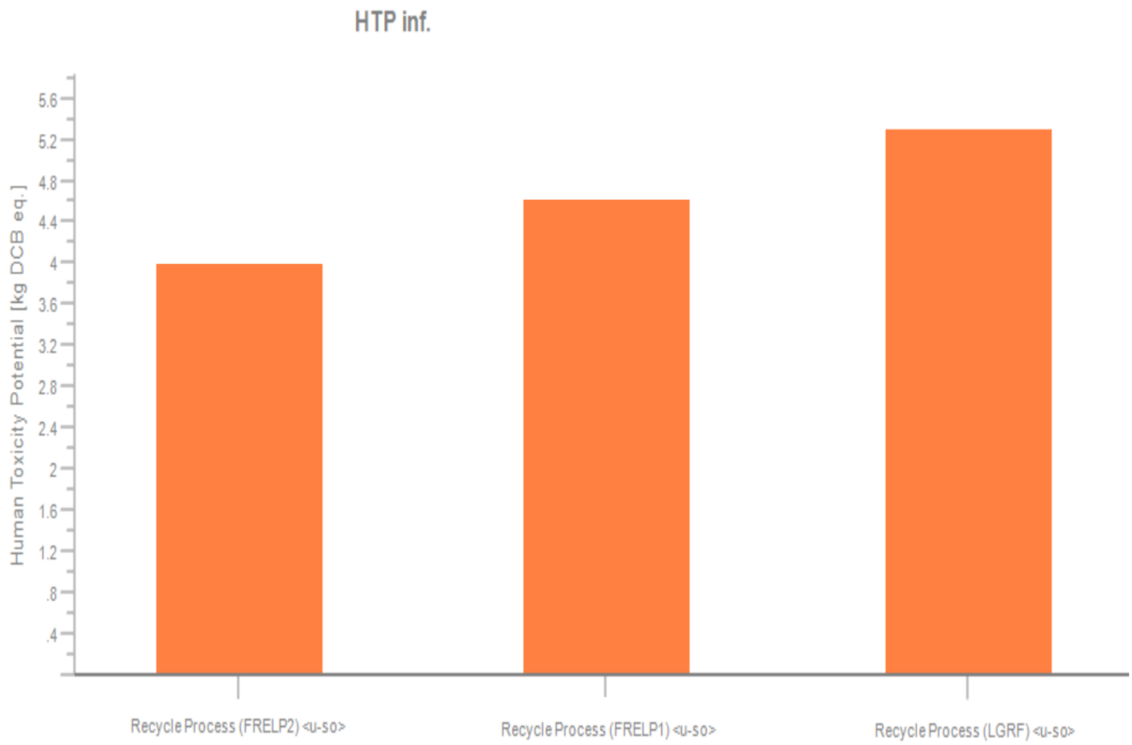
GaBi Diagram:GWP_LCA of multi-Si Solar Panel Recycle - Inputs



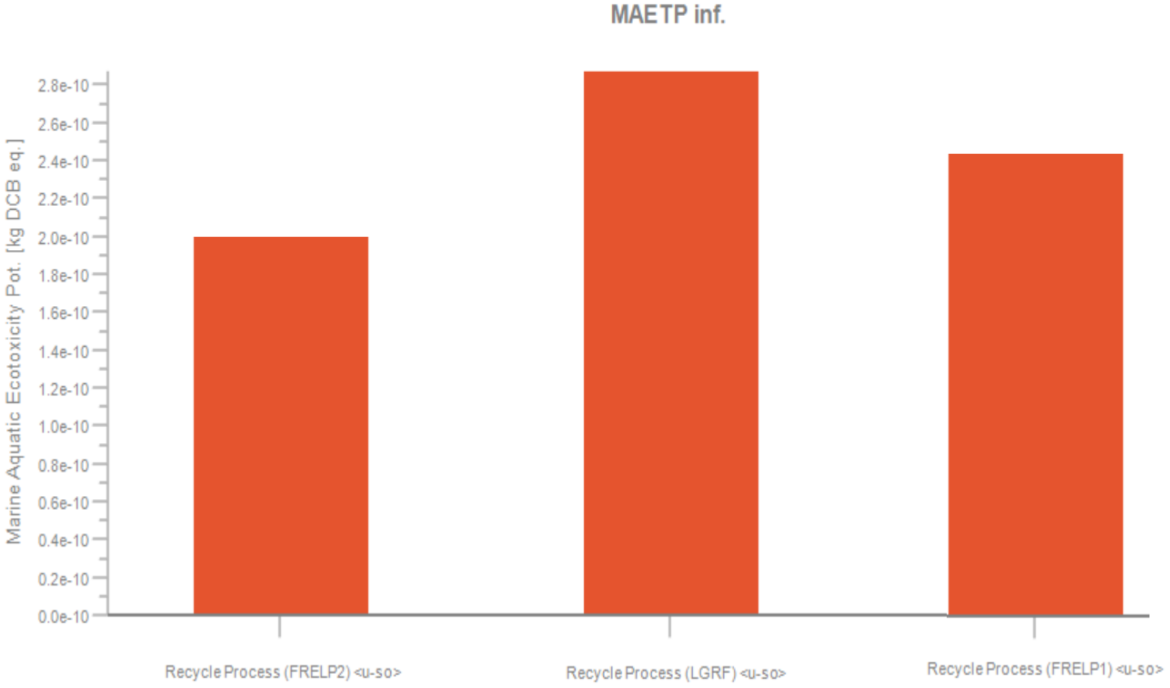
GaBi Diagram:FAETP_LCA of multi-Si Solar Panel Recycle - Inputs



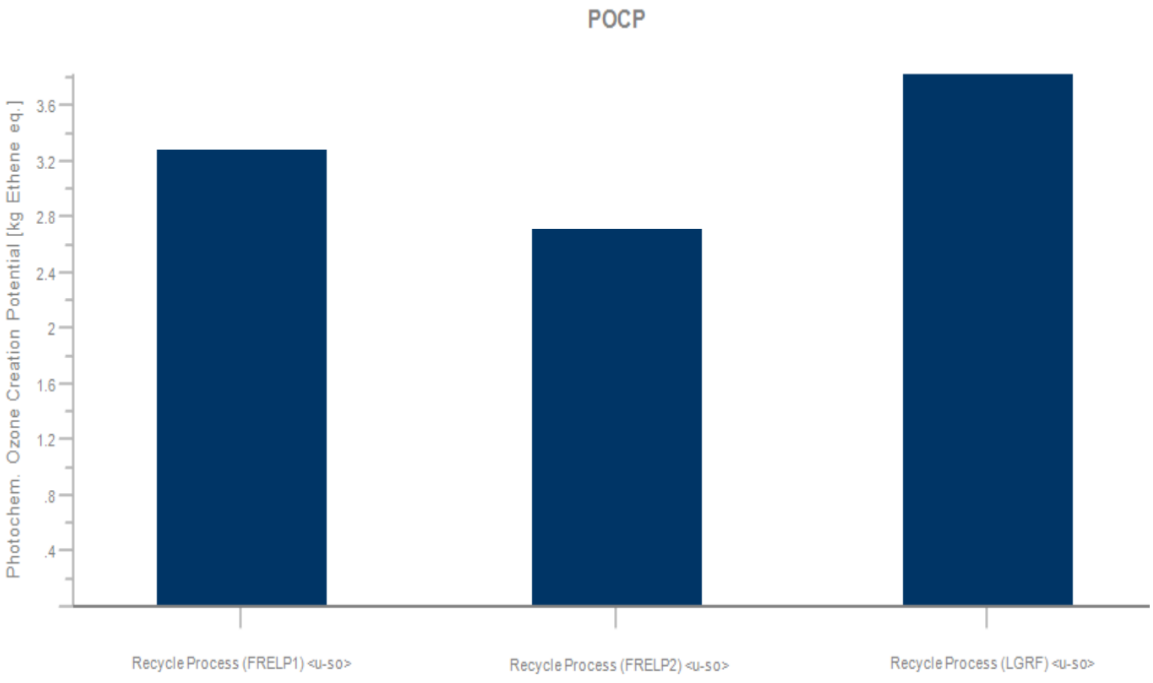
GaBi Diagram:human tox_LCA of multi-Si Solar Panel Recycle - Inputs



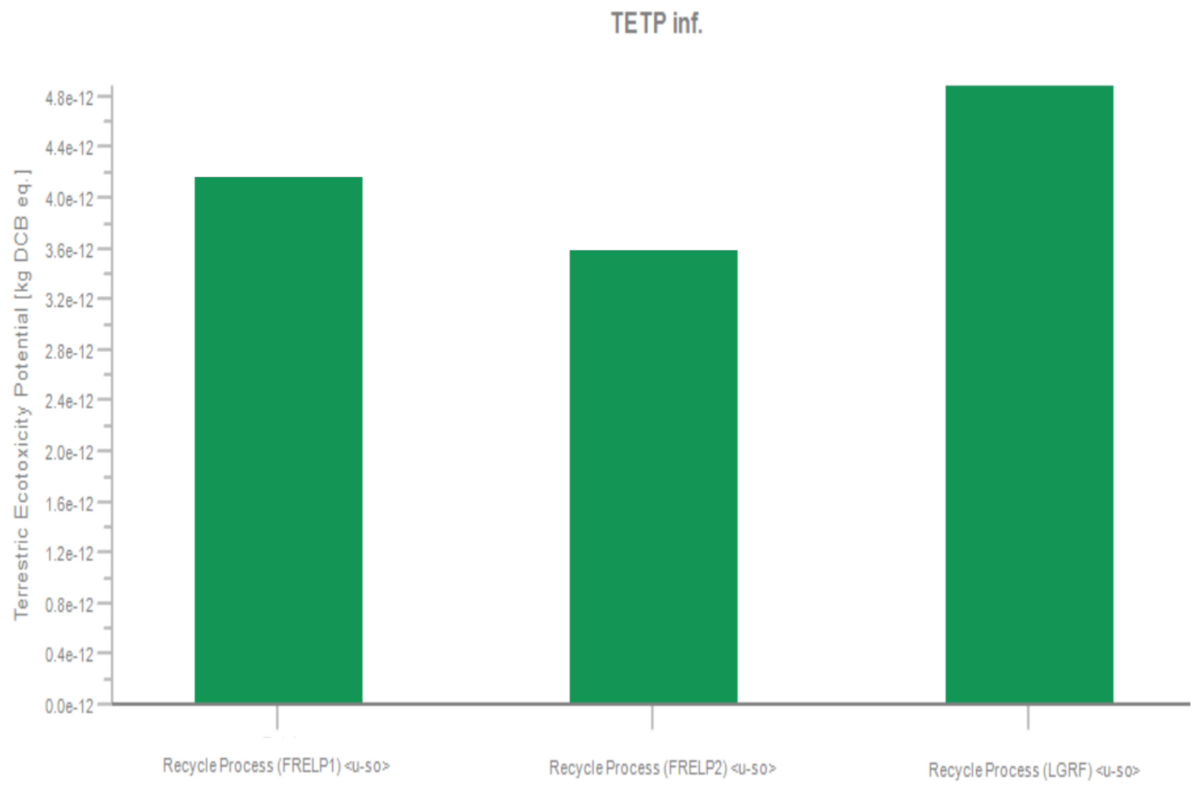
GaBi Diagram:Marine aquatic ecotox_LCA of multi-Si Solar Panel Recycle - Inputs



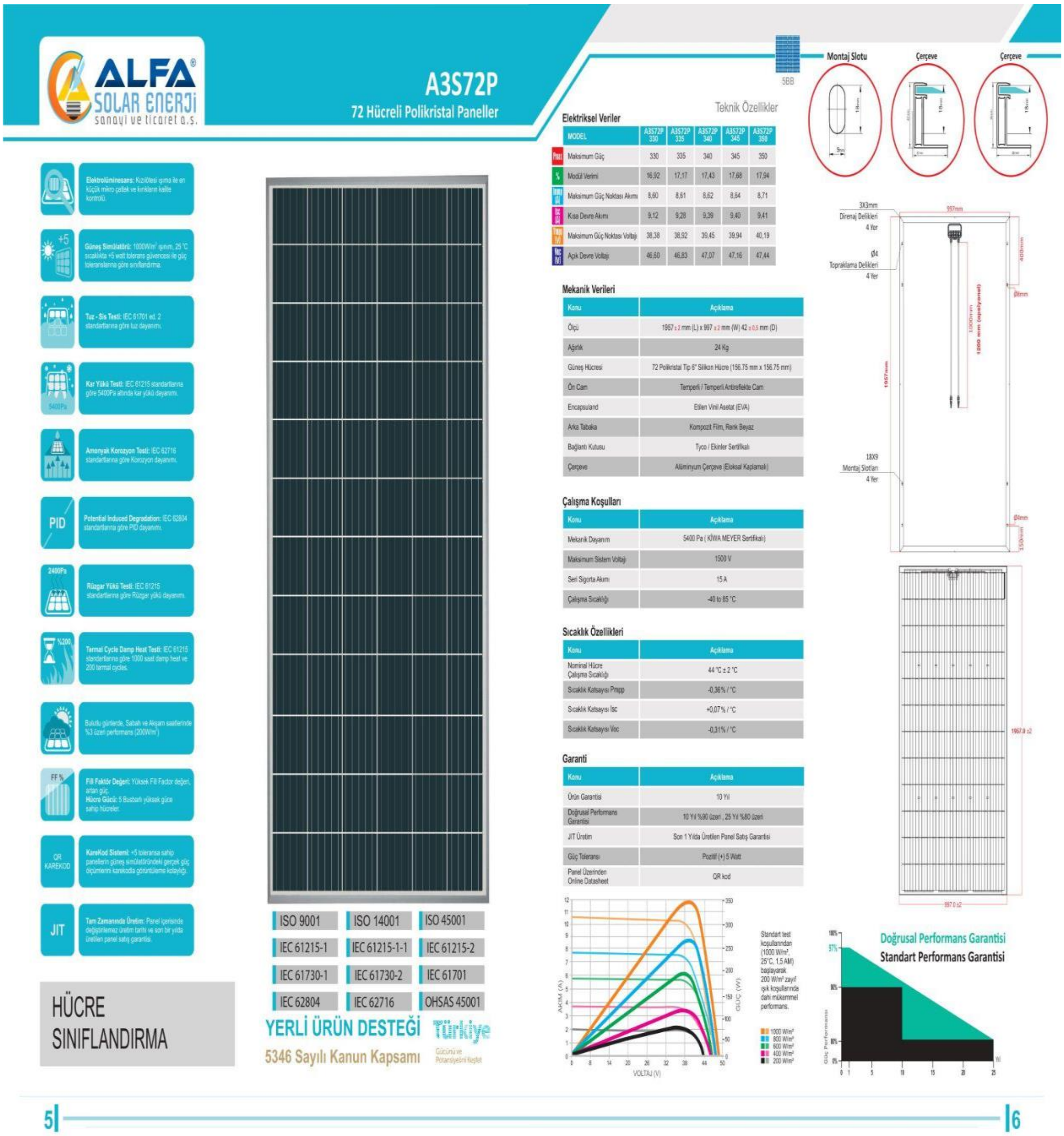
GaBi diagram:POCP_LCA of multi-Si Solar Panel Recycle- Inputs



GaBi diagram:Terrestrial ecotox_ of multi-Si Solar Panel Recycle - Inputs



APPENDIX C: FEATURES OF MULTI-SI SOLAR PANEL



Elektriksel Veriler

MODEL	A3S72P 330	A3S72P 335	A3S72P 340	A3S72P 345	A3S72P 350
Maksimum Güç	330	335	340	345	350
Modül Verimi	16,92	17,17	17,43	17,68	17,94
Maksimum Güç Noktası Akımı	8,60	8,61	8,62	8,64	8,71
Kısa Devre Akımı	9,12	9,28	9,39	9,40	9,41
Maksimum Güç Noktası Voltajı	38,38	38,92	39,45	39,94	40,19
Açık Devre Voltajı	46,60	46,83	47,07	47,16	47,44

Mekanik Verileri

Konu	Açıklama
Ölçü	1957 ±2 mm (L) x 997 ±2 mm (W) 42 ±0,5 mm (D)
Ağırlık	24 Kg
Güneş Hücresi	72 Polikristal Tip 6" Silikon Hücre (156.75 mm x 156.75 mm)
Ön Cam	Temperli / Temperli Antirefleksiyonlu Cam
Encapsuland	Etilen Vinil Asetat (EVA)
Arka Tabaka	Kompozit Film, Renk Beyaz
Bağlantı Kutusu	Tyco / Ekinler Sertifikalı
Çerçeve	Alüminyum Çerçeve (Eloksal Kaplamalı)

Çalışma Koşulları

Konu	Açıklama
Mekanik Dayanım	5400 Pa (KİWA MEYER Sertifikalı)
Maksimum Sistem Voltajı	1500 V
Seri Sigorta Akımı	15 A
Çalışma Sıcaklığı	-40 to 85 °C

Sıcaklık Özellikleri

Konu	Açıklama
Nominal Hücre Çalışma Sıcaklığı	44 °C ± 2 °C
Sıcaklık Katsayısı Pmpp	-0,36 % / °C
Sıcaklık Katsayısı Isc	+0,07 % / °C
Sıcaklık Katsayısı Voc	-0,31 % / °C

Garanti

Konu	Açıklama
Ürün Garantisi	10 Yıl
Doğrusal Performans Garantisi	10 Yıl %90 üzeri , 25 Yıl %80 üzeri
JIT Üretim	Son 1 Yılda Üretilen Panel Satış Garantisi
Güç Toleransı	Pozitif (+) 5 Watt
Panel Üzerinden Online Datasheet	QR kod