Trade-offs of End-of-Life Strategies for Cadmium Telluride Solar Cells

Master thesis on the environmental impacts of thin-film solar cells made from cadmium telluride.

by

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Abstract

Solar generated energy is an alternative to fossil fuel generated energy. However, solar modules have a lifetime and as sales are increasing, waste of solar modules is increasing as well. Cadmium telluride solar cells consist of a material that has a high intrinsic toxicity, cadmium, and a material that is scarce, tellurium. Effective recycling of these materials is therefore needed to lower their impact on the environment. In literature, studies were found that looked at the impacts of the life cycle of CdTe solar cells of which many excluded the recycling stage. As multiple pathways exist for recycling of CdTe solar modules, it is key is to see how they compare to each other. There are a few studies that did include or assessed only a recycling stage. These assessments are all done with distinctive methods, assumptions, and boundaries, making it very hard to compare these results. In literature, a lack in competent comparison between recycling pathways, including qualitative and quantitative aspect, was identified. The goal of this research was to find qualitative and quantitative trade-offs of potential End-of-Life strategies that are able to lower environmental impacts of CdTe solar modules. By conducting harmonization on existing environmental impact data found in literature and assessing environmental impacts in a Life Cycle Assessment, the quantitative trade-offs were found. Qualitative trade-offs were found in an assessment that include maturity of technology, costs of the technology, and value of recovered material. General quantitative trade-offs that were found were that recycling lowered the environmental impacts, but energy needed for recycling had a large contribution to the remaining impacts. Additionally, the use of chemical recycle processes lowered impacts, however the chemicals that were used gave a large contribution to the impacts remaining due to extraction of chemicals and treatment of wastewater. General qualitative trade-offs could be found in the fact that high recovery values often have high costs related to them. Especially the use of chemicals does retrieve a lot of material, but I expensive. In summary, trade-offs can be found in energy and chemicals use and in costs versus value retrieved. The results of this study add knowledge on the trade-offs of each recycle strategy. This can be weighed against each other and be helpful in deciding which recycle pathways to follow when the incoming CdTe solar module waste needs to be disposed of.

Acknowledgements

This thesis was written over the course of six months. In these months, I have learned valuable lessons on applying academic skills and handling setbacks. This thesis will put an end to my Masters' degree of Industrial Ecology, in which I have learned many new technologies and methods to help tackle the climate problem our world is facing. I have certainly enjoyed the past 2.5 years.

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Introduction

Problem Statement

Solar generated energy is one of the most applied and promising approaches to tackle the extensive emission of greenhouse gases by fossil fuel generated energy (Fraunhofer ISE 2022). The generation of solar energy itself requires no emission of greenhouse gases. However, the processes before and after a solar module ends up on the roof do have an impact. Materials and energy are needed to manufacture a complete solar module. Furthermore, energy and material are needed to dispose or recycle a solar module. Next to that there is transportation, machinery, and labour, needed to support the full life cycle of a solar module. Everything has a certain impact on the environment transcending just the emission of greenhouse gases. Impacts can differ greatly when different types of semiconductors are used (Mahmoudi et al. 2019). A semiconductor is the photoactive layer of a solar module in which the electricity is generated under influence of light. Semiconductors can be assigned to three different generations (Smets et al. 2016; Bagher et al. 2015).

First-generation solar cells make use of silicon as a semiconductor. These are the solar cells that currently have the largest market share and have been installed the most. In these solar cells a distinction is made between polycrystalline and monocrystalline cells. Polycrystalline semiconductors consist of multiple silicon crystals. Monocrystalline semiconductors consist of a single silicon crystal (Smets et al. 2016; Bagher et al. 2015; Fraunhofer ISE 2022). Commercially available first-generation solar cells increased in efficiency from 15% ten years ago to over 20% today. In 2021, over 180 GWp of first generation solar cells have been produced (Fraunhofer ISE 2022).

Second-generation solar cells are thin-film solar cells that have amorphous silicon, CIGS, or cadmium telluride (CdTe) as semiconductor material. Thin-film solar cells have the characteristic that the layers off which the solar cells are made are much thinner than the layers used in first generation solar cells. This makes them cheaper to produce and more appliable to use in Building Integrated Photovoltaics. Additionally, it is possible to create flexible solar cells from this material. Efficiencies are a bit lower compared to first generation solar cells. Second-generation solar cells hold an efficiency of 13% for CIGS solar cells to 19% for CdTe solar cells. These technologies are already commercially available, but at the moment only hold about 5-6%, approximately 10 GWp, of the total market share. Within this generation, CdTe is most used (Fraunhofer ISE 2022; Bagher et al. 2015; Smets et al. 2016).

Finally, third-generation solar cells are rather new designs, that have not been fully commercialized yet. In the category of third generation solar cells, you can find dye-sensitized solar cells, GaAs solar cells, Perovskite solar cells, organic solar cells, and quantum dot cells. At the moment, these cell designs have a low efficiency (< 20% in lab conditions) and instable materials, so they still have a long way to go toward market-readiness (Chen 2019; Bagher et al. 2015).

The last decades there was a big rise in the installation of solar cells to generate energy. As the lifetime of a solar cell is between 25 and 30 years, a turning point is reached (Smets et al. 2016). The solar cells have to be discarded and there will be more and more solar waste. The expectation is that the solar waste will grow to minimum of 60 million tonnes in 2050 (Figure 1). As all these different types of solar cells reach their End-of-Life, it is necessary to handle this waste properly. The solar cells can be decommissioned in a few ways: landfilling, incineration, recycling, and reusing. Of these approaches reusing might be the most favorable, after all the modules can just be sent to a different party. However, the efficiency of the module drops by about 0.5% each year, after 25 years the efficiency is 12 to 15% lower. Eventually, the efficiency is too low to effectively generate solar power and these modules need to be wasted as well (Rodriguez 2021). As solar modules consist of various rare and potentially toxic metals recycling seems to be most favorable. In this process the metals and other

valuable materials can be recovered from the modules and in doing so, lower the pressure on the critical rare materials that need to be mined. Next to that, recycling will also help to lower the amount of potentially toxic materials that end up in the environment (Ludin et al. 2018; Weckend et al. 2016; Held 2009).

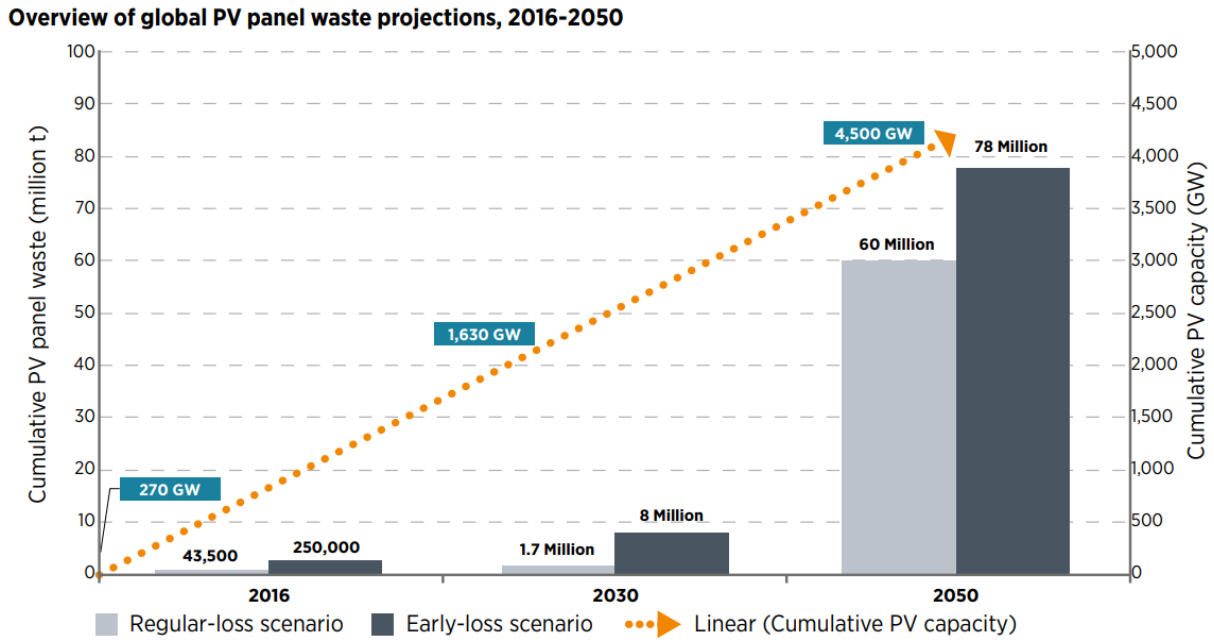

Figure 1: prediction of amount of global solar waste for 2030 and 2050 (Weckend et al. 2016).

One of the materials with the highest intrinsic toxicity that can be found in solar modules is cadmium. Although stable when it is contained in the form of CdTe, it can be very damaging for human health when it is released as a cadmium ion or metal. It can for example be a cause of chronic kidney diseases. However, cadmium is relatively abundant and can mostly be acquired as a by-product of mining operations. The opposite is true for the other component of CdTe, Tellurium. Tellurium is one of the rarest materials on earth, but has a lower intrinsic toxicity than cadmium (Vellini et al. 2017; Centers for Disease Control and Prevention 2017). Even though there are some drawbacks in using CdTe as a semiconductor material, the demand has been rising. The total market volume is expected to rise even further from € 8.8 billion in 2022 to € 1754 billion in 2028 (Fraunhofer ISE 2022; Market Data Forecast 2023). This combination of the increasing production and decommissioning of solar modules with a semiconductor of which one element has a high intrinsic toxicity and one considerably scarce element makes proper recovery of these elements essential (Fraunhofer ISE 2022).

Recovery of these materials can be done with various methods. These methods have their own impacts on the environment as well. One may have a different environmental performance than another. Even compared to incinerating or landfilling solar cells, it is not always true that recycling lowers the environmental impact of the life cycle. Investigating the environmental performance of the recycling processes will give insights into which processes would be favourable to apply and which would not (Rocchetti and Beolchini 2015). Alternatively, recycling could also help making solar modules more economically viable (Kim et al. 2016).

Research Gap

Multiple analyses on the environmental performance of CdTe solar cells have been conducted. When analysing the environmental performance of a product it is important to consider the full life cycle. When the End-of-Life stage is not studied, there could be a lack of awareness on the potential

profitability of recycling. This might give the appearance that recycling does not contribute to value creation, both economically and environmentally, resulting in low incentive to recycle (Mahmoudi et al. 2019).

According to Perez-Gallardo et al. (2018) the End-of-Life stage is commonly excluded from the studies that conduct an analysis on environmental performance of solar cells. A reason for this is that solar cells, including the ones made from CdTe, are a fairly new technique. Especially for the recycling processes, there is limited to no data available to conduct an accurate analysis (Perez-Gallardo et al. 2018). This also means that, generally, most work is focused on the production and use of solar cells, thus neglecting the impacts of the End-of-Life stage (Maani et al. 2020).

Mahmoudi et al. (2019) conducted a literature review on the published studies that reported on the End-of-Life stage of photovoltaic modules. Out of 70 studies, 43 studied the recycling and/or the recovery phase of the End-of-Life stage. 10 out of 43 used an LCA to analyse environmental impacts and report on the End-of-Life stage (Mahmoudi et al. 2019).

Kato et al. (2001) acknowledges the importance of the decommissioning and recycling of CdTe solar cells but does not consider it in the LCA as the focus is on production and use phase (Kato et al. 2001). Raugei et al. (2007) conducts an LCA with the system boundaries around the module production processes, as the purpose is to analyse the production and use of thin film solar cells (Raugei et al. 2007). In another paper (Raugei et al. 2005), in which the same research group conducted an LCA on CdTe solar cells, the End-of-Life stage is not considered as well. The reason for this is because there was not a general recycling strategy that was applied on larger scale at the time.

Research has been done on the environmental impact of the End-of-Life stages of CdTe solar modules. The pathway of First Solar has been covered with an LCA by Held (2009), Vellini et al. (2017) and Stolz et al. (2017). They used all different assessment criteria and analysed different output products which makes direct comparison impossible. The comparison with other pathways was not within the scope of the study. Multiple LCAs have been conducted on (parts of) different recycle pathways compared to one other pathway. They all Many different LCA methodologies have been applied to these studies as well, analysing different recoverable products using different criteria. (Berger et al. 2010; Giacchetta et al. 2013; Marchetti et al. 2018; Pagnanelli et al. 2019; Rocchetti and Beolchini 2015).

Tao and Yu (2015) did make a comparison between different recycling steps of CdTe solar module. In this paper they describe advantages and disadvantages of many methods on a qualitative basis. Next to that they show LCA results of two different studies that analysed separate methods. However, these results are put into the context of the necessity of recycling and not so much comparing between different methods (Tao and Yu 2015). A similar study was conducted by Marwede et al. (2013) in which different recycling steps were compared qualitatively. This is a review of different researches that have been conducted towards End-of-Life strategies of CdTe solar modules (Marwede et al. 2013).

In summary, there is no extensive comparison done on the environmental impacts of different recycle pathways. Next to that, there is an absence of literature on comparing these pathways on both qualitative data, as quantitative LCA data.

Research Objective

The goal of this research was to investigate quantitative and qualitative trade-offs of potential EoL strategies that could lower the environmental impacts of CdTe thin-film solar cells. Completing this goal helped give a clearer overview of what potential EoL strategies could be applied and what their trade-offs are. By analysing this for CdTe solar cells the knowledge gap was partly closed. This goal was translated into the following research question:

What are the quantitative and qualitative trade-offs of potential End-of-Life strategies that could lower the environmental impact of thin-film solar cells made of CdTe?

Research Approach and Sub-questions

To answer the main research question an analysis was performed on qualitative and quantitative characteristics of potential End-of-Life strategies for CdTe solar cells. Quantitative data consisted of environmental impact data of different strategies. The qualitative part assessed non-environmental criteria. An exploratory modelling approach was used in this study. Accordingly, this research was divided into three parts. In the first part, a literature review was performed for the initial understanding and input of the research. Information was acquired on the material used in CdTe solar cells, the production process of CdTe solar cells, and potential mature and innovative End-of-Life strategies that could be applied to CdTe solar cells. This data was gathered by translating these components into three sub-questions:

Q1.1 What are CdTe solar cells made of?

Q1.2 How are CdTe solar cells produced?

Q1.3 What End-of-Life techniques can be applied to the materials that are used in CdTe solar cells?

In the second part of the research, LCA results of previous studies were analysed and harmonized to show hotspots of the recycling techniques from literature. Additionally, a comparative LCA of different End-of-Life strategies was performed to show hotspots when identical methods were applied. These goals were translated into two sub-questions:

Q2.1 What are hotspots on environmental performance that can be identified in literature?

Q2.2 What are hotspots on environmental performance identified by the conducted LCA?

The third and final part of the research was completed by combining the previous quantitative analysis with a qualitative assessment to show a comparison between environmental impacts and non-environmental criteria. The following sub-question was answered in this section:

Q3.1 What are qualitative trade-offs of End-of-Life strategies of CdTe solar modules?

Together with the answers to part 2, part 3 was used to answer the main research question.

Literature Review

Cadmium Telluride Solar Modules

In this literature review it was explored what the structure of a cadmium telluride solar cell consists of, what the applied production process of these modules is, and what recycle strategies are applied. This description answered the first three sub-questions.

Structure of CdTe Solar Modules

Cadmium telluride (CdTe) can be easily applied as thin-film, as absorbing all protons only takes a few micro meters of material. A solar cell with CdTe as semiconductor exists of five layers (Figure 2). The CdTe solar cells that are commonly used are in superstrate configuration, so this research will use this structure to describe CdTe solar cells (Bosio et al. 2018). The first layer (top layer) is a glass superstrate with ethyl-vinyl acetate (EVA) on which the second layer of transparent conducting oxide (TCO) or transparent front contact is deposited. This layer is made from highly conductive and transparent tin-doped indium oxide, also called indium tin oxide (ITO). The third layer is an intermediate layer made from cadmium sulphide (CdS) that is deposited on the second layer to enhance electrical and growth properties. The fourth layer is the absorber layer, semiconductor, made from CdTe. The fifth and final layer is the back contact which contains copper (Cu) in combination with zinc telluride (ZnTe) (Smets et al. 2016; Reese 2022; Romeo and Artegiani 2021; Bosio et al. 2018; Maani et al. 2020). Each of the layers has a different thickness and together make that the module is only 6.8 mm thick (Berger et al. 2010). Important to note is that the unit of this analysis is 1 m^2 of CdTe solar module. However, a regular CdTe solar module has a surface of 0.72 m^2. From this we can deduct that a typical CdTe solar module has a volume of about 4.9E-03 m^3 with a weight of around 12 kilograms.

Table 1: structure of a CdTe solar module with layer thickness (Berger et al. 2010).

	Kg/m^2	Thickness layer (µm)
Glass	15.8	6400
EVA	6.2E-01	450
TCO (ITO)	2.7E-03	0.5
CdS	8.3E-03	0.4
CdTe	3.3E-02	3.5
Back contact (Cu, Zn, Te)	1.2E-01	0.4
CdTe solar module (1 m^2)	16.6	6854.8

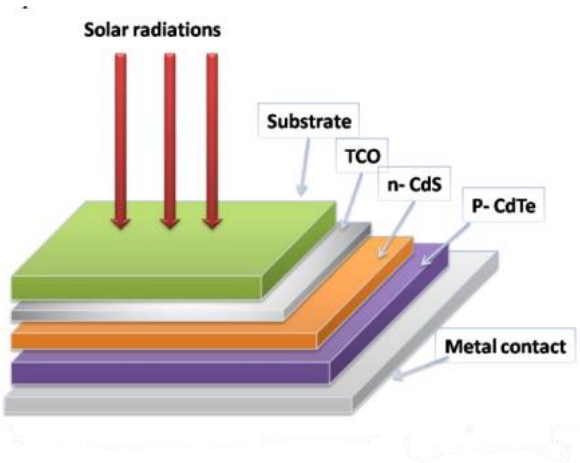

Figure 2: structure of a CdTe thin-film solar module (Kapadnis et al. 2020).

Production of CdTe Solar Modules

Solar modules with cadmium telluride as semiconductor can be produced in multiple ways. However, similar for all production methods is that the different layers are deposited on top of each other. The following steps were identified for the production pathway. Alternatives are possible, but the choice was made to use these processes as they have been applied most and show the best results. In Figure 3, the production pathway is shown.

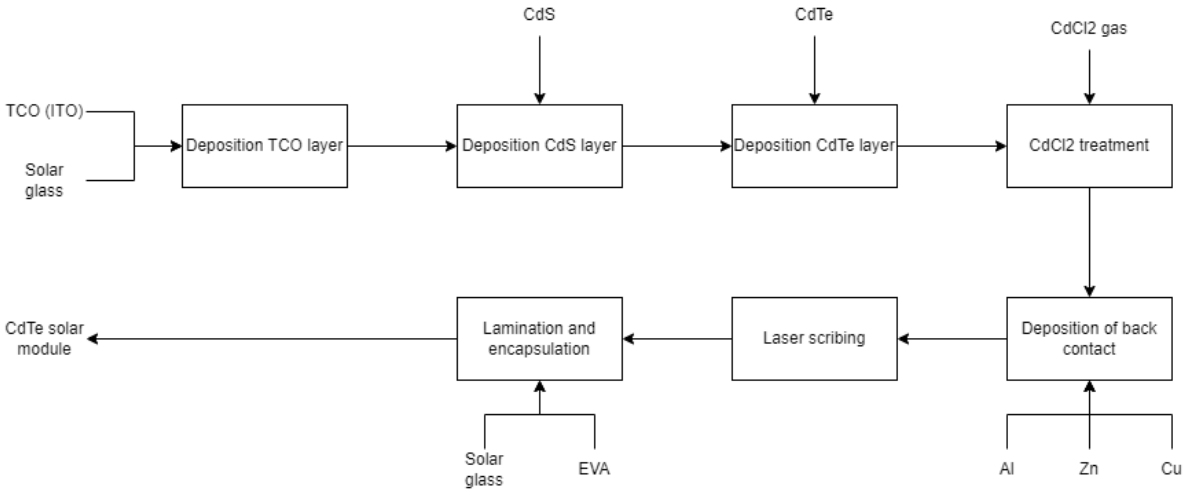

Figure 3: schematic overview of layer deposition in CdTe solar module production.

Deposition of TCO Layer

The first step is to deposit the TCO layer on top of the float glass. This can be done with various methods. The TCO layer is made from indium tin oxide (ITO) and RF magnetron sputtering is the most industrialized and cost-effective deposition method. Thus, for this research project, RF magnetron sputtering is chosen to deposit the TCO layer on the glass substrate (Liu 2016). RF magnetron sputtering makes use of a sputtering gas (Argon) to transfer the ITO from the cathode to the glass substrate (Tchenka et al. 2021).

Deposition of CdS Layer

To deposit the cadmium sulphide layer on top of the glass with TCO numerous techniques can be used. The CdS layer is here deposited by the method of RF sputtering. This method is one of the best in achieving smooth and uniform surfaces. Accompanied by a sputtering gas like argon the CdS particles are deposited on the substrate in a homogenous way (Doroody et al. 2021).

Deposition of CdTe Layer

The substrate glass with a TCO and CdS layer is subjected to Vapour Trasnport Deposition (VTD) to deposit the CdTe layer. For the CdTe layer this type of production method, next to Closed Space Sublimation, has already been applied widely on an industrial scale (Bosio et al. 2018; Liu 2016). First CdTe is transferred into a gaseous state by a vaporizer. Subsequently, a carrier gas transports the gaseous CdTe particles to a different chamber. There, the CdTe particles get deposited on the substrate, growing a CdTe layer (Romeo and Artegiani 2021).

Treatment with Cadmium Chloride

To increase the efficiency of the solar cell the deposited layers get treated with cadmium chloride. Without this treatment the cells would only have a solar conversion efficiency of around 2%. With this treatment the efficieny will increase to more than 20% (Liu 2016; Major et al. 2014). The substrate is

treated with cadmium chloride in methanol solution. After this, the substrate is blown off by nitrogen gas and is cleaned with distilled water. Cadmium chloride will not remain on the substrate (Liu 2016).

Deposition of Back Contact

As a back contact copper is used. To prevent movement of copper particles throughout the rest of the module a buffer layer of copper doped zinc telluride (ZnTe:Cu) is applied to the module. The back contact is mainly deposited by RF sputtering at room temperature on top of the CdTe layer in about 800 seconds (Uličná et al. 2017). This combinattion is the industrially applied most and has the least drawbacks (Romeo and Artegiani 2021).

Laser Scribing

Laser scribing steps are applied to ensure that the solar module has individual solar cells that are connected in series. There are three types of laser scribes done. The first laser scribe is done on the TCO layer. The second laser scribe is done on the CdS/CdTe layer. The third and final laser scribe is done on the back contact. These laser scribes are done parallelly and adjacent to each other, creating multiple cells within the solar module (Figure 4) (Bosio et al. 2006).

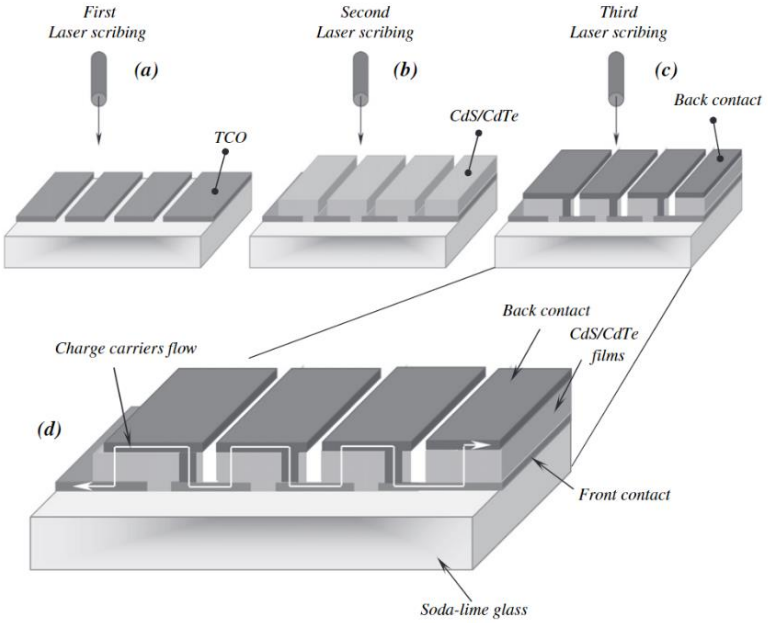

Figure 4: structure of a CdTe solar module after laser scribing steps (Bosio et al. 2006).

Lamination and Encapsulation

Finally, the module gets laminated with EVA (ethylene vinyl acetate) film and encapsulated by a back glass. This final step produces a complete module that can be placed.

As all these layers are deposited directly on top of each other, the recycling process is a bit harder than that of other solar cells; it is not possible to separate the individual layers of thin-film solar cells and reuse them (Kuczyńska-Łażewska et al. 2021).

End-of-Life Processes of CdTe Solar Modules

Multiple pathways exist for recycling CdTe solar modules. These pathways consist of mechanical, thermal, and chemical treatment methods which all have different options. These different treatment methods are also combined for many of the processes. Almost all pathways start with the mechanical process of physically disintegrating the CdTe solar modules. After physical disintegration the module fragments are treated to remove the EVA layer and separate the glass from the semiconductor materials. This could be done thermally, chemically, mechanically, or with a combination of these treatment methods. In the end, the goal of the recycling pathways is to generate metals and glass of high purity that replace the inputs of the production process of CdTe solar modules.

Physical Disintegration

The treatment of spent CdTe solar modules starts with physical disintegration to have module fragments that are more easily accessed in the further treatment pathways. The physical disintegration is done in multiple ways. Firstly, it could be done by shredding the spent module into large pieces of 1 cm or larger. This is considered a primary process before physically breaking down the module into treatable pieces (Giacchetta et al. 2013; Toro et al. 2013). Hammer milling as a follow up of shredding will break the modules further down into pieces with a particular size distribution. This size distribution can be brought back to three fractions. A coarse fraction with a diameter larger than 1 mm makes up 10% of the weight. This coarse fraction consists of glass and EVA. Another 10% of the weight is made up from a fine fraction which contains valuable metals (Cd, Te, Zn, Cu) and glass. The remaining 80% of the weight can be attributed to glass, that can be recovered after the glass treatment processes. A sieving process ensures that the different fragment sizes get treated by different processes (Giacchetta et al. 2013; Held 2009; Marchetti et al. 2018; Toro et al. 2013).

Hammer milling could also be used as a primary disintegration method before treatment with chlorine gas, in which it breaks the module down into treatable pieces of 10 cm (Diequez Campo et al. 2003). Another way of physically breaking down the modules is using a two blade rotor crusher which mostly gives module fragments larger than 1 mm (Granata et al. 2014).

Removal of EVA Layer

Incineration

After breaking the spent CdTe module down into treatable pieces, the materials that are present within these fragments need to be treated or removed from the mix. One of these materials is the EVA layer that was deposited between the back glass and semiconductor layers. After sieving, this means that only the coarse fraction needs to be treated in this process. One of the ways of removing the EVA layer is by incineration in an oxygen containing environment. Ideally, the EVA layer is broken down fully into gaseous carbon dioxide and water (Diequez Campo et al. 2003; Berger et al. 2010; Granata et al. 2014; Toro et al. 2013).

Solvent Treatment

The EVA layer could also be chemically removed by a washing treatment with a solvent of cyclohexane-acetone. EVA is then dissolved, and decreasing the adhesive effect, leading to detachment of EVA from the glass fragments. After solid-liquid separation there will be a liquid mixture with dissolved EVA and solid glass freed of any adhesives (Toro et al. 2013).

Vibrating Screening

This process is used to separate remaining EVA from the glass fragments. Glass fragments will fall through the screen and EVA will remain on top of the screen. However, this can only be applied after the removal of semiconductor and other material. This means that this process can only be applied to

a mix consisting of EVA and glass in which the EVA layer is not adhesive to the glass anymore (Held 2009; Grainger 1998).

Removal of Semiconductor Layer

Dry Etching

The semiconductor layer consisting of CdTe needs to be extracted to get recyclable metals as input for the semiconductor production process. The process of dry etching treats disintegrated, non-sieved module fragments with chlorine gas, generating gaseous $CdCl_2$ and $TeCl_4$. These gases can be excavated from the module fragments. As the module fragments also contain a CdS layer, this will etch away as well, forming $CdCl_2$ and SCl_2. Finally, the TCO layer consisting of ITO is partly etched away as well. Dry etching with chlorine gas does not etch away all of the TCO layer from the glass. The remaining TCO layer can be removed from the glass by treating it with HCl gas. In turn this generates $InCl_3$, $SnCl_4$, and H_2O (Diequez Campo et al. 2003).

Leaching

Leaching is a chemical process in which sieved fine fractions get treated to retrieve the valuable metals. There are two types of leaching applied in CdTe removal: alkaline leaching and acid leaching. Alkaline leaching is performed in two steps. In the first step sodium hydroxide is used, at a pH ranging from 10 to 11, to dissolve telluride as sodium tellurite (Na_2TeO_3). Other material present is insoluble, so by solid-liquid separation the tellurite can be separated from the solids. In the second step, at a pH between 12 and 14, again sodium hydroxide is used to extract zinc in liquid form. Cadmium and copper are present in the solid residue and are extracted by precipitation using sulfuric acid (Toro et al. 2013).

Acid leaching is performed in successive stages using an aqueous solution of sulphuric acid and hydrogen peroxide. This will subsequently solubilize cadmium, telluride, copper, and zinc ions into a leaching solution. The solid residue consists of glass that can be treated in further glass treatment processes. A precipitation process is performed by the subsequent addition of alkaline agents, like sodium hydroxide, for different pH values to the leaching solution, the metals can be recovered as precipitates (Toro et al. 2013; Fthenakis et al. 2006).

Attrition

Separating semiconductor material from the glass can also be done in a wet-chemical grinding process, attrition. This process makes use of frictional forces to remove the semiconductor layer from the glass (Giacchetta et al. 2013; Berger et al. 2010; Marchetti et al. 2018). For this research attrition is described as one process together with either flotation or centrifugal extraction. From the attrition process, separated material flows into these succeeding processes.

Flotation is a solid liquid separation that separates the mixture based on hydrophobicity. Air bubbles are used in the fluid to adhere to the more hydrophobic materials. This will push these materials to the surface. From here these materials can be extracted. Heavy material will accumulate on the bottom and can be extracted from there. The bubbles are produced by saturating a portion of the fluid with pressurized air (Giacchetta et al. 2013). For flotation a flotation agent is needed to exploit the hydrophobicity. One agent that might be used in CdTe solar module material separation is potassium amyl xanthate (KAX) (Berger et al. 2010). Another option for separating the materials after attrition is centrifugal extraction. This technique does not need any chemicals and makes use of the density and weight of the particles in solution. Particles with a larger mass will move to the outside, particles with a small mass will move to the inside. The liquid containing heavy particles is removed in the shaft and the liquid containing light particles is removed in the centre (Marchetti et al. 2018; Chemical Engineering World 2020). After the process of attrition in combination with flotation or centrifugal extraction, the recovered material should be cleaned and purified (Giacchetta et al. 2013). Possibly,

attrition could be used as a pre-treatment process before etching and leaching, to lower the amount of chemicals that are required for these processes (Tao and Yu 2015).

Vacuum Blasting

In this technique a vacuum gets created on the surface of the module fragments. A blast medium is used to excavate the semiconductor layer from the glass. Key here is that the EVA layer has already been removed. The surface of the fragments is hit with a high energy by a blast medium. An industrial vacuum cleaner removes the blast medium and the semiconductor layer (Berger et al. 2010).

Recovery of metals

Precipitation

From the dry etching process gaseous $CdCl_2$ and $TeCl_4$ are formed. These can be precipitated individually. Firstly, a cold trap is used to cool the gas mixture to 350 ^oC at which $CdCl_2$ precipitates. This is removed from the mixture. In a next cold trap, the gas is cooled to 150 ^oC at which $TeCl_4$ precipitates. These precipitates are now available for further treatment (Diequez Campo et al. 2003). As said before, could precipitation also be applied to the solution containing metals coming from the leaching process. A three-stage process with increasing pH is used to get the metals in the least soluble state. The pH is controlled by sodium hydroxide. The slurry is thickened and after filtration, the filter contains all the metals. The water is sent to wastewater treatment (Tao and Yu 2015; Held 2009).

Ion Exchange

The liquid phase coming from a leaching process contains metals like cadmium and tellurium. This solution can be sent through a cation exchange resin or a chelating resin. These resins will selectively hold a metal, leaving the rest in solution. With this technique cadmium, tellurium and other metals can be separated from each other as the resin will hold different materials at different pH. Cadmium and tellurium are separated by running the solution through a cation exchange resin at a pH between 0 and 1. Cadmium will be retained, and other metals will still be in the solution. To extract other metals the pH is changed so that metal is retained. Eventually the resin will be fully loaded with a metal. The metal needs to be eluted from the resin. Before elution the resin needs to be rinsed as a small number of unwanted metals, like tellurium, are still present. Tellurium is removed with Na_2SO_4 in water. Cadmium is eluted from the resin by sulfuric acid or hydrochloric acid, generating $CdSO_4$ or $CdCl_2$. To recover cadmium as a metal, the eluting solution is submitted to electroplating or evaporation. The resin is rinsed with an aqueous solution of sulfuric acid or hydrochloric acid. It can then be used for a next ion exchange cycle (Fthenakis and Wang 2005).

Electroplating

Cadmium is eluted as $CdSO_4$. In an electrolytic cell $CdSO_4$ is separated into cadmium metal and H_2SO_4. Sulfuric acid can be reused in previous processes. Cadmium metal can be send to a recycle facility for the final step to obtain recyclable cadmium (Fthenakis and Wang 2005).

Glass Treatment

After extracting glass, the glass needs to be rinsed before it can be used as a primary material for glass production. After acid leaching the glass fragments need to be repeatedly rinsed with dilute sulfuric acid solution. After this the fragments can be recycled in a glass treatment plant (Fthenakis and Wang 2005; Giacchetta et al. 2013). Glass fragments coming from flotation get washed with water in a washing machine (Marchetti et al. 2018).

An overview of all these possible steps can be seen in Figure 5.

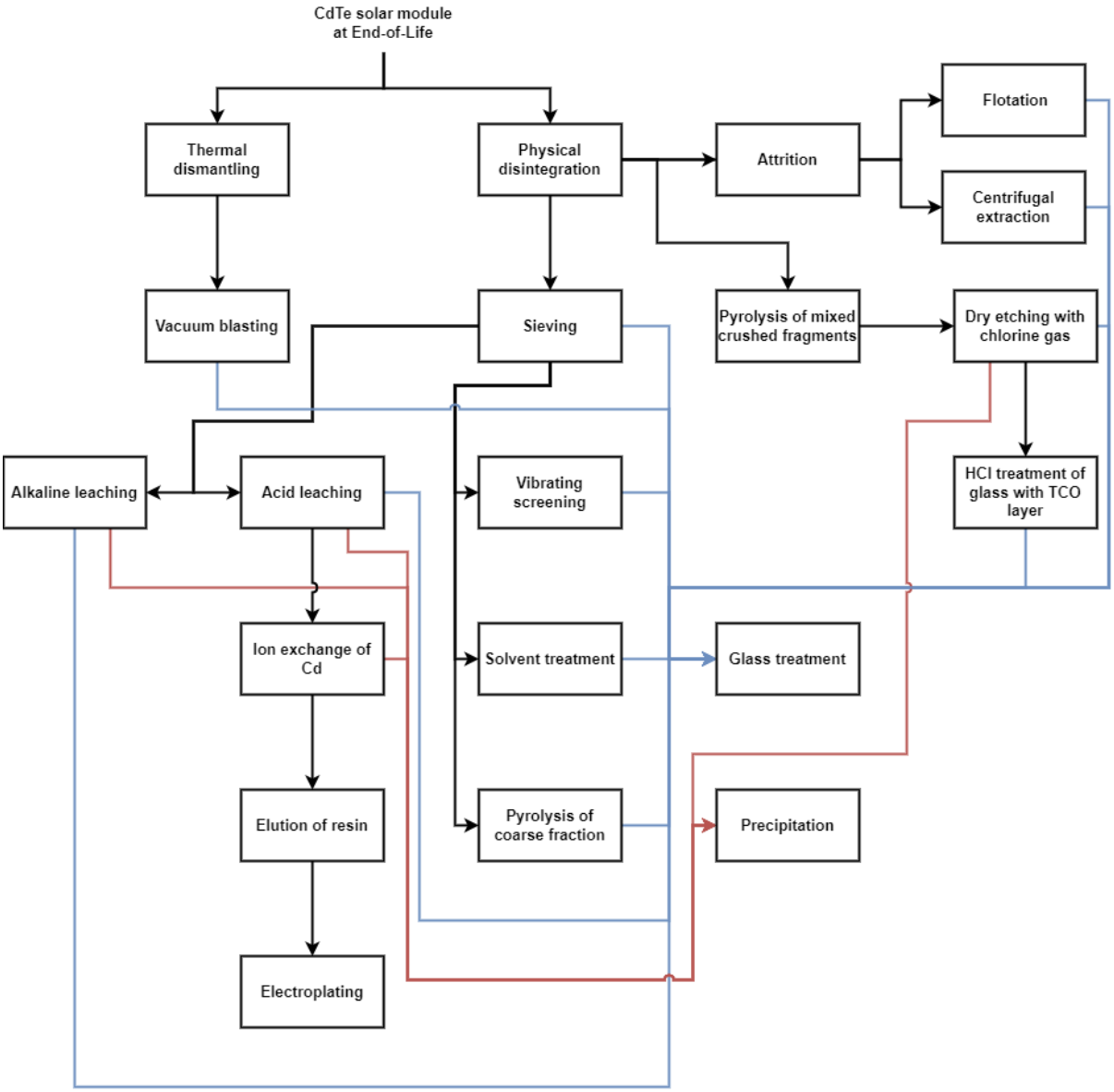

Figure 5: overview of possible processes that could be used in the recycling of CdTe solar modules.

Life Cycle Assessment Data

As stated in the description of the research gap, LCA studies have been performed on possible recycling strategies of CdTe solar modules. LCA is a tool to calculate potential environmental impacts and identify hotspots for processes within a life cycle of a product. In this section these studies were analysed based on the most important criteria related to LCA studies. The functional unit entails the unit of analysis for an LCA. Different functional units for identical systems could possibly generate totally different impacts. The scope of the study places the products and processes in a certain geographical location and timeline. The chosen impact assessment methodology expresses what impact categories will be assessed. For different impact assessment methodologies different, sometimes non-comparable, impact categories exist. Next to these criterium, different studies make use of different software, databases, and data origins for their LCAs. Additionally, each study sets its own system boundaries, decisive for what is and what is not includes in the model. Finally, every study is subject to many assumptions that can differ from or show similarity to other studies.

By applying these criteria to the LCA, hotspots can be identified. These hotspots show the parts of the processes within the analysed life cycle of CdTe solar modules in which environmental performance gets influenced greatly.

Table 2 summarizes the specifications of an LCA conducted on the recycle pathway of First Solar (Held 2009).

Table 2: LCA specification by Held (2009).

Source	Held (2009)
Recycle pathway	First Solar: 1. Physical disintegration (shredding and hammer milling) 2. Acid leaching 3. Precipitation of leaching product 4. Vibrating screening 5. Glass washing
Goal	Quantifying the environmental performance of a CdTe module over its whole life cycle.
Functional unit	1 m2 of spent CdTe modules
Geographical scope	Germany
Temporal scope (year studied)	2009
Impact assessment methodology	CML2001
Impact categories	Acidification; Eutrophication; Global warming; Photochemical ozone creation; Primary energy demand
LCA software	GaBi 4
Database for LCI	GaBi 4
Data origin	Primary data: industry data Secondary data: GaBi 4 databases
System boundaries	Spent module comes in and gets physically disintegrated to the recovery of energy, land filling, and wastewater treatment. The recovery of metals from the filter cake and glass cullet treatment are not included.
Main assumptions	- Recycling data of module provided by industry. - Data on end-of-life of external material provided by GaBi 4 database. - Recycling benefit accounted for as credits. - Energy generated by incineration replaces energy input of external sources. - Glass cullet substitutes primary material of glass, avoiding CO_2 emissions and reduces energy. - 95% of semiconductor material is recycled by 3rd party. - Lamination material is fully burned, generating recoverable energy. - Other outgoing material is landfilled. - Liquid waste is treated in waste treatment plant.

Held (2009) conducted a comparative LCA on two End-of-Life phases, with and without material recycling. For this analysis the GaBi 4 software and the corresponding GaBi database has been used. The datasets from this database that were used, were all from Germany, as this is where the recycling plant is located. The primary data was based on data of the industry. Secondary data was based on the GaBi datasets. The functional unit was 1 m^2 of spent CdTe modules. The impact methodology assessment was based on CML2001. The impact categories that were considered are acidification, eutrophication, global warming, photochemical ozone creation, and primary energy demand.

CdTe Module recycling per m²		Primary energy from resources (net cal. value) [MJ]	AP [kg SO2-Equiv.]	EP [kg Phosphate-Equiv.]	GWP [kg CO2-Equiv.]	POCP [kg Ethene-Equiv.]
CdTe module recycling	Auxiliaries (recycling process)	29,86	2,64E-03	2,24E-04	1,76E+00	2,43E-04
	Electrical power (recycling process)	60,12	6,59E-03	5,07E-04	3,84E+00	4,45E-04
	Glass cullet recycling	*-74,87*	*-1,53E-02*	*-2,16E-03*	*-7,23E+00*	*-1,63E-03*
	Waste incineration and energetic recovery, lamination foil	-3,98	-2,45E-04	-2,58E-05	9,54E-02	-2,34E-05
	Disposal of wastes (glass fines, filter wastes, others)	0,18	9,38E-05	1,08E-05	1,22E-02	1,19E-05
	Waste water treatment, liquid solutions	0,49	3,60E-04	1,23E-04	1,51E-01	1,96E-05
Junction box and lead wires	Waste incineration, plastic materials	-5,64	-3,41E-04	-3,52E-05	1,72E-01	-3,26E-05
	Copper recycling	*-18,64*	*-7,20E-03*	*-4,28E-04*	*-1,30E+00*	*-4,88E-04*
Total* (incl. material recycling credits)		***-12,49***	***-1,34E-02***	***-1,80E-03***	***-2,50E+00***	***-1,45E-03***
Total* (without material recycling credits)		**81,03**	**9,10E-03**	**8,03E-04**	**6,03E+00**	**6,63E-04**

* *negative values describe environmental benefits accounted as credit within the life cycle assessment*

Figure 6: results of Life Cycle Assessment conducted by Held (2009).

Compared to the scenario without recycling, the scenario with recycling lowers the primary energy demand, acidification potential, eutrophication potential, global warming potential and photochemical ozone creation potential. A hotspot that can be identified for the scenario including recycling, is the recycling of glass cullet. This process accounts for the largest reduction in impact categories, followed by copper recycling. Another hotspot that could be identified is the electrical power needed for the recycling process, which has the largest contribution in all categories. The treatment of wastes after recycling account for the highest impacts. Waste incineration does lower impacts of all categories but global warming. Waste disposal and waste water treatment contribute to all impact categories (Held 2009).

Table 3: overview of hotspots from Held (2009).

	Hotspot
Primary energy use	Higher without recycling
Electrical power	Electricity use contributes the most to all impact categories.
Waste incineration	Increased impact for global warming
Waste disposal	Positive impact on all categories
Wastewater treatment	Positive impact on all categories, second largest contributor.

Table 4 shows the specifications of two recycle pathways as described in the RESOLVED project. One pathway treats damaged CdTe solar modules, the other treats undamaged solar module (Berger et al. 2010).

Table 4: LCA specification by Berger et al. (2010).

Source	Berger et al. (2010)
Recycle pathway	Damaged modules: - Physical disintegration (shredding and hammer milling) - Attrition - Flotation of attrition product - Purification - Incineration Undamaged modules: - Thermal dismantling - Vacuum blasting - Flotation of blasted product - Purification - Incineration
Goal	Analysing different recycling inventions for CdTe
Functional unit	1 m2 of spent CdTe modules
Geographical scope	EU
Temporal scope (year studied)	2010
Impact assessment methodology	CML 2 Baseline 2000 extended with NREU indicator
Impact categories	Acidification; Eutrophication; Global warming; Ozone layer depletion; Photochemical ozone creation; Primary energy demand
LCA software	Unknown
Database for LCI	Unknown
Data origin	Treatment of damaged modules: data from laboratory experiments.
System boundaries	Spent module until recovered glass and mix of photovoltaic materials
Main assumptions	- Single details of process have been neglected due to lack of data. - Vacuum blasting is not included in results. - Energy consumption for thermal treatment will dominate LCA. - Small quantity of cadmium is emitted due to thermal treatment. - Emission factor of 5 x 10^{-5} kg/kg Cd is used based on modern hazardous waste incinerator. - Impacts of cadmium and tellurium recovery are not accounted for, because of limited reduction in impacts. External recovery is assumed.

The RESOLVED project has been analysed using a comparative LCA between the recycling process for damaged modules, the recycling process for undamaged modules, and modules that were not treated in a recycling process. The two recycling strategies include the purification of the semiconductor material, but not the production of the PV module. The main outputs of this process are semiconductor material and glass. The glass is sent to a glass recycling company. The semiconductor material is sent to a recovery plant. These impacts are not accounted for in this LCA.

Impact category	Unit	RS-0	RS-1	RS-2
Global warming potential (GWP 100)	kg CO_2 eq	592	413	752
Ozone layer depletion (ODP)	kg CFC-11 eq	3.80E−05	3.20E−05	5.80E−05
Photochemical ozone creation potential (POCP)	kg C_2H_4	0.16	0.10	0.15
Acidification potential (AP)	kg SO_2 eq	4.23	2.50	3.65
Eutrophication potential (EP)	kg PO_4^{3-} eq	0.31	0.20	0.30
Non-renewable energy	MJ primary	11,158	9121	16,049

Figure 7: impact scores of the processes proposed by the RESOLVED project (Berger et al. 2010).

A hotspot that was identified for recycling damaged modules are the energy use in the attrition process and in the wet separation process. For recycling undamaged modules, vacuum blasting has not been accounted for because of data deficiency. Another hotspot that has been identified is the energy consumption of the thermal treatment. This treatment also releases some cadmium to the air. Impacts of the recovery of cadmium and tellurium have not been included in the LCA, as model production is not included.

The recycling process for undamaged module has a lower contribution in every impact category compared to both the recycle process for damaged modules and the End-of-Life without recycling. The recycle process for damaged modules has a larger impact than the End-of-Life without recycling in the categories of Global Warming, Ozone Layer Depletion, and Primary Energy Use. It has a lower impact in the categories of Photochemical Ozone Creation, Acidification, and Eutrophication (Berger et al. 2010).

Table 5: overview of hotspots from Berger et al. (2010).

	Hotspot
GWP	Higher impact because of higher energy input for attrition and flotation.
GWP	Higher impact because of energy input for thermal treatment.
All categories	There is a higher impact for the treatment of damaged modules

The recycling pathway as described by First Solar has also been analysed in a different LCA. In Table 6 the specifications of this LCA can be seen. Table 7 shows the hotspots as found for this study (Rocchetti and Beolchini 2015).

Table 6: LCA specification by Rocchetti & Beolchini (2014).

Source	Rocchetti & Beolchini (2014)
Recycle pathway	First Solar: 1. Physical disintegration (shredding and hammer milling) 2. Acid leaching 3. Precipitation of leaching product 4. Vibrating screening 5. Glass washing 6. Recovery of tellurium
Goal	Comparing the impacts on the environment of conventional and innovative recycling of the end-of-life of CIGS and CdTe modules, identifying critical issues for the environment.
Functional unit	1 m2 of PV panels that were both recycled and landfilled
Geographical scope	Southern Europe
Temporal scope (year studied)	2014
Impact assessment methodology	CML2001
Impact categories	Abiotic depletion; Acidification; Eutrophication; Global warming; Ozone layer depletion; Photochemical ozone creation
LCA software	GaBi 5.0 Professional
Database for LCI	EcoInvent 2.2
Data origin	Data on reagents and energy from EcoInvent 2.2 database
System boundaries	Only recycling scenarios or landfilling. From crushing spent CdTe module to recovery of Tellurium and glass.
Main assumptions	- Landfilling done without treatment. - Results of landfilling scenario represented by mean values. - Similar processes were chosen when process was not found. - Neglected transport. - Accounted for lower impacts by credits. - Includes recovery of Tellurium. - Conventional process: crushing, recovery of glass, thermal treatment of EVA, disposal of remainder material to landfill.

Rocchetti and Beolchini (2015) conducted a comparative LCA between a conventional recycling process, landfilling, and their innovative recycling process. The conventional process retrieves energy due to incineration and glass. The innovative recycling retrieves glass and the semiconductor material.

The innovative recycling process shows, compared to landfilling and conventional recycling, the lowest and even negative emissions in the impact categories of abiotic depletion, acidification, eutrophication, ozone layer depletion, and photochemical ozone creation. In the category of global warming the innovative process doesn't show negative emissions but it does show a lower impact.

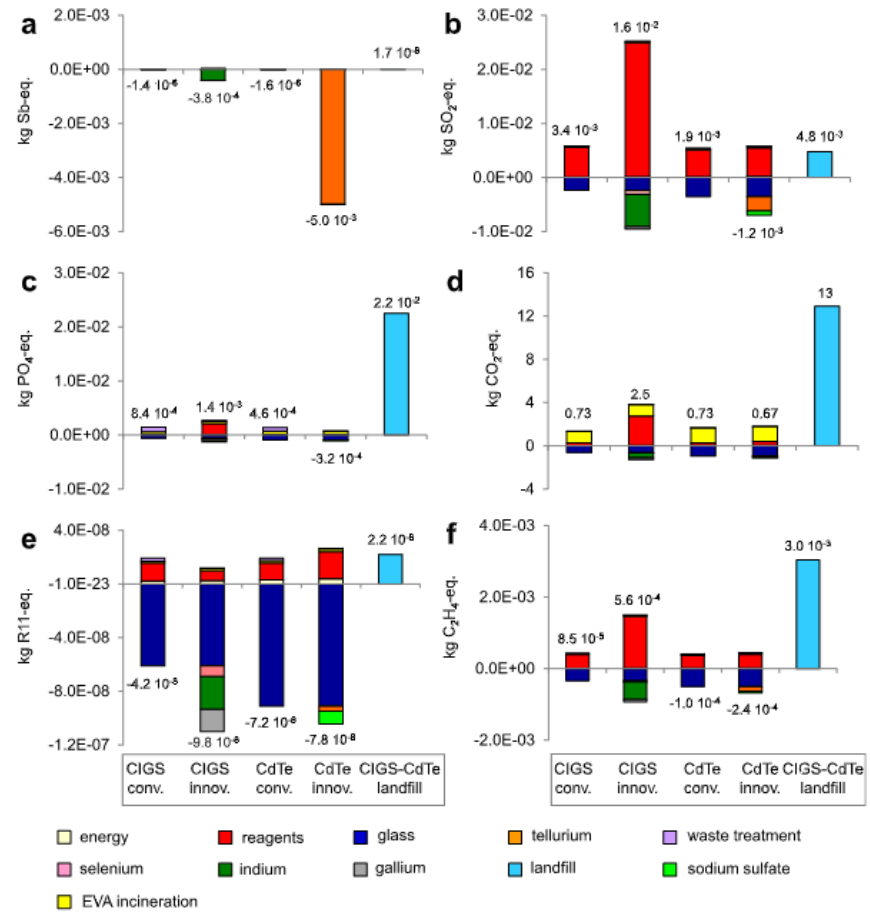

Figure 8: impact scores of the processes by Rocchetti and Beolchini (2015) with categories: a) abiotic depletion; b) acidification; c) eutrophication; d) global warming; e) ozone layer depletion; f) photochemical ozone creation.

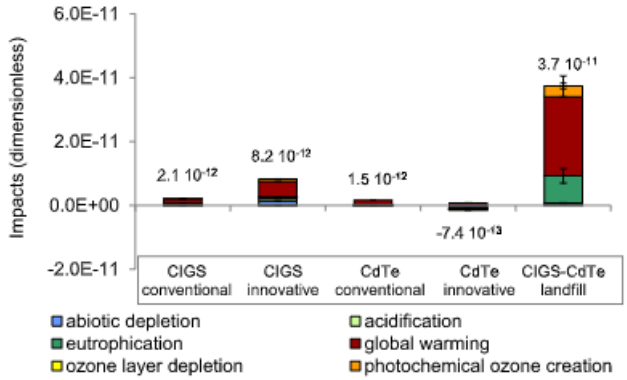

Figure 9: weighted impact of processes (Rocchetti and Beolchini 2015).

When the weighted impacts are compared, it can be seen that the overall compared environmental impacts of the innovative process are negative. The largest contribution to the positive side of the environmental impacts is due to global warming potential. The ones that contribute most to keeping the overall impacts negative are abiotic depletion potential and eutrophication potential. The hotspot within the global warming category that has the largest contribution is the incineration of the EVA layer. On the other side, the incineration of the EVA layer does produce energy, which has a negative contribution. Another hotspot that could be identified is the usage of reagents within both recycle processes. The reagents that were used for the recovery of valuable materials show a positive impact for the acidification potential, the eutrophication potential, the ozone layer depletion potential, and

the photochemical ozone creation potential. Almost all of the negative contributions can be attributed to the recovery of valuable material.

Compared to the production process, however, the recycling process represents only a small contribution to the total lifetime emissions of a CdTe solar module (Rocchetti and Beolchini 2015).

Table 7: overview of hotspots from Rocchetti & Beolchini (2015).

	Hotspot
GWP	Has highest contribution to positive impacts of CdTe recycling due to incineration of EVA layer.
AP, EP, OLDP, POCP	Increased impacts by the usage of reagents to recover Tellurium.
EP	Increased impact by wastewater treatment and incineration of EVA layer.
EP, OLDP	Glass recovery lowers the impact.

This section describes the third LCA that was performed on the recycle process of First Solar (Vellini et al. 2017). Specifications of this LCA can be found in Table 8.

Table 8: LCA specification by Vellini et al. (2017).

Source	Vellini et al. (2017)
Recycle pathway	First Solar: 1. Physical disintegration (shredding and hammer milling) 2. Acid leaching 3. Precipitation of leaching product 4. Vibrating screening 5. Glass washing
Goal	Analysing primary energy use and environmental impacts of the entire life cycle of silicon and CdTe modules by looking at disposal and recycling of these modules.
Functional unit	1 m2 of photovoltaic module area
Geographical scope	Europe
Temporal scope (year studied)	2017
Impact assessment methodology	CML2001
Impact categories	GWP, AP, EP, POCP, OLDP, HTP, TETP, MAETP, FAETP, ADP, ADFP, PEDP
LCA software	GaBi 5.0
Database for LCI	EcoInvent 2.2
Data origin	Foreground and background data is coming from the EcoInvent 2.2 database.
System boundaries	Raw material extraction, production, transport, use, and end-of-life.
Main assumptions	- Environmental impacts of the use phase are negligible. - Two inverters are included as they need to be replaced after 15 years. - Cadmium is acquired as by-product of zinc refinement. - Cadmium and tellurium are purified before CdTe, CdCl2, and CdS can be synthesized. - Module is produced by Vapour Transport Deposition, CdCl2 spraying and sputtering. - The module is landfilled at the end of life (Scenario disposal). - All materials that are not reused, are landfilled. - For the comparative scenarios (recycling and disposal), the production process is the same.

Vellini et al. (2017) conducted a different analysis on the process by First Solar. For this they included all impact categories of the CML2001 method and added Primary Energy Use. This study is performed with the system boundaries cradle-to-grave, the LCA includes raw material extraction, production, transportation, use, and end-of-life. The life cycle of CdTe modules with and without recycling with the First Solar process are compared to each other. The impact of the scenario without recycling is compared to the ratio between impact without recycling and impact with recycling. The recycling process causes a positive impact in the categories of global warming, abiotic depletion of fossil, eutrophication, and primary energy. For the other categories the recycling process shows a lower impact compared to the scenario without recycling. Especially for human toxicity, freswater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, and abiotic depletion, the recycling process has great influence in lowering the impacts of the life cycle of CdTe solar modules. For the other categories the recycling of the modules does not contribute significantly to lowering impacts.

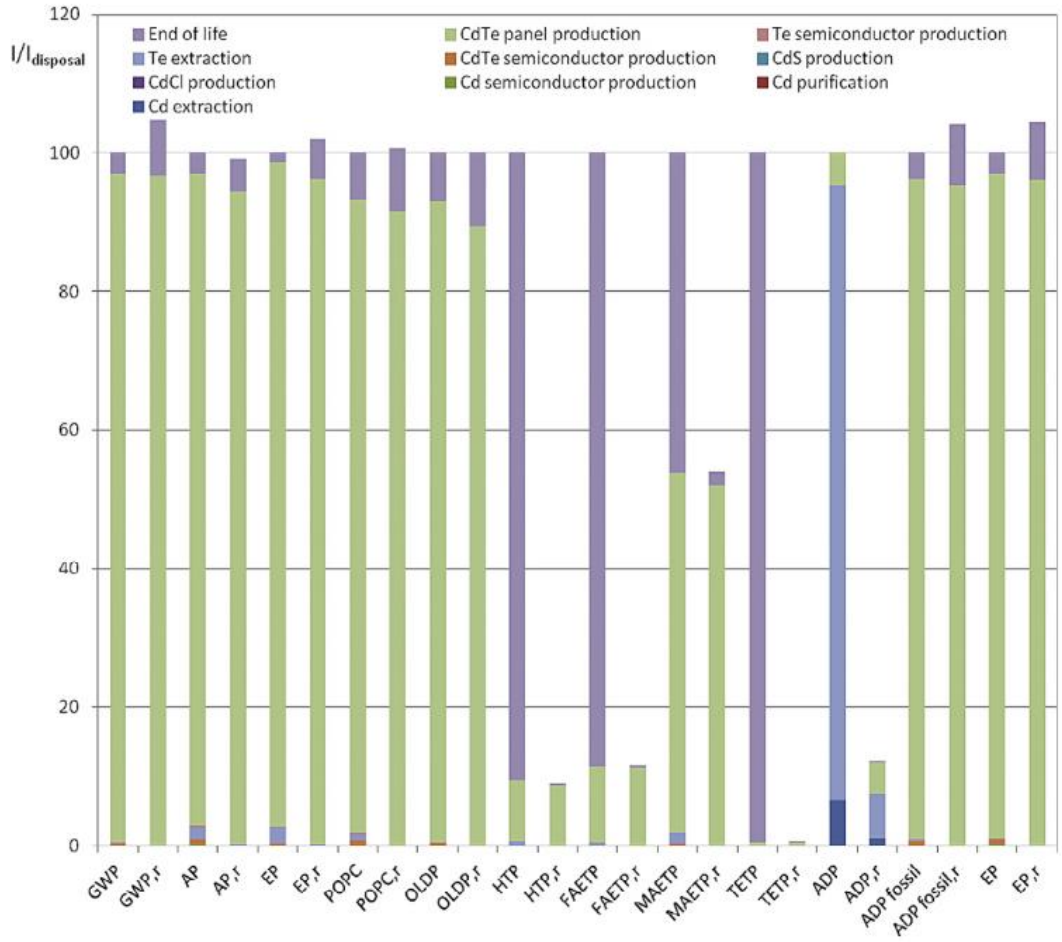

Figure 10: Impacts scores of life cycle of CdTe modules with and without recycling (Vellini et al. 2017).

The decreasing impacts can largely be attributed to the recovery and reuse of semiconductor material, as cadmium is a very toxic material. Similar to the analysis conducted by Held (2009), the electrical power required for the recycling process is one of the largest contributor to the positive impacts. A takeaway from this analysis is that the production process is having a much larger contribution to the environmental impact then the disposal stage. Thus, the recycle scenario is only marginally lowering impacts in most categories (Vellini et al. 2017).

Table 9: overview of hotspots from Vellini et al. (2017).

	Hotspot
GWP, EP, and OLDP	Increase due to use of fossil fuels.
HTP, FAETP, MAETP, and TETP	Landfilling increases the toxicity impacts. A recycling process reduces impacts.
HTP and TETP	Decrease due to recovery and reuse of semiconductor.
ADP	High impact related to material extraction. Reduced by recycling process of CdTe.
GWP, AP, EP, POCP, and OLDP	Panel production contributes the most, disposal has almost no influence. Recycling process hardly changes outcome.
ADP, GWP, OLDP, EP, and POCP	Incremental increases due to recycling

Table 10 describes the LCA specification as used by Giacchetta et al. (2013). This LCA analyses the environmental performance of attrition and flotation processes used in CdTe recycling.

Table 10: LCA specification by Giacchetta et al. (2013).

Source	Giacchetta et al. (2013)
Recycle pathway	1. Physical disintegration 2. Attrition 3. Flotation
Goal	To determine only the environmental impact of the pre-treatment (recycling) process.
Functional unit	Photovoltaic panel CdTe
Geographical scope	Europe
Temporal scope (year studied)	2013
Impact assessment methodology	IMPACT 2002+ method
Impact categories	CA, NCA, RI, IR, OLD, RO, AET, TET, TAN, AA, AEU, LO, GW, NRE, ME
LCA software	SimaPro 7.1
Database for LCI	Ecoinvent; "Electricity, medium voltage, production UCTE, at grid/UCTE S" dataset
Data origin	Data on foreground processes from test facility of company leader (unnamed). Background processes from EcoInvent.
System boundaries	Pre-treatment process: from spent module to residues and disposed materials, including transportation of modules to recycling site. Exclusion of materials that can be reused.
Main assumptions	- Impacts of manufacturing, assembly, and usage are excluded. - Impacts of reusable materials have been excluded. - Transportation has been included. - For normalization the data is related to regional average data. - There is a high level of automatization in the recycling stage. - The method can recycle broken modules, intact modules, and scrap. - Recovery of materials is done by a third-party company and are not included in the LCA. - Elements that where present in low concentration were neglected. - For the transport, modules come from a region of maximum 500 km from the facility.

Giacchetta et al. (2013) describe the recycling/pre-treatment process of CdTe modules. In this the processes of physical disintegration, attrition, and flotation are analysed. The recovery of valuable metals from the flotation product and the treatment of glass are not included. However, transport related to the collection activities of the modules are included. To conduct this LCA, the SimaPro 7 software in combination with IMPACT 2002+ method has been used. Data was provided by the EcoInvent database and a test facility of a PV company.

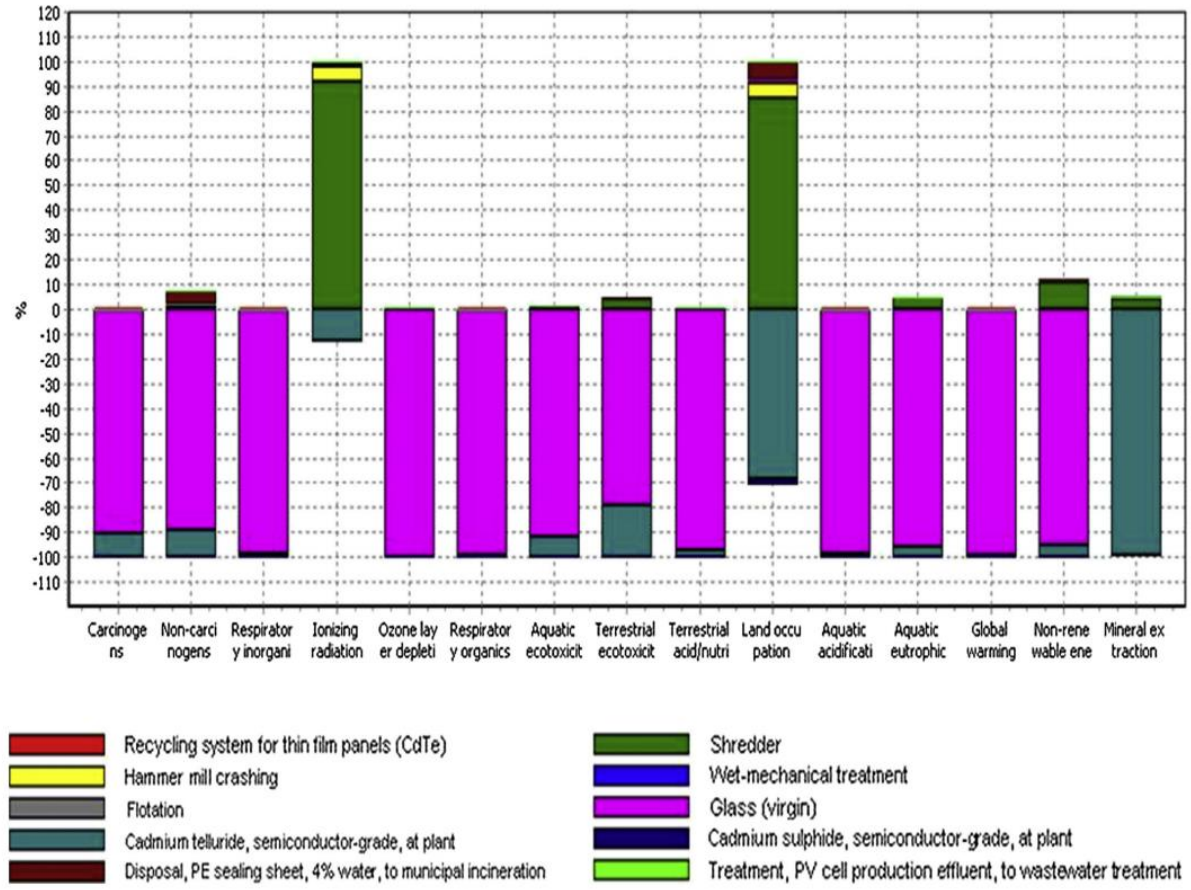

Figure 11: impact assessment for categories of impact.

The recycling process shows positive environmental impacts for ionizing radiation and land occupation. These positive impacts can mostly be attributed to the use of a shredder to physically disintegrate the modules. The shredder also shows an increasing effect on the impact of non-renewable energy, terrestrial ecotoxicity, and mineral extraction. Negative impacts can in most categories be attributed to the recovery of glass. The recovery of CdTe also contributes to a decreased impact in most categories. In the category of mineral extraction, the recovery of CdTe contribute most to the negative impact. After normalization it can be seen that the shredder has the largest effect on the non-renewable energy (Giacchetta et al. 2013).

Table 11: overview of hotspots from Giacchetta et al. (2013).

	Hotspots
IR and LO	Overall positive impacts due to the use of a shredder.
IR, TET, LO, NRE, and ME	Increased impacts due to use of shredder.
CA, NCA, RI, OLD, RI, AET, TET, TAN, AA, AEU, GW, NRE	Overall negative impacts due to the recovery of glass.
ME	Overall negative impacts due to recovery of CdTe.
CA, NCA, IR, AET, TET, TAN, LO, AEU, NRE, ME	Decrease impacts due to recovery of CdTe.

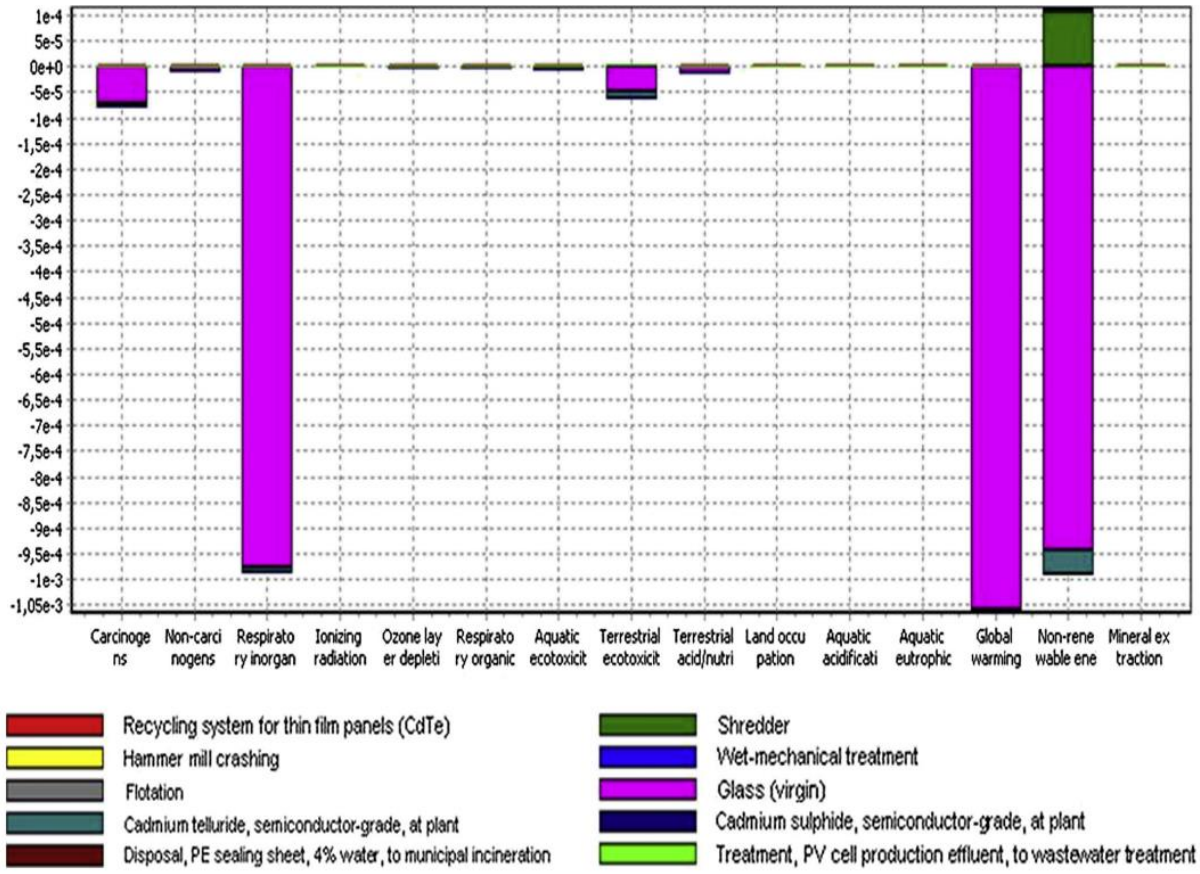

Figure 12: normalization of the impact results.

Marchetti et al. (2018) conducted a second LCA on attrition and flotation processes and compared those to attrition in combination with centrifugal extraction. The specifications of this LCA can be found in Table 12.

Table 12: LCA specification by Marchetti et al. (2018).

Source	Marchetti et al. (2018)
Recycle pathway	Double Green Process: 1. Physical disintegration 2. Attrition 3. Flotation **OR** Centrifugal extraction 4. Washing
Goal	To evaluate the impact of the recycling system.
Functional unit	The PV panel
Geographical scope	Europe
Temporal scope (year studied)	2018
Impact assessment methodology	IMPACT 2002+
Impact categories	CA, NCA, RI, IR, OLD, RO, AET, TET, TA, LO, AA, AEU, GW, NRE, ME
LCA software	Unknown
Database for LCI	EcoInvent database and the 'Electricity, medium voltage, production UCTE, at grid/UCTE S' dataset.
Data origin	Foreground data from testing facility, literature and processes by First Solar and RESOLVED. Background data from EcoInvent.
System boundaries	Only recycling system. Exclusion of fabrication, assembly, and use.
Main assumptions	- Fabrication, assembly, and use are excluded from analysis as the impact of the recycling system was evaluated. - This process is an update of the process by Giacchetta et al. (2013). - Process is highly automated because of automatic transport and feed. - Power needed for automatization has been included. - CdTe is recovered at a rate of 90% after flotation. - CdTe is recovered at a rate of 80% after centrifugal extraction.

Marchetti et al. (2018) have optimized the process developed by Giacchetta et al. (2013) (same research group). Two recycling strategies for CdTe modules are compared, one that uses flotation as separation mechanism and one that uses centrifugal extraction as separation mechanism. In this analysis only the recycling system is analysed, from spent CdTe module to materials that need to be purified, incinerated, or treated. The washing of glass is included in the analysis. The IMPACT 2002+ method, using all impact categories, has been used to analyse the environmental impact of both processes.

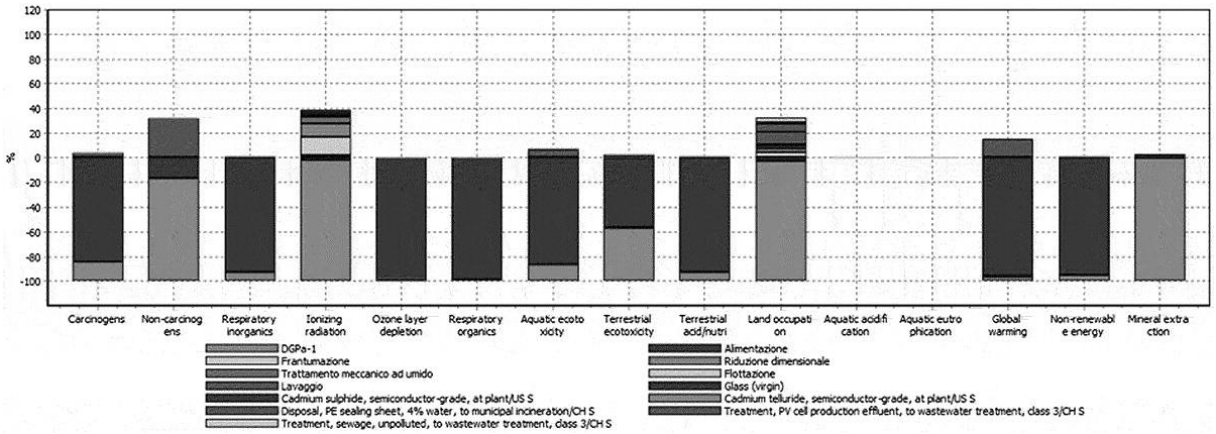

Figure 13: LCA results of recycling process with flotation.

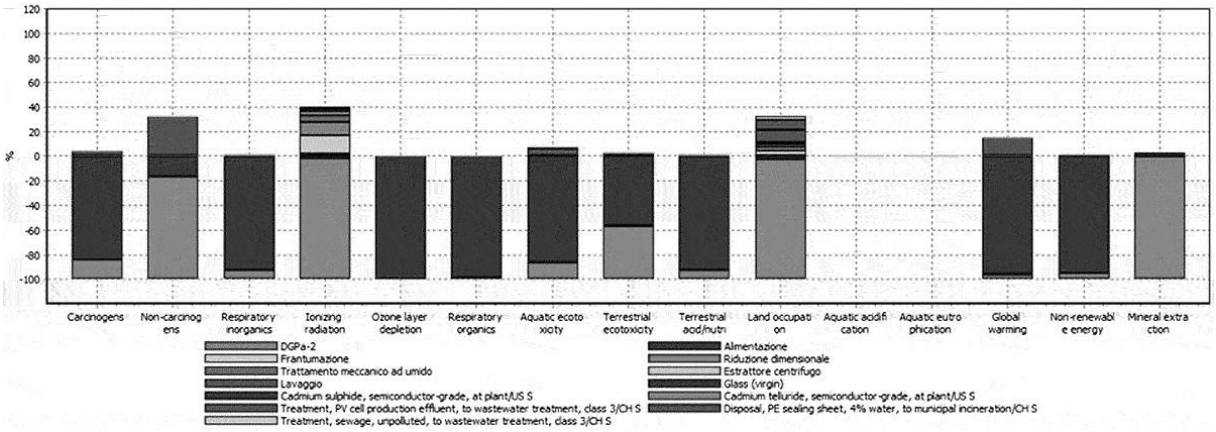

Figure 14: LCA results of recycling process with centrifugal extraction.

Waste that needs to be incinerated contributes most to the environmental load of the recycling processes. This is true for using both flotation and the centrifugal extractor. This is the only point the two processes differ. The difference is that a centrifugal extractor has a higher ionizing radiation potential. The rest is the same or negligible for both processes. Both processes have a negative effect on all impact categories (Marchetti et al. 2018).

Table 13: overview of hotspots from Marchetti et al. (2018).

	Hotspots
CA, NCA, RI, IR, OLD, RO, AET, TET, TA, LO, AA, AEU, GW, NRE, ME	Incineration of the residue accounts for increasing impacts in all categories.
IR	Centrifugal extraction increases the impact in ionizing radiation category.

A final LCA on First Solar's recycling process has been performed by Stolz et al. (2017) and the LCA details can be found in Table 14.

Table 14: LCA specification by Stolz et al. (2017).

Source	Stolz et al. (2017)
Recycle pathway	First Solar: 1. Physical disintegration (shredding and hammer milling) 2. Acid leaching 3. Precipitation of leaching product 4. Vibrating screening 5. Glass washing
Goal	To compile life cycle inventories of the recycling of c-Si and CdTe PV modules.
Functional unit	The recycling of 1 kg of used unframed CdTe PV modules at the place of installation.
Geographical scope	Germany
Temporal scope (year studied)	2017
Impact assessment methodology	ILCD Midpoint 2011
Impact categories	PM, FET, HTNC, HTC, MFRRD, CC
LCA software	SimaPro v8.4.0
Database for LCI	DQRv2:2016 and EcoInvent 2.2
Data origin	Foreground data based on publicly available data. Background data based on EcoInvent 2.2.
System boundaries	From spent modules at location of installation to the recovery of valuable materials.
Main assumptions	- Framed CdTe modules can be neglected. - Allocation is done economically. - Benefits are accounted for as credits for the avoided impact. - Other impact categories are neglected as they are not perceived as equally relevant. - Long-term emissions are not included. - Average transport distance is 678 km. - Modules are first transported by a 7.5-ton lorry from the installation to a collection point over a distance of 100 km. Then the modules are transported to the recycling plant by a >16-ton lorry. - Prices for economic allocation were based on First Solar's information, exchange rates of 2016, EUWID, and USGS. - Takeback and recycling of modules are considered separately from potentially avoided burdens by recovery of materials. - Net environmental benefits are based on environmental impacts and avoided burdens

Stolz et al. (2017) conducted a LCA on the recycle process by First Solar. In this analysis the net environmental benefits where calculated based on environmental impacts and avoided burdens. The SimaPro v8.4.0 software in combination with the EcoInvent 2.2 database was used to conduct the inventory analysis. The chosen impact assessment methodology was ILCD Midpoint 2011 of which the impact categories particulate matter, freshwater ecotoxicity, human toxicity (non-cancer effects and cancer effects, mineral fossil & renewable resources, and climate change were analysed. In this analysis transportation from the place of installation to the recycling plant was considered as well, just like the recovery of valuable metals. Economic allocation was chosen to assign burdens to the different materials.

Impact category	CdTe
Particulate matter	-1.6
Freshwater ecotoxicity	-0.41
Human toxicity, non-cancer effects	-1.4
Human toxicity, cancer effects	0.71
Mineral, fossil & renew. resources	-750
Climate change	-0.28

Figure 15: net environmental impacts: potential benefits divided by impacts. Negative number means that benefits are X times higher than impacts.

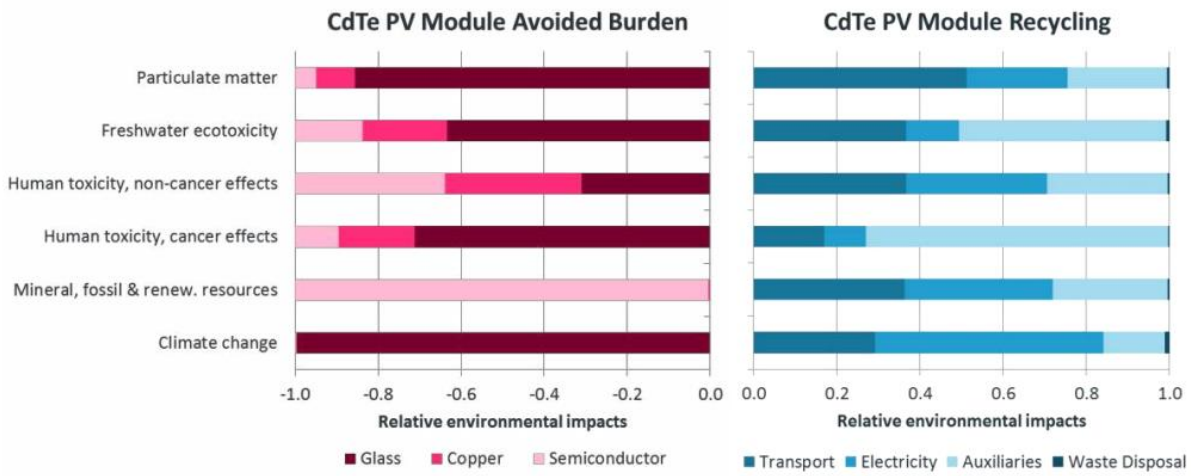

Figure 16: relative contributions of materials to avoided burden (left) and environmental impact (right).

The main hotspot identified is that the recycling process increases the human toxicity, cancerous effects potential. This can be largely attributed to the usage of chemicals in the treatment processes. These chemicals also contribute predominantly in the freshwater ecotoxicity impacts. Most of the avoided burdens come from the recovery of glass. However, the avoided burdens for the impact category of mineral, fossil & renewable resources outweigh the environmental impacts by a factor 750. This can be attributed to the recovery of semiconductor material. Transportation is also a large contributor in the particulate matter category. Electricity is the largest contributor to climate change potential. In this study it is also emphasized that the treatment of spent modules only contributes in a small amount to the total life cycle emissions of a CdTe solar module (Stolz et al. 2017).

Table 15: overview of hotspots from Stolz et al. (2017).

	Hotspots
HTC	Recycling process increases the cancerous effects on humans. Mainly caused by the use of hydrogen peroxide.
MFRRD	Avoided burdens are 750 times higher than the impacts due to recovery of CdTe.
PM, FET, CC	Avoided burdens can be attributed to glass recovery.
FET	Large contributing factor is the use of chemicals.

Finally, an LCA has been conducted on solvent and thermal treatments in combination with acid leaching. The LCA specifications can be found in Table 16 (Pagnanelli et al. 2019).

Table 16: LCA specification by Pagnanelli et al. (2019).

Source	Pagnanelli et al. (2019)
Recycle pathway	Solvent or thermal treatment: 1. Physical disintegration 2. Sieving 3. Solvent treatment of **OR** thermal treatment of coarse fraction. 4. Acid leaching of fine fraction
Goal	Comparing solvent and thermal processes
Functional unit	1000 kg of end-of-life panel
Geographical scope	Europe
Temporal scope (year studied)	2019
Impact assessment methodology	ILCD midpoint and PEF
Impact categories	AP, CC, TE, POF, HTNC, HTC
LCA software	GaBi
Database for LCI	Database for Life Cycle Engineering, EcoInvent 2.0
Data origin	All data from database for life cycle engineering. Data on glass cullet and solar glass from EcoInvent 2.0. Data on emissions of thermal treatment from literature.
System boundaries	Only End-of-Life management: crushing of spent module to acid leaching, solvent treatment, and thermal treatment.
Main assumptions	- CdTe module is frameless. - Excluded impact categories are not used based on maturity of category. - EVA after solvent treatment is disposed of as plastic waste in landfilling sites. - Positive effects are accounted for as credits. - Metal filaments recovered from physical disintegration are completely of copper. - The data per kg of glass was halved from the EcoInvent database, as at least 50% reduction was assumed. - Sustainability is described by comparison between loads and benefits. - Physical disintegration is not presented as impact was too low.

Pagnanelli et al. (2017) compares two recycling methods in which a coarse fraction gets treated by two different methods, thermal treatment, and solvent treatment. The LCA includes only the End-of-Life: physical disintegration, acid leaching, and one of the two methods. It is conducted in GaBi software using the GaBi databases and EcoInvent 2.0. Impact assessment is done by ILCD midpoint using the impact categories acidification, climate change, terrestrial eutrophication, photochemical ozone creation, and human toxicity (both cancer and non-cancer effects). Other impact categories are excluded as they are not mature enough to be used.

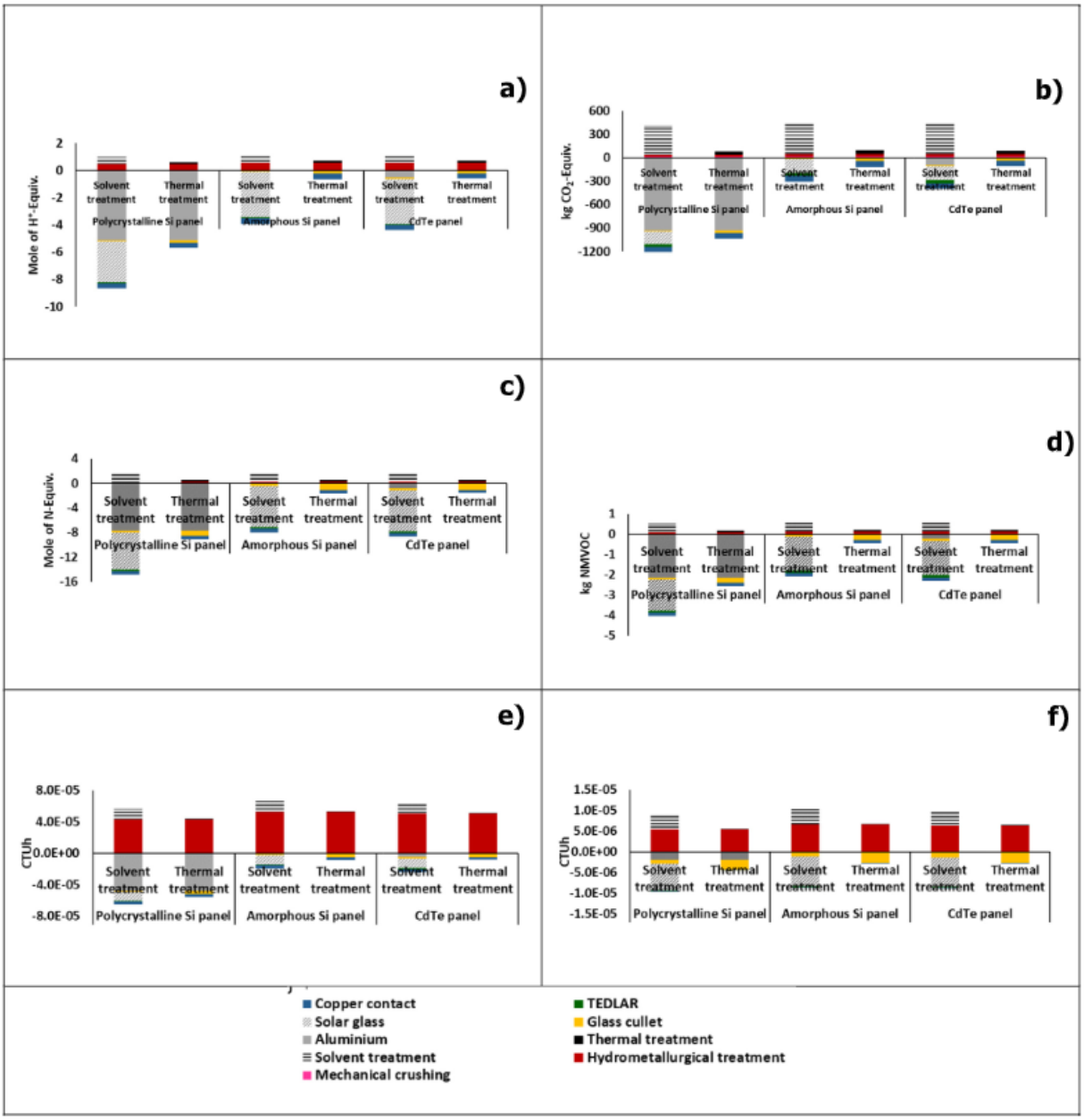

Figure 17: potential impacts for solvent treatment and thermal treatment of CdTe panels.

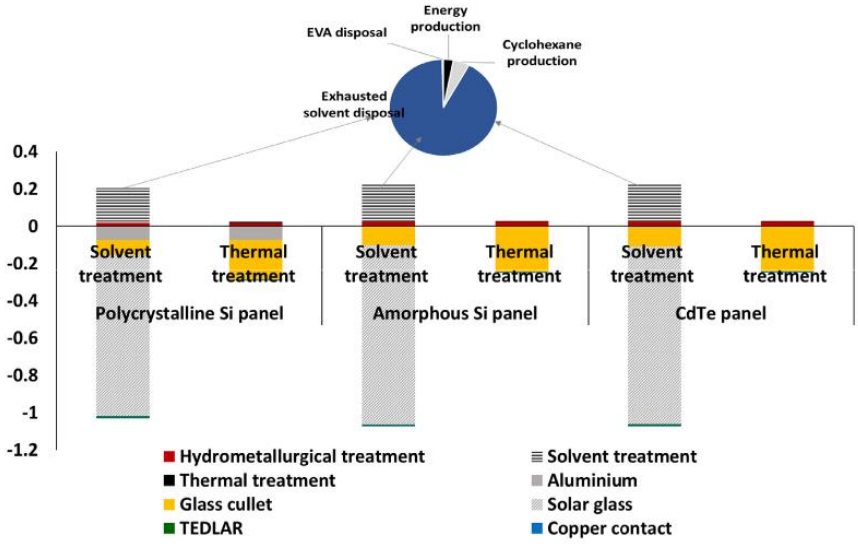

Figure 18: normalized and weighted environmental impacts of PV recycling.

From the results of the conducted LCA the solvent treatment has lower environmental impacts than the thermal treatment in most categories. This can be attributed to the recovery of solar glass, which is of higher value for the solvent treatment. The thermal treatment outperforms the solvent treatment in the climate change category, because of the use of cyclohexane in the thermal treatment that needs to be treated afterwards. Acid leaching for the fine fraction makes the human toxicity potentials of both pathways positive and increases the impacts of all categories. It is stated that the recycling impact is only a small part of the total impact that is mainly represented by the production. Overall, the solvent treatment option has a bigger negative impact than the thermal treatment option.

Table 17: overview of hotspots from Pagnanelli et al. (2019).

	Hotspots
CC	Positive impact due to the use of cyclohexane.
HTNC, HTC	Positive impact due to acid leaching.
AP, CC, TE, POF, HTNC, HTC	All categories have an increasing impact due to acid leaching.

Methods

This chapter describes the research methods that were applied in this study. First, the basics of harmonising life cycle assessment data was discussed and how this was be applied in this study. Secondly, the specifications of the comparative life cycle assessment that was conducted in this study were described. Finally, the models that were used for the qualitative assessment were explained.

Harmonization of LCA Results from Literature

Life cycle assessments have been done on multiple End-of-Life stages. As they are all done using different criteria, there is a need to harmonize this data to compare different EoL stages correctly. When harmonization is done, numerous elements need to be taken into account.

First, the goal and scope of the conducted LCA's need to be examined. This means comparing functional units and system boundaries. In terms of functional unit it is necessary to compare similar reference flows in order to look at quantitative data differences. For example, 100 kg of a product will generate an impact 100 times as big as 1 kg of that product (if all other assumptions are similar). For the system boundaries even more attributes can differ. In every study there will be a decision made on which processes to include and exclude, what products to cut-off and where the process flow begins and ends. Different choices give different outcomes, so identifying the different boundaries might help understand why certain results differ.

Secondly, the approach taken to allocate impacts across co-products is an important factor. This means knowing how environmental burdens of one multi-functional process are divided over the individual products that come out of this process and how much of the potential impacts can be attributed to the functional unit. This can be done by multiple methods. System expansion makes use of 'avoided burdens'. Co-products that are not part of the functional unit replace products in a different system, thus lowering the potential impacts of that system. These burdens can then be called 'avoided' and are substracted from the potential impacts of the functional unit. Economic allocation means that the burdens are divided based on the value of the co-products. More burdens are then assigned to more valuable products. Alternatively, physical allocation can be applied in which burdens get divided based on their mass. A co-product with a greater mass is assigned more burdens than a co-product with a smaller mass. Another allocation method is allocation at the point of substitution. In this allocation approach burdens are either only attributed to one co-product or treatment of co-products happens in the same process flows, meaning no multifunctionality is modelled. Different allocation methods could provide for different results. Burdens could shift greatly when different allocation methods are applied. An example of this is that a heavier material might be much less valuable then the lighter material. In physical allocation the burdens will be mostly on the heavy material, but in economic allocation this burden will rest more on the lighter material (Guinée et al. 2002; Williams and Eikenaar 2022).

A third element that could be applied differently in LCA is the way recycling is modelled. The cut-off or recycled content approach means that a cut-off is applied at the place where the material that is to be recycled leaves the product system. The burdens are then allocated to the product that need treatment in the recycling process. Another approach is closed-loop recycling. This means that all material that is recycled will be used in the same product again. Burdens are then allocation to the production of the material. More recycled material means that the burdens will be lower as well (Williams and Eikenaar 2022).

Finally, the choice of life cycle impacts assessment method is key in comparing different LCAs done on the same topic. Multiple methods using their own impact categories could be chosen to conduct a LCA.

Some of these categories are interchangeable because they use the same characterization factor, most are not. When using different methods it might thus be hard to make a valid comparison. Next to that the database used for the Life Cycle Inventory influences results as well. Some have more recent data then others, or make use of different sources and allocation methods.

Recognizing that all these factors influence the outcomes of an LCA, the conducted analyses on CdTe solar module recycling strategies were harmonized based on functional unit, system boundaries, allocation methods, LCIA methods and LCI sources. Hotspots that were identified in the studies were then placed in context and related to each other (Jourdaine et al. 2020; Santero and Hendry 2016).

Functional units that were chosen all entail the CdTe modules. The differences are found in the quantity of the CdTe module. This was harmonized by assuming that 1 m^2 of CdTe module has a weight of 16.6 kg (Giacchetta et al. 2013). Variation on this assumption is discussed in the limitations section of this report. As most are in terms of 1 m^2 of CdTe module, the results of the other units can be transformed by multiplying with a factor that scales the results to 1 m^2. Another thing to note is that hotspots are found based on relative impacts, so the unit does not matter for the identification of the hotspots.

The **system boundary** can be divided into three types. The boundary between the product system and the environment is the distinction between flows that have not been subjected to human transformation (environmental flow) and flows that are part of the product system (economical flow). This boundary is again crossed when a product is discarded to the environment (from economical to environmental flow). Another type of boundary is the boundary between relevant and irrelevant processes to the product system. Relevant processes are analysed within the product system, irrelevant processes are cut-off. Cut-off is applied when there is a lack of accessible data. In basic terms it means that the burdens of that process are ignored, potentially influencing the outcomes of the LCA greatly. The third boundary is the boundary between product systems. This essentially means that a co-product of a multi-functional process will not be investigated in the studied product system and will be allocated to other product systems (Guinée et al. 2002). Most LCA studies identified in the literature review only analysed the product system related to the End-of-Life stage of the CdTe solar module. This meant that the other processes are cut-off from their analysis. This resulted in the exclusion of the material extraction phase, production phase, and use phase. Only Vellini et al. (2017) includes all these processes of the life cycle. An important difference to keep in mind is that products are cut-off at different places. Most studies cut the processes off at the point where valuable materials are present in a mix and only need a recovery and purification step. This step is included by Rocchetti & Beolchini (2014) and by Stolz et al. (2017). One on one comparison with recycle strategies that exclude these steps is not possible, but as the function of the system remains the same the results can be related to each other. Important here is to discuss the different outputs. It might mean that one recycling pathway maybe perceived as having a lower impact, while it is not sure if the excluded processes do contribute to these impacts. (Santero and Hendry 2016).

The study conducted by Vellini et al. (2017) comprises of the whole life cycle of CdTe solar modules. Comparing the impacts of this life cycle including recycling with the assessments done only on recycling is not possible. However, this study compares the impacts of a life cycle with recycling to a life cycle without recycling. The difference in impacts can be allocated to the recycling processes in place. These relative differences on the other hand are better suited to be compared to the recycling processes analysed in the other assessments.

To compare **Life Cycle Impact Assessment results**, the relative change between the recycling processes and the process of disposal they are related to were observed. All studies have conducted a

comparative LCA between scenarios with recycling and without recycling. The differences between these scenarios can be placed in relative values. These relative differences can be compared between studies. Important here is that system boundaries are not neglected. Stolz et al. (2017) covers the recovery of valuable metals, which is neglected in some studies. The contribution of this recovery to the impact categories is about 15% (Stolz et al. 2017). Based on this, the studies that excluded the recovery of valuable materials assumed an increase of 15% for this comparison of the impact results.

Hotspots were identified for all studies. These hotspots cover the processes and materials that contribute in large amounts to increased environmental impacts. The ones that are presented here are only the ones that were identified within the recycling systems. Hotspots outside these boundaries are not mentioned.

Comparative Life Cycle Assessment

To analyse processes that have not been covered in literature and to give a comparison based on the same parameters, a comparitive LCA has been executed. The framework that can be seen in Figure 19 shows the structure that was followed for this LCA.

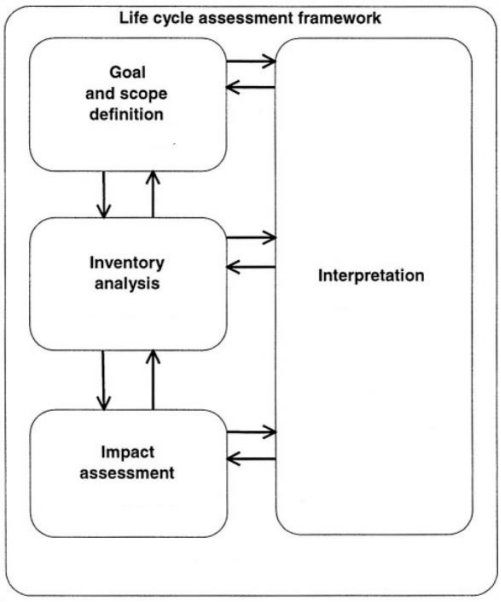

Figure 19: life cycle assessment framework as proposed by Guinee et al. (2002).

Goal and Scope Definition

The goal of the LCA in this chapter is to find the hotspots of environmental impacts related to different recycle strategies within the life cycle of CdTe solar modules. Based on this comparative analysis, trade-offs can be found on using one recycling technique over the other.

The database that is used for this LCA is the EcoInvent v3.8. This database originates from 2021 and is used as a base year for all background data. For the other data, literature was used which does not date back more than 20 years. The geographical scope is global as most solar input comes from global markets within this database. The system boundaries are set to be cradle-to-grave, including the recycle processes. This starts from the harvesting of material to the decommissioning of the module.

Function, Functional Unit, Alternatives, and Reference Flows

The different recycle pathways are all assessed individually and compared. This means they have the same function and functional unit, but different reference flows. These can be found in Table 18. The recycling of 1 m^2 CdTe solar module was chosen as functional unit as the literature is harmonized towards this.

Table 18: Function, functional unit, alternatives, and reference flows of conducted LCA.

Function	Recycling of CdTe solar module
Functional unit	The recycling of 1 m^2 CdTe solar module
Alternatives	1. Recycling using acid leaching. 2. Recycling using alkaline leaching. 3. Recycling using acid leaching and ion exchange. 4. Recycling using solvent treatment. 5. Recycling using pyrolysis. 6. Recycling using vibrating screening. 7. Recycling using glass washing. 8. Recycling using attrition and centrifugal extraction. 9. Recycling using attrition and flotation. 10. Recycling using thermal treatment and vacuum blasting. 11. Recycling using dry etching and HCl treatment.
Reference flows	1. The recycling of 1 m^2 CdTe solar module using acid leaching. 2. The recycling of 1 m^2 CdTe solar module using alkaline leaching. 3. The recycling of 1 m^2 CdTe solar module using acid leaching and ion exchange. 4. The recycling of 1 m^2 CdTe solar module using solvent treatment. 5. The recycling of 1 m^2 CdTe solar module using pyrolysis. 6. The recycling of 1 m^2 CdTe solar module using vibrating screening. 7. The recycling of 1 m^2 CdTe solar module using glass washing. 8. The recycling of 1 m^2 CdTe solar module using attrition and centrifugal extraction. 9. The recycling of 1 m^2 CdTe solar module using attrition and flotation. 10. The recycling of 1 m^2 CdTe solar module using thermal treatment and vacuum blasting. 11. The recycling of 1 m^2 CdTe solar module using dry etching and HCl treatment.

Inventory Analysis

System Boundaries

The economy-environment boundary is the boundary within which the system is analysed. The input of the system are the materials that get extracted in mining processes. The output of the system are materials that are not able to be recycled and that will be discarded to the environment. Everything in-between is included in the life cycle assessment.

Flow Charts and Unit Processes

In Figure 20 the flowchart of the acid leaching process can be seen. This is an example of how the process flows are presented in this paper. The flowcharts of the other alternatives can be found in Appendix A.

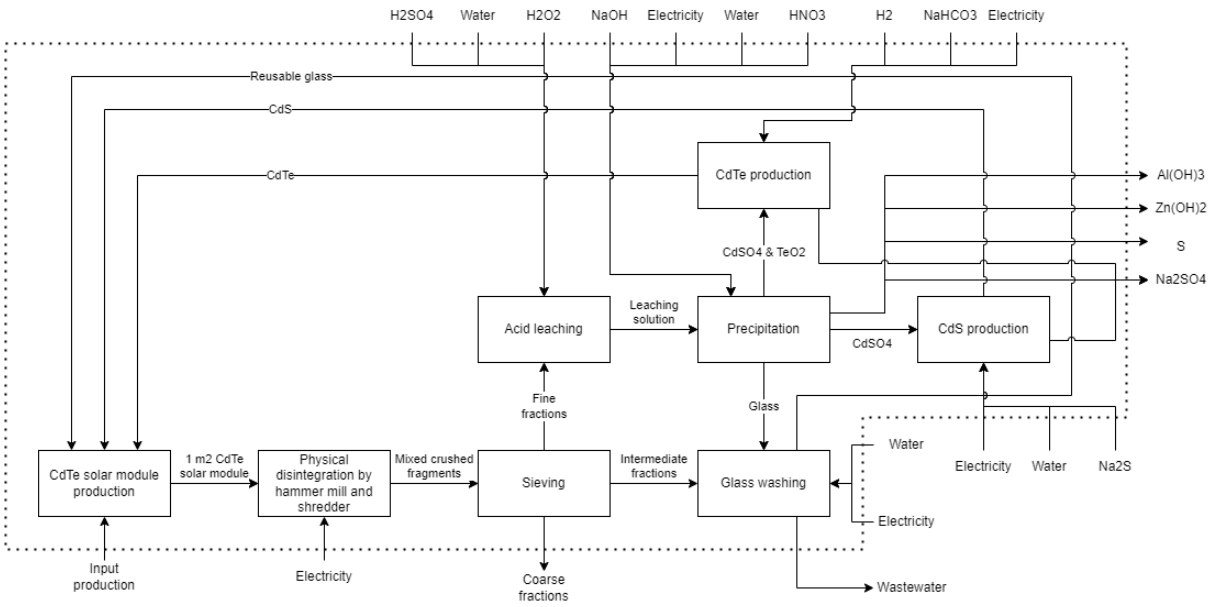

Figure 20: flowchart of reference flow 1 the recycling of 1 m2 CdTe solar module using acid leaching.

The unit processes are represented as illustrated in Table 19. These consist of economic and environmental in- and outflows. In this table the acid leaching process can be seen. A fine fraction together with sulfuric acid and hydrogen peroxide go in. Assumed here is that solid-liquid separation took place as well. This means a liquid stream with metals goes out as an economic flow to the precipitation steps and a solid residue of glass goes out as an economic flow to waste glass treatment. From the environment, water was taken to get dissolved chemicals and metals. In this process there is no direct outflow of material to the environment. The other unit processes can be found in Appendix B.

Table 19: unit process of acid leaching.

Unit process:	**Acid leaching**		
Economic flows	*Amount*	*Unit*	*Product*
In:	1.66	kg	fine fraction (< 1 mm)
	6.45E-02	kg	H2SO4
	3.18E-02	kg	H2O2
Out:	7.12E-01	kg	liquid stream
	9.40E-01	kg	solid residue
Environmental flows			
In:	5.68E-04	m3	H2O
Out:	-	-	-

Impact Assessment Methodology

For impact assessment the impact assessment methodology of EF version 3.0 was chosen. This methodology makes use of the impact categories as shown in Table 20. The impact assessment was executed in the Activity Browser software (Steubing et al. 2020).

Table 20: specifications of impact assessment methodology EFv3.0.

Impact category	**Characterisation factor**	**Unit of indicator result**
acidification	AP	mol H+-eq

climate change	GWP100	kg CO2-eq
freshwater ecotoxicity	FEP	CTUe
abiotic depletion of fossil fuels	ADP (FF)	MJ, net calorific value
freshwater eutrophication	FETP	kg PO4-eq
marine eutrophication	METP	kg N-eq
terrestrial eutrophication	TETP	mol N-eq
human toxicity, carcinogenic	HTCP	CTUh
human toxicity, non-carcinogenic	HTNCP	CTUh
ionising radiation	IRP	kBq U235-eq
land use	LUP	dimensionless
abiotic depletion of elements	ADP (E)	kg Sb-eq
ozone depletion	ODP	kg CFC-11-eq
particulate matter formation	PMFP	disease incidence
photochemical ozone formation	POFP	kg NMVOC-eq
water use	WUP	m3 world eq deprived

Multifunctionality and Allocation

For this study, economic allocation is applied. This choice was made as the mass of the solar cell consists largely of glass, which has a considerable low value (Appendix C). When the choice was made for physical allocation much of the burdens is attributed to glass. Using economic allocation means that burdens were divided based on the value of the product that goes out. This seems the most appropriate allocation method as small quantities of the metals are more worth than large quantities of glass.

Assumptions

A major assumption that is applied to the full study is that capital goods like industrial equipment and factories are excluded from the LCA. This choice was made because the impacts of capital goods are based on very rough estimates, raising the uncertainty of the whole model results. The LCA study will be more reliable if capital goods are excluded. Next to that, capital goods show no relevance in most impact categories of studies (Silva et al. 2018).

Another major assumption is that chemical reactions are all performed without excess, unless stated otherwise in the methods analysed. This means that the reactions all have the exact right amounts of reactants going in and products going out.

For the full study it is also assumed that emissions are based on recovery efficiencies of processes. Everything that is not recovered is assumed to be emitted in water if they are solved or in air if they are not.

Important to note is that not everything will be used as an input for the production processes. The choice was made to only account for the recovery of glass, CdTe, and CdS. This assumption was made because treating the full mix covers these three materials for every combination. This means that recovery of EVA, ITO layer and back contact are not considered in this study. EVA is not considered as it is mostly incinerated or solved, non-recoverable. The ITO layer and back contact are not included as most studies exclude the recovery of these materials as well.

For the assumptions made in the individual process, see the Appendix D.

Qualitative Assessment

Next to the quantitative LCA analyses, additional insights can be obtained by qualitatively investigating of social and economic characteristics of the different pathways. This gives different perspectives on which decisions on the recycle pathways can be based. Additionally, combining quantitative and qualitative results could provide more valid conclusions, as more criteria will be used to analyse the different options. The more criteria, the more concise the description of each recycle technique and pathway (Lund 2012).

For this research, the indicators that will be considered in terms of a qualitative analysis are:

- Maturity
- Costs
- Value of recovered material

(Maani et al. 2020; Tao and Yu 2015)

The maturity of the technology encompasses the age and development of the technology. Mature technologies have received substantial upgrades and a majority of faults have been removed. This means that efficiencies and performances are close to their maximum point. The understanding and control of this type of technology is well developed, leading to safe implementation. Less mature technologies are less developed and might show unexpected features. This causes a drop in safety of implementation (Lezama-Nicolás et al. 2018). The maturity of the recycle pathways was assessed by two characteristics. The first one is the Technology Readiness Level (TRL). Within this model the technology was rated based on the characteristics as can be seen in Figure 21. The higher the TRL, the more the technology has been tested and tried, leading to less faulty technology (Tzinis 2021).

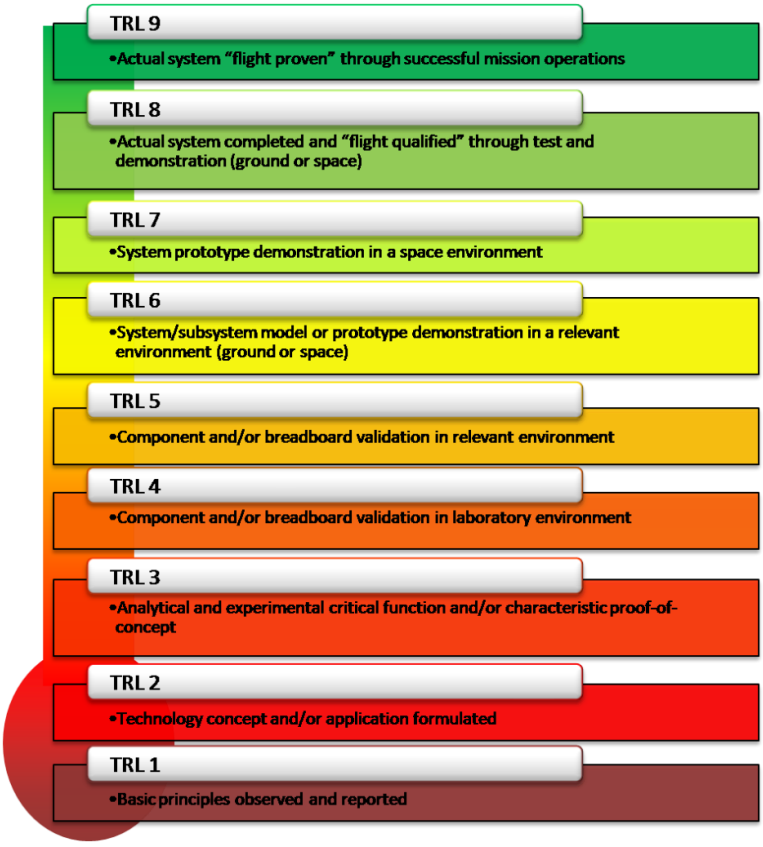

Figure 21: The different levels of the Technology Readiness Level model (Tzinis 2021).

The second assessment method that was used is the Technology Adoption Life Cycle (TALC). In this model the rate of adoption was assessed. As can be seen in Figure 22, a technology that is placed more to the right has a high adoption level. The connection between high adoption level and maturity is that the technology is more adopted when it is more mature (Mirthinti 2023).

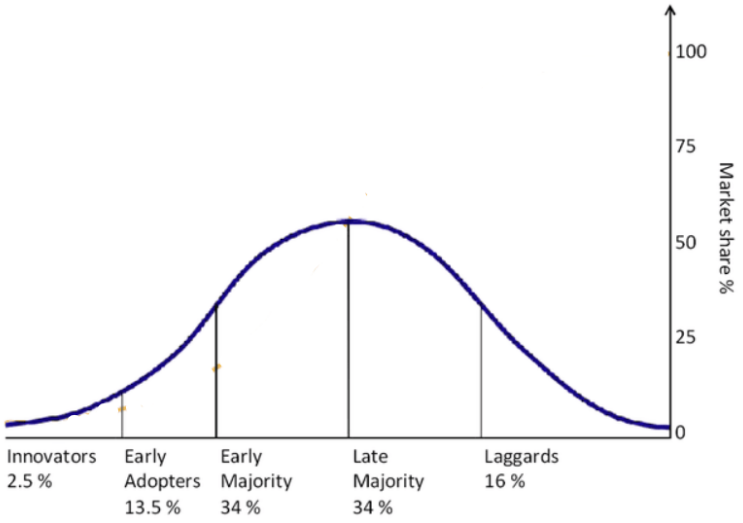

Figure 22: The Technology Adoption Life Cycle (Mirthinti 2023).

The TRL and TALC models together make an assessment on how mature the technology is. For this it is assumed that both models have an equal share for the rate of maturity. An important distinguishment between these models is that the TRL shows how advanced the technology is and that the TALC shows how much this technology is applied.

The cost of technology includes all the costs related to materials, factories, and machinery used in the recycle process. Additionally, a recycling technology that has not been implemented yet, could be having higher costs as all infrastructure needs to be developed and other investments need to be done. The costs could also be reduced by subsidies that are in place for certain technologies. From Deng et al. (2019) it can be seen that processes that focus on glass recovery have the lowest operation costs, followed by mechanical processes in combination with chemical processes that recover metals. The highest costs can be found for thermal processes in combination with chemical processes for the recovery of metals (Deng et al. 2019). This trend can be seen in Figure 23.

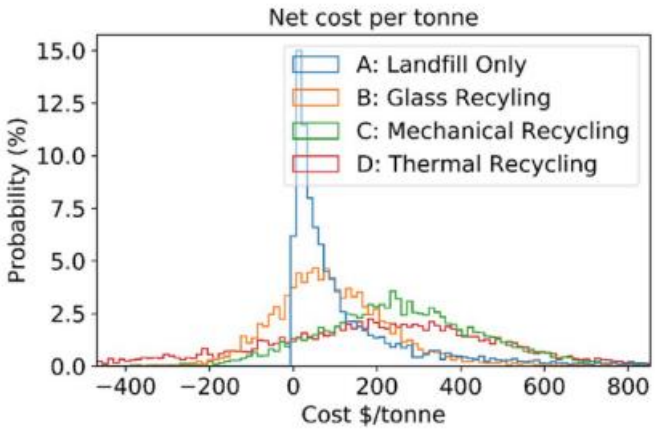

Figure 23: costs of treatment processes (Deng et al. 2019).

The recycling methods do not all recover the same material. The type of material that each recycling method recovers can also be an indication of how valuable each technology can be. For example, when glass is the main product that is recycled the technology might be less valuable than a technology that recovers and recycles CdTe. Thus, the recovery value was based on the materials that were recovered. Only the recovery of glass gives the lowest score as glass has the lowest economic value and is the least scarce material. Recovery of CdTe and CdS gives high scores as they have a large value and consist of toxic and scarce material. If everything is recovered, this gives the highest score. The value of the recycled material can be found in Appendix C.

The mentioned indicators will be graded from 1 to 3. High maturity, low costs, and high value of recovered materials are attributed a score of 3. The different recycle techniques are compared to each other. Take note that in this analysis only the techniques and not the full possible pathways are discussed. When full pathways are taken it might be unclear which processes contribute mostly to the different criteria.

Results and Discussion

In this chapter the results of the analyses are presented. First the results of harmonization are presented. These results are expressed in the discovered hotspots for each study, showing where studies agree and disagree upon. The second part of this chapter shows the results of the conducted LCA. These results consist of an impact assessment and an interpretation section. The interpretation section entails a contribution analysis, a hotspot analysis, a global sensitivity analysis, and a local sensitivity analysis. The final part presents the results of the qualitative assessment.

Results of Harmonization

From the harmonization effort, hotspots could be identified for all LCAs that have been conducted. In Appendix E an overview is given of all identified hotspots. Most studies analysed different pathways, giving some hotspots that differ because of direct relation to a process that is only found in that pathway analysed. On the other side, hotspots were also found for multiple studies that analysed different recycle pathways.

There were multiple studies conducted on the recycle pathway as defined by First Solar (Held 2009; Rocchetti and Beolchini 2015; Vellini et al. 2017; Stolz et al. 2017). Three of these studies found similar hotspots for the usage of chemicals and reactants that were used for acid leaching to recover the valuable metals. Because of the use of these chemicals, additional hotspots were identified for the treatment of wastewater. Only Vellini et al. (2017) did not find these hotspots, this could be attributed to the fact that the LCA in this study was conducted on the full life cycle, while the others were not. By zooming in on the recycle processes, those studies found these additional hotspots. Another thing two studies analysing this pathway agree on is the hotspot for energy use and incineration processes (Held 2009; Vellini et al. 2017). Energy that was used in these processes increases potential impacts and is a large contributor for multiple impact categories. Incineration of EVA and waste was a large contributor to global warming. However, the other studies by Rocchetti & Beolchini (2014) and Stolz et al. (2017) did not find these hotspots. This was partly attributed to the exclusion of incineration of waste and EVA in these studies.

Additional energy use needed for recycling processes was found to be a hotspot for two other studies as well. This was attributed to the use of attrition processes, thermal treatments, and shredding processes (Berger et al. 2010; Giacchetta et al. 2013). Similar results were also discovered for the use of chemicals. All additional studies that analysed recycle pathways that included chemical processes identified the same hotspots for the use of chemicals and wastewater treatment.

Next to hotspots, most studies agreed on the recovery of glass as a major contributor to lowering potential impacts. As Vellini et al. (2017) described the full life cycle, it was seen that potential impacts decreased due to recovery of semiconductor material.

Results of LCA

Impact Assessment

The results of the LCA are represented by relative data to the impacts of the production of CdTe modules. Overall, it was found that processes like alkaline leaching and acid leaching, that mainly focus on the recovery of the metals, lower the impacts. Acid leaching in combination with ion exchange on the other hand causes higher impacts in multiple categories. Processes that mainly focus on the recovery of glass do not contribute as much to lowering the environmental impacts. In many categories these glass recovery processes cause even an increase of impacts, as can be seen for the case of pyrolysis. The washing of glass contributes to higher impacts in seven categories, but contrarily lowers impacts in nine other categories. Processes that cover the recovery of both valuable metals and glass lower the impacts in most categories with a high factor. To get a better view of what processes have what kind of effect on the impacts, the processes that treat similar parts are compared to each other.

Acid leaching, alkaline leaching, and ion exchange focus on recovering of valuable metals from the sieved fine fractions only. Comparing these three gives the following results (Figure 24).

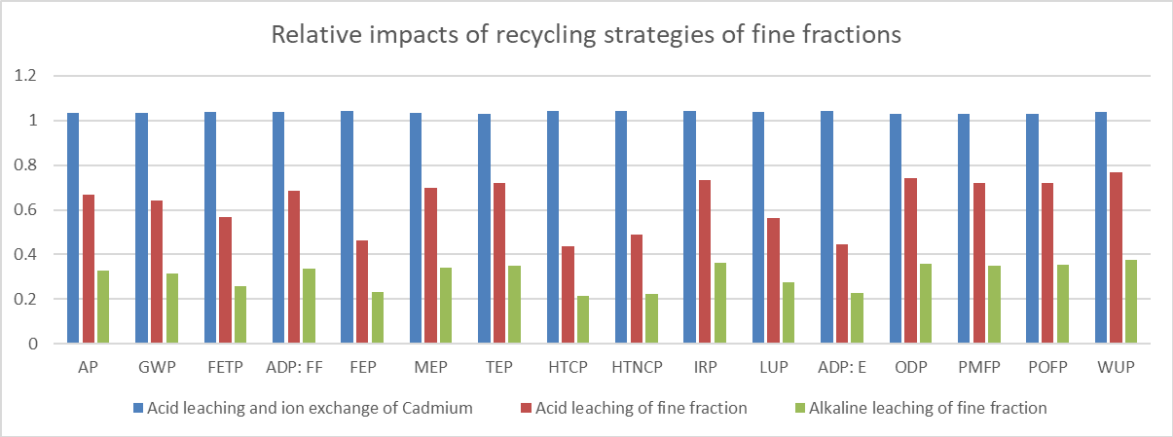

Figure 24: relative impacts of recycling strategies of fine fractions compared to production of CdTe modules.

Alkaline leaching lowers the impacts in all categories by more than two times at least. The largest reduction of impacts can be seen in the human toxicity (both cancerous and non-cancerous) and abiotic depletion categories. Similar to alkaline leaching, is a reduction detected for acid leaching in all categories. This impact reduction is almost twice as little compared to alkaline leaching. The combination of acid leaching and ion exchange causes an increase in impact for all categories. This means that ion exchange cancels out the reduced impacts caused by acid leaching. This might be related to the extra steps that were modelled that were needed for ion exchange. The increase is not very much, so this could still be a viable recycling process.

In terms of glass recovery a comparison could be made between pyrolyis, solvent treatment, and vibrating screening. This will also include the washing of the intermediate fraction, as this only consists of glass. This gives the following results (Figure 25).

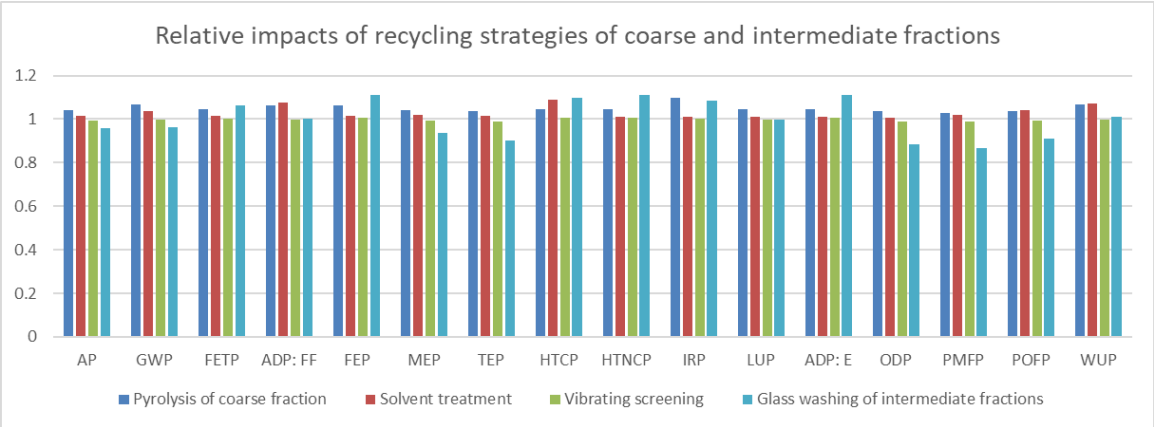

Figure 25: relative impacts of recycling strategies of coarse and intermediate fractions compared to production of CdTe modules.

In figure 25 it can be seen that pyrolysis has an increasing potential for all impact categories. Pyrolysis shows the most increased potential impacts for acidification, global warming, marine and terrestrial eutrophication, ionising radiation, land use, ozone depletion, and particulate matter formation. In the impact categories of freshwater eutrophication, human toxicity, and abiotic depletion, the washing of glass causes the most increased impacts. Besides that, an increasing potential impacts in abiotic depletion and water use is seen for this process. However, glass washing shows a large reduction of potential impacts in the other categories. Solvent treatment causes an overall increase in potential impacts in all categories. In the categories of abiotic depletion and water use it shows the most increased potential impacts. Vibrating screening causes almost no difference in impacts. In some impact categories the potential impacts are a little bit higher in the others a little bit lower. On the other hand this means that overall, vibrating screening might be favorable as it has no large increased impacts in any category.

There are also methods that don't treat fraction individually, but treat the whole mix together. These are attrition with flotation, attrition with centrifugal extraction, thermal treatment with vacuum blasting, and pyrolysis with dry etching and HCl treatment.

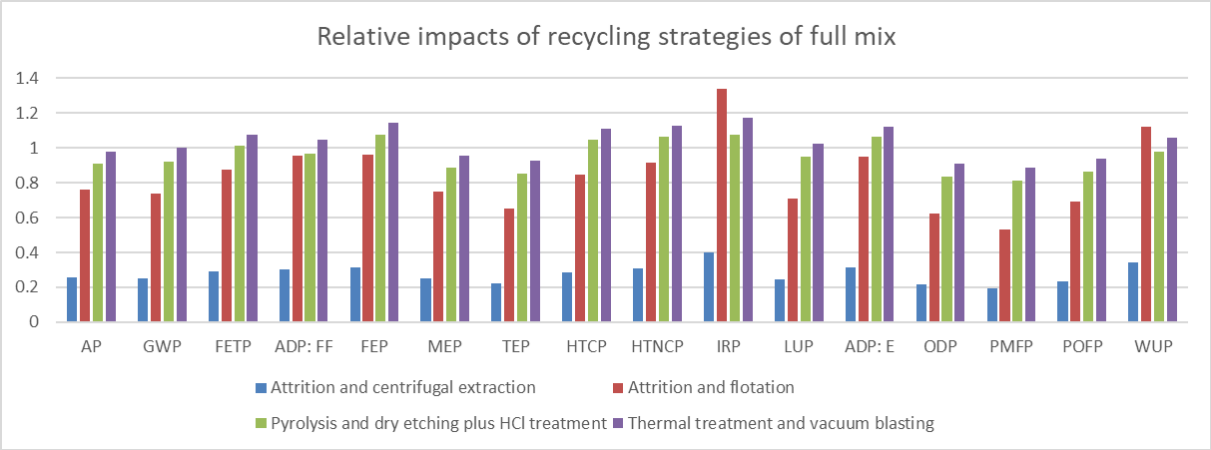

Figure 26: relative impacts of recycling strategies of full mix normalised to production of CdTe modules.

A large reduction in potential in every impact categories can be seen in the usage of attrition in combination with centrifugal extraction. Looking at attrition in combination with flotation it shows that potential impacts are reduced as well in almost all categories. Only the water use potential and the ionising radiation potential of this process combination are increased. However, in both categories

these are the highest impacts identified. Pyrolysis and dry etching show potential impacts that are mostly a reduction in the impact categories. This process does show increasing potential impacts for freshwater ecotoxicity, freshwater eutrophication, human toxicity, ionising radiation and abiotic depletion of elements. The combination of the processes thermal treatment and vacuum blasting shows increasing potential in most impact categories. For acidification, marine and terrestrial eutrophication, ozone depletion, particulate matter formation, and photochemical ozone formation it shows potential reductions. In the other categories this combination of processes shows increased potential impacts. It showed the highest increased potentials for freshwater ecotoxicity, abiotic depletion, freshwater eutrophication, human toxicity, and land use.

Interpretation: Contribution Analysis

A contribution analysis was performed to see what processes throughout the life cycle of CdTe module contributes the most to the impact scores of the LCA. Note that a contribution analysis only says something about what part of the total impacts can be attributed to a certain process and not about the magnitude of the impacts. The contribution analysis for all impact categories can be found in Appendix F.

Overall, the contribution analysis shows that extraction of raw materials and production of glass and semiconductor materials show a large contribution to most impact categories. Recycle pathways that recover more materials show a decreased contribution of the extraction and production processes as input material is replaced. The generation of energy, both electricity and heat, is another significant contributor to most impact categories. For recycle pathways that use more energy, this contribution is increased. Additionally, processes that make use of chemicals show noticeable contributions of the production of these chemicals and the treatment of wastewater after recycling. These contributions are not as large as the previous, but are largely assigned to the actual recycling processes, making them a hotspot for the recycling pathways.

Additionally, there are some observations done that only apply to one or a few impact categories. Within global warming, it can be seen that the pyrolysis of EVA is a notable, even though not much more than 1%, contributor to the impacts. For the leaching process, the potential impact on freshwater ecotoxicity and human toxicity categories can partly be attributed to the unrecovered materials. These unrecovered materials have been modelled as emissions and no treatment was assumed. A large contribution can be spotted in the abiotic depletion of fossil fuels and photochemical ozone formation due to benzene production for the input of the solvent treatment. The impacts on freshwater and marine eutrophication are largely contributed by waste and wastewater treatment processes. For both combined attrition processes the wastewater treatment contributes more. For marine eutrophication, the process of nylon 6,6 production is also a noticeable contributor to thermal treatment and vacuum blasting, pyrolysis and dry etching, and glass washing. In land use, a negative contribution can be seen attributed to recultivation practices. When impacts are lowered more, it can be seen that the actual installed CdTe solar module starts to contribute to the land occupancy. In the impact category of ozone depletion transportation is the largest contributor. Next to that, the electrolysis of chlor-alkali contributes to the attrition processes, glass washing, pyrolysis and dry etching, solvent treatment, and thermal treatment and vacuum blasting. Finally, the potential water use impacts are greatly contributed by EVA production processes.

Hotspots of LCA

The hotspots that were discussed, are based on the impact assessment and the contribution analysis. The relative impacts identified which processes increase or decrease potential impacts compared to CdTe solar modules for which categories. Using the contribution analysis, it was identified what the actual causes of these changing potential impacts are.

General Hotspots

The contribution analysis showed that only a small part of impacts can be related to recycling processes. Large contributors to the potential impacts are mostly related to production processes. The production of glass, acquiring and treatment of metals, and energy production are the highest contributors. The processes that are able to lower material input more, also show lower potential impacts in categories that are heavily influenced by this material. The processes that focus more on recovery of valuable metals show a greater reduction in potential impacts.

Other important hotspots that were identified is that processes that make use of chemicals show greater contribution to the impact categories. However, processes that make use of chemicals lower the overall impacts. Another interesting thing to see is that processes that cover the full mix show a larger contribution of wastewater treatment in some impact categories. Processes that burn EVA show a contribution in the impact category of global warming. All hotspots can be found in Appendix G.

Recycle Pathway Specific Hotspots

In this section, only the hotspots related to the recycling pathways are discussed. The overall hotspots of production processes, extraction processes and energy production can be found for all pathways.

Table 21: Hotspots related to recycling pathways from conducted LCA, impact categories with no mentionable hotspots are omitted.

	Global warming	Freshwater ecotoxicity	Abiotic depletion of fossil fuels	Freshwater eutrophication	Marine eutrophication	Terrestrial eutrophication
Acid leaching				Unrecoverable material precipitation	Wastewater treatment	
Acid leaching and ion exchange						
Alkaline leaching				Unrecoverable material precipitation		
Pyrolysis of coarse fraction	Pyrolysis of EVA					
Solvent treatment	Benzene and acetone production		Benzene and acetone production			
Vibrating screening						
Glass washing						
Attrition and centrifugal extraction		Treatment of wastewater	Energy production	Treatment of wastewater	Energy production Treatment of wastewater	Energy production
Attrition and flotation		Treatment of wastewater	Energy production	Treatment of wastewater	Energy production Treatment of wastewater	Energy production
Pyrolysis and dry etching plus HCl treatment	Pyrolysis of EVA				Wastewater treatment	
Thermal treatment and vacuum blasting	Incineration of EVA					

	Human toxicity, carcinogenous	Human toxicity, non-carcinogenous	Ozone depletion	Particulate matter formation	Photochemical ozone formation	Water use
Acid leaching	Unrecoverable material precipitation	Unrecoverable material precipitation	Petroleum production			Acetic acid production
Acid leaching and ion exchange						
Alkaline leaching	Unrecoverable material precipitation	Unrecoverable material precipitation				
Pyrolysis of coarse fraction						
Solvent treatment			Chlor-alkali electrolysis	Benzene and acetone production	Benzene and acetone production	Benzene and acetone production
Vibrating screening						
Glass washing						
Attrition and centrifugal extraction	Energy production	Energy production	Energy production	Energy production	Energy production	Acetic acid production
Attrition and flotation	Energy production	Energy production	Energy production	Energy production	Energy production	Acetic acid production
Pyrolysis and dry etching plus HCl treatment				Energy production	Energy production	
Thermal treatment and vacuum blasting						

Treatment of Fine Fractions

Acid leaching showed decreased impacts for all impact categories (Figure 24). The production of acetic acid was identified as a hotspot for the water use impact category. This process is related to the production of the leaching reactants. Another hotspot that can be assigned to this recycle pathway is the emissions that are related to unrecoverable material. It was assumed that material that were not recovered by acid leaching were emitted via water. This means that this hotspot can be found in the impact category of freshwater ecotoxicity and human toxicity (carcinogenic and non-carcinogenic). Wastewater treatment after the washing of the retrieved glass, is identified as a hotspot as well, as it contributes more to marine eutrophication.

For **acid leaching in combination with ion exchange** the potential impacts are higher for all categories (Figure 24). Most of these increased impacts are caused by processes that contribute less than 1% (appendix F), as this was the lowest limit of inclusion of processes. The increased impacts differ from 3 to 4% higher compared to CdTe solar modules. As there was little change in contribution of the process, no distinguishable hotspots related to the recycling could be found.

For **alkaline leaching** it can be seen that all impacts have been reduced to at least 38% of the original impacts (Figure 24). Of these reduced impacts, water use is the one that has been reduced the least. Similar hotspots of acid leaching were identified for alkaline leaching. The potential impacts in the freshwater ecotoxicity and human toxicity (carcinogenic and non-carcinogenic), show a contribution of the materials that could not be recovered in alkaline leaching.

Treatment of Coarse Fractions

The **pyrolysis** of the coarse fraction shows increased impacts for all impact categories. As pyrolysis of the coarse fraction consists of burning the EVA layer from glass cullet, there is not much material that is used as re-input for the production processes. The only noticeable hotspot is the contribution of the burning off of EVA to the global warming potential (Table 21).

Solvent treatment shows increased potential impacts for all impact categories. The highest relative impacts can be seen for human toxicity, cancerous, water use, and abiotic depletion of fossil fuels. This can be partly attributed to the production of benzene and acetone that are needed in this treatment process. These processes contribute also to global warming, particulate matter formation, and photochemical ozone formation. Within ozone depletion, chloro-alkali electrolysis shows a small share of contribution to the impacts.

In **vibrating screening,** it can be seen that most impact categories show a reduced potential impact. Only for the categories of freshwater ecotoxicity, freshwater eutrophication, human toxicity, and abiotic depletion of elements a slight increase of potential impacts can be seen. These differences are so small, that the parts that change the impacts are not identifiable.

Treatment of Intermediate Fractions

The intermediate fractions are treated in the process of **glass washing**. Glass washing has an increased effect on the potential impacts of human toxicity, freshwater eutrophication, freshwater ecotoxicity and abiotic depletion of fossil fuels and elements. Contributing to these impact categories is mostly the acquiring and treatment of metals. As this process contributes only to the recovery of glass, it can be seen that the other impact categories have a reduced impact which is mainly attributed to the lower contributions of glass production.

Treatment of Full Mix

The combination of **attrition and centrifugal extraction** shows the lowest impacts in almost all categories. This can be attributed to the closed-loop recycling of materials that was applied in this study. Related to this recycling process a hotspot was identified in the treatment of wastewater. This is a large contributor to the potential impacts on freshwater ecotoxicity, freshwater eutrophication, and marine eutrophication. Additionally, energy needed for this process contributes more to the impact categories of abiotic depletion of fossil fuels, marine eutrophication, terrestrial eutrophication, human toxicity, ozone depletion, particulate matter formation, and photochemical ozone formation. The potential impact of water use is more contributed by acetic acid production.

Similar things are to be seen for the combination of **attrition and flotation**, but with less reduction of impacts than attrition and centrifugal extraction. For almost all impact categories a decrease of potential impacts can be seen when using the combination of attrition and flotation. Hotspots can be identified in wastewater treatment and energy production.

For **Dry etching and HCl treatment**, the pyrolysis of EVA was identified as a hotspot in the impact category of global warming impacts. For marine eutrophication, wastewater treatment is a larger contributor. For particulate matter formation and photochemical ozone formation the contribution of energy use is larger for the potential impacts.

The combination of **thermal treatment and vacuum blasting** is a bit different as a process, as modules are broken down thermally. Related to this recycling process, the incineration of EVA is a large contributor to the potential impacts on global warming.

Comparison of Hotspots from Literature and Model

A combined overview of hotspots is needed to address both the hotspots in CdTe recycling processes that were identified in literature, as the hotspots identified in the model executed in this research project. In Table 22, a comparison between the identified hotspots can be seen. Key takeaways from this analysis are that replacing input materials might have the highest effect in lowering potential impacts. This means that processes that show great potential for this recovery are more favourable based on environmental impacts. The use of chemicals contributes to both lowering impacts as

contributing more to the impacts remaining. The treatment of wastewater also shows greater contribution to impacts.

Table 22: comparison of hotspots found in literature and hotspots found in the conducted LCA.

Hotspots from literature	Hotspots from conducted LCA
Increasing impacts due to the use of chemicals.	Production processes show largest contribution to impacts.
Increasing impacts because of wastewater treatment.	Energy use is large contributor to impact categories.
Increasing impacts because of acquiring of chemicals.	Use of chemicals shows large contribution to the impacts.
Increasing impacts because of additional energy requirements.	Pyrolytic processes increase impacts.
	Processes that cover full mix show large contribution of wastewater treatment to impacts.

Consensus was found for most of the analyses done in literature and the analysis done by the model. In both cases the use of chemicals is identified as a hotspot. Similar effects were seen as well. For both the cases in literature and the modelled case it can be seen that using chemicals will lower the overall potential impacts. However, these chemicals show a larger contribution to the potential impacts that remain. The acquiring of the chemicals raises the potential impacts in some categories for both cases.

Another hotspot that is identified for both is the treatment of wastewater. For the cases in literature however, the wastewater treatment actually contributes to higher impacts. For the modelled cases wastewater treatment shows higher contribution to the impacts. However, the overall impacts have been lowered.

In terms of energy use, the cases in literature identified an increase in the use of energy for the recycle processes. In the modelled cases this increase of energy use is hardly detected. On the other hand, it was discovered that the contribution of energy production processes is larger. This can be seen in the cases that recover more material and thus lower the contribution of the processes that produce material, leaving more for energy use to contribute.

A hotspot that was identified within the modelled cases that make use of pyrolytic processes is that pyrolysis of the EVA layer increases potential impacts. This effect was not determined in the processes from literature.

Interpretation: Global Sensitivity Analysis

The parameters that were used in the LCA are divided into two sections. Parameters exist on flows that have multiple sources for their quantities or efficiencies. These parameters have a lowest and highest value between which an uncertainty is applied. Other parameters are based on these parameters and are expressed in formulas that link back to the values of the first set of parameters. The parameters of this study can be found in Appendix H.

The conducted LCA in this study was subject to many parameters that expresses a variety of values. These values give a certain uncertainty to the outcomes of the model. A global sensitivity analysis (GSA) is conducted to show which of these parameters influence the model outcomes most and have the largest contribution to the uncertainty of the model. These sensitivities are expressed as a number between 0 and 1. The closer to 1, the higher the sensitivity of the model outcome for that parameter (Blanco et al. 2020). Together with the contribution analysis, it could be identified if the potential impacts of hotspots can be lowered much by changing values of a parameter.

One of the results from the GSA show that, within the process of vibrating screening, the parameter MASS_Glass_VS shows the greatest uncertainty compared to the other parameters (0.4) for the climate change impact category (Appendix I). This parameter entails the amount of glass that can be recovered in the vibrating screening process, so is dependent on the efficiency of the process. This

sensibility could be attributed to the fact that the recovered glass is used as an input for the production processes of the CdTe module. Thus, the recovery rate of the glass is an influential factor for the potential climate change impacts.

Interpretation: Local Sensitivity Analysis

A local sensitivity analysis was performed in this section. For this, values of parameters were changed manually to see what influence they have on the outcomes of the LCA model. In the previous sections it was found that the use of chemicals increases the potential impacts in many categories. There are a few parameters that are set around the input of chemicals. The potential impacts of the minimum value and maximum value are compared to each other to see how sensitive the model is to variation in these values.

Figure 27: local sensitivity results for parameters of sodium hydroxide going into alkaline leaching, tellurium dioxide recovered in alkaline leaching and acid leaching, and cadmium telluride recovered from attrition processes.

For alkaline leaching, the input of sodium hydroxide could vary from 5.26E-03 kg to 8.95E-2, thus it could increase by 17 times. This difference in input was expressed as the parameter MASS_NaOHin_ALK. However, the sensitivity of the results in all impacts categories falls below 0.06 (Figure 27). This means that the impact scores are not very sensitive to the changing input of chemicals in this process.

Indicated as well, was that recovering more of the input material lowers the potential impacts. The amount of material that could be recovered was dependent on the efficiency of the process. To see

how different recoverable amounts influence the model a few parameters related to CdTe were analysed. These were MASS_TeO2_ALK and MASS_TeO2_AL, as the amount of CdTe that could be produced is related to the amount of tellurium that could be recovered in the leaching processes. For alkaline leaching the recovery rate of TeO2 has a much lower influence on the end results than the with acid leaching. However, even for acid leaching the change of recovery rate does not have a very big influence overall (< 0.03).

Similarly, the attrition processes were modelled to retrieve CdTe directly. For this the parameters of MASS_CdTe_FL and MASS_CdTe_CE was investigated. As can be seen, the potential impact scores are not very sensitive to changes in efficiency of the attrition and centrifugal extraction process. However, all impact categories are sensitive to the efficiency of the attrition and flotation process (about 0.14). Related to centrifugal extraction is the process of flotation more sensitive.

Results of Qualitative Assessment

The results of the qualitative assessment can be seen in Table 23. For processes that treat the fine fractions, acid leaching scores the highest. Alkaline leaching and ion exchange score lower due to a lower TALC. The processes that recover valuable metals have high costs. For the processes that retrieve only glass, the score is lowered as glass is not a very valuable recoverable material. However, from these processes the highest score can be assigned to vibrating screening. Of the process that include all materials in their recycle pathway, the highest score can be assigned to either attrition combined with both centrifugal extraction and flotation. The combination of dry etching and HCl treatment has score lower score due to its high costs.

Table 23: qualitative assessment of recycling processes.

	Maturity		Costs	Value of recovered material	Total
	TRL	TALC			
Acid leaching	3	3	1	2	2.25
Alkaline leaching	3	2	1	2	2
Attrition	3	2	3	-	2.67
Centrifugal extraction	3	2	3	3	2.75
Dry etching	3	2	1	3	2.25
Flotation	3	2	3	3	2.75
Incineration of EVA	3	2	2	1	2.00
Ion exchange	3	2	1	2	2
Physical disintegration	3	3	3	-	3
Solvent treatment	2	1	1	1	1.25
Thermal treatment	3	2	2	-	2.33
Vacuum blasting	2	1	3	2	2
Vibrating screening	3	3	3	1	2.5

Maturity

In terms of maturity, there was looked at two things: the TRL and the TALC. Most of the analysed processes have already reached a TRL of 9 as they are applied in commercial installations. Vacuum blasting can be found on TRL 6, as it has moved past the research phase and is being tested in a pilot. Solvent treatment is still in its research phase and is tested in laboratory conditions. This means this process is in TRL 4. Attrition and flotation processes are a bit further than vacuum blasting and can be found in TRL 7. However, centrifugal extraction is an already proven technique (Lunardi et al. 2018; Tao and Yu 2015; Marchetti et al. 2018). TRL 1-3 get a score of 1, TRL 4-6 get a score of 2, TRL 7-9 get a score of 3.

The TALC was based on how much the technology is applied. The TRL indicates that many processes have reached the level on which they can be applied in commercial applications. However, only processes that can be found in the pathway of First Solar are applied on large industrial scale (Fthenakis et al. 2020). A score of 3 was applied to processes that are found in this pathway, a score of 2 is applied to commercialized processes that are not used in this pathway. A score of 1 was applied to processes that are not commercialized yet.

Costs

Processes that make use of mechanical recycling show the lowest costs. These are attrition, centrifugal extraction, flotation, physical disintegration, vacuum blasting, and vibrating screening (Deng et al. 2019). High costs can be found for the processes that make use of chemicals, like acid leaching, alkaline leaching, dry etching, ion exchange, and solvent treatment (Deng et al. 2019; Toro et al. 2013). Thermal processes fall in between the costs for mechanical and chemical treatment, so thermal treatment and incineration of EVA are awarded a score of 2 (Deng et al. 2019).

Value of Recoverable Material

Some processes are not recovering any material as they only separate material from each other, so were not awarded a score in this category. These processes are attrition, incineration of EVA, physical disintegration, solvent treatment, and thermal treatment. Another thing important to keep in mind, is that the processes only recover a material that needs to be purified and treated afterwards. Acid leaching, alkaline leaching, ion exchange, and vacuum blasting set the basis for recovery of the valuable metals and a small amount of glass. Centrifugal extraction, dry etching, and flotation separate and extract glass and valuable metals and set the basis for the highest recovering value. Vibrating screening incineration of EVA, and solvent treatment only retrieve glass so have the lowest score.

Limitations

This study was subject to many limitations, which will be discussed in the next section. Discussing these limitations will help putting this study into context of real-life situations. The limitations of this study cover the data gaps, modelling choices, and other assumptions. As this study is majorly based on models, one thing needs to be remembered. A model is only an approximation of reality and will never be a perfect depiction of real-life scenarios.

Data Limitations

The LCAs that were harmonization showed great differences in methodology and data sources. These LCAs were mostly conducted based on data that was generated in research facilities only the researchers had access to. Most of the times the total data output was shown, without the results of the full interpretation section of LCA. This meant it is hard to distinguish what kind of processes influence impacts the most in those studies and what kind of data they used as input for their Life Cycle Inventory. This also meant that Impact assessment results could not be compared to each other. These are reasons the harmonization effort was mainly done based on hotspots that were identified by those studies. Another thing is that the studies investigated different systems with different boundaries. Some hotspots that could have been found outside of the set boundaries were not mentioned in the harmonization of these pathways. These cut-offs are mostly placed at the line between separated material and purification processes, as most studies sent their separated streams to third-party treatment facilities (Tao and Yu 2015; Held 2009).

Data age is another thing of interest in this study. Some of the sources that were used for the processes that were analysed in this study were almost 20 years old. In the example of dry etching in combination with HCl treatment, the source of Diequez Campo et al. (2003), might be too old to be relevant as technologies might have improved or withdrawn over the years. Next to that, it means that data sources from very distinct technology ages are compared to each other. One thing that was noticed is that more recent sources contained more data than the older ones. This could be of influence on the results, as one source includes more than the other. This was solved by using more recent data sources for the Life Cycle Inventory, and only using the old sources as a general process description.

Data availability was limited in this area of research. As already mentioned in the research gap, many studies excluded recycling in their LCA as their was limited data available. This lack of data was still

true for this research, meaning many assumptions had to be made for the display of processes and material flows. For reaction mechanisms that were modelled for the chemical processes, it was assumed that everything reacted theoretically correct. This is not true in reality, as excesses are often applied to make sure almost everything that should react has reacted. This needs to be kept in mind, as it could mean more chemicals are needed for these processes, resulting in higher potential impacts. Energy use of the recycling processes is also largely based on data that was found for comparable processes. These comparable processes were either found in literature or in the Ecoinvent database. This could cause another discrepancy in the impacts that were found. Efficiencies of a process were not always. Especially in studies that described process steps, but did not mention quantitative material flows. For these processes, comparable data was extracted from literature. Additionally, an uncertainty of 3% was found on the amount of recovered material (Pagnanelli et al. 2017). This uncertainty was applied to efficiencies from secondary data applied to processes. To cover for these uncertainties in data, many parameters were set to include data from multiple sources and to see what kind effect the changing of the data has on the model. From the sensitivity analyses, it is known that these parameters do not influence the model outcomes significantly, insinuating that large differences in these uncertain value do not have a large impact.

This research tried to get a grasp of all recycling methods available. However, not all recycle pathways have been covered in this study. Some pathways have purposely or unpurposely been skipped. The pathways that have unpurposely been skipped are the ones that were not discovered in the literature review. This could happen because the process has hardly been described or was not covered in other papers. One pathway that has been purposely skipped was the pathway that uses HNO_3 as a leaching solution, as little data was found on this process by SENSE (Tao and Yu 2015). Sources that referred to the SENSE project were not accessible anymore and finding the exact process structure of this pathway was too hard. The delamination by irradiation with a laser was also skipped as it was not perceived as a feasible pathway (Tao and Yu 2015). Another thing that could have been covered were the recovery of more metals by electroplating. Now, only the recovery of cadmium was covered with this, but the recovery of copper, zinc, tellurium might also be viable with this option (Fthenakis and Wang 2005).

Limitations of LCA Model

The conducted LCA is based on many assumptions and modelling choices. These choices were made to keep the modelling effort within the timeframe that was meant for this thesis. More limitations are applied to the LCA that was conducted in this study.

One major exclusion in the LCA model, that should be covered in further studies, is the process of purification. This research does not include the purification steps that are needed to get recovered materials of the same purity as the original input materials. This choice was made to make the study more comparable to the LCAs that were found in literature. Most of these studies cut-off their processes at the point that materials were recovered, but not purified yet. This purification was then done by a third-party company. Excluding this step could mean that impacts will be higher, leading to a smaller effect of the recovery of input material, as chemicals and energy are needed. Additionally, leaching processes are often applied as a further treatment of attrition processes (Marchetti et al. 2018). In this model attrition processes in combination with centrifugal extraction and flotation are treated as processes that are able to directly recover purified metals and glass. However, in reality these processes are only applied to separate the different materials from each other. This means that the low impacts that can be found for the attrition processes might be much higher and more comparable to the impacts found for leaching processes.

An LCA should give an overview of the full life cycle of a product. This LCA does cover most of the life cycle, but does not cover the recovery of some material. Materials that are covered is CdTe, CdS, and

glass. The other materials, used in laminate, the TCO layer, and back contact, are only partly covered or not at all. Starting with the EVA layer, some recycle pathways incinerate this layer. This incineration process has been included in the study. However, when pathways don't incinerate the EVA layer, the emissions contributing to removal of EVA are not accounted for. Then, there is also the case of recovery of EVA. This has not been applied to any of the pathways, EVA is simply removed from the recoverable mix. Recovery of the back contact has also not been included in this study. The back contact consists of copper, zinc, and tellurium. These metals are treated in most processes and collected as precipitates. However, copper and zinc are not accounted for in the recovery phase of this LCA. The attrition processes do not include the back contact at all. The treatment of the TCO layer is only covered in the HCl treatment process. However, the outcome of this process gives precipitates of indiumchloride and tinchloride which are not used in recovery. It would have been better to exclude this process to get less discrepancy when comparing the different pathways. As this process has input of chemicals and the products are not used in recovery, the potential impacts may end up higher.

Adding to that is that different outputs are modelled for different processes. These outputs are treated differently for some of the processes. Most modelled processes treat outputs related to cadmium, tellurium, and glass as reusable input for production processes. However, the dry etching and HCl treatment does not apply this and the recovered products are treated as cut-off out of the product system. This was done because this process recovered the metals as chlorides. Different purification steps need to be taken for these kinds of precipitates to be used as recyclable input. By not including the closed-loop recycling of these materials, the impact of this process might be much higher. On top of that was the LCA performed on processes that treat different parts of the fragments. These processes need to be combined to give a pathway to fully treat the mix. Now was assumed that the difference in relative impacts of a process that treated the coarse fraction could be added to the difference in relative impacts of a proces treating fine fractions. However, this is not completely true as that means that physical disintegration was accounted for twice. As electricity use from physical disintegration was not found as a hotspot, this of no influence on the results.

As an input to the model 1 m^2 of spent CdTe module was chosen. It was assumed that this module had a weight of 16.6 kg. However, multiple other configurations and masses exist for CdTe solar modules. This configuration was chosen as it is directly followed from the CdTe solar module structure that was applied in this study and as the number was taken from one of the more recent studies (Maani et al. 2020).

The method with which recycling is applied needs to be addressed subsequently. In this research the choice was made to apply a closed-loop recycling strategy that uses output products as a direct input of the production processes. However, as purification steps have been excluded, this might give cause to expect that the data is not fully representable. This could have been avoided by using a credit system in which recovered material get awarded credits, based on avoidance of environmental burdens, for example. This way the treatment steps and the end products get judged. However, this also means that it will be harder to see what effect recycling has on the full life cycle. By knowing that purification steps were excluded for all process pathways, the relative differences between the recycling pathways would hardly change.

Furthermore, limited data on the processes related to CdTe solar module treatment exists. The majority of processes are presented by a basic depiction. This means that most processes only cover input like water, air, electricity and the main product inflows. The output is mostly covered by wastewater and main product outflows. Emissions are based on the product in- and outflows. Other material that is needed in the treatment pathway is largely excluded from the analysis. This is similar for the production processes. For the production processes this choice can be motivated as closed-

loop recycling is applied. This means that the most important thing to identify for potential impacts in production processes is the relative change of these impacts, not necessarily the quantity. Another thing is that carrier gasses are excluded from the analysis. Carrier gasses might give a totally different composition of the main product outflow, altering the outcomes of the processes that are present further along the pathway. For glass washing the depiction as a basic process means that the chemicals that are needed to fully cleanse the glass cullet is not covered. However, the wastewater treatment is done by the external Ecoinvent process that does cover chemicals that are used. This means only the production of these chemicals is not covered. Furthermore, are capital goods are included in the analysis as well. According to Silva et al. (2018), the date on capital goods is based on very rough estimates, making the model actually less valid. Next to that, are impacts related to capital goods too low to be of any influence to the total impact assessment.

A point of discussion can be noted in the way emissions are presented in the activity browser. Cadmium and tellurium can only be emitted as Cd in water and Te in air. It is not possible to show emmission of for example cadmiumsulfates or telluriumoxides. This means emission of Cd and Te could have a higher or lower effect based on if the molecules are present as a salt or a metal.

The allocation method that was chosen in this study was economic allocation. This choice was made because the economic values of seem to better relate to the intrinsic toxicity and damage the more valuable materials could do to the environment. However, this study did not include the results related to different allocation methods. The impacts might have shifted, giving new insights and hotspot if these other allocation methods were used.

Recycling contrubuted for only a small part to the total impacts of the full life cycle of the CdTe solar modules. Only processes that contributed to 1% or more to the impact categories were included in the analysis. This could mean that hotspots related to recycling might have been missed. However, if these hotspots don't show up in the contribution analysis, they also might be too little to be of great concern.

Limitations of Qualitative Assessment

The qualitative part was based on concepts that were found in literature. There are many more concepts that can define the qualitative performance of a pathway. For maturity the choice was made to use two concepts: Technology Readiness Level and Technology Adoption Life Cycle. This choice was made because these two concepts together give a complete overview of how well a technology has developed and how well it has been applied. The costs were based on a model by Deng et al. (2019). In this study a model of costs was displayed. Many more models for determination of costs are possible. This study was chosen as it developed this model based on recycling processes of photovoltaic modules. This close to the situation explored in this study.

Considering the determination of costs, costs related to setting up infrastructure for new pathways and subsidies that might be received when using certain recycling strategies were not included. As adoption was considered by the Technology Adoption Life Cycle it could be said that infrastructure is taken in consideration in another category. Subsidies could subsequently lower costs for a recycle pathway, making them more attractive for implementation.

Another limitation to the qualitative part of the study was that there was no weight applied to the different categories. It might be that some categories are valued higher than other. This could make the trade-offs shift in different directions. The choice was made to apply this weight, because the categories were already ranked from 1 to 3. This is already a weight applied to the different possibilities

within a category. Applying weight to the categories as well could cause double counting of the influence of possibilities.

Conclusion

The main research question of this study was:

What are the quantitative and qualitative trade-offs of potential End-of-Life strategies that could lower the environmental impact of thin-film solar cells made of CdTe?

To answer this question, the study was divided into three parts. The first part addressed the background of CdTe solar modules, how they are produced and what End-of-Life strategies exist. The second part analysed the quantitative trade-offs of the identified End-of-Life strategies. The third and final part analysed the qualitative trade-offs. Bringing these trade-offs together answered the main research question.

Key Findings of Study

Overall, recycling processes do not have a large impact on the total life cycle impacts of CdTe solar modules. Largely, the impacts can be attributed to production processes of the module, especially contributed by the energy that is used and the extraction of primary material. It can be said that overall impacts are lower when less material needs to be extracted from the environment.

One key finding of this study is that the use of chemicals in recycling processes causes increasing potential impacts on the environment. However, using chemicals also makes it possible to recover much of the valuable materials, indirectly lowering the total impacts of the processes. One thing to note here, is that all processes need chemicals to obtain recoverable material that could be used as an input for production processes. Indirectly the use of chemicals influences the wastewater treatment. Wastewater treatment is another large contributes to the impact of recycling processes. These impacts are related to the amount of glass that needs to be treated, the material that is present on the glass, and the chemicals that are used to recycle the CdTe solar module. Essentially this means, the more glass treated, the higher the impacts of wastewater treatment. The LCA hotspots analysis shows that the option of using attrition combined with centrifugal extraction shows the lowest potential impact on the environment. The process of alkaline leaching shows low impacts as well. When this process is combined with a process that treats the coarse fraction, the potential impacts might be even lower. Vibrating screening is a process that shows the lowest impacts for this part of the mix.

From the quantitative analysis it can be seen that most techniques have already achieved high technology readiness level. The technology adoption life cycle scores are lower, as they depend on how many of the technologies are actually applied. Costs get higher as more chemicals are used and lower when processes become more mechanical. Recovery values are highest for processes that recover glass and valuable metals and lowest for processes that only recover glass.

In Table 24 the discovered trade-offs of each pathway are assessed. In this table a pathway consists of combined techniques to treat all fractions.

Table 24: recycling pathways represented with both quantitative as qualitative trade-offs.

Pathway	Quantitative trade-offs	Qualitative trade-offs
1. Physical disintegration, sieving, acid leaching, and vibrating screening	+ Lower potential impacts due to acid leaching + Lower potential impacts due to vibrating screening + High recovery yields of acid leaching - Increased impact by using chemicals - Increased impact by wastewater treatment	+ High combined maturity + Already adopted at large-scale + Low costs of vibrating screening + Combined recovery of all valuable materials - High costs of acid leaching
2. Physical disintegration, sieving, acid leaching, and incineration	+ Lower potential impacts due to acid leaching + High recovery yields of acid leaching - Higher potential impacts due to pyrolysis	+ High combined maturity + Low costs of pyrolysis - High costs of acid leaching

	- Increased impact by using chemicals - Increased impact by wastewater treatment - Increased impact by incineration of EVA	
3. Physical disintegration, sieving, acid leaching, and solvent treatment	+ Lower potential impacts due to acid leaching + High recovery yields of acid leaching - Higher potential impacts due to solvent treatment - Increased impact by using chemicals - Increased impact by wastewater treatment	+ High maturity of acid leaching + Combined recovery of all valuable materials - Low maturity of solvent treatment - High costs of acid leaching - High costs of solvent treatment - Low combined score
4. Physical disintegration, sieving, alkaline leaching, and vibrating screening	+ Lower potential impacts due to alkaline leaching + Lower potential impacts due to vibrating screening + High recovery yields - Increased impact by using chemicals - Increased impact by wastewater treatment	+ High combined maturity + Low costs of vibrating screening + Combined recovery of all valuable materials - High costs of alkaline leaching
5. Physical disintegration, sieving, alkaline leaching, and incineration	+ Lower potential impacts due to alkaline leaching + High recovery yields of alkaline leaching - Higher potential impacts due to pyrolysis - Increased impact by using chemicals - Increased impact by wastewater treatment - Increased impact by incineration of EVA	+ High combined maturity + Low costs of pyrolysis + Combined recovery of all valuable materials - High costs of alkaline leaching
6. Physical disintegration, sieving, alkaline leaching, and solvent treatment	+ Lower potential impacts due to alkaline leaching + High recovery yields of alkaline leaching - Higher potential impacts due to solvent treatment - Increased impact by using chemicals - Increased impact by wastewater treatment	+ High maturity of acid leaching + Combined recovery of all valuable materials - Low maturity of solvent treatment - High costs of alkaline leaching - High costs of solvent treatment - Low combined score
7. Physical disintegration, sieving, acid leaching, ion exchange, and vibrating screening	+ High recovery yields + Lower potential impacts due to vibrating screening - Higher potential impacts due to ion exchange - Increased impact by using chemicals - Increased impact by wastewater treatment	+ High maturity + Combined recovery of all valuable materials + Low costs of vibrating screening - High costs of acid leaching and ion exchange
8. Physical disintegration, sieving, acid leaching, ion exchange, and incineration	+ High recovery yields - Higher potential impacts due to incineration of EVA - Higher potential impacts due to ion exchange - Increased impact by using chemicals - Increased impact by wastewater treatment - Increased impact by incineration of EVA	+ High maturity + Combined recovery of all valuable materials - High costs
9. Physical disintegration, sieving, acid leaching, ion exchange, and vibrating screening	+ High recovery yields - Higher potential impacts due to solvent treatment - Higher potential impacts due to ion exchange - Increased impact by using chemicals - Increased impact by wastewater treatment	+ High maturity of alkaline leaching and ion exchange + Combined recovery of all valuable materials - Low maturity solvent treatment - High costs
10. Physical disintegration, attrition, and flotation	+ Lower impacts for 14 impact categories - High impacts for 2 impact categories - Increased impact by wastewater treatment - Increased impact by energy use - Leaching needed for purification	+ High maturity (2.5) + Low costs + Recovery of all valuable materials
11. Physical disintegration, attrition, and centrifugal extraction	+ Low impacts - Increased impact by wastewater treatment - Increased impact by energy use - Leaching needed for purification - Lower recovery rate than flotation	+ High maturity (2.5) + Low costs + Recovery of all valuable materials

12. Physical disintegration, pyrolysis, dry etching, and HCl treatment	+ Lower impacts for 10 impact categories - Higher impacts for 6 impact categories - Increased impact by using chemicals - Increased impact by incineration of EVA	+ High maturity + Recovery of all valuable materials - High costs
13. Thermal disintegration and vacuum blasting	+ Lower impacts for 7 impact categories - Higher impacts for 9 impact categories - Increased impact by using chemicals - Increased impact by incineration of EVA	+ Low costs - Low maturity - No recovery of all valuable materials

The contribution of recycling stages to the total life cycle stages is little. However, the aim should be to recover as much material as possible. For leaching processes that treat fine fractions consisting of valuable metals trade-offs were found. The use of chemicals in these processes causes for high recovery rates of the materials and lower potential impacts. These processes are also considered very mature. However, high costs are associated with these processes. Subsequently these processes cause for an increase of impacts due to the extraction of chemicals and treatment of wastewater after recycling. Coarse fraction can be treated in mechanical, thermal, and chemical pathways to remove EVA from the glass. Vibrating screening shows low impacts, high maturity, and low costs. Incineration of EVA has a high maturity and has low costs but causes higher potential impacts. Solvent treatment with acetone and cyclohexane has high costs, higher potential impacts, and low maturity. Attrition in combination with flotation or centrifugal extraction treats the fractions together. It is shown that all potential impacts are lowered for the combination with centrifugal extraction. It's a mature, low-cost technology but should be followed-up with a process like acid leaching. Next to that, does the process show increased impacts of energy use. Similar things are found for attrition in combination with flotation. A difference is that this combination shows increased potential impacts for two impact categories. Dry etching and HCl treatment show a high maturity, while treating the full mix. Lowers potential impacts in 10 impact categories, increases potential impacts in 6 categories. Has high costs and shows increased contribution of chemicals and EVA incineration to potential impacts. Finally, thermal treatment and vacuum blasting show lower potential impacts for 7 impact categories. Has high costs, is not very mature and causes increased potential impacts in 9 categories.

The trade-offs of the recycle strategies are attributed to the environmental impacts they cause, the contribution of their processes to these impacts, the costs of the processes, what material is recovered and the maturity of the techniques. Based on these characteristics the matrix in Figure 28 is presented. The numbers are related to the pathways as described in Table 24.

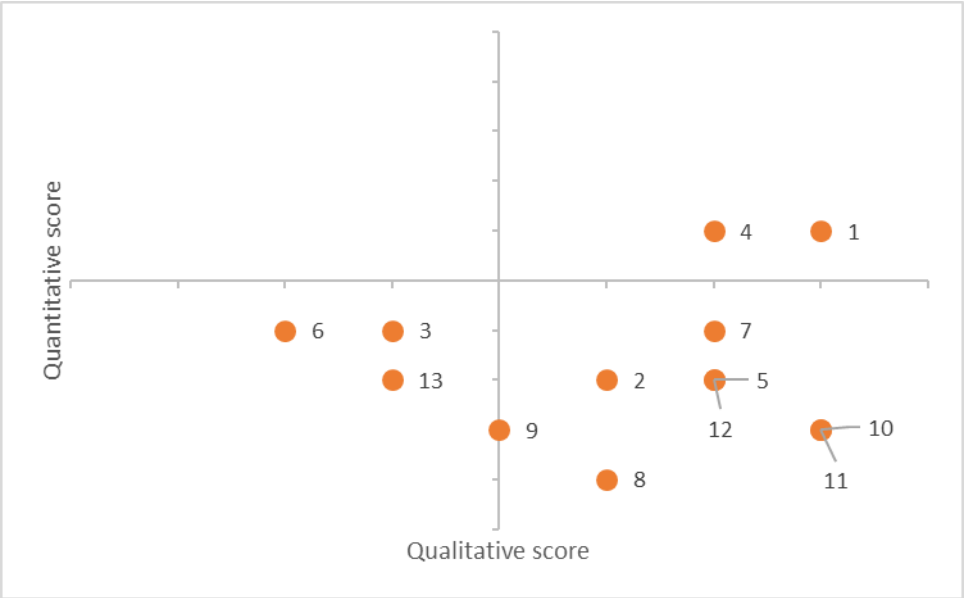

Figure 28: matrix with qualitative and quantitative scores of process combinations.

In this matrix it can be seen that process 4 and 1 score positively on both quantitative, as qualitative credentials. These are the processes that combine acid (1) or alkaline (4) leaching with vibrating screening. Processes 3, 6, and 13 have low scores in both categories and are not considered very favourable. A thing in common is that these are pathways that make use of thermal processes. The other processes score positively on qualitative characteristics but have lower scores for their quantitative features. There are no processes that have a high quantitative score, but a low qualitative score.

Further Research

This study needs to be seen as a basis of iteration by other studies. Increasing the models' accuracy will help get more insights into the potential environment impacts of each recycle pathway. This entails including more processes steps and finding more accurate data for processes. The inclusion of more processes is needed to also account for the impacts of purification steps after separating materials from the mix. A follow-up study could also improve the data quality of the Life Cycle Assessment. This could be done by including more process details for every process step and testing processes in a test facility. This increases the accuracy of the individual processes within the recycle pathways.

Interesting follow-up topics might be on the implementation of new recycle pathways. A policy analysis could be conducted, based on the results of this thesis, to explore how new recycle pathways should be commercially applied to motivate better recycling of CdTe solar modules or other types of modules. For this study the discovered trade-offs can be part of the analysis.

A similar study to this one could be conducted on other types of next generation solar modules, like dye-sensitised modules or organic modules. Knowing the trade-offs of other module type will help in the search for better, low impact recycling strategies.

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Appendix

Appendix A - Flowcharts of Recycling Pathways.

Every recycle pathway has its own product flow. Flowcharts of all recycle pathways are shown here. All, include physical disintegration and glass washing process, with exception of the thermal treatment pathway in which no physical disintegration takes place. The dotted line represents the boundaries of the product system. Products that are placed outside the dotted line, go either in or out of the system as a cut-off.

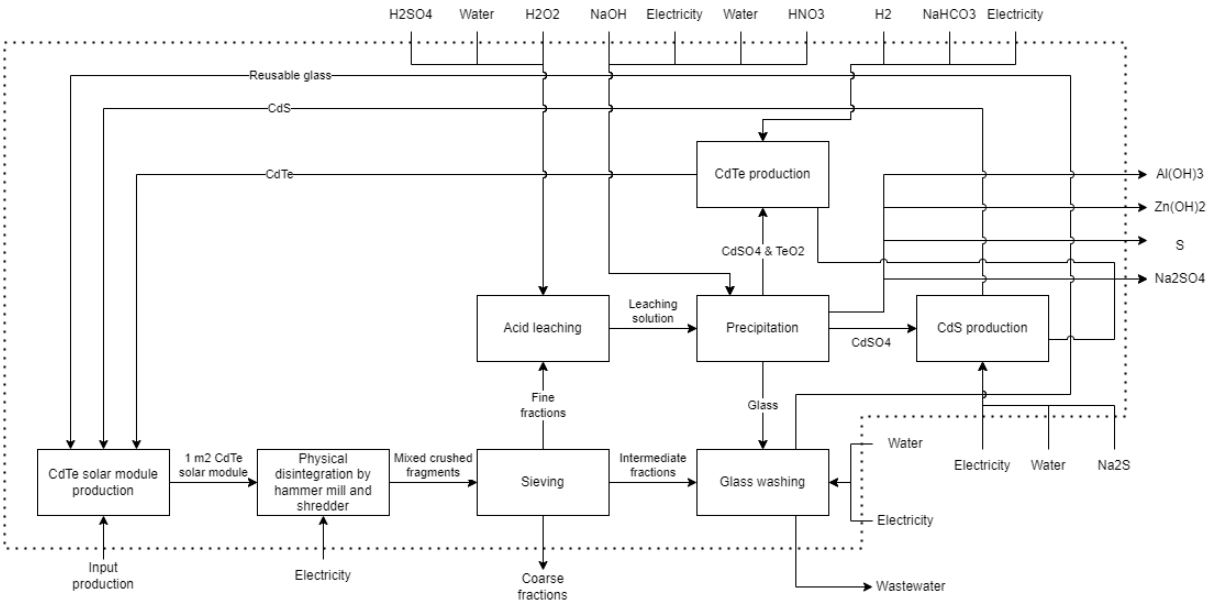

Figure A. 1: flowchart of reference flow 1 the recycling of 1 m2 CdTe solar module using acid leaching.

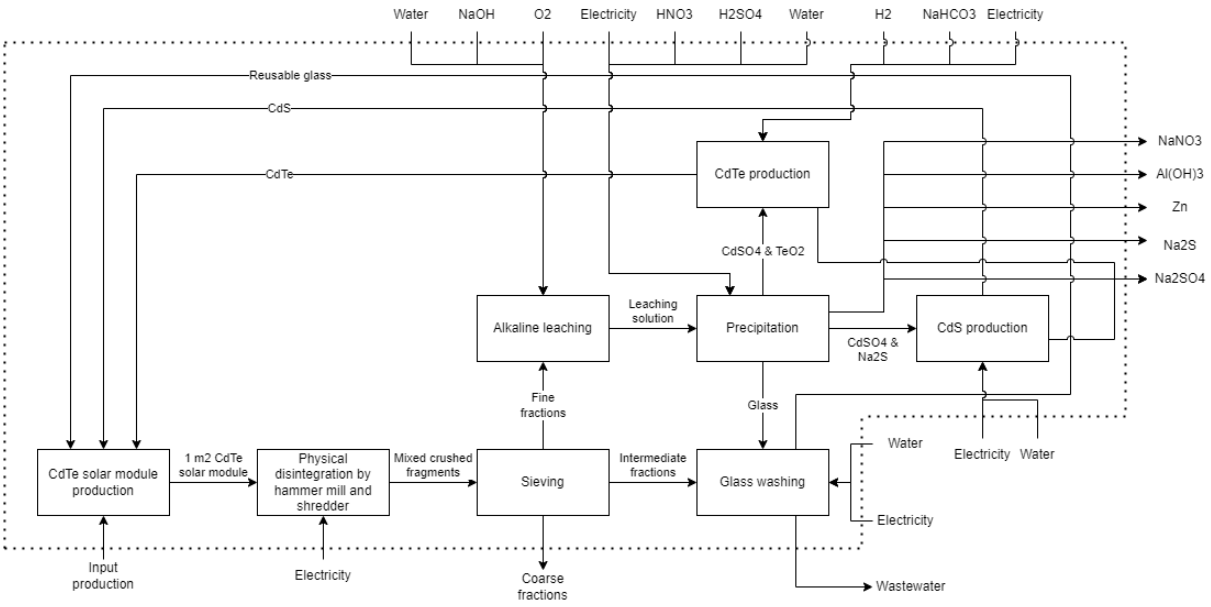

Figure A. 2: flowchart of reference flow 2 the recycling of 1 m2 CdTe solar module using alkaline leaching.

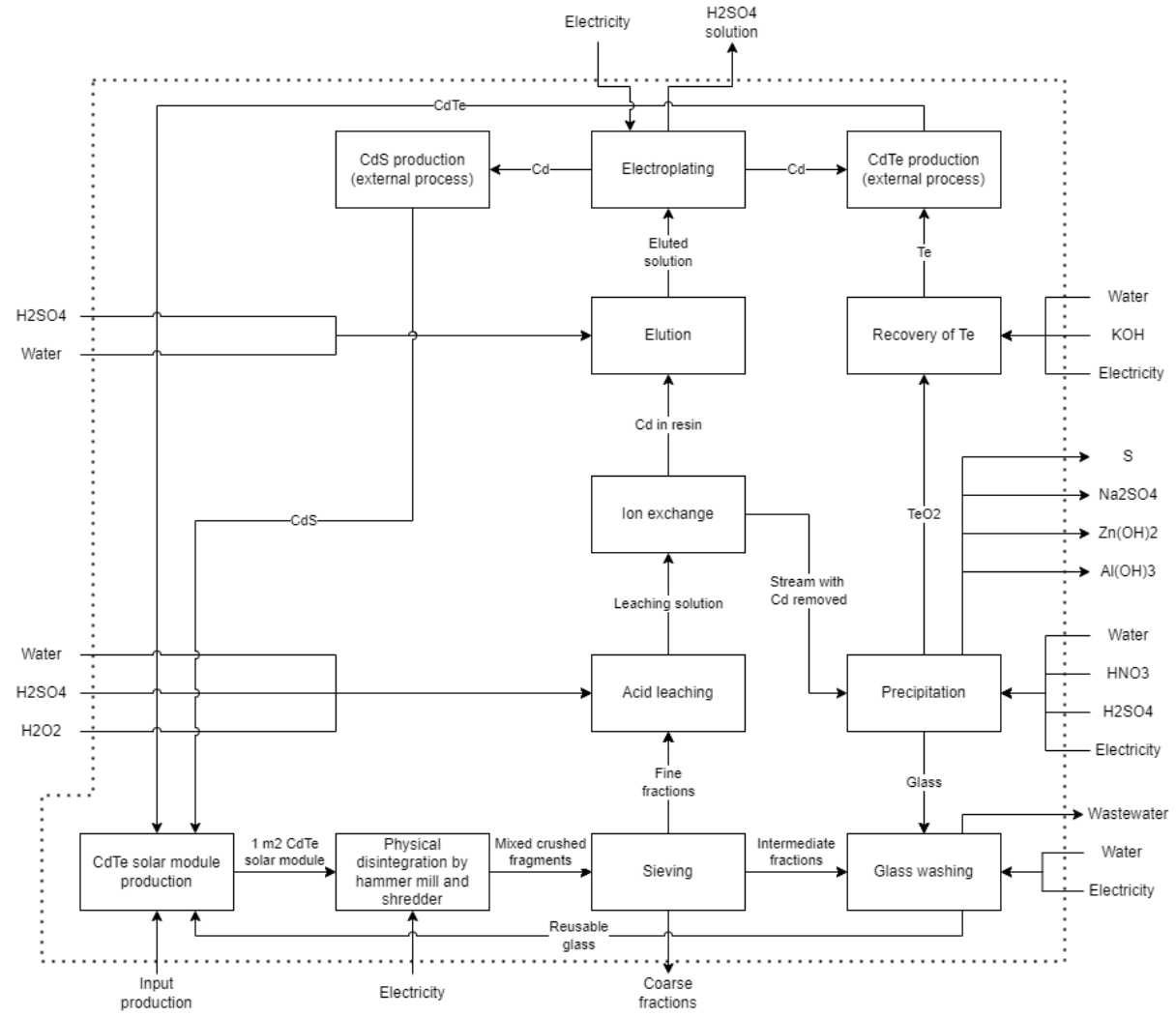

Figure A. 3: flowchart of reference flow 3 the recycling of 1 m2 CdTe solar module using acid leaching and ion exchange.

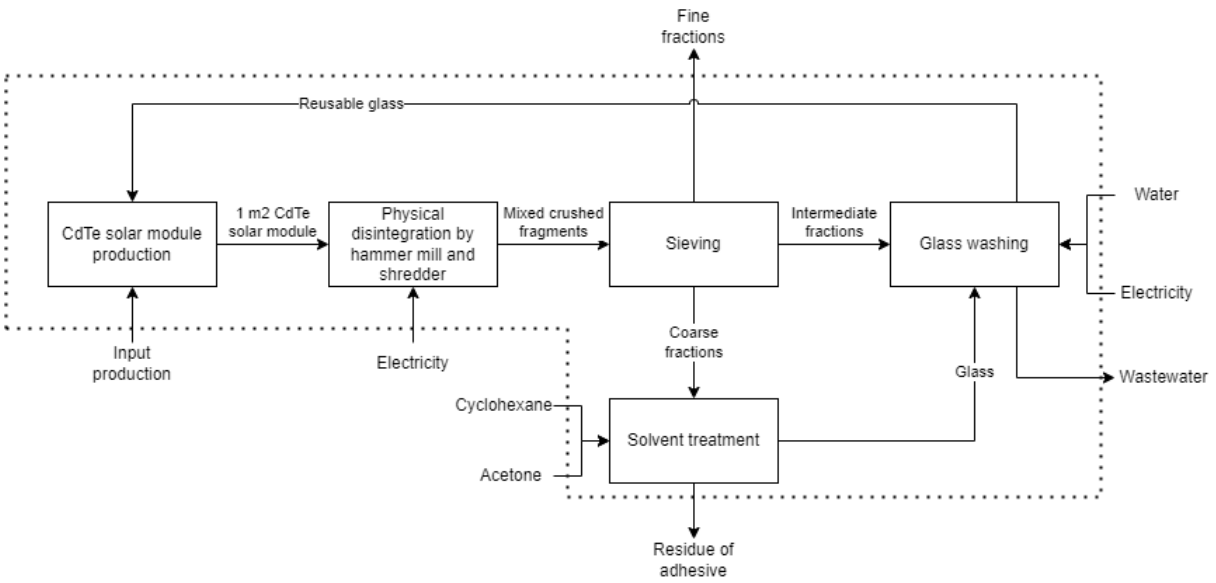

Figure A. 4: flowchart of reference flow 4 the recycling of 1 m2 CdTe solar module using solvent treatment.

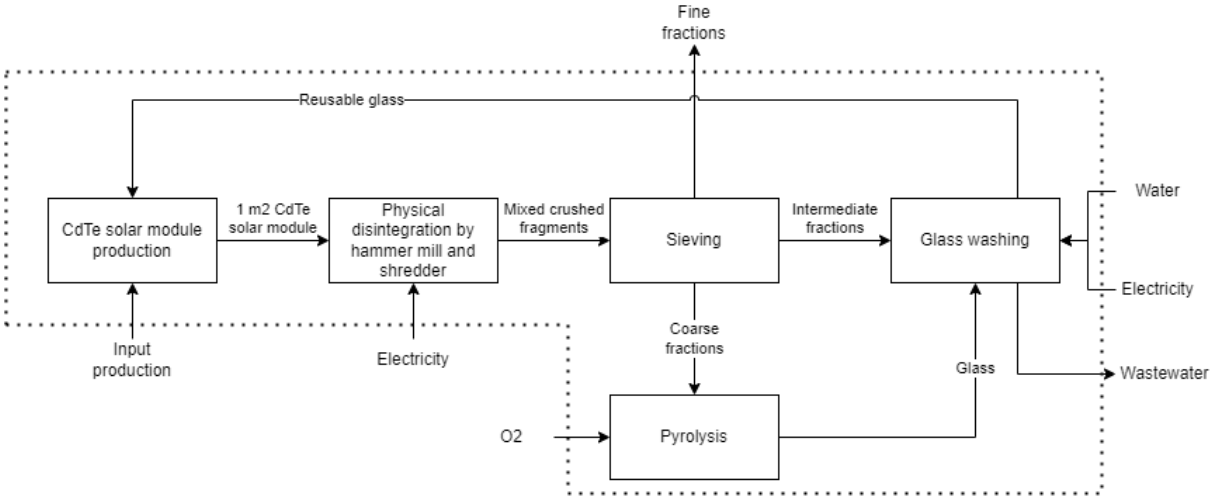

Figure A. 5: flowchart of reference flow 5 the recycling of 1 m2 CdTe solar module using pyrolysis.

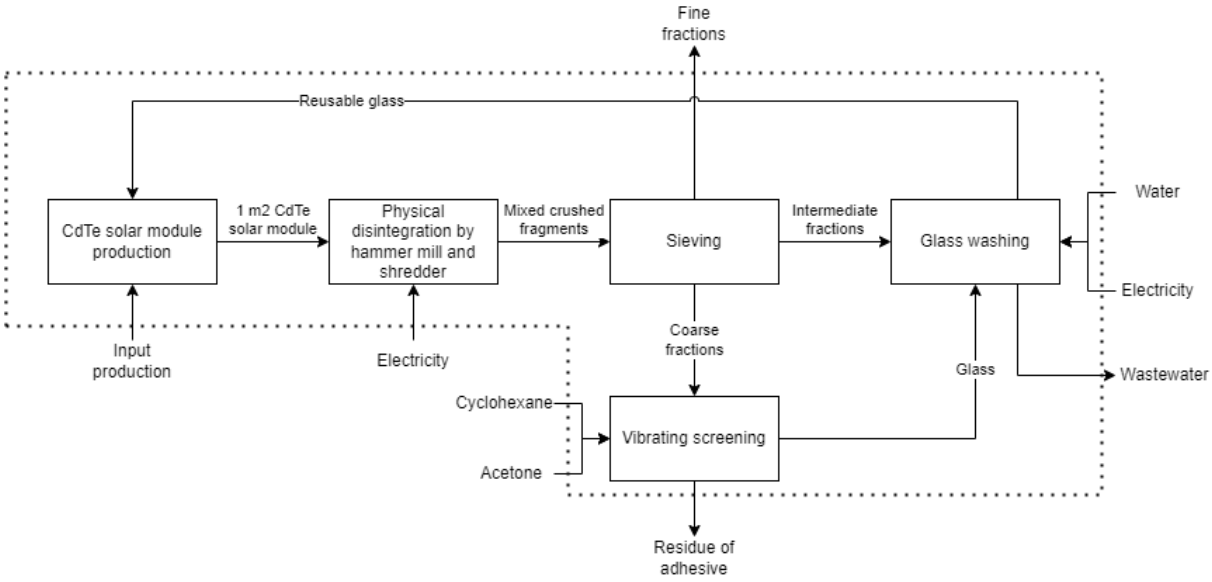

Figure A. 6: flowchart of reference flow 6 the recycling of 1 m2 CdTe solar module using vibrating screening.

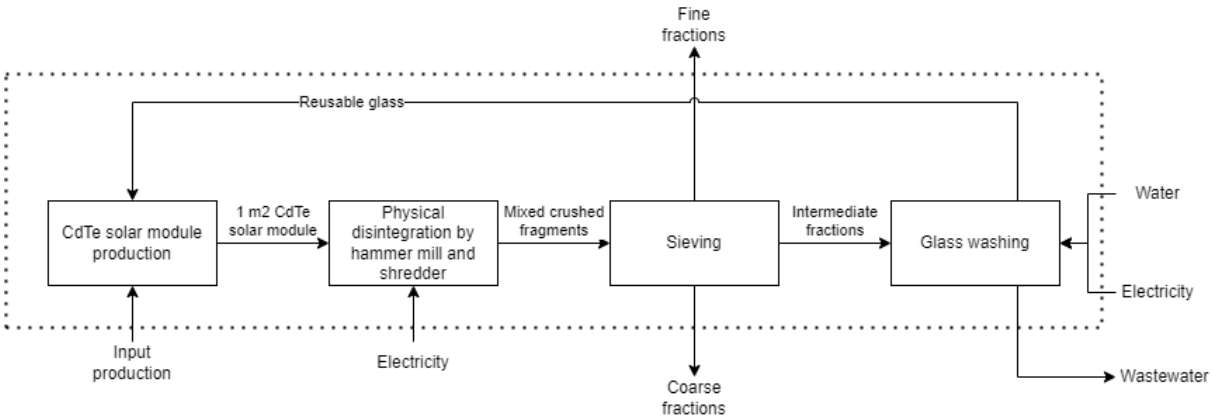

Figure A. 7: flowchart of reference flow 7 the recycling of 1 m2 CdTe solar module using glass washing.

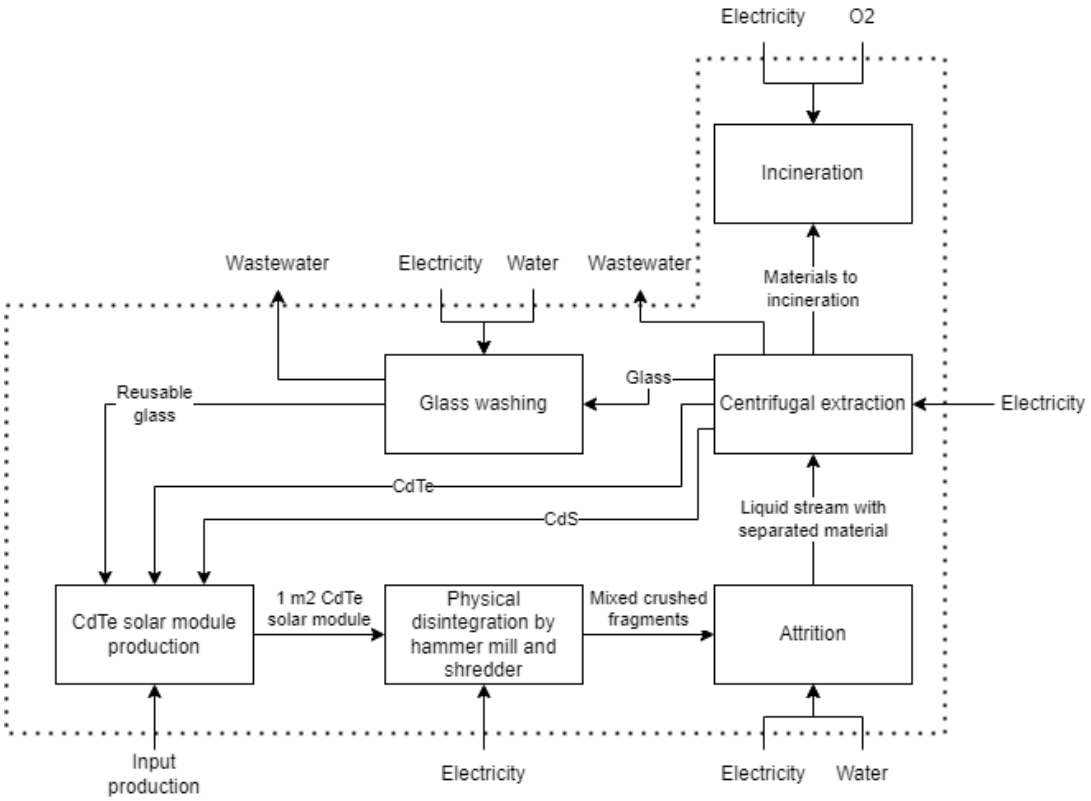

Figure A. 8: flowchart of reference flow 8 the recycling of 1 m2 CdTe solar module using attrition and centrifugal extraction.

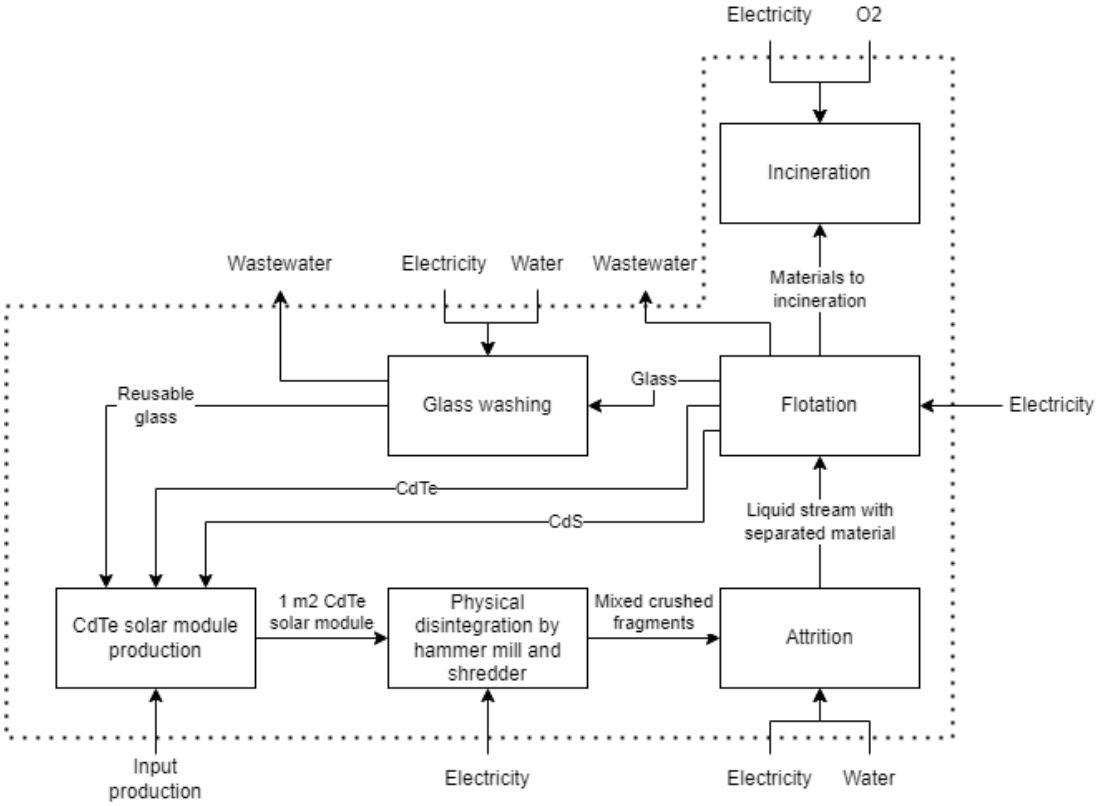

Figure A. 9: flowchart of reference flow 9 the recycling of 1 m2 CdTe solar module using attrition and flotation.

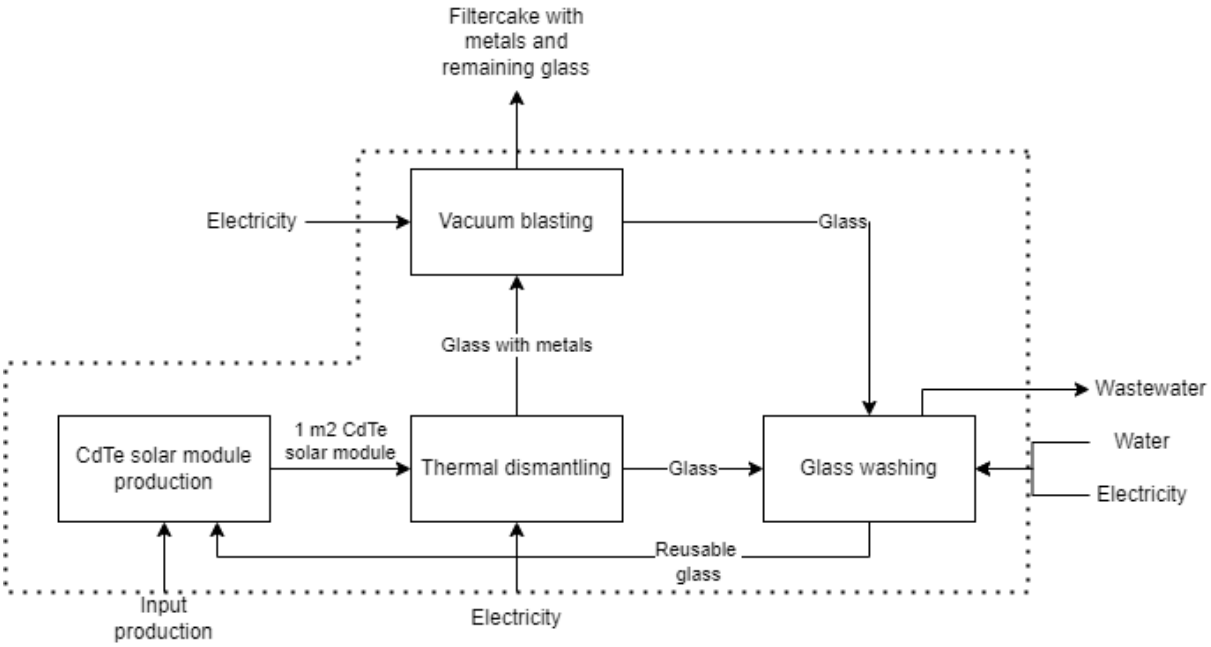

Figure A. 10: flowchart of reference flow 10 the recycling of 1 m2 CdTe solar module using thermal dismantling and vacuum blasting.

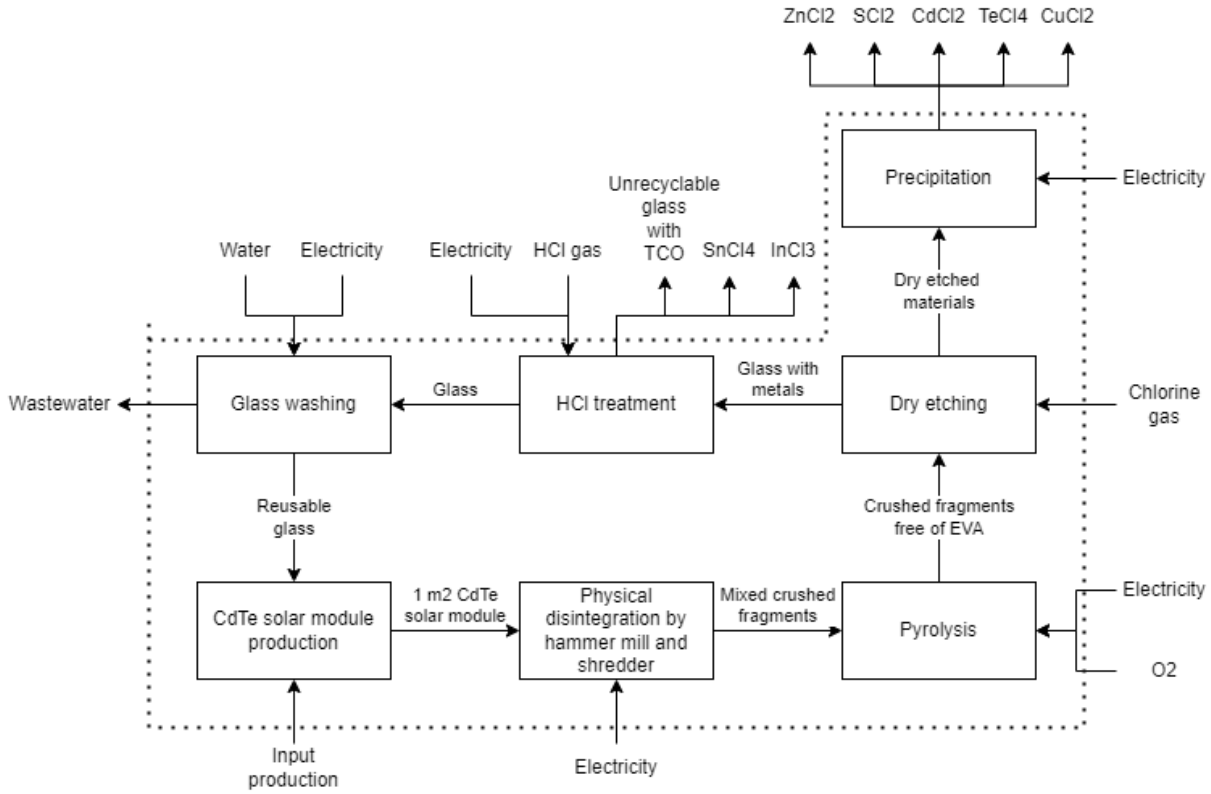

Figure A. 11: flowchart of reference flow 11 the recycling of 1 m2 CdTe solar module using dry etching and HCl treatment.

Appendix B - Unit Processes as Applied in the LCA Model

In this appendix the unit processes of all modelled steps can be seen. They each have their own economic and environmental in- and outputs.

Table B. 1: unit process physical disintegration

Unit process:	RC1 Physical disintegration (shredder + hammer mill)		
Economic flows	*Amount*	*Unit*	*Product*
In:	1	m2	CdTe solar module
	0.117172483	kWh	electricity
Out:	16.6	kg	mixed crushed fragments
Environmental flows			
In:			
Out:			

Table B. 2: unit process sieving

Unit process:	RC2 Sieving		
Economic flows	*Amount*	*Unit*	*Product*
In:	16.6	kg	mixed crushed fragments
Out:	1.66	kg	coarse fraction (> 1 mm)
	13.28	kg	intermediate fraction (0.1 - 1 mm)
	1.66	kg	fine fraction (< 0.1 mm)
Environmental flows			
In:			
Out:			

Table B. 3: unit process alkaline leaching

Unit process:	RC3 Alkaline leaching		
Economic flows	*Amount*	*Unit*	*Product*
In:	1.6600E+00	kg	fine fraction (<0.1 mm)
	5.2579E-02	kg	NaOH
	3.4288E-02	kg	H2SO4
	1.7432E-02	kg	HNO3
	9.2981E-08	kWh	electricity
Out:	2.2796E-02	kg	Al(OH)3
	2.8386E-08	kg	Zn
	3.8773E-02	kg	CdSO4
	2.0973E-02	kg	TeO2
	2.2337E-02	kg	NaNO3
	1.4571E+00	kg	Glass
	2.1848E-02	kg	Na2SO4
	4.4841E-03	kg	Na2S
Environmental flows			
In:	1.3279E-02	kg	O2
	2.5628E-04	m3	H2O
Out:	4.66E-04	m3	H2O

	0.000415106	kg	Aluminium
	0.000784671	kg	OH
	0.000803723	kg	Sodium
	0.001679112	kg	Sulfate
	0.001100376	kg	Cadmium
	0.00088253	kg	Tellurium
	0.000221324	kg	Oxygen
	0.000857631	kg	Nitrate
	9.21233E-05	kg	sulfur

Table B. 4: unit process acid leaching

Unit process:	**RC4 Acid leaching**		
Economic flows	*Amount*	*Unit*	*Product*
In:	1.66	kg	fine fraction (< 1 mm)
	6.45E-02	kg	H2SO4
	3.18E-02	kg	H2O2
Out:	7.12E-01	kg	liquid stream containing ZnSO4, Al2(SO4)3, CdSO4, H2TeO3, and glass remainder
	9.40E-01	kg	solid residue with glass
Environmental flows			
In:	5.68E-04	m3	H2O
Out:			

Table B. 5: unit process solvent treatment

Unit process:	**RC5 Solvent treatment of coarse fraction**		
Economic flows	*Amount*	*Unit*	*Product*
In:	1.66	kg	Coarse fraction (d > 1 mm)
	4.52599	kg	cyclohexane
	1.95216	kg	acetone
Out:	1.039160E+00	kg	intermediate fraction (0.1 - 1 mm)
	7.098990E+00	kg	residue of adhesive
Environmental flows			
In:			
Out:			

Table B. 6: unit process vibrating screening

Unit process:	**RC6 Vibrating screening**		
Economic flows	*Amount*	*Unit*	*Product*
In:	1.66	kg	coarse fraction (> 1 mm)
	0.000155625	kWh	electricity
Out:	6.208400E-01	kg	EVA foil with glass
	1.039160E+00	kg	glass
Environmental flows			
In:			
Out:			

Table B. 7: unit process incineration of coarse fraction

Unit process:	**RC7 Incineration of coarse fraction**		
Economic flows	*Amount*	*Unit*	*Product*
In:	1.66	kg	Coarse fraction (d > 1 mm)
	4	kWh	electricity
Out:	1.04E+00	kg	Glass
Environmental flows			
In:	4.50E+00	kg	Oxygen
Out:	1.44E+00	kg	CO2 (g)
	4.92E-04	m3	H2O (g)
	3.20E+00	kg	Oxygen

Table B. 8: unit process thermal dismantling

Unit process:	**RC8 Thermal dismantling**		
Economic flows	*Amount*	*Unit*	*Product*
In:	1	m2	CdTe solar module
	40	kWh	electricity
Out:	7.40E+00	kg	Glass with metals
	7.11891	kg	Glass
Environmental flows			
In:			
Out:	4.92E-04	m3	H2O
	1.44E+00	kg	CO2

Table B. 9: unit process pyrolysis of mixed crushed fragments

Unit process:	**RC10 Pyrolysis of mixed crushed fragments**		
Economic flows	*Amount*	*Unit*	*Product*
In:	16.6	kg	mixed crushed fragments
	40	kWh	electricity
Out:	1.59791600E+01	kg	EVA free crushed fragments
Environmental flows			
In:	4.50E+00	kg	Oxygen
Out:	1.44E+00	kg	CO2 (g)
	4.92E-04	m3	H2O (g)
	3.20E+00	kg	Oxygen

Table B. 10: unit process of dry etching

Unit process:	**RC11 Dry etching with chlorine gas**		
Economic flows	*Amount*	*Unit*	*Product*
In:	1.59791600E+01	kg	EVA free crushed fragments
	1.486883448E-01	kg	Chlorine gas
Out:	2.8979229E-01	kg	CdCl2 & TeCl4 & SCl2 & CuCl2 & ZnCl2 & glass mix
	7.9115600E+00	kg	Glass with TCO layer

	7.1189100E+00	kg	Clean glass
Environmental flows			
In:			
Out:	7.31E-09	kg	O2

Table B. 11: unit process HCl treatment

Unit process:	**RC12 HCl treatment of glass with TCO layer**		
Economic flows	*Amount*	*Unit*	*Product*
In:	7.911560E+00	kg	Glass with TCO layer
	1.337799E-03	kg	HCl gas
	1.600379E-04	kWh	electricity
Out:	7.118003E+00	kg	Glass
	2.582357E-04	kg	SnCl4
	2.142333E-03	kg	InCl3
	7.911560E-01	kg	Unrecyclable glass with TCO
Environmental flows			
In:			
Out:	3.315917E-07	m3	H2O

Table B. 12: unit process of precipitation of materials from dry etching

Unit process:	**RC13 Precipitation of all materials from dry etching**		
Economic flows	*Amount*	*Unit*	*Product*
In:	2.897923E-01	kg	CdCl2 & TeCl4 & SCl2 & CuCl2 & ZnCl2 & glass mix
	1.738754E-02	kWh	electricity
Out:	3.409569E-02	kg	Precipitated CdCl2
	3.540349E-02	kg	Precipitated TeCl4
	5.619980E-03	kg	Precipitated SCl2
	2.001835E-01	kg	Precipitated CuCl2
	5.917296E-08	kg	Precipitated ZnCl2
Environmental flows			
In:			
Out:	9.212328E-05	kg	Sulphur
	1.197795E-03	kg	Tellurium
	1.100436E-03	kg	Cadmium
	4.980000E-03	kg	Copper
	1.494110E-09	kg	Zinc
	7.119259E-03	kg	Cl2

Table B. 13: unit process attrition

Unit process:	**RC14 Attrition**		
Economic flows	*Amount*	*Unit*	*Product*
In:	16.6	kg	mixed crushed fragments
	0.028060417	kWh	electricity
Out:	18.26	kg	liquid stream with separated materials

Environmental flows			
In:	0.001664995	m3	H2O
Out:			

Table B. 14: unit process flotation

Unit process:	**RC15 Flotation of attrition product**		
Economic flows	*Amount*	*Unit*	*Product*
In:	18.26	kg	liquid stream with separated materials
	0.0085324	kWh	electricity
Out:	1.49684E+01	kg	glass
	2.98569E-02	kg	CdTe
	7.30093E-03	kg	CdS
	1.66499E-03	m3	wastewater
	1.59445E+00	kg	materials to incineration
Environmental flows			
In:			
Out:			

Table B. 15: unit process centrifugal extraction

Unit process:	**RC16 Centrifugal extraction**		
Economic flows	*Amount*	*Unit*	*Product*
In:	18.26	kg	liquid stream with separated materials
	0.0171229	kWh	electricity
Out:	14.96838715	kg	glass
	0.02687125	kg	CdTe
	0.00757375	kg	CdS
	0.001664995	m3	wastewater
	1.597167847	kg	materials to incineration
Environmental flows			
In:			
Out:			

Table B. 16: unit process precipitation of acid leaching products

Unit process:	**RC18 Precipitation of acid leaching products**		
Economic flows	*Amount*	*Unit*	*Product*
In:	0.711966744	kg	liquid stream containing ZnSO4, Al2(SO4)3, CdSO4, H2TeO3, and glass remainder
	0.036916271	kg	NaOH
	0.034864081	kg	HNO3
	0.042718005	kWh	electricity
Out:	0.022795775	kg	Al(OH)3
	0.062267597	kg	Na2SO4
	0.000000043	kg	Zn(OH)2
	0.020973226	kg	TeO2
	0.038773335	kg	CdSO4

	0.001750342	kg	Sulfur
Environmental flows			
In:	0.000098973	m3	H2O
Out:	0.025457806	kg	NO2 (aq)
	0.001100376	kg	Cadmium (aq)
	1.49E-09	kg	Zinc (aq)
	0.000882530	kg	Tellurium (aq)
	0.000415106	kg	Aluminium (aq)
	0.001060881	kg	Sodium (aq)
	9.21E-05	kg	Sulfur (aq)
	0.000697867	m3	H2O
	0.001190093	kg	OH (aq)
	0.005259034	kg	SO4 (aq)
	0.001074228	kg	O2 (aq)

Table B. 17: unit process ion exchange of Cd

Unit process:	**RC19 Ion exchange of Cd**		
Economic flows	*Amount*	*Unit*	*Product*
In:	7.12E-01	kg	liquid stream containing ZnSO4, Al2(SO4)3, CdSO4, H2TeO3, and glass remainder
Out:	1.659834E-02	kg	Cd contained in resin
	6.95E-01	kg	liquid stream containing Zn, Al, Te, an Cd remainder
Environmental flows			
In:			
Out:			

Table B. 18: unit process elution of resin

Unit process:	**RC20 Elution of resin**		
Economic flows	*Amount*	*Unit*	*Product*
In:	1.66E-02	kg	Cd contained in resin
	1.45E-02	kg	H2SO4
Out:	5.26E-02	kg	eluted solution
Environmental flows			
In:	2.16E-05	m3	H2O
Out:			

Table B. 19: unit process electroplating

Unit process:	**RC21 Electroplating**		
Economic flows	*Amount*	*Unit*	*Product*
In:	5.26E-02	kg	eluted solution
	7.58E-02	kWh	electricity
Out:	1.6598340E-02	kg	Cd
	3.60E-02	kg	H2SO4 solution
Environmental flows			

In:			
Out:			

Table B. 20: unit process precipitation of stream after ion exchange of Cd

Unit process:	**RC22 Precipitation of liquid stream after ion exchange**		
Economic flows	*Amount*	*Unit*	*Product*
In:	6.95E-01	kg	liquid stream containing Zn, Al, Te, an Cd remainder
	3.69E-02	kg	NaOH
	3.49E-02	kg	HNO3
	4.17E-02	kWh	electricity
Out:	6.23E-02	kg	Na2SO4
	2.28E-02	kg	Al(OH)3
	4.32E-08	kg	Zn(OH)2
	2.10E-02	kg	TeO2
	1.75E-03	kg	Sulfur
Environmental flows			
In:	9.90E-05	m3	H2O
Out:	0.025457806	kg	NO2 (aq)
	1.66E-06	kg	Cadmium (aq)
	1.49E-09	kg	Zinc (aq)
	8.83E-04	kg	Tellurium (aq)
	4.15E-04	kg	Aluminium (aq)
	1.06E-03	kg	Sodium (aq
	1.84E-03	kg	Sulfur (aq)
	1.19E-03	kg	OH (aq)
	3.24E-03	kg	SO4 (aq)
	1.07E-03	kg	O2 (aq)
	6.96E-04	m3	H2O

Table B. 21: unit process CdTe production after acid leaching

Unit process:	**RC23 From acid leaching: CdTe production from CdSO4 and TeO2**		
Economic flows	*Amount*	*Unit*	*Product*
In:	2.74E-02	kg	CdSO4
	0.020973226	kg	TeO2
	2.21E-02	kg	NaHCO3
	0.000796352	kg	H2
	3.92E-01	kWh	electricity
Out:	3.15E-02	kg	CdTe
	1.87E-02	kg	Na2SO4
Environmental flows			
In:			
Out:	1.16E-02	kg	CO2
	9.50E-06	m3	H2O

Table B. 22: unit process CdS production after acid leaching

Unit process:	RC24 From acid leaching: CdS production		
Economic flows	*Amount*	*Unit*	*Product*
In:	1.14E-02	kg	CdSO4
	0.004259876	kg	Na2S
	3.07E-05	kWh	electricity
Out:	7.89E-03	kg	CdS
	1.09E+01	kg	Na2SO4 solution
Environmental flows			
In:	0.010911045	m3	H2O
Out:			

Table B. 23: unit process CdTe production after alkaline leaching

Unit process:	RC25 From alkaline leaching: CdTe production from CdSO4 and TeO2		
Economic flows	*Amount*	*Unit*	*Product*
In:	2.74E-02	kg	CdSO4
	2.0973E-02	kg	TeO2
	2.21E-02	kg	NaHCO3
	0.000796352	kg	H2
	3.92E-01	kWh	electricity
Out:	3.15E-02	kg	CdTe
	1.87E-02	kg	Na2SO4
Environmental flows			
In:			
Out:	0.005783407	kg	CO2
	7.12547E-06	m3	H2O

Table B. 24: unit process CdS production after alkaline leaching

Unit process:	RC26 From alkaline leaching: CdS production		
Economic flows	*Amount*	*Unit*	*Product*
In:	1.14E-02	kg	CdSO4
	0.004259876	kg	Na2S
	3.07E-05	kWh	electricity
Out:	7.89E-03	kg	CdS
	1.09E+01	kg	Na2SO4 solution
Environmental flows			
In:	1.09E-02	m3	H2O
Out:			

Table B. 25: unit process recovery of Te from TeO2

Unit process:	RC27 Recovery of Te from TeO2 preparation		
Economic flows	*Amount*	*Unit*	*Product*
In:	2.09732E-02	kg	TeO2
	2.94939E-03	kg	KOH

	0.001258394	kWh	electricity
Out:	1.34E-02	kg	Te (s)
Environmental flows			
In:	1.90E-06	m3	H2O
Out:	4.75E-07	m3	H2O
	2.06E-03	kg	Potassium
	4.63E-03	kg	Oxygen
	3.35E-03	kg	Tellurium

Table B. 26: unit process incineration of flotation residue

Unit process:	**RC28 Incineration of flotation residue**		
Economic flows	*Amount*	*Unit*	*Product*
In:	1.59445E+00	kg	materials to incineration
	3.84206E+00	kWh	electricity
Out:			
Environmental flows			
In:	1.306428946	kg	O2
Out:	0.002343103	kg	Cd
	0.001777317	kg	Te
	0.000221778	kg	SO2
	1.43629762	kg	CO2
	0.000491554	m3	H2O
	0.00077923	kg	O2

Table B. 27: unit process incineration of centrifugal extraction residue

Unit process:	**RC29 Incineration of centrifugal extraction product**		
Economic flows	*Amount*	*Unit*	*Product*
In:	1.59717E+00	kg	materials to incineration
	3.84860E+00	kWh	electricity
Out:			
Environmental flows			
In:	1.306935414	kg	O2
Out:	0.005412931	kg	Cd
	0.003364645	kg	Te
	0.000161216	kg	SO2
	1.43629762	kg	CO2
	0.000491554	m3	H2O
	0.001346129	kg	O2

Table B. 28: unit process glass washing

Unit process:	**RC30 Glass washing vibrating screening**		
Economic flows	*Amount*	*Unit*	*Product*
In:	1.039160E+00	kg	Glass
	1.203138E-04	kWh	electricity

Out:	1.039160E+00	kg	clean glass
	0.001182164	m3	wastewater
Environmental flows			
In:	1.182164E-03	m3	H2O
Out:			

Appendix C - Values for Economic Allocation

Economic values of most material is found at one main distributor of chemicals used in industries called Sigma-Aldrich (Merck 2022). The price of solar glass was found in a research by the National Renewable Energy Laboratory (Horowitz et al. 2017). The price for EVA was found with a large distributor of solar material. The average price per kg was taken (Alibaba.com 2023). Finally, there could an economic value be placed on wastewater (Hernández-Sancho et al. 2015). The values represented in table C.1 show the prices of the material after treatment. Assumed was that these recovered materials had a value of 10% of the original price (Stolz et al. 2017).

Table C. 1: economic values of material used in study.

Material	Price	Unit
Al(OH)3	3.86	€/kg
Al2(SO4)3	8.40	€/kg
Aluminium	33.40	€/kg
Cadmium	139.00	€/kg
CdCl2	147.00	€/kg
CdS	47.20	€/kg
CdSO4	106.00	€/kg
CdTe	678.00	€/kg
Copper	33.00	€/kg
CuCl2	41.40	€/kg
EVA	1.78	€/kg
H2SO4	3.17	€/L
H2TeO3	293.00	€/kg
InCl3	1580.00	€/kg
Na2S	6.04	€/kg
Na2SO4	5.29	€/kg
NaNO3	16.60	€/kg
SCl2	6.08	€/kg
SnCl4	386.00	€/kg
Solar glass	0.29	€/kg
Sulfur	4.16	€/kg
TCO(ITO)	559.00	€/kg
TeCl4	657.00	€/kg
Tellurium	171.00	€/kg
TeO2	277.20	€/kg
Wastewater	1.50	€/m3
Zinc	20.60	€/kg
Zn(OH)2	3.86	€/kg
ZnSO4	78.80	€/kg

Appendix D - Assumptions of Life Cycle Assessment

In this study many assumptions have been made for the recycling processes. These assumptions can be seen in table D.1.

Table D. 1: Assumptions made in LCA on recycling strategies of CdTe modules.

Life cycle stage	Source for quantities	Main assumptions
Production		
Deposition of TCO layer	(Tchenka et al. 2021)	TCO layer is deposited by RF sputtering.
Deposition of CdS layer	(Doroody et al. 2021)	CdS layer is deposited by RF sputtering
Deposition of CdTe layer	(Kato et al. 2001; Espinosa et al. 2015)	CdTe layer is deposited by vapour transport deposition
CdCl2 treatment	(Major et al. 2014)	
Deposition of back contact	(Uličná et al. 2017)	Back contact is deposited by sputtering.
Laser scribing	(Kato et al. 2001)	
Lamination	(Kato et al. 2001)	
Recycling		
Physical disintegration	(Marchetti et al. 2018; Giacchetta et al. 2013)	All material that went into the shredder and hammer mill, went out
Sieving	(Toro et al. 2013)	Sieving distribution is: 10% fine fractions, 80% intermediate fractions, 10% coarse fractions
Thermal dismantling	(Tao and Yu 2015; Granata et al. 2014; Pagnanelli et al. 2019)	EVA layer is fully incinerated. 50% of glass can be directly recycled (front glass). 50% of glass needs further treatment (back glass).
Vacuum blasting	(Airblast 2013)	Metals from filter cake are recovered externally.
Treatment of fine fractions		
Alkaline leaching	(Toro et al. 2013)	Only the amount of NaOH that is needed is used as input. Water is taken from the environment. CdTe reacts fully with NaOH to get Cd(OH)2 and Na2TeO3. ZnO and Al2O3 react fully with NaOH to get Na2Zn(OH)4 and NaAl(OH)4.
- Precipitation of leaching product	(Toro et al. 2013; Ecoinvent 2021)	$NaAl(OH)_4$ and $Cd(OH)_2$ react with H_2SO_4 to $Al(OH)_3$, Na_2SO_4, $CdSO_4$ and water. Na_2TeO_3 reacts with HNO_3 to TeO_2, $NaNO_3$ and water.
Acid leaching	(Toro et al. 2013; Fthenakis and Wang 2005; Tao and Yu 2015; Held 2009; Pagnanelli et al. 2019)	Only the amount of H2SO4 that is needed is used as input. ZnO reacts fully to ZnSO4, Al and Al2O3 react fully to Al2(SO4)3. CdTe reacts fully to H2TeO3 and CdSO4.
- Precipitation of leaching product	(Toro et al. 2013; Fthenakis and Wang 2005; Ecoinvent 2021)	NaOH reacts fully with Al and Zn to get precipitates of Al(OH)3, Zn(OH)2 and Na2SO4. HNO3 will fully precipitate Te with TeO2 and NO2 as products. Water input is directly related to molarity.
Acid leaching and ion exchange	(Toro et al. 2013; Fthenakis and Wang 2005; Tao and Yu 2015; Held 2009; Pagnanelli et al. 2019)	Only the amount of H2SO4 that is needed is used as input. ZnO reacts fully to ZnSO4, Al and Al2O3 react fully to Al2(SO4)3. CdTe reacts fully to H2TeO3 and CdSO4.
- Ion exchange	(Fthenakis and Wang 2005)	Resin will be fully regenerated, so no input needed of resin.
- Elution of resin	(Fthenakis and Wang 2005)	H2SO4 removes Cd by reaction to CdSO4 and H2. All Cd is removed from resin, clean resin can be fully used again.
- Electroplating	(Fthenakis and Wang 2005; Moign et al. 2009)	Cd is directly recoverable. H2SO4 solution is used again for elution. Electrical input of electroplating is similar for all material.
- Precipitation of leaching product	(Toro et al. 2013; Fthenakis and Wang 2005; Ecoinvent 2021)	NaOH reacts fully with Al and Zn to get precipitates of Al(OH)3, Zn(OH)2 and Na2SO4. HNO3 will fully precipitate Te with TeO2 and NO2 as products. Water input is directly related to molarity.
Treatment of coarse fraction		
Solvent treatment	(Toro et al. 2013)	Coarse fraction only consists of EVA and glass.

		Only cyclohexane, acetone and water are needed. Mixture cyclohexane-acetone is 70:30 mass%. Residue of adhesive consists of EVA and mixture of glass, acetone, and cyclohexane.
Vibrating screening	(Camco 2023; Tao and Yu 2015)	Coarse fraction only consists of EVA and glass. At least 90% of glass can be recovered.
Pyrolysis	(Maani et al. 2020; Mulazzani et al. 2022; Diequez Campo et al. 2003)	Coarse fraction only consists of EVA and glass. Oxygen that is consumed is equal to oxygen that is needed to fully decompose EVA layer.
Treatment of intermediate fraction		
Glass washing	(Marchetti et al. 2018; Blengini et al. 2012; Ecoinvent 2021)	Only water and electricity are needed. Wastewater is treated in plant that treats wastewater from PV production.
Treatment of full mix		
Attrition	(Marchetti et al. 2018; Giacchetta et al. 2013)	Everything that goes into this process is further treated in the next process.
Centrifugal extraction	(Marchetti et al. 2018; Pagnanelli et al. 2017)	Water that went in, is outputted as wastewater. Remainder of materials is incinerated by reaction with oxygen.
Flotation	(Marchetti et al. 2018; Giacchetta et al. 2013; Pagnanelli et al. 2017)	Water that went in, is outputted as wastewater. Remainder of materials is incinerated by reaction with oxygen.
Dry etching	(Dai et al. 2019; Diequez Campo et al. 2003; Ecoinvent 2021)	Cl2 gas reacts fully with CdS, CdTe, and Cu to create CdCl2, SCl2, TeCl4, and CuCl4. After dry etching 50% of the glass is clean (back glass). The other 50% still has the TCO layer of ITO (front glass).
- Precipitation of dry etched product	(Diequez Campo et al. 2003; Ecoinvent 2021; Dai et al. 2019)	Precipitation is done with cold traps Material will precipitate at their own precipitation temperature without contamination.
HCl treatment	(Diequez Campo et al. 2003)	ITO fully reacts as SnO2 and In2O3 with HCl to create SnCl4, InCl3 and water.
Production of new material		
CdTe production	(Zhang et al. 2020)	Cd and Te precipitates will react to CdTe. Outcomes of production will be used as input directly.
CdS production	(Silambarasan et al. 2011)	Cd precipitate will react with Na2S to form CdS Outcomes of production will be used as input directly.
Overall		
Factories and machinery	(Silva et al. 2018)	Are not accounted for.
Reaction mechanisms		Full complete reactions take place without excess of chemicals.
Emissions		Based on recovery efficiencies. If not recovered it will be emitted.
Recovery of material		Only recovery of glass, CdTe, and CdS is considered.

Appendix E - Hotspots of Recycling Processes Discovered by Harmonization

Table E.1 presents all hotspots that were found by harmonizing the LCA data from different studies. These hotspots entail parts of the full cycle that cause high impacts or have a large contribution to impacts.

Table E. 1: results of harmonization of LCAs from literature.

Source	Processes covered	Hotspots identified in CdTe recycling
Held (2009)	- Physical disintegration (shredding and hammer milling) - Acid leaching - Precipitation of leaching product - Vibrating screening - Glass washing	- Electricity use is largest contributor to increasing impact in all categories. - Waste incineration is large contributor to global warming potential. - Waste disposal increases impact in all categories. - Treatment of wastewater is large contributor in all impact categories, due to use of chemicals.
Berger et al. (2010)	- Physical disintegration (shredding and hammer milling) **OR** thermal dismantling - Attrition **OR** vacuum blasting - Flotation - Purification - Incineration	- Energy use for attrition and flotation is large contributor to global warming potential of damaged modules. - Energy use for thermal treatment of undamaged modules is large contributor to global warming potential. - Physical disintegration combined with attrition has a higher impact than thermal treatment combined with vacuum blasting.
Rocchetti & Beolchini (2014)	- Physical disintegration (shredding and hammer milling) - Acid leaching - Precipitation of leaching product - Vibrating screening - Glass washing - Recovery of Tellurium	- Incineration of EVA layer has high contribution to global warming potential and eutrophication potential. - Use of reagents to recover tellurium is largest contributor to increasing impacts on acidification potential, eutrophication potential, ozone layer depletion potential, and photochemical ozone creation potential. - Wastewater treatment has increasing effect on eutrophication potential due to use of reagents.
Vellini (2017)	- Physical disintegration (shredding and hammer milling) - Acid leaching - Precipitation of leaching product - Vibrating screening - Glass washing	- Use of fossil fuels for electricity has an increasing effect on global warming potential, eutrophication potential, and ozone layer depletion potential.
Giacchetta et al. (2013)	- Physical disintegration - Attrition - Flotation	- Use of shredder largest contributor to ionizing radiation potential and land occupation potential. Also contributes to increasing impact of terrestrial ecotoxicity potential, non-renewable energy use potential, and mineral extraction potential.
Marchetti et al. (2018)	- Physical disintegration - Attrition - Flotation **OR** Centrifugal extraction - Washing	- Incineration of non-recoverable attrition residue increases potential in all impact categories. - Using centrifugal extraction instead of flotation gives an increased ionizing radiation potential.
Stolz et al. (2017)	- Physical disintegration (shredding and hammer milling) - Acid leaching - Precipitation of leaching product - Vibrating screening - Glass washing	- Use of chemicals, like hydrogen peroxide, in acid leaching increases the human toxicity, cancerous effects potential and the freshwater ecotoxicity potential.
Pagnanelli et al. (2019)	- Physical disintegration - Sieving - Solvent treatment of **OR** thermal treatment of coarse fraction. - Acid leaching of fine fraction	- Use of cyclohexane in solvent treatment increase climate change potential - Use of chemicals from acid leaching is the largest contributor to the positive impact on human toxicity potential for both cancer and non-cancer effects. - Acid leaching contributes to increasing impacts on all categories.

Appendix F - Contribution Analysis of Life Cycle Assessment

This Appendix present the contribution analysis of the conducted LCA. A contribution analysis shows which processes contribute to the potential impacts in each impact category. The contribution had to be at least 1% to be included in the figures. All impact categories are represented in the following figures.

F.1 Acidification

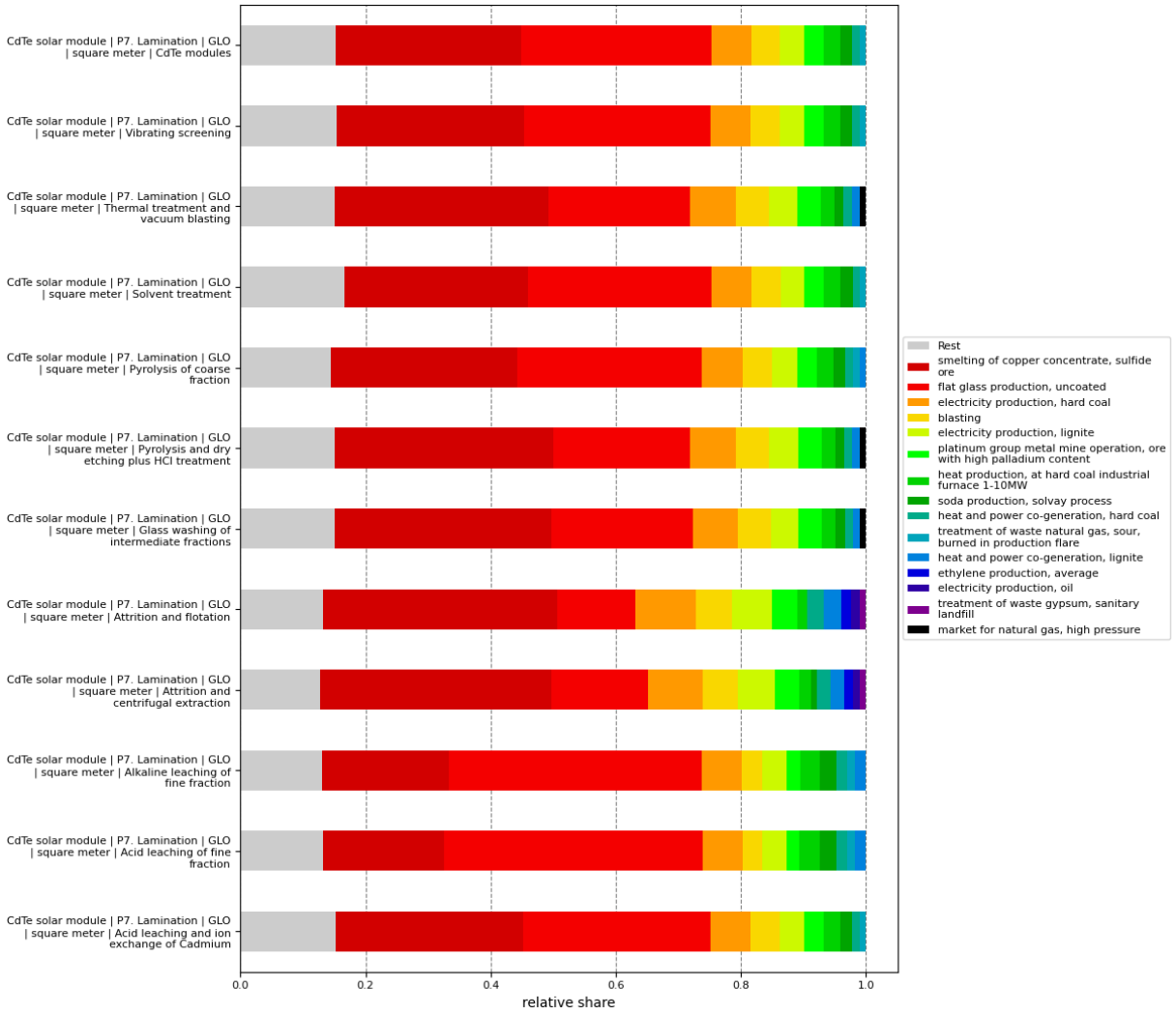

Figure F. 1: contribution analysis in impact category of acidification.

For the acidification potential it could be seen that copper treatment and flat glass use are the largest contributors for the most processes. These two processes can be related to the production of CdTe solar modules. For the processes that use attrition this share is a bit smaller as electricity use contributes more. They also have a noticeable share in the processes of ethylene production and treatment of waste gypsum. The production of new glass for alkaline and acid leaching contributes largely to these processes. This might be the case as these processes contain less glass, as they treat the fine fraction.

F.2 Global warming

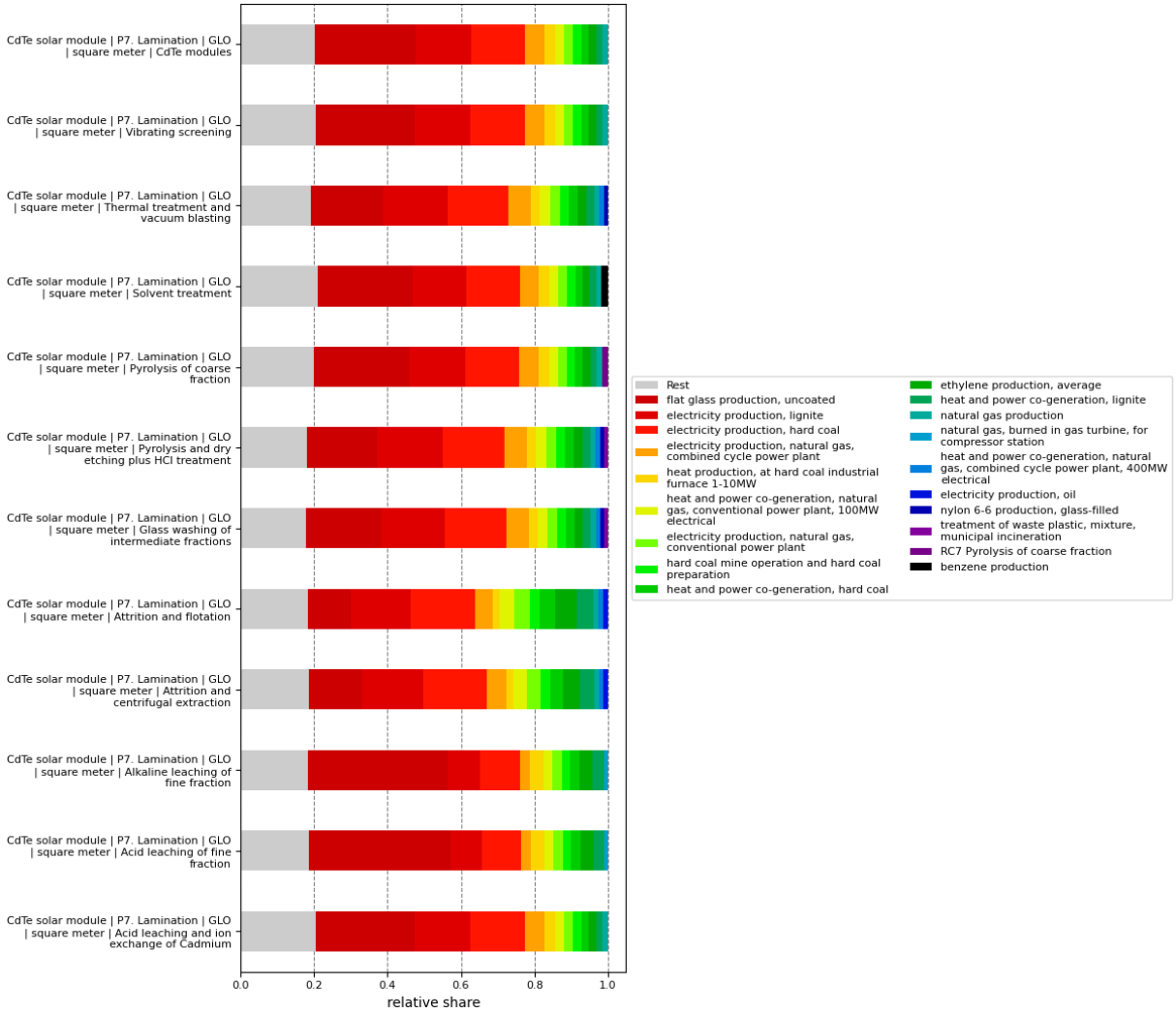

Figure F. 2: contribution analysis in impact category of global warming.

Largely contributing to the global warming potential is the production of solar glass and the use of electricity and heat for all processes. The production of ethylene is a noticeable contributor here as well. This contributor is larger for the processes that make use of attrition. The usage of benzene also contributes considerable to the global warming potential of the solvent treatment. For the pyrolysis of coarse fractions it can be seen that the actual pyrolysis contributes for more than 1% to the global warming potential. Interestingly enough, it can be seen that the contribution of electricity use is the largest for the leaching processes.

F.3 Freshwater ecotoxicity

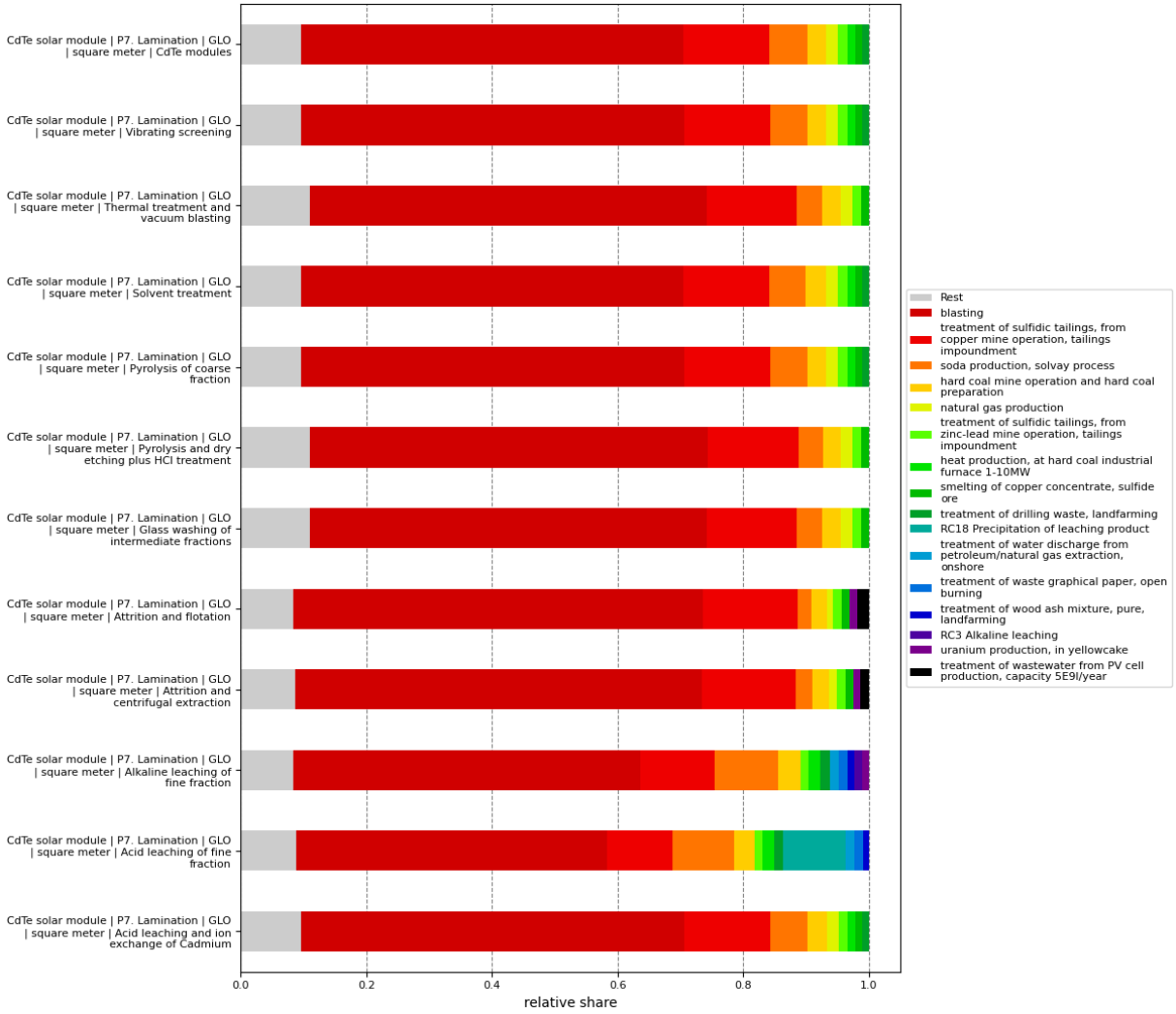

Figure F. 3: contribution analysis in impact category of freshwater ecotoxicity.

Blasting processes that are needed for the production of CdTe solar cells contribute majorly to all processes. The relative share of the sulfuric tailing treatment, also applied in production, is unneglectable. For acid leaching a large contribution comes from the precipitation of the acid leaching products. For alkaline leaching the actual leaching causes a noticeable impact. The treatment of wastewater is a remarkable contributor to the freshwater ecotoxicity potential.

F.4 Abiotic depletion of fossil fuels

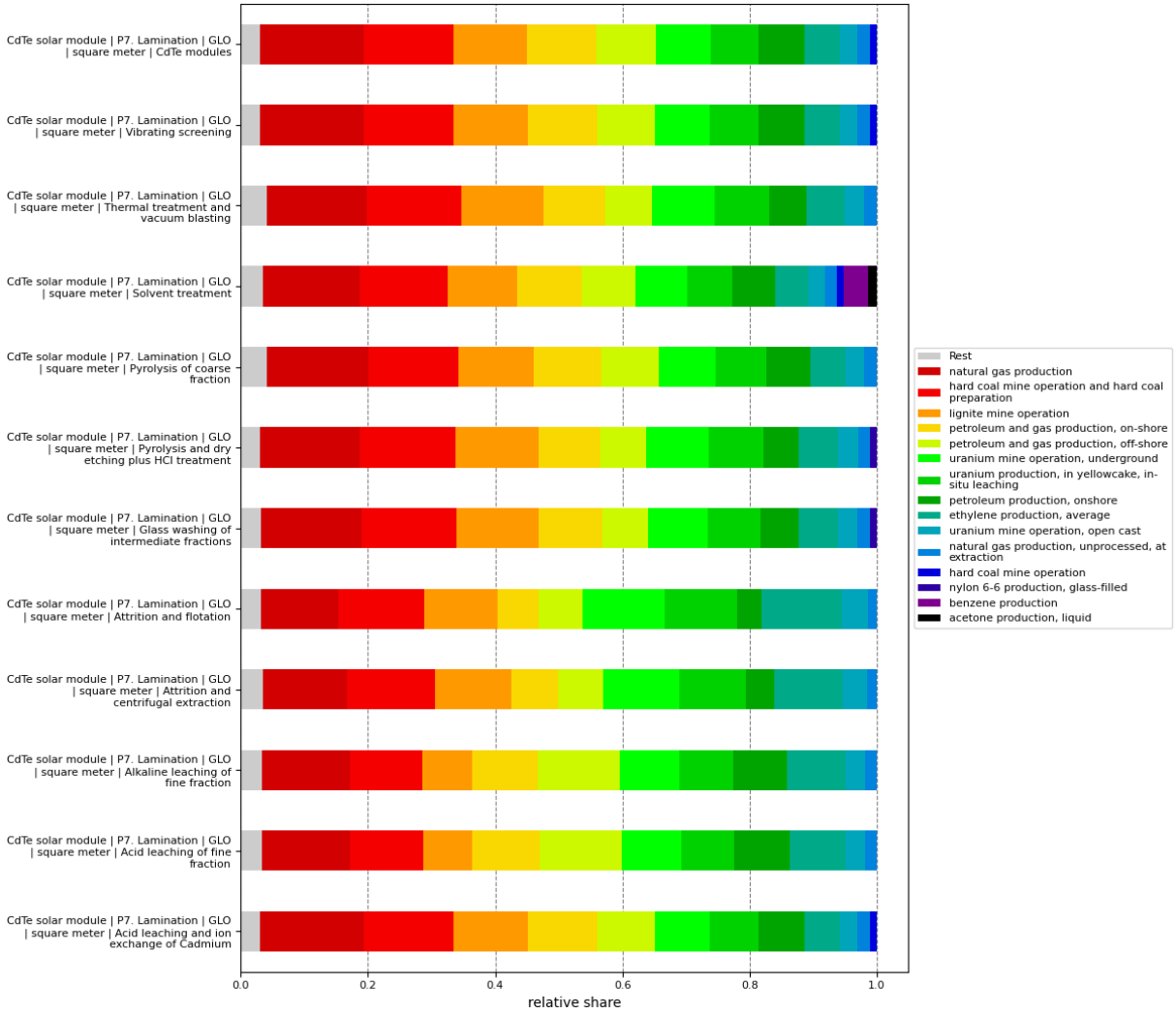

Figure F. 4: contribution analysis in impact category of abiotic depletion of fossil fuels.

Contributions for abiotic depletion potential are more even divided. However, the majority of contributions can be prescribed to the production of CdTe solar modules. For solvent treatment it can be seen that benzene production is a significant contributor. The contributions shift a little bit based on the outputs of the recycle processes.

F.5 Abiotic depletion of elements

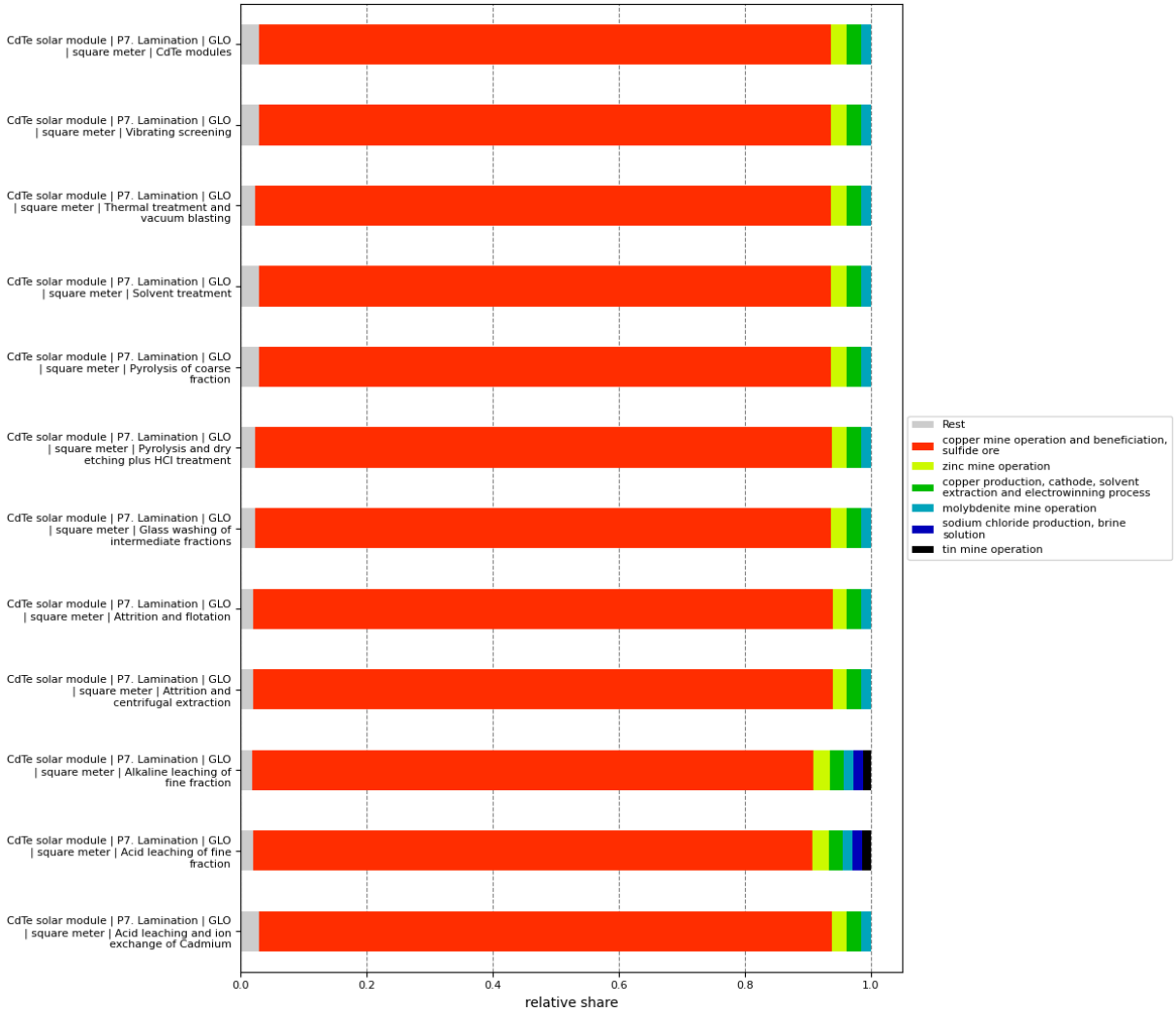

Figure F. 5: contribution analysis in impact category of abiotic depletion of elements.

The potential abiotic depletion of elements is largely caused by mining operations of copper and zinc. For alkaline and acid leaching a contribution can be seen of molybdenite and tin mining and sodium chloride production.

F.6 Freshwater eutrophication

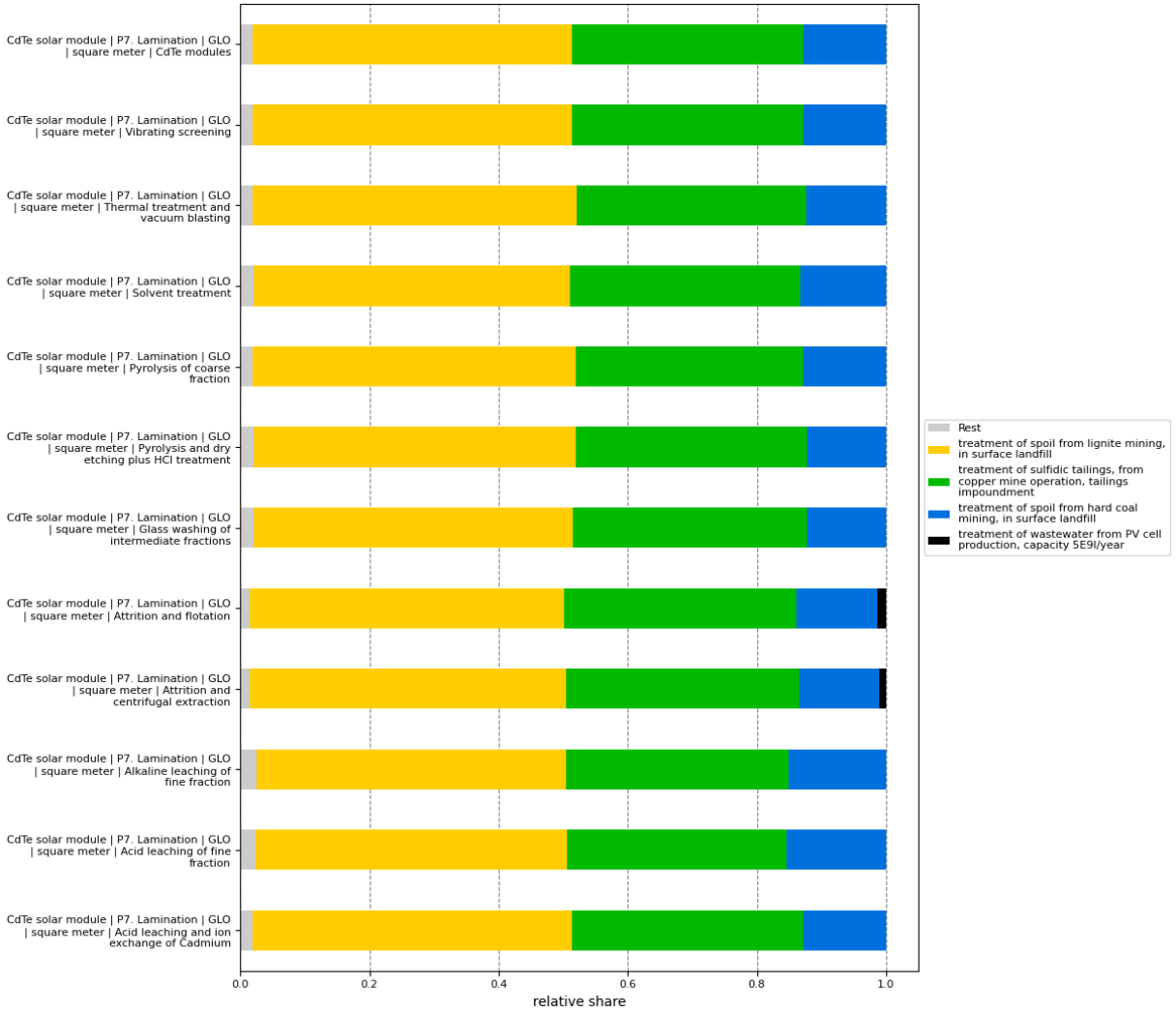

Figure F. 6: contribution analysis in impact category of freshwater eutrophication.

The freshwater eutrophication potential is primarily influenced by the production processes. It can be observed, that processes that include attrition contribute a bit more to this potential as they have more wastewater to treat. For the other processes this means that they hardly have a contribution to freshwater eutrophication.

F.7 Marine eutrophication

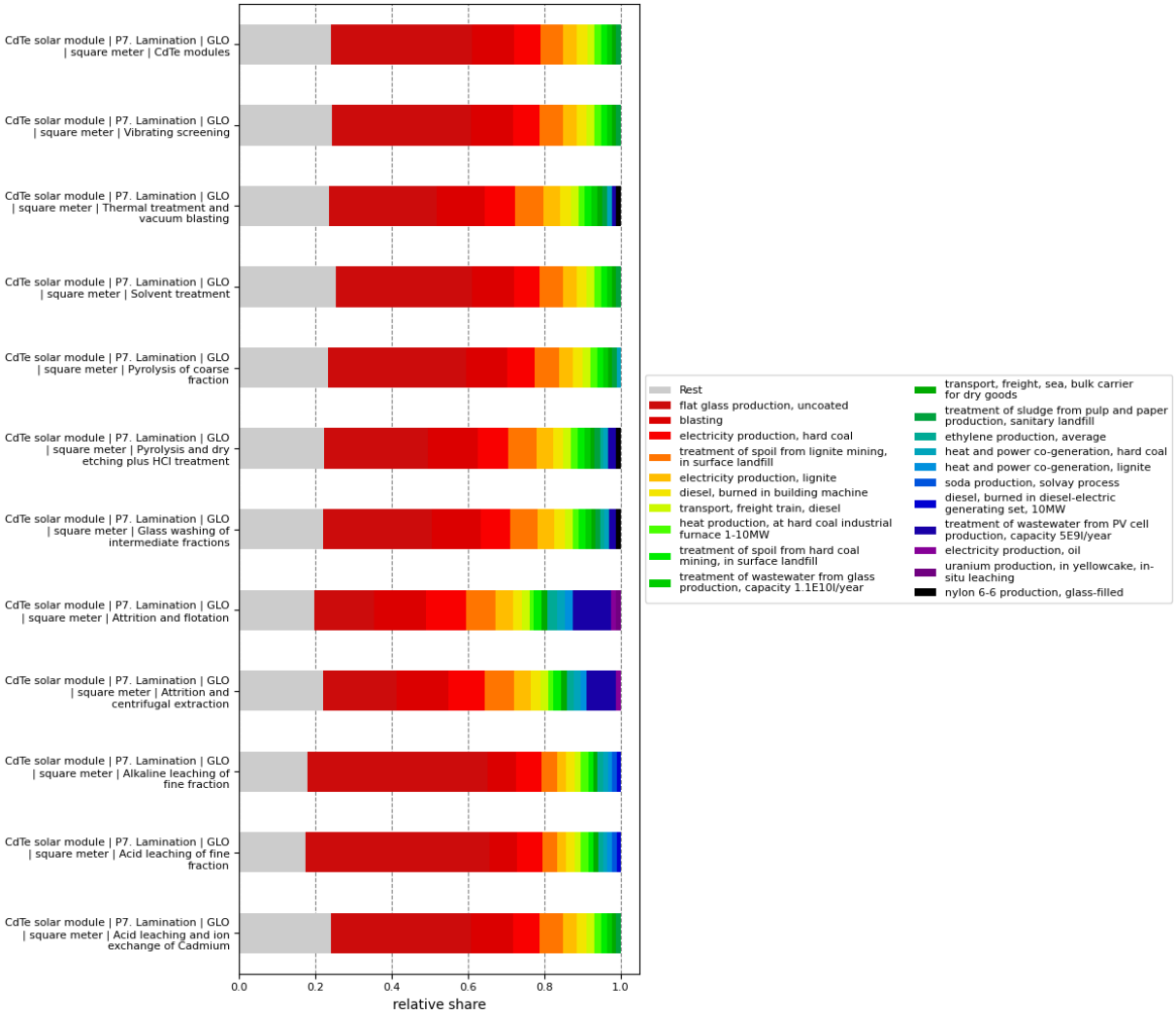

Figure F. 7: contribution analysis in impact category of marine eutrophication.

Processes that are related to the production of glass seem to have the largest contribution to the marine eutrophication potential. Different contributions of glass production can be seen for the different recovery percentages of glass. Electricity use in the production is a secondary contributor. The processes that include glass as an output experience a significant contribution from wastewater treatment process. The process of nylon 6,6 production is also a noticeable contributor to thermal treatment and vacuum blasting, pyrolysis and dry etching, and glass washing.

F.8 Terrestrial eutrophication

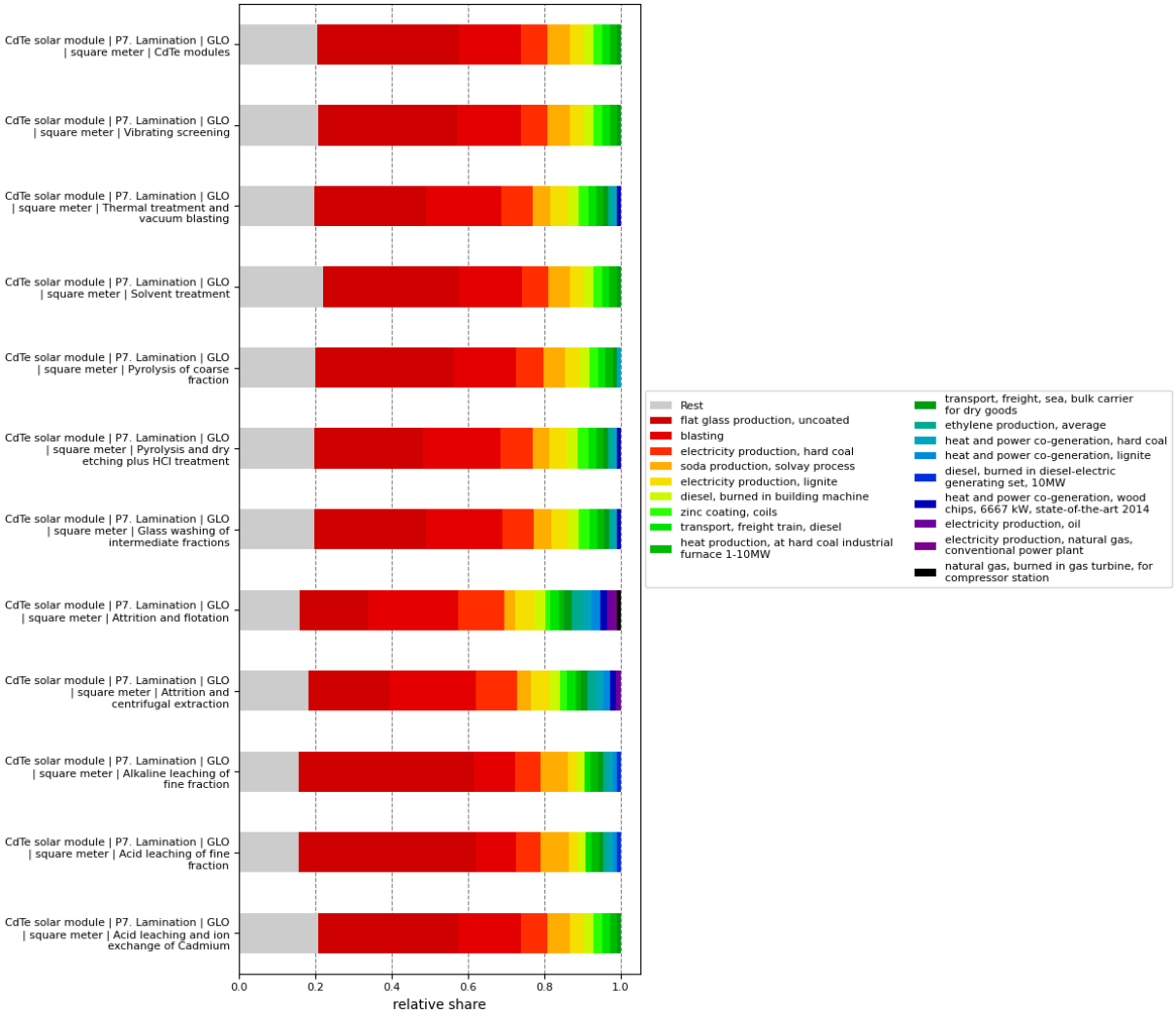

Figure F. 8: contribution analysis in impact category of terrestrial eutrophication.

Similar to the previous impact categories, are the production of glass and usage of electricity the largest contributors to the terrestrial eutrophication potential. Electricity is an even larger contributor for the processes that include attrition. A few processes are significantly influenced by the usage of ethylene.

F.9 Human toxicity, cancerous

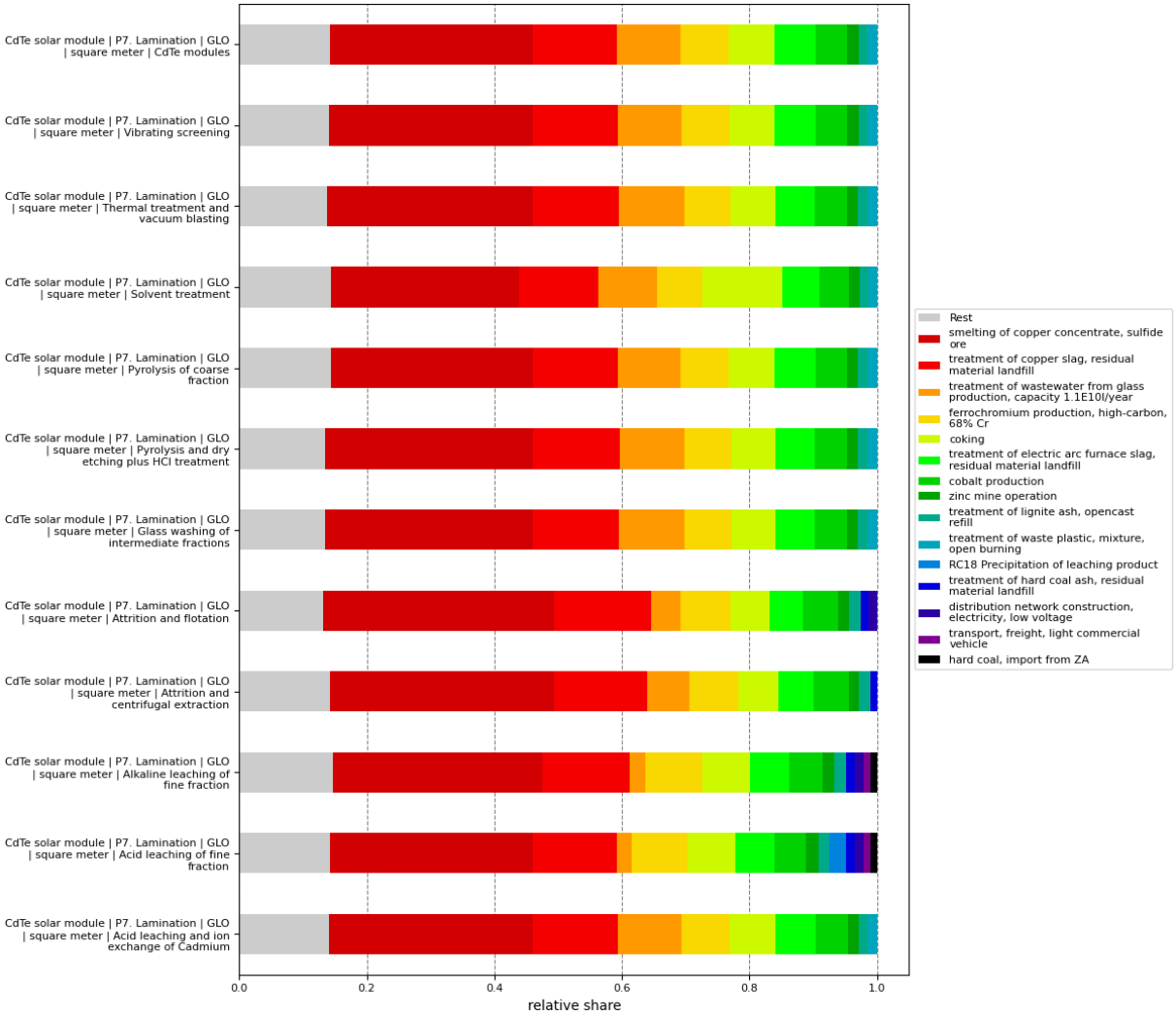

Figure F. 9: contribution analysis in impact category of human toxicity, cancerous.

Production processes, especially the acquiring of metals, contribute the most to the human toxicity, cancerous potential. Within acid leaching the process of precipitation contributes significantly to this impact category. For both acid and alkaline leaching, the impacts are contributed by transport processes and less contribution can be seen in wastewater treatment.

F.10 Human toxicity, non-cancerous

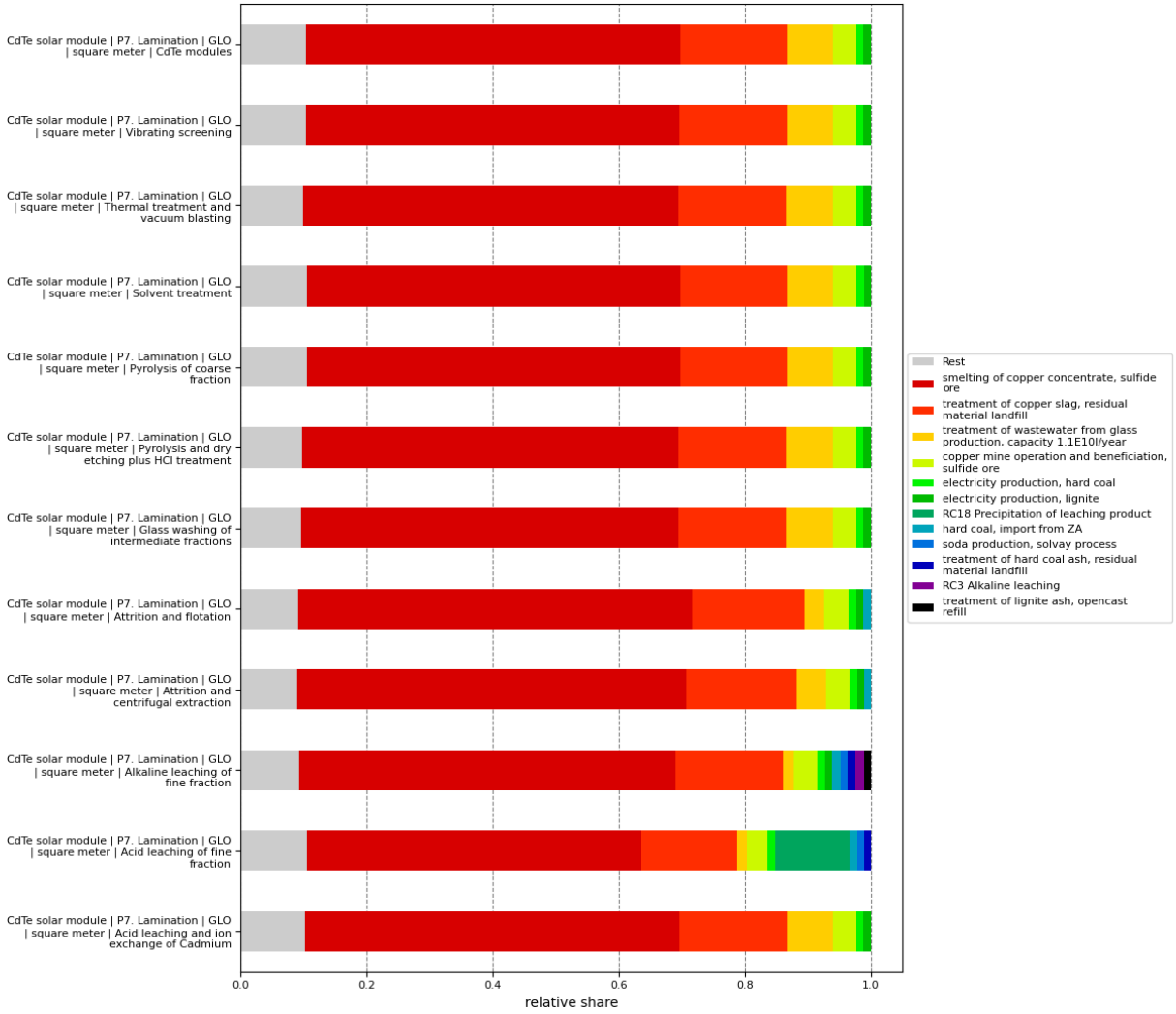

Figure F. 10: contribution analysis in impact category of human toxicity, non-cancerous.

An interesting thing is that for most recycle strategies the contribution division is almost identical. Only real differences can be identified for the attrition pathways, acid leaching, and alkaline leaching for which the wastewater treatment shows a lower contribution. An interesting significant contributor to the non-cancerous human toxicity potential is the precipitation of acid leaching product. Within the treatment pathway of alkaline leaching, it can be noticed that the actual alkaline leaching process is a significant contributor as well.

F.11 Ionising radiation

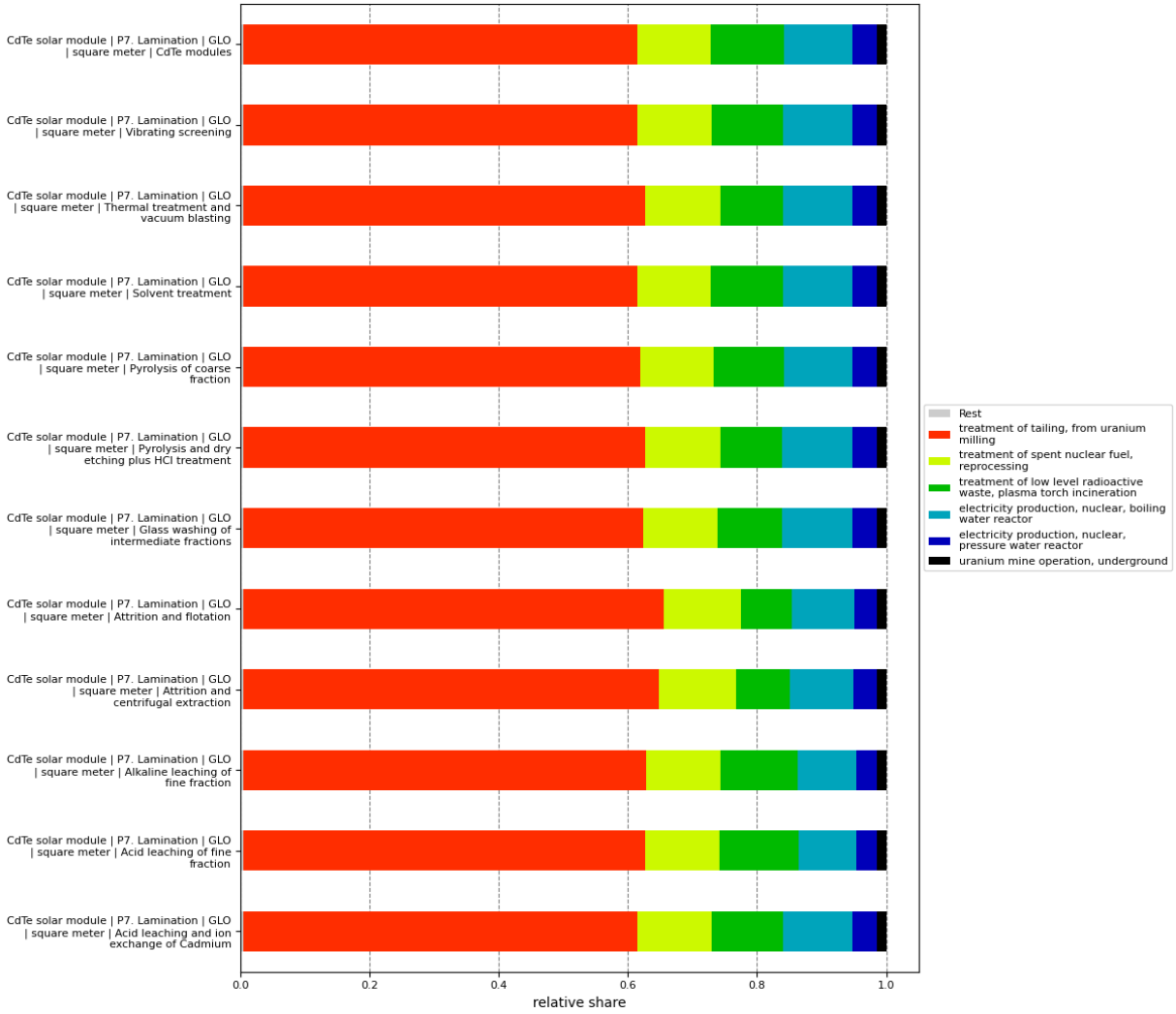

Figure F. 11: contribution analysis in impact category of ionising radiation.

For the potential impacts on ionising radiation the treatment of uranium milling contributes the most. The other large contributors are also related to the treatment of nuclear material. This can all be related back to production processes of CdTe solar modules. There is minor difference for the different recycle processes.

F.12 Land use

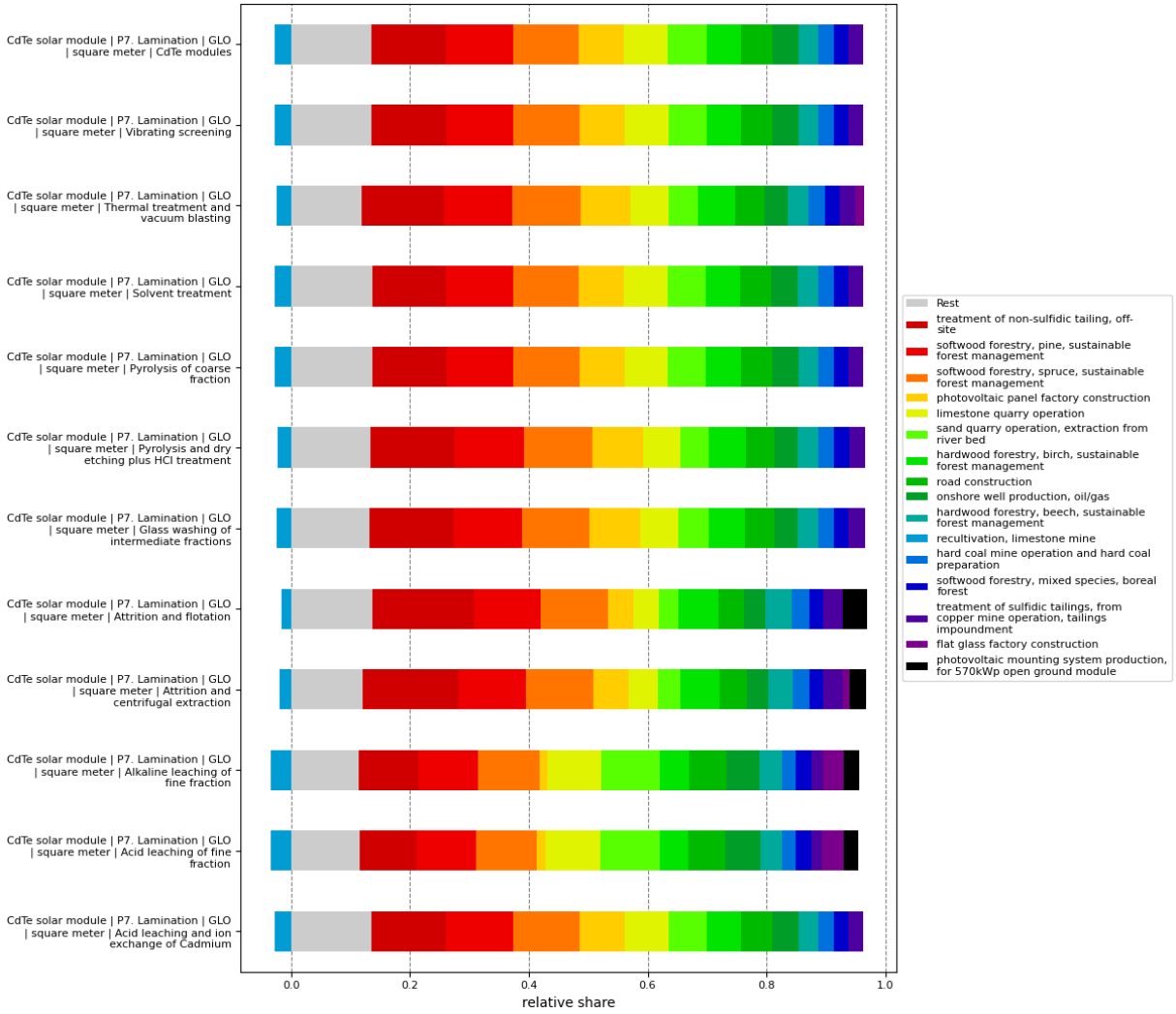

Figure F. 12: contribution analysis in impact category of land use.

Within the impact category of land use there is not one large contributor, but multiple smaller contributors. Most of the contribution comes from forestry processes that are needed for the production processes. Mining operations take up a small part of the land use potential as well for most processes. A contributor for land use potential that exists in all processes is the photovoltaic panel factory. For alkaline and acid leaching this contribution is lower and a higher contribution for glass production can be seen. Recultivation of the limestone mine causes a negative contribution in all processes.

F.13 Ozone depletion

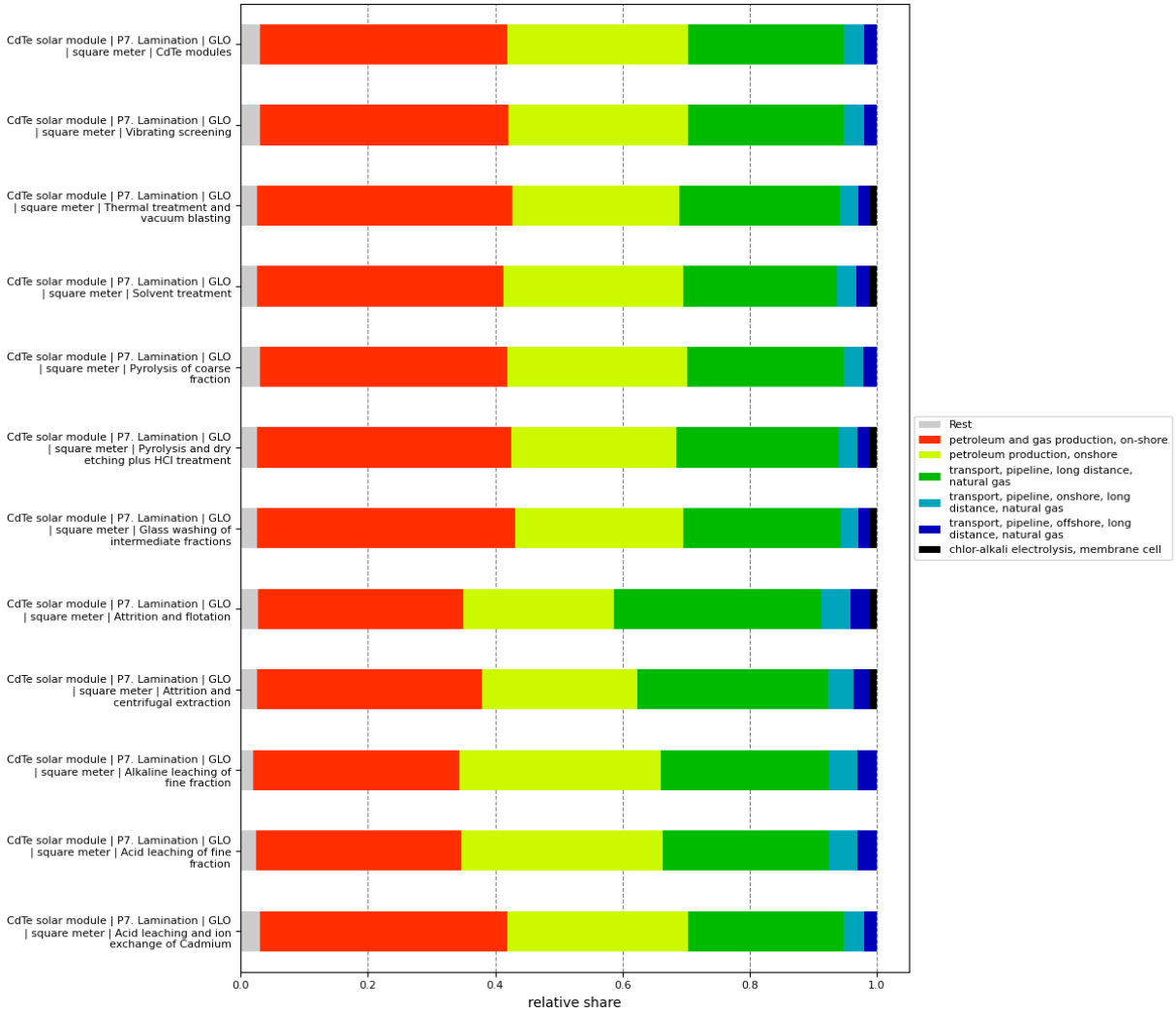

Figure F. 13: contribution analysis in impact category of ozone depletion.

The ozone layer depletion potential is mainly caused by transport processes. The use of petroleum stands for the major part, followed by the production of pipelines. For the processes containing attrition the contribution of petroleum is lower. For these processes, the contribution of pipelines is higher. Chlor-alkali electrolysis contributes to the attrition processes, glass washing, pyrolysis and dry etching, solvent treatment, and thermal treatment and vacuum blasting.

F.14 Particulate matter formation

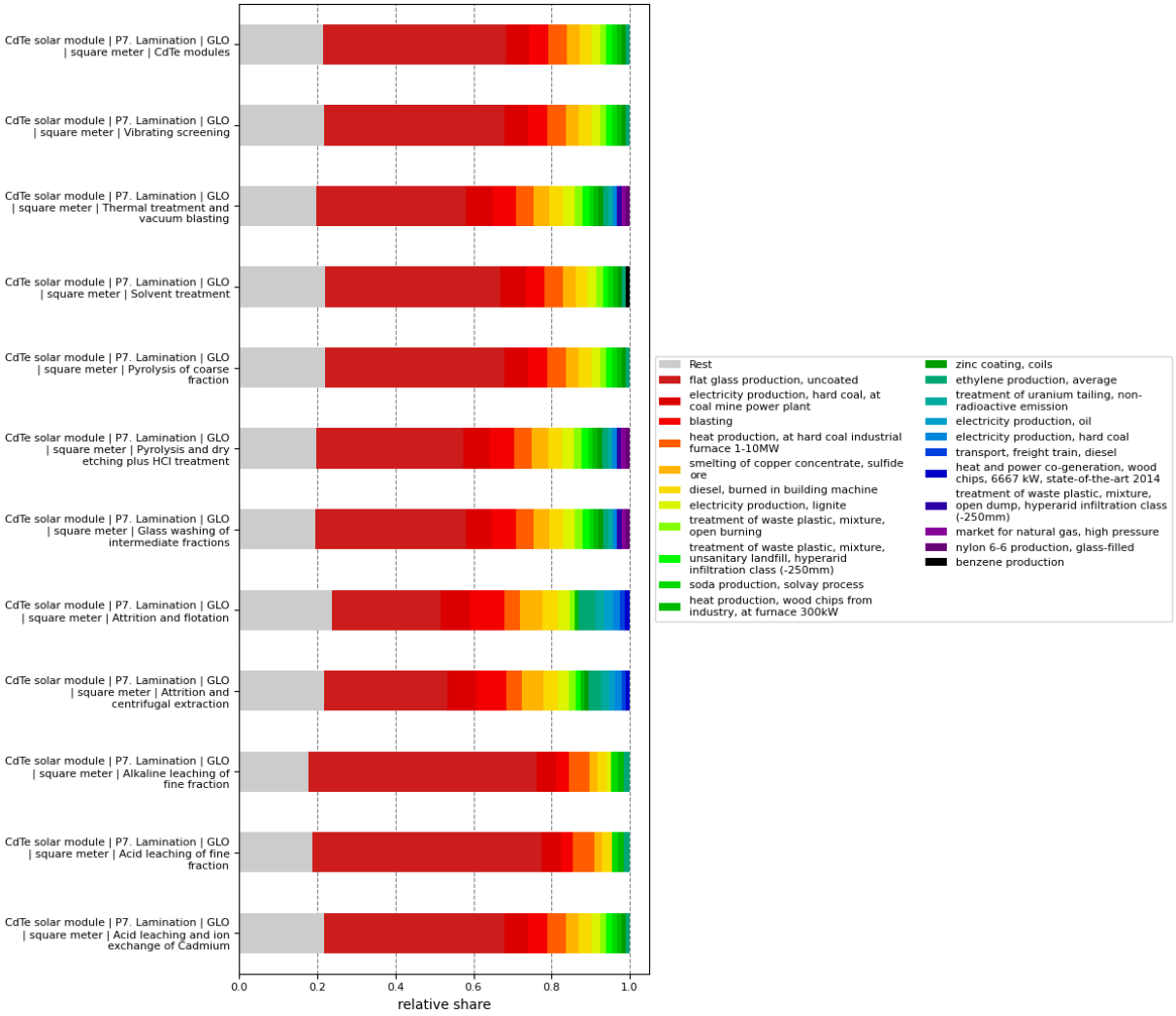

Figure F. 14: contribution analysis in impact category of particulate matter formation.

The potential impacts of particulate matter formation is greatly influenced by the production of solar glass. Next to that it can be seen that the production of electricity and heat are large contributors as well. For thermal treatment and vacuum blasting, pyrolysis and dry etching, and glass washing it can be noticed that even more is contributed by heat and electricity production.

F.15 Photochemical ozone formation

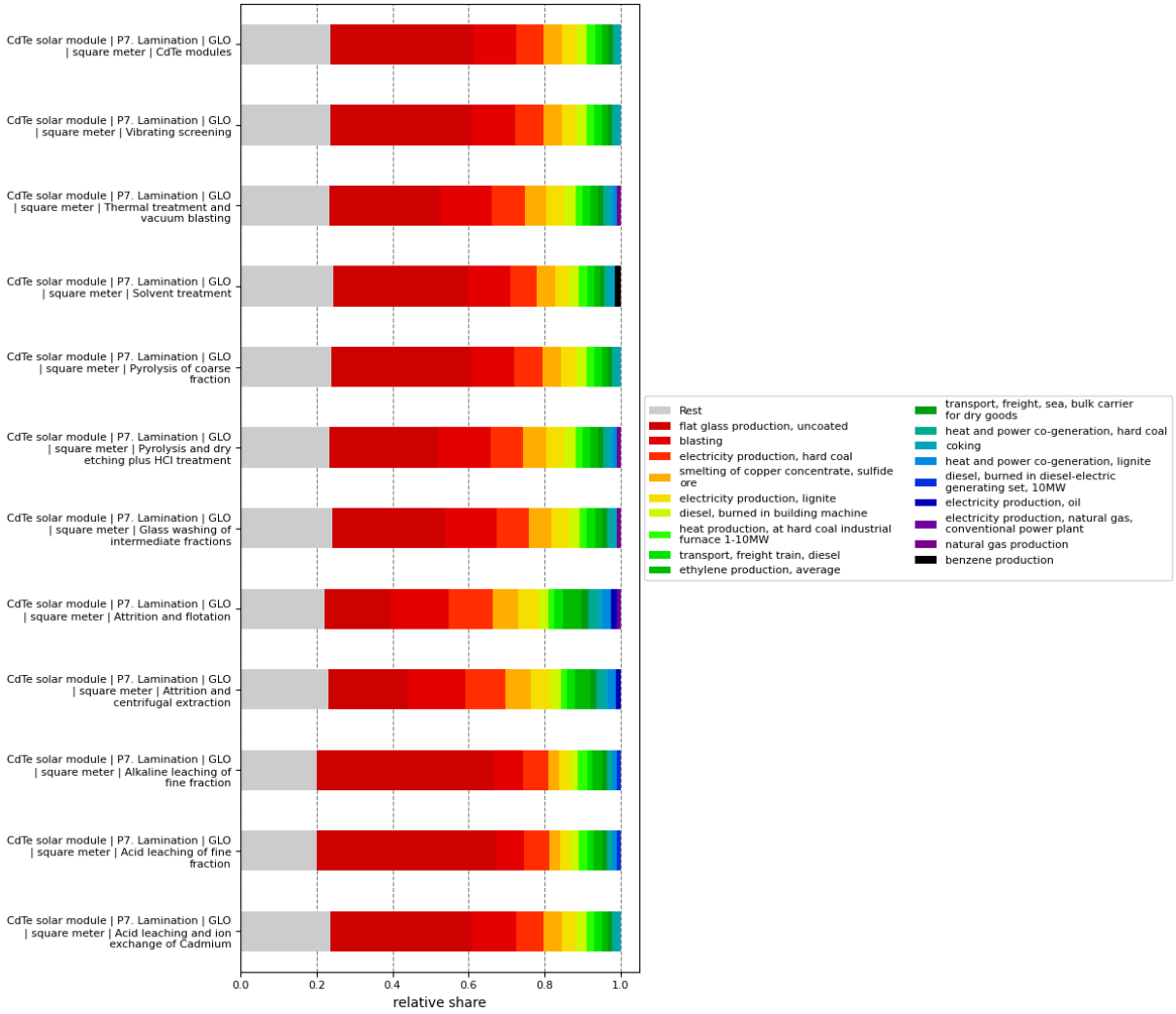

Figure F. 15: contribution analysis in impact category of photochemical ozone formation.

Solar glass production is a large contributor to the potential impacts of photochemical ozone formation. Interesting to see is that its contribution is fairly low for the attrition processes. For these processes it is observed that heat and power generation have a larger contribution. Benzene production contributes remarkably to the solvent treatment processes.

F.16 Water use

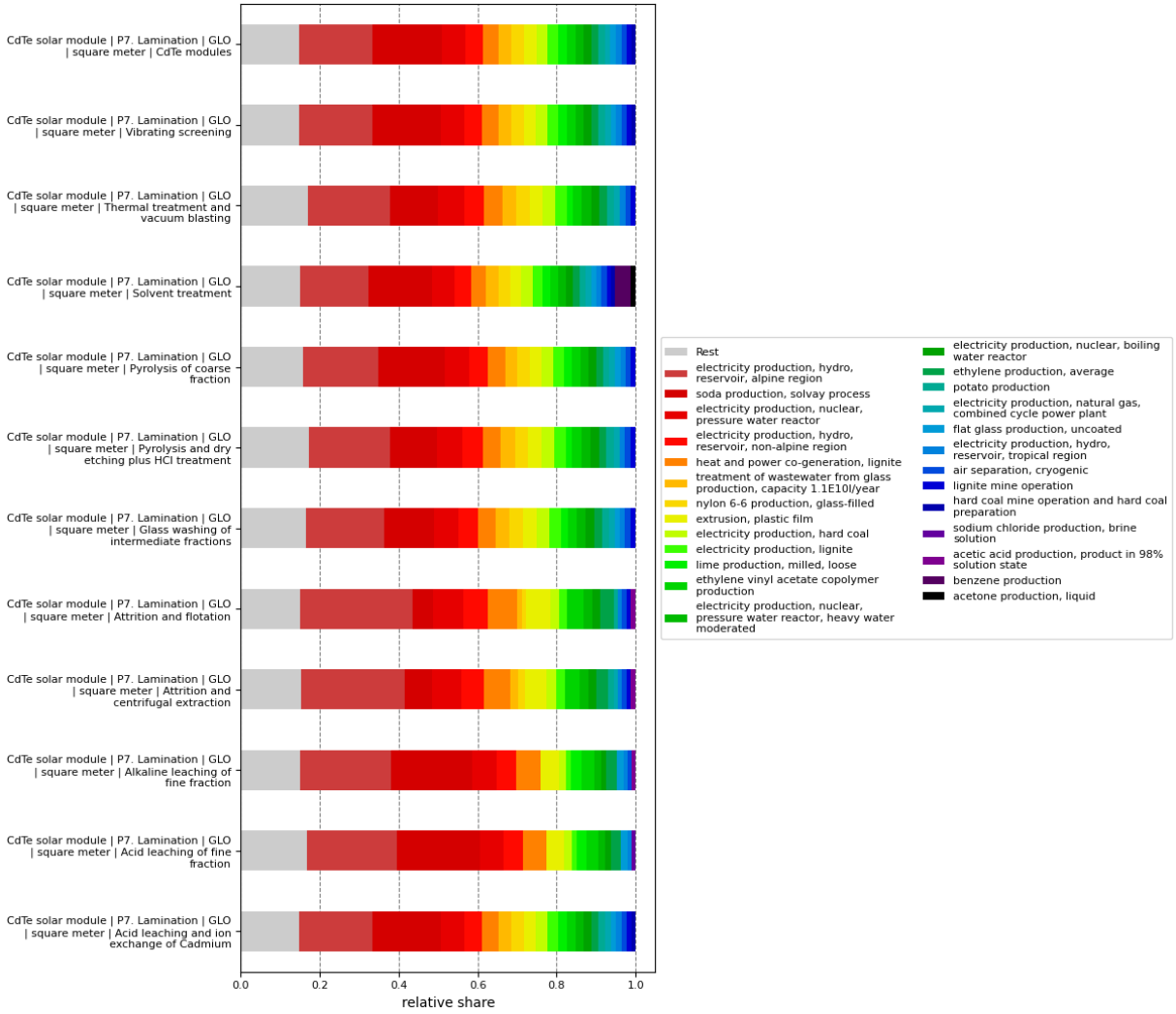

Figure F. 16: contribution analysis in impact category of water use.

Electricity and heat production contribute the most to the potential impacts of water use. Interestingly, the EVA production processes contribute noticeably to this impact category. For solvent treatment there is a large contribution in water use potential for the production of solvents.

Appendix G – Hotspots From LCA

The Life Cycle Assessment that was conducted identified hotspots for each recycling process. The hotspot for each process, including the impact categories they have and influence on are represented in table G.1.

Table G. 1: summary of hotspots found in the LCA per process.

Process	Hotspots
Acid leaching	- Solar glass production is large contributor to A, GW, ME, TE, PMF, and POF. - The acquiring and treatment of metal input is a large contributor to A, FET, ADP (FF), ADP (E), FE, HTC, and HTNC. - The production of electricity and heat is a large contributor for A, GW, ADP (FF), OD, and WU. - Lower potential impacts in all categories. - Reduced contribution of metal input processes for acidification - Majority of impacts related to production processes. - Highest relative impacts in WU, OD, TE, PMF, POF (>0.7) - Acetic acid production (for recycling process) contributes to WU. - For OD large contribution of petroleum use. Petroleum and gas production is decreased. - TE, PMF, and POF are largely contributed by solar glass production. - Precipitation process contributes to FET, HTC, and HTNC. - For ME the contribution of glass production is increased, treatment of wastewater from PV production contributes more. - Glass factory contributes more in LU.
Acid leaching and ion exchange	- Solar glass production is large contributor to A, GW, ME, TE, PMF, and POF. - The acquiring and treatment of metal input is a large contributor to A, FET, ADP (FF), ADP (E), FE, HTC, and HTNC. - The production of electricity and heat is a large contributor for A, GW, ADP (FF), OD, and WU. - Potential impacts are slightly higher for all impact categories. - More processes in rest category that contribute less than 1%.
Alkaline leaching	- Solar glass production is large contributor to A, GW, ME, TE, PMF, and POF. - The acquiring and treatment of metal input is a large contributor to A, FET, ADP (FF), ADP (E), FE, HTC, and HTNC. - The production of electricity and heat is a large contributor for A, GW, ADP (FF), OD, and WU. - Low potential impacts for all categories - Highest relative impacts in WU, OD, POF, TE, and PMF (>0.35) - Lowest relative impacts for HTC, HTNC, ADP (E), FET, and FE - For FET, HTC, and HTNC, the unprecipitated leaching products have a noticeable contribution. - Lowers contribution of mining operations in ADP (E).
Pyrolysis of coarse fraction	- Solar glass production is large contributor to A, GW, ME, TE, PMF, and POF. - The acquiring and treatment of metal input is a large contributor to A, FET, ADP (FF), ADP (E), FE, HTC, and HTNC. - The production of electricity and heat is a large contributor for A, GW, ADP (FF), OD, and WU. - Increased impact in all categories - Highest impact for A, GW, ME, TE, LU, OD, and PMF. - Glass production and electricity use are major contributors to the impact categories. - For the global warming potential, the actual process of pyrolysis of the EVA layer is a contributor.
Solvent treatment	- Solar glass production is large contributor to A, GW, ME, TE, PMF, and POF. - The acquiring and treatment of metal input is a large contributor to A, FET, ADP (FF), ADP (E), FE, HTC, and HTNC. - The production of electricity and heat is a large contributor for A, GW, ADP (FF), OD, and WU. - Increased impacts for all categories. - High impacts for HTC, WU, and ADP (FF) - Contribution of benzene and acetone production to GW, ADP (FF), PMF, POF, and WU - Contribution of chlor-alkali electrolysis to OD.
Vibrating screening	- Solar glass production is large contributor to A, GW, ME, TE, PMF, and POF. - The acquiring and treatment of metal input is a large contributor to A, FET, ADP (FF), ADP (E), FE, HTC, and HTNC. - The production of electricity and heat is a large contributor for A, GW, ADP (FF), OD, and WU. - Slight increase in potential impacts for FET, FE, HTC, HTNC, and ADP (E).
Glass washing	- Solar glass production is large contributor to A, GW, ME, TE, PMF, and POF.

	- The acquiring and treatment of metal input is a large contributor to A, FET, ADP (FF), ADP (E), FE, HTC, and HTNC. - The production of electricity and heat is a large contributor for A, GW, ADP (FF), OD, and WU. - Increased impact of HTC, HTNC, FET, FE, ADP (E), and ADP (FF) - Reduced impact of other categories due to glass production reduction.
Attrition and centrifugal extraction	- Solar glass production is large contributor to A, GW, ME, TE, PMF, and POF. - The acquiring and treatment of metal input is a large contributor to A, FET, ADP (FF), ADP (E), FE, HTC, and HTNC. - The production of electricity and heat is a large contributor for A, GW, ADP (FF), OD, and WU. - Lowest impact scores for all categories but FET, FE, HTC, HTNC, and ADP (E). - Contribution of energy production larger for ADP (FF), ME, TE, HTC, HTNC, OD, PMF, and POF. - Treatment of wastewater contributes more to FET, FE, and ME. - Acetic acid production contributes to WU.
Attrition and flotation	- Solar glass production is large contributor to A, GW, ME, TE, PMF, and POF. - The acquiring and treatment of metal input is a large contributor to A, FET, ADP (FF), ADP (E), FE, HTC, and HTNC. - The production of electricity and heat is a large contributor for A, GW, ADP (FF), OD, and WU. - Less potential impacts for most impact categories. - For WU increased potential impacts contributed by higher energy use. - Contribution of energy production larger for ADP (FF), ME, TE, HTC, HTNC, OD, PMF, and POF. - Treatment of wastewater contributes more to FET, FE, and ME. - Acetic acid production contributes to WU.
Pyrolysis and dry etching plus HCl treatment	- Solar glass production is large contributor to A, GW, ME, TE, PMF, and POF. - The acquiring and treatment of metal input is a large contributor to A, FET, ADP (FF), ADP (E), FE, HTC, and HTNC. - The production of electricity and heat is a large contributor for A, GW, ADP (FF), OD, and WU. - Increased potential impacts for FE, FET, HTC, HTNC, and ADP (E). - Potential impact of global warming contributed by pyrolysis. - Wastewater treatment contribute to ME. - Energy use contributes more to PMF and POF.
Thermal treatment and vacuum blasting	- Solar glass production is large contributor to A, GW, ME, TE, PMF, and POF. - The acquiring and treatment of metal input is a large contributor to A, FET, ADP (FF), ADP (E), FE, HTC, and HTNC. - The production of electricity and heat is a large contributor for A, GW, ADP (FF), OD, and WU. - Increasing potential impacts for FET, ADP (FF), ADP (E), FE, HTC, HTNC, and LU.

Appendix H - Parameters for Life Cycle Assessment Model

The LCA model was subject to many uncertain in- and outputs. These uncertainties are displayed as parameter with an even distribution form lowest to highest value.

Table H. 1: parameters of LCA model

Parameter	Unit	Variability		Explanation of parameter	Source
		Lowest value	Highest value		
Electricity_HM+SHR	kWh	1.17E-01	2.22E+00	Electricity use of hammer mill and shredder.	(Giacchetta et al. 2013; Marchetti et al. 2018)
MASS_NaOHin_ALK	kg	5.26E-03	8.95E-02	Input alkaline leaching	(Toro et al. 2013)
VOL_H2Oin_ALK	m3	2.56E-04	3.32E-04	Input alkaline leaching	(Toro et al. 2013)
MASS_GLASS_ALK	kg	1.35E+00	1.47E+00	Output alkaline leaching	(Tao and Yu 2015; Pagnanelli et al. 2017)
MASS_AlOH3_ALK	kg	2.21E-02	2.35E-02	Output alkaline leaching	(Tao and Yu 2015; Held 2009)
MASS_Zn_ALK	kg	2.75E-08	2.93E-08	Output alkaline leaching	(Tao and Yu 2015; Held 2009)
MASS_CdSO4_ALK	kg	3.75E-02	4.00E-02	Output alkaline leaching	(Tao and Yu 2015; Held 2009)
MASS_TeO2_ALK	kg	2.03E-02	2.16E-02	Output alkaline leaching	(Tao and Yu 2015; Held 2009)
MASS_NaNO3_ALK	kg	2.16E-02	2.30E-02	Output alkaline leaching	(Tao and Yu 2015; Held 2009)
MASS_Na2SO4_ALK	kg	2.01E-02	2.14E-02	Output alkaline leaching	(Tao and Yu 2015; Held 2009)
MASS_Na2S_ALK	kg	4.13E-03	4.39E-03	Output alkaline leaching	(Tao and Yu 2015; Held 2009)
VOL_H2Oin_AL	m3	8.78E-05	5.68E-04	Input acid leaching	(Fthenakis and Wang 2005; Toro et al. 2013)
MASS_Glass_AL	kg	1.35E+00	1.47E+00	Output acid leaching	(Tao and Yu 2015; Pagnanelli et al. 2017)
Electricity_VS	kWh	9.60E-04	1.90E-02	Electricity use of vibrating screening	(Camco 2023)
MASS_Glass_VS	kg	9.36E-01	1.04E+00	Output vibrating screening	(Pagnanelli et al. 2017)
MASS_O2in_PY_CF	kg O2	3.00E+00	4.50E+00	Input of pyrolysis	(Diequez Campo et al. 2003)
Electricity_PY_CF	kWh	7.97E-02	2.41E+00	Electricity use of pyrolysis	(Maani et al. 2020; Mulazzani et al. 2022)
MASS_Glass_Thermal	kg	7.30E+00	7.50E+00	Output thermal treatment	(Tao and Yu 2015; Granata et al. 2014; Pagnanelli et al. 2017)
Electricity_TT	kWh	1.77E+00	4.00E+00	Electricity use of thermal treatment	(Maani et al. 2020; Mulazzani et al. 2022)
AIR_IN_PY_MCF	kg O2	3.00E+00	4.50E+00	Input pyrolysis	(Diequez Campo et al. 2003)
Electricity_PY_MCF	kWh	7.97E-02	2.41E+00	Electricity use of pyrolysis	(Maani et al. 2020; Mulazzani et al. 2022)
MASS_Glass_DE	kg	6.96E+00	7.12E+00	Output dry etching	(Diequez Campo et al. 2003; Held 2009)
MASS_Glass_HCl	kg	6.96E+00	7.12E+00	Output HCl treatment	(Diequez Campo et al. 2003; Held 2009)
MASS_SnCl4_HCl	kg	2.64E-04	2.81E-04	Output HCl treatment	(Diequez Campo et al. 2003; Held 2009)
MASS_InCl3_HCl	kg	2.19E-03	2.33E-03	Output HCl treatment	(Diequez Campo et al. 2003; Held 2009)
Electricity_HCl	kWh/kg	4.75E-01	9.36E+01	Electricity use of HCl treatment	(Dai et al. 2019; Ecoinvent 2021)
MASS_CdCl2_PRCP_DE	kg	3.30E-02	3.52E-02	Output precipitation (DE)	(Held 2009; Pagnanelli et al. 2017)
MASS_TeCl4_PRCP_DE	kg	3.43E-02	3.65E-02	Output precipitation (DE)	(Held 2009; Pagnanelli et al. 2017)
MASS_SCl2_PRCP_DE	kg	5.44E-03	5.80E-03	Output precipitation (DE)	(Held 2009; Pagnanelli et al. 2017)

MASS_CuCl2_PRCP_DE	kg	1.94E-01	2.07E-01	Output precipitation (DE)	(Held 2009; Pagnanelli et al. 2017)
MASS_ZnCl2_PRCP_DE	kg	5.73E-08	6.10E-08	Output precipitation (DE)	(Held 2009; Pagnanelli et al. 2017)
Electricity_PRCP_DE	kWh/kg	6.00E-02	1.18E+01	Electricity use of precipitation (DE)	(Dai et al. 2019; Ecoinvent 2021)
Electricity_ATT	kWh/kg	2.75E-02	3.11E-02	Electricity use of attrition	(Giacchetta et al. 2013)
Electricity_FL	kWh	8.22E-03	8.58E-03	Electricity use of flotation	(Giacchetta et al. 2013)
MASS_Glass_FL	kg	1.45E+01	1.54E+01	Output flotation	(Marchetti et al. 2018; Pagnanelli et al. 2017)
MASS_CdTe_FL	kg	2.89E-02	3.09E-02	Output flotation	(Marchetti et al. 2018; Pagnanelli et al. 2017)
MASS_CdS_FL	kg	7.05E-03	7.55E-03	Output flotation	(Marchetti et al. 2018; Pagnanelli et al. 2017)
MASS_Glass_CE	kg	1.45E+01	1.54E+01	Output centrifugal extraction	(Marchetti et al. 2018; Pagnanelli et al. 2017)
MASS_CdTe_CE	kg	2.59E-02	2.79E-02	Output centrifugal extraction	(Marchetti et al. 2018; Pagnanelli et al. 2017)
MASS_CdS_CE	kg	7.32E-03	7.82E-03	Output centrifugal extraction	(Marchetti et al. 2018; Pagnanelli et al. 2017)
Electricity_VB	kWh	4.62E-05	7.20E-01	Electricity use of vacuum blasting	(Airblast 2022, 2013)
EFF_VB		8.80E-01	9.00E-01	Efficiency of vacuum blasting	(Pagnanelli et al. 2017)
Electricity_PRCP_AL	kWh/kg	6.00E-02	1.18E+01	Electricity use of precipitation (AL)	(Dai et al. 2019; Ecoinvent 2021)
VOL_H2Oin_PRCP_AL	m3	8.78E-05	5.68E-04	Input precipitation (AL)	(Pagnanelli et al. 2017; Tao and Yu 2015; Held 2009)
MASS_AL(OH)3_AL	kg	2.28E-02	2.35E-02	Output precipitation (AL)	(Pagnanelli et al. 2017; Tao and Yu 2015; Held 2009)
MASS_Zn(OH)2_AL	kg	4.32E-08	4.45E-08	Output precipitation (AL)	(Pagnanelli et al. 2017; Tao and Yu 2015; Held 2009)
MASS_Na2SO4_AL	kg	6.23E-02	6.42E-02	Output precipitation (AL)	(Pagnanelli et al. 2017; Tao and Yu 2015; Held 2009)
MASS_TeO2_AL	kg	2.10E-02	2.16E-02	Output precipitation (AL)	(Pagnanelli et al. 2017; Tao and Yu 2015; Held 2009)
MASS_S_AL	kg	1.75E-03	1.81E-03	Output precipitation (AL)	(Pagnanelli et al. 2017; Tao and Yu 2015; Held 2009)
MASS_CdSO4_AL	kg	3.88E-02	4.00E-02	Output precipitation (AL)	(Pagnanelli et al. 2017; Tao and Yu 2015; Held 2009)
MASS_NO2_EMM_AL	kg	2.42E-02	2.49E-02	Emission precipitation (AL)	(Pagnanelli et al. 2017; Tao and Yu 2015; Held 2009)
MASS_Cd_RESIN_IO	kg	1.61E-02	1.66E-02	Output ion exchange	(Fthenakis and Wang 2005; Pagnanelli et al. 2017)
Electricity_EP	kWh/kg	4.57E+00	5.02E+00	Electricity use of electroplating	(Moign et al. 2009; Fthenakis and Wang 2005)
Electricity_PRCP_AL_IO	kWh/kg	6.00E-02	1.18E+01	Electricity use of precipitation (AL_IO)	(Dai et al. 2019; Ecoinvent 2021)
VOL_H2Oin_PRCP_AL_IO	m3	8.78E-05	5.68E-04	Input precipitation (AL_IO)	(Pagnanelli et al. 2017; Tao and Yu 2015; Held 2009)
MASS_ALOH3_PRCP_AL_IO	kg	2.28E-02	2.35E-02	Output precipitation (AL_IO)	(Pagnanelli et al. 2017; Tao and Yu 2015; Held 2009)
MASS_Na2SO4_PRCP_AL_IO	kg	6.23E-02	6.42E-02	Output precipitation (AL_IO)	(Pagnanelli et al. 2017; Tao and Yu 2015; Held 2009)

MASS_ZnOH2_PRCP_AL_IO	kg	4.32E-08	4.45E-08	Output precipitation (AL_IO)	(Pagnanelli et al. 2017; Tao and Yu 2015; Held 2009)
MASS_TeO2_PRCP_AL_IO	kg	2.10E-02	2.16E-02	Output precipitation (AL_IO)	(Pagnanelli et al. 2017; Tao and Yu 2015; Held 2009)
MASS_S_PRCP_AL_IO	kg	1.75E-03	1.81E-03	Output precipitation (AL_IO)	(Pagnanelli et al. 2017; Tao and Yu 2015; Held 2009)
MASS_NO2_EMM_AL_IO	kg	2.42E-02	2.49E-02	Emission precipitation (AL_IO)	(Pagnanelli et al. 2017; Tao and Yu 2015; Held 2009)
Electricity_CdTe_PROD	kWh/kg	3.50E+00	1.24E+01	Electricity use of CdTe production	(Ecoinvent 2021)
Electricity_CdS_PROD	kWh/kg	3.89E-03	4.28E-03	Electricity use of CdS production	(Ecoinvent 2021)
Electricity_Te_REC	kWh/kg	6.00E-02	1.18E+01	Electricity use of Te recovery	(Zhang et al. 2020)
Electricity_FL_INC	kWh	7.97E-02	2.41E+00	Electricity use of incineration	(Mulazzani et al. 2022; Maani et al. 2020)
VOL_H2O_GW	m3/kg	8.30E-04	1.14E-03	Input glass washing	(Blengini et al. 2012; Ecoinvent 2021)
Elecitricity_GW	kWh/kg	1.16E-04	1.40E-03	Electricity use of glass washing	(Blengini et al. 2012; Ecoinvent 2021)

Table H.2 shows parameters that follow from the predetermined amounts set on parameters in table H.1. The parameters of H.2 are calculated according to the formulas presented next to them.

Table H. 2: parameters of LCA model based on other parameters.

Parameter	Unit	Formula	Explanation of parameter
VOL_H2O_EMM_ALK	m3	(0.23*MASS_AlOH3_ALK+ 0.17*MASS_CdSO4_ALK+ 0.11*MASS_TeO2_ALK)/997	Input alkaline leaching
MASS_Al_EMM_ALK	kg	0.35* (0.024-MASS_AlOH3_ALK)	Emission alkaline leaching
MASS_OH_EMM_ALK	kg	0.65* (0.024-MASS_AlOH3_ALK)	Emission alkaline leaching
MASS_Na_EMM_ALK	kg	0.27* (0.024-MASS_NaNO3_ALK)+ 0.32* (0.022-MASS_Na2SO4_ALK)+ 0.59* (0.0045-MASS_Na2S_ALK)	Emission alkaline leaching
MASS_SO4_EMM_ALK	kg	0.46* (0.041-MASS_CdSO4_ALK)+ 0.68* (0.022-MASS_Na2SO4_ALK)	Emission alkaline leaching
MASS_Cd_EMM_ALK	kg	0.54* (0.041-MASS_CdSO4_ALK)	Emission alkaline leaching
MASS_Te_EMM_ALK	kg	0.8* (0.022-MASS_TeO2_ALK)	Emission alkaline leaching
MASS_O2_EMM_ALK	kg	0.2* (0.022-MASS_TeO2_ALK)	Emission alkaline leaching
MASS_NO3_EMM_ALK	kg	0.73* (0.024-MASS_NaNO3_ALK)	Emission alkaline leaching
MASS_S_EMM_ALK	kg	0.41* (0.0045-MASS_Na2S_ALK)	Emission alkaline leaching
MASS_LIQSTR_AL	kg	1.76-MASS_Glass_AL+ (VOL_H2Oin_AL*997)	Output acid leaching
MASS_Foil_Glass_VS	kg	1.66-MASS_Glass_VS	Output vibrating screening
MASS_O2out_PY_CF	kg O2	MASS_O2in_PY_CF-1.31	Output pyrolysis
MASS_Glass_Metals_Thermal	kg	16.6-MASS_Glass_TT	Output thermal treatment
AIR_OUT_PY_MCF	kg O2	AIR_IN_PY_MCF-1.31	Output pyrolysis

MASS_MIX_DE	kg	8.1999-MASS_GLASS_DE	Output dry etching
MASS_leftover	kg	16.6-MASS_Glass_DE-MASS_Glass_HCl-MASS_SnCl4_HCl-MASS_InCl3_HCl	Output HCl treatment
MASS_Cd_PRCP_EMM_DE	kg	0.61*(0.036-MASS_CdCl2_PRCP_DE)	Emission precipitation after dry etching.
MASS_Te_PRCP_EMM_DE	kg	0.47*(0.037-MASS_TeCl4_PRCP_DE)	Emission precipitation after dry etching.
MASS_S_PRCP_EMM_DE	kg	0.31*(0.059-MASS_SCl2_PRCP_DE)	Emission precipitation after dry etching.
MASS_Cu_PRCP_EMM_DE	kg	0.47*(0.021-MASS_CuCl2_PRCP_DE)	Emission precipitation after dry etching.
MASS_Zn_PRCP_EMM_DE	kg	0.48*(6.2E-5MASS_ZnCl2_PRCP_DE)	Emission precipitation after dry etching.
MASS_Cl2_PRCP_EMM_DE	kg	0.39*(0.036-MASS_CdCl2_PRCP_DE)+0.53*(0.037-MASS_TeCl4_PRCP_DE)+0.69*(0.059-MASS_SCl2_PRCP_DE)+0.53*(0.021-MASS_CuCl2_PRCP_DE)+0.52*(6.2E-5-MASS_ZnCl2_PRCP_DE)	Emission precipitation after dry etching.
MASS_INCMAT_FL	kg	16.6-MASS_Glass_FL-MASS_CdTe_FL-MASS_CdS_FL	Output flotation
MASS_INCMAT_CE	kg	16.6-MASS_Glass_CE-MASS_CdTe_CE-MASS_CdS_CE	Output centrifugal extraction
MASS_Glass_VB	kg	(16.6-MASS_Glass_TT-0.78)*EFF_VB	Output vibrating screening
MASS_FC_VB	kg	16.6-MASS_Glass_TT-MASS_Glass_VB	Output vibrating screening
MASS_Cd_EMM_AL	kg	(0.0408-MASS_CdSO4_AL)*0.54	Emission acid leaching
MASS_Zn_EMM_AL	kg	(4.54E-8-MASS_Zn(OH)2_AL)*0.66	Emission acid leaching
MASS_Te_EMM_AL	kg	(0.0221-MASS_TeO2_AL)*0.8	Emission acid leaching
MASS_Al_EMM_AL	kg	(0.024-MASS_Al(OH)3_AL)*0.35	Emission acid leaching
MASS_Na_EMM_AL	kg	(0.066-MASS_Na2SO4_AL)*0.32	Emission acid leaching
MASS_S_EMM_AL	kg	(0.00184-MASS_S_AL)	Emission acid leaching
MASS_OH_EMM_AL	kg	(4.54E-8-MASS_Zn(OH)2_AL)*0.34+(0.024-MASS_Al(OH)3_AL)*0.65	Emission acid leaching
MASS_SO4_EMM_AL	kg	(0.066-MASS_Na2SO4_AL)*0.68+(0.0408-MASS_CdSO4_AL)*0.46	Emission acid leaching
MASS_O2_EMM_AL	kg	(0.0221-MASS_TeO2_AL)*0.2	Emission acid leaching
VOL_H2O_EMM_AL	m3	0.23*MASS_TeO2_AL+2.62E-2+VOL_H2Oin_PRCP_AL	Emission acid leaching
MASS_LIQSTR_IO	kg	1.76-MASS_Glass_AL+(VOL_H2Oin_AL*997)-MASS_Cd_RESIN_IO	Output ion exchange
MASS_SOLUTION_EL	kg	3.6E-2+MASS_Cd_RESIN_IO	Output elution
Electircity_EP_IO	kWh	Electricity_EP*MASS_RESIN_Cd_IO	Electricity use of electroplating
MASS_Cd_EMM_AL_IO	kg	(0.0166-MASS_Cd_RESIN_IO)	Emission acid leaching and ion exchange

MASS_Zn_EMM_AL_IO	kg	(4.54E-8-MASS_ZnOH2_PRCP_AL_IO)* 0.66	Emission acid leaching and ion exchange
MASS_Te_EMM_AL_IO	kg	(0.0221-MASS_TeO2_PRCP_AL_IO)* 0.8	Emission acid leaching and ion exchange
MASS_Al_EMM_AL_IO	kg	(0.024-MASS_AlOH3_PRCP_AL_IO)* 0.35	Emission acid leaching and ion exchange
MASS_Na_EMM_AL_IO	kg	(0.066-MASS_Na2SO4_PRCP_AL_IO)* 0.32	Emission acid leaching and ion exchange
MASS_S_EMM_AL_IO	kg	(0.00184-MASS_S_PRCP_AL_IO)	Emission acid leaching and ion exchange
MASS_OH_EMM_AL_IO	kg	(4.54E-8-MASS_ZnOH2_PRCP_AL_IO)* 0.34+ (0.024-MASS_AlOH3_PRCP_AL_IO)* 0.65	Emission acid leaching and ion exchange
MASS_SO4_EMM_AL_IO	kg	(0.066-MASS_Na2SO4_PRCP_AL_IO)* 0.68	Emission acid leaching and ion exchange
MASS_O2_EMM_AL_IO	kg	(0.0221-MASS_TeO2_PRCP_AL_IO)* 0.2	Emission acid leaching and ion exchange
VOL_H2O_EMM_AL_IO	m3	0.23* MASS_TeO2_PRCP_AL_IO+ 2.62E-2+ VOL_H2Oin_PRCP_AL_IO	Emission acid leaching and ion exchange
MASS_NaHCO3_CdTe_PROD_AL	kg	1.05*MASS_TeO2_AL	Input CdTe production after acid leaching
MASS_H2_CdTe_PROD_AL	kg	0.04*MASS_TeO2_AL	Input CdTe production after acid leaching
MASS_CdSO4_CdTe_PROD_AL	kg	1.31*MASS_TeO2_AL	Input CdTe production after acid leaching
MASS_CdTE_INPUT_AL	kg	1.5*MASS_TeO2_AL	Output CdTe production after acid leaching
MASS_Na2SO4_CdTe_PROD_AL	kg	0.89*MASS_TeO2_AL	Output CdTe production after acid leaching
MASS_CO2_EMM_CdTe_PROD_AL	kg	0.55*MASS_TeO2_AL	Emission CdTe production after acid leaching
VOL_H2O_EMM_CdTe_PROD_AL	kg	0.45*MASS_TeO2_AL/997	Emission CdTe production after acid leaching
MASS_CdSO4_CdS_PROD_AL	kg	MASS_CdSO4_AL-1.31* MASS_TeO2_AL	Input CdS production after acid leaching
MASS_Na2S_CdS_PROD_AL	kg	0.37*(MASS_CdSO4_AL-1.31* MASS_TeO2_AL)	Input CdS production after acid leaching
MASS_Na2SO4_CdS_PROD_AL	kg	1756*(MASS_CdSO4_AL-1.31* MASS_TeO2_AL)	Output CdS production after acid leaching
MASS_CdS_INPUT_AL	kg	0.69*(MASS_CdSO4_AL-1.31* MASS_TeO2_AL)	Output CdS production after acid leaching
VOL_H2O_CdS_PROD_AL	m3	0.95*(MASS_CdSO4_AL-1.31* MASS_TeO2_AL)	Input CdS production after acid leaching
MASS_NaHCO3_CdTe_PROD_ALK	kg	1.05*MASS_TeO2_ALK	Input CdTe production after alkaline leaching
MASS_H2_CdTe_PROD_ALK	kg	0.04*MASS_TeO2_ALK	Input CdTe production after alkaline leaching
MASS_CdSO4_CdTe_PROD_ALK	kg	1.31*MASS_TeO2_ALK	Input CdTe production after alkaline leaching
MASS_CdTE_INPUT_ALK	kg	1.5*MASS_TeO2_ALK	Output CdTe production after alkaline leaching
MASS_Na2SO4_CdTe_PROD_ALK	kg	0.89*MASS_TeO2_ALK	Output CdTe production after alkaline leaching
MASS_CO2_EMM_CdTe_PROD_ALK	kg	0.55*MASS_TeO2_ALK	Emission CdTe production after alkaline leaching
VOL_H2O_EMM_CdTe_PROD_ALK	kg	0.45*MASS_TeO2_ALK/997	Emission CdTe production after alkaline leaching
MASS_CdSO4_CdS_PROD_ALK	kg	MASS_CdSO4_AL-1.31* MASS_TeO2_ALK	Input CdS production after alkaline leaching
MASS_Na2S_CdS_PROD_ALK	kg	0.37*(MASS_CdSO4_ALK-1.31* MASS_TeO2_ALK)	Input CdS production after alkaline leaching

MASS_Na2SO4_CdS_PROD_ALK	kg	1756*(MASS_CdSO4_ALK-1.31* MASS_TeO2_ALK)	Output CdS production after alkaline leaching
MASS_CdS_INPUT_ALK	kg	0.69*(MASS_CdSO4_ALK-1.31* MASS_TeO2_ALK)	Output CdS production after alkaline leaching
VOL_H2O_CdS_PROD_ALK	m3	0.95*(MASS_CdSO4_ALK-1.31* MASS_TeO2_ALK)	Input CdS production after alkaline leaching
VOL_H2Oin_Te_REC	m3	0.09* MASS_TeO2_PRCP_AL_IO/997	Input Te recovery
MASS_Te_REC	kg	0.64* MASS_TeO2_PRCP_AL_IO	Output Te recovery
MASS_K_EMM_Te_REC	kg	1.27*0.31* MASS_TeO2_PRCP_AL_IO	Emission Te recovery
MASS_O2_EMM_Te_REC	kg	1.27*0.19* MASS_TeO2_PRCP_AL_IO	Emission Te recovery
MASS_Te_EMM_Te_REC	kg	1.27*0.5* MASS_TeO2_PRCP_AL_IO	Emission Te recovery
VOL_H2O_EMM_Te_REC	m3	0.11* MASS_TeO2_PRCP_AL_IO/997	Emission Te recovery
MASS_O2in_FL_INC	kg	1.3+ (0.0332-MASS_CdTe_FL)* 0.2+ (0.0083-MASS_CdS_FL)*0.33	Input incineration of flotation product
MASS_Cd_FL_INC	kg	(0.0322-MASS_CdTe_FL)*0.47+ (0.0083-MASS_CdS_FL)*0.78	Emission incineration of flotation product
MASS_Te_FL_INC	kg	(0.0322-MASS_CdTe_FL)*0.53	Emission incineration of flotation product
MASS_SO2_FL_INC	kg	(0.0083-MASS_CdS_FL)*0.22	Emission incineration of flotation product
MASS_O2_EMM_FL_INC	kg	(0.0332-MASS_CdTe_FL)*0.13+ 0.12*((0.0083-MASS_CdS_FL)* 0.89+ (0.0332-MASS_CdTe_FL)*0.54)	Emission incineration of flotation product.
Electricity_CE_INC	kWh	(16.6- MASS_Glass_CE- MASS_CdTe_CE-MASS_CdS_CE)*0.04	Electricity use of incineration of centrifugal extraction product.
MASS_O2in_CE_INC	kg	1.3+(0.0332-MASS_CdTe_CE)* 0.2+ (0.0083-MASS_CdS_CE)*0.33	Input incineration of centrifugal extraction product.
MASS_Cd_EMM_CE_INC	kg	(0.0332-MASS_CdTe_CE)*0.47+ (0.0083-MASS_CdS_CE)*0.78	Emission incineration of centrifugal extraction product.
MASS_Te_EMM_CE_INC	kg	(0.0322-MASS_CdTe_CE)*0.53	Emission incineration of centrifugal extraction product.
MASS_SO2_EMM_CE_INC	kg	(0.0083-MASS_CdS_CE)*0.22	Emission incineration of centrifugal extraction product.
MASS_O2_EMM_CE_INC	kg	(0.0332-MASS_CdTe_CE)*0.13+ 0.12*((0.0083-MASS_CdS_CE)* 0.89+ (0.0332-MASS_CdTe_CE)*0.54)	Emission incineration of centrifugal extraction product.

Appendix I - Results of Global Sensitivity Analysis

A GSA was executed on the conducted LCA. Table I.1 presents the influence of parameters on the vibrating screening. The lower the number, the less influence the parameter has on the potential impacts that are calculated.

Table I. 1: Global sensitivity analysis of the vibrating screening process.

Parameter	Sensitivity
Electricity_HCl	**0.091073**
Electricity_Te_REC	**0.086066**
Electricity_PRCP_AL	**0.097654**
Electricity_CdTe_PROD_AL	**0.110289**
Electricity_PY_CF	**0.095569**

Electricity_TT	**0.092987**
Electricity_HM_SHR	**0.091279**
MASS_O2in_PY_CF	**0.105151**
MASS_Glass_FL	**0.109762**
MASS_Glass_CE	**0.105457**
Electricity_VB	**0.113217**
Electricity_EP	**0.081636**
MASS_Glass_TT	**0.104501**
MASS_Glass_HCl	**0.093535**
MASS_Glass_DE	**0.100737**
MASS_Glass_ALK	**0.104557**
MASS_Glass_AL	**0.098227**
MASS_Glass_VS	**0.407433**
MASS_NaOHin_ALK	**0.101593**
EFF_VB	**0.091633**
Electricity_VS	**0.103285**
MASS_CuCl2_PRCP_DE	**0.106745**
Electricity_ATT	**0.096902**
MASS_CdSO4_ALK	**0.108573**
MASS_TeCl4_PRCP_DE	**0.108447**
MASS_CdCl2_PRCP_DE	**0.09219**
MASS_CdTe_FL	**0.107169**
MASS_CdTe_CE	**0.117439**
MASS_Na2SO4_AL_IO	**0.113491**
MASS_Na2SO4_AL	**0.096971**
MASS_NaNO3_ALK	**0.107439**
MASS_AlOH3_ALK	**0.095043**
Electricity_GW	**0.093761**
MASS_Na2SO4_ALK	**0.103953**
MASS_TeO2_ALK	**0.096064**
MASS_CdSO4_AL	**0.100291**
MASS_NO2_EMM_AL	**0.102613**
MASS_AlOH3_AL	**0.113523**
MASS_NO2_EMM_AL_IO	**0.092211**
MASS_ALOH3_PRCP_AL_IO	**0.108154**
MASS_TeO2_AL	**0.102222**
MASS_TeO2_PRCP_AL_IO	**0.100504**
MASS_CdS_CE	**0.107964**
MASS_RESIN_Cd_IO	**0.094484**
VOL_H2Oin_AL	**0.104696**
VOL_H2Oin_PRCP_AL_IO	**0.101591**
VOL_H2Oin_PRCP_AL	**0.092896**
MASS_CdS_FL	**0.101768**
Electricity_CdS_PROD	**0.094666**
Electricity_FL	**0.09742**
MASS_SCl2_PRCP_DE	**0.09234**

VOL_H2O_GW	**0.106232**
MASS_Na2S_ALK	**0.114523**
MASS_InCl3_HCl	**0.090481**
VOL_H2Oin_ALK	**0.09962**
MASS_S_AL	**0.097613**
MASS_S_PRCP_AL_IO	**0.099465**