National Institute for Public Health
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Recycling of solar panels

Comparison of scenarios for a more circular and safe product chain

RIVM letter report 2023-0442

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Colophon

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J.P.A. Lijzen (project leader), RIVM
F. Heens (author), RIVM
E. Dekker (author), RIVM
M. van Bodegraven (author), RIVM
M. Hof (author), RIVM

Contact:
Johannes Lijzen
Duurzaamheid, Milieu en Gezondheid
Johannes.lijzen@rivm.nl

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Synopsis

Recycling of solar panels

Comparison of scenarios for a more circular and safe
product chain

The Netherlands has set a target of a circular economy by 2050. This entails that raw and manufactured materials, such as those in solar panels, are recycled. Currently, no raw materials are recovered from End-of-Life solar panels. It is expected that the first generation of solar panels will start to be taken out of use in large numbers in five years' time. It is important to be prepared for this and to recycle the panels safely and sustainably. Various technologies to recycle solar panels are being developed. RIVM has detailed four options for recycling the glass, solar cells and back sheets of solar panels.

The materials recovered from solar panels can be reused as raw materials for various applications. For this study, we looked into which recycling options appear to be feasible in practice and how environmentally friendly they are. We compared these four options to the current situation (the baseline), in which the solar panels are shredded, the glass is crushed and used as an abrasive medium in the metal industry, and the remainder is then processed for various applications, such as for road bases.

Our analysis shows that all four options are more circular and environmentally friendly than the baseline. Energy consumption differs for each option, but is much lower than for the baseline. This is due to various factors, including the fact that it costs more energy to process new raw materials into solar panels than to work with recycled raw materials. The option whereby glass is recycled into new glass for solar panels is the most circular one. In this case, the raw material silicon can also be recycled for use in new solar panels. This is technologically complex, but feasible.

In the recycling process, attention must be paid to hazardous substances in solar panels: lead, antimony and per- and polyfluoroalkyl substances (PFAS). Lead is contained in soldering materials and antimony is added to make the glass brighter. The backsheets of solar panels contain PFAS as fluoropolymers, as a result of which PFAS can be released when they are incinerated. The way in which solar panels are recycled determines if and how substances are released and whether humans and the environment are exposed to them.

RIVM advises the Ministry of Infrastructure and Water Management (IenW) to stimulate the technological developments that enable the recycling of solar panels. This would ensure that these or comparable recycling options are feasible in five years' time.

RIVM also recommends IenW to stimulate design for recycling for solar panels. This applies, for example, to developing other encapsulant materials between the glass and the backsheet to enable easier dismantling. It is also important to minimise the use of hazardous substances. Panels without lead and PFAS are already available on the market.

Keywords: solar panels, recycling, innovation, circular economy, environmental impact, substances of concern, safe design

Publiekssamenvatting

Recycling van zonnepanelen

scenario’s voor een circulaire en veilige productketen

Nederland streeft naar een circulaire economie in 2050. Een onderdeel daarvan is grondstoffen en materialen recyclen, zoals zonnepanelen. Op dit moment worden grondstoffen uit zonnepanelen na gebruik nog niet teruggewonnen. Naar verwachting zullen over ruim vijf jaar de eerste grote hoeveelheden zonnepanelen als afval vrijkomen. Het is belangrijk om hierop voorbereid te zijn en ze veilig en duurzaam te kunnen recyclen. Er zijn verschillende technologieën in ontwikkeling om zonnepanelen te recyclen. Het RIVM heeft vier mogelijkheden uitgewerkt om het glas, de zonnecellen en het achterblad ervan te recyclen.

De teruggewonnen materialen uit zonnepanelen kunnen opnieuw worden gebruikt als grondstof voor verschillende toepassingen. In dit onderzoek is gekeken is welke mogelijkheden in de praktijk uitvoerbaar lijken en hoe milieuvriendelijk ze zijn. De vier varianten zijn vergeleken met de huidige situatie (de basisvariant). Daarin wordt vermalen glas van zonnepanelen als schuurmiddel in de metaalindustrie gebruikt en daarna verwerkt in bijvoorbeeld funderingsmateriaal voor wegen.

Uit de analyse blijkt dat alle vier de varianten meer circulair en milieuvriendelijker zijn dan de basisvariant. Het energiegebruik verschilt iets per variant maar is veel lager dan dat van de basisvariant. Dat komt onder andere doordat het meer energie kost om nieuwe grondstoffen voor zonnepanelen te maken dan met gerecyclede grondstoffen te werken. Het meest circulair is de variant waarin van glas nieuw glas voor zonnepanelen wordt gemaakt. In deze variant kan ook de grondstof silicium worden herwonnen voor nieuwe zonnecellen. Dit is technologisch ingewikkeld maar wel mogelijk.

Bij de recycling is aandacht nodig voor gevaarlijke stoffen in zonnepanelen: lood, antimoon en PFAS. Lood zit in het soldeermateriaal en antimoon zorgt voor de helderheid van het glas. PFAS zitten als fluorpolymeren in het achterblad van zonnepanelen, waardoor bij verbranding PFAS kunnen vrijkomen. De manier van recyclen bepaalt of en hoe de stof vrijkomt en mens en milieu eraan kunnen worden blootgesteld.

Het RIVM raadt het ministerie van Infrastructuur en Waterstaat (IenW) aan de technologische ontwikkelingen om zonnepanelen te recyclen, te stimuleren. Dan zijn over vijf jaar deze of vergelijkbare recyclingmogelijkheden haalbaar.

Het RIVM beveelt IenW ook aan te stimuleren dat bij het ontwerp rekening wordt gehouden met recycling. Dit geldt bijvoorbeeld voor de manier waarop de zonnecellen aan het glas en het achterblad worden gelijmd. Verder is het belangrijk om gevaarlijke stoffen zo min mogelijk te gebruiken. Zonnepanelen zonder lood en zonder PFAS zijn al te koop.

Kernwoorden: zonnepanelen, recycling, innovatie, circulaire economie, milieu-impact, zorgwekkende stoffen, veilig ontwerp

Content

Summary

At European and national level, targets have been set for achieving a circular economy (CE) in which recycling of waste flows plays an important role. The Netherlands aspires to have a fully circular economy by 2050. With the new National Circular Economy Programme 2023-2030, the Dutch government is taking the next step to accelerate and scale up the process, by means of more intensive policy, and concrete targets for (sixteen) specific product groups.
For the product group ‘solar PV systems’, the ambition is to obtain high-grade circular processing of solar PV panels that become available for recycling. Several measures have been proposed. In the updated waste policy framework that is being developed, Circular Materials Plan (CMP), specific attention will be given to the solar panel product chain.

The attention for solar panels in these policy frameworks, can be explained by the large increase of installation and the expected volumes of end-of-life (EoL) of solar panels. In 2035, the Dutch material flow of discarded panels is expected to consist of approximately 10,000 tonnes per year, which will grow strongly from then onwards to an expected 230,000 tonnes in 2045. Additionally, realising closed material loops by 2050 means that the industry has to redesign and produce products in a way that materials can be dismantled easily and recycled while maintaining its material value.

The aim of this study was to explore and compare current and future recycling options for the product group solar panels with the Safe and sustainable loops (SSML) framework. SSML was developed by RIVM to assess options for material recycling in terms of circularity, environmental impact (global warming potential and land use) and potential risks of chemical substances for humans and the environment. The result of such an analysis provides insight into the advantages and disadvantages of the considered (innovative) processing methods for policy makers and industry in different categories.

Applying SSML on future recycling processes gives the opportunity to show the advantages and disadvantages related to sustainability and safety for human health and the environment. Identifying the potential (most realistic) future recycling scenarios and data for these scenarios is crucial for the comparison. Although a complete LCA or multicyclic LCA could give more detail, SSML is a screening method making it possible to identify the most important aspects and make these transparent for recycling technology for which data are scarce because it is still in development.

The main research question for the solar panel case was: *What are the environmental benefits and drawbacks of different recycling methods and what conclusions can be drawn on innovative recycling processes of end-of-life solar panels in the Netherlands?*

Recycling scenarios

Based on the inventory of the current recycling process and identified future recycling processes we determined five scenarios for recycling of solar panels:

- Baseline scenario: downcycling. The baseline recycling includes shredding, crushing and sorting of materials s. The shredded glass (with parts of the solar cell and backsheet) is used as an abrasive in the metal industry, followed by processing in the metal production process together with steel scrap. The metal slag is used as road foundation. Silicon and silver are not recycled.
- 2a. 'Mechanical recycling with hotknife delamination+ incineration'. This scenario recovers glass wool and metallurgic grade silicon. Recovery of silver, copper and aluminium.
- 2b. 'Mechanical recycling with waterjet delamination and incineration'. This scenario recovers new solar glass and metallurgic grade silicon. Recovery of silver, copper and aluminium.
- 3a. 'Thermal recycling by incineration of the whole panel'. This scenario recovers glass wool and metallurgic grade silicon from the bottom ash. Recovery of silver, copper and aluminium.
- 3b. 'Thermal: Pyrolysis enabling the recovery of the solar cells intact or as larger fragments'. This scenario recovers solar grade glass and solar grade silicon. Recovery of silver, copper and aluminium.

Environmental impact, circularity and substances of concern

All future recycling scenarios for solar panels are more circular and have a lower environmental impact than the baseline scenario. Recycling of solar glass to new solar glass (scenario 2b and 3b) has a higher circularity score. Pyrolysis (scenario 3b), has the lowest *environmental impact.* However, because of uncertainties in the estimated energy demand, differences between the future recycling options are relatively small. Once the recycling methodologies are further developed from pilot scale to full scale more data will be available to lower the uncertainties in calculations.
Delamination of solar cells from the solar glass contributes to a cleaner glass fraction and opens possibilities for high value recycling. The development of processes for the recycling of solar glass and recovery of high purity silicon (solar grade silicon) can contribute to *circularity* and reduction of the climate impact of solar panels as both glass and solar grade silicon production are very energy intensive processes.

The *critical raw materials (CRM)* present in solar panels are solar grade silicon, copper and antimony and should be recovered. Silver and copper can be recovered with the technologies included in the scenarios. Lead (Pb) might also be recovered during copper recycling, but it is too uncertain to be part of the scenarios.

Some *substances of concern* are present in solar panels. Lead belongs to the group of the Dutch substances of very high concern (in Dutch ZZS).

The Dutch government takes priority action on ZZS substances[1] as they are hazardous to people and the environment. Examples include substances that are carcinogenic, impede reproduction, or bioaccumulate in food chains.

During recycling, potential exposure of humans and the environment to lead should be prevented. The fate of lead during recycling depends on the specific recycling process. In case the glass is removed first, this could avoid contamination of the glass with other substances. After removal of the glass, a thermal treatment can provide access to the solar cells for the recycling of silicon and silver. Technically, lead can be extracted after thermal treatment.

Other substances of concern are antimony and PFAS. Antimony is used as an additive in the solar glass to improve the light transmission. Antimony is a substance of concern (not a ZZS), because it is self-classified as known human reproductive toxicant (1A) according to CLP and (Dutch) environmental quality standards are applicable.
Solar glass is not yet being recycled to new solar glass. One of the foreseeable applications for the recycled solar glass is foam glass used for construction. Exposure of antimony to the environment in this application needs to be controlled. Antimony-free glass can be used in production of PV modules. However, the use of this type of solar glass is not yet significant in volume. Glass manufacturers in Europe are currently reluctant to accept recycled solar glass that contains antimony due to potential health risks for workers and technical reasons. Creating closed-loop recycling schemes for solar glass requires adequate traceability about the antimony content of the glass. As such glass containing antimony can be recycled in specific glass recycling facilities and does not cause contamination of glass production process that are free of antimony.
PFAS (fluoropolymers like PVDF (polyvinylidene fluoride) or PVF (polyvinylfluoride)) are used in the backsheet. Recycling of backsheets containing fluoropolymers itself is not possible. Depending on the incineration temperature and conditions PFAS are emitted to air during incineration (and/or end up in bottom/fly ashes). Presence of PFAS makes pyrolysis of solar panels hardly impossible, because pyrolysis would lead to the formation of unwanted (by-)products.

Recommendations for sustainability

First, we recommend to further develop and optimise delamination technology. Pure fractions make it possible to recycle solar glass to new solar glass, hence closed loop recycling. Second, we recommend to further develop recycling technologies for the recycling of solar cells to high quality solar grade silicon. This will reduce the energy demand, because it saves the energy intensive production of virgin silicon. Third, we recommend to end the shredding of complete solar panels to glass cullet mixed with solar cells and polymers, and to temporarily store the panels until delamination techniques will become available. This prevents downcycling and the loss of critical metals. Fourth, we recommend to generate more data on the energy demand of (full scale) recycling processes, e.g. the specific

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[1] Although the Dutch ZZS substances cover a broader range than the Substances of Very High Concern (SVHC) under REACH, they are identified based on the same hazard criteria as the SVHC substances (i.e. REACH article 57 (1907/2006).

recycling of solar glass to solar glass or consumption glass to glass wool. On a pilots scale these data are still uncertain.

Recommendations on substances of concern

With regard to potential risks of ZZS and other substances of concern we recommend to review the potential exposure to workers and take appropriate measures, avoid the generation of dust and emissions to the environment during dismantling and crushing, and to avoid emissions of toxic substances (e.g. lead, antimony, PFAS) to air and soil.
The fate and risks of ZZS and other substances of concern in case of recycling of materials, needs more research. An example is recycling of solar glass into foam glass to be used as foundation material.
Also more research is necessary to understand to which extent emissions of PFAS can occur as a result of (future) solar panel recycling processes (incineration and leaching).

Recommendation related to Design-for-recycling

The current design of solar panels is not yet optimized for recycling. The use of ethylene vinyl acetate (EVA) as encapsulant makes the separation of materials difficult. The development of other encapsulant materials is required to enable easier dismantling. It is recommended to stimulate this development.
Concerning substances of concern, substitution is the preferred way to avoid risks in the entire life cycle. For antimony, lead and PFAS backsheet, alternatives are already available in the market but not widely applied yet. Policy measures (such as the review of the RoHS directive and the REACH restriction proposal for PFAS) can accelerate the transition to safer alternatives.
The concentration of antimony in the glass is not passed on in the supply chain, therefore rules for manufactures to disclose this information would encourage the solar glass recycling and avoid contamination of other (antimony-free) glass recycling processes.

Reflection on the SSML methodology

With regard to circularity, SSML applies a weight-based approach. This means that heavy materials like glass dominate the outcome of the calculated circularity scores. It might be worthwhile to focus more on the recovery of solar grade silicon, as the production of solar grade silicon is an energy intensive process. This means that although circularity indicators are more transparent and easy to calculate, estimation of the environmental impact is essential for the comparison of scenarios.
Currently the main focus of the module on ZZS is the presence of ZZS in EoL-products and the potential concentrations in secondary resources and new products. For some compounds also emissions to air and water during recycling are important pathways to take into account. We recommend to consider drafting a guidance on how to verify potential exposure to chemicals during recycling. The application of SSML on scenarios for future recycling processes, being in an early stage, make the data collection challenging, because these data are still scarce. Still, a screening method makes it possible to identify the most important aspects and make these aspects transparent.

1 Introduction

1.1 Context

At European and national level, targets have been set for achieving a circular economy (CE) in which recycling of waste flows plays an important role. The EU 'new Circular Economy Action Plan' (EC, 2020) includes the ambition to scale up CE and be climate neutral by 2050, with economic growth decoupled from resource use. On the Dutch national level, the National Circular Economy Programme of the central government sets ambitions, targets and measures for a CE[2] (IenW, 2023a). Next to that, targets and measures have been set for 16 product groups within four priority product chains (plastics, consumer goods, construction and manufacturing). One of the product groups is solar panels (within the manufacturing industry). In the Circular Materials Plan (CMP) that is being developed as a successor to the National Waste Management Plan (Dutch: LAP3) a plan is included to stimulate circularity of the solar panel product group (IenW, 2023b).

Since 2019, Dutch solar power production in the Netherlands has more than tripled (CBS, 2022). Additionally, realising closed material loops by 2050 means that products coming to the market have to be designed and produced in a way that materials can be dismantled easily and recycled while maintaining its material value. Most solar panels installed in the Netherlands however are produced in China; influencing the design of panels coming from China and countries outside the EU of course will be a challenge. For products already in use, its service life could be extended (e.g. for solar fields that have to be removed after the permission ends) and (material) recycling should focus on as much value retention as possible.

Right now, there are only a limited amount of panels that have reached their end-of-life (EoL). Recycling of solar panels is still in an early stage of development (TNO, 2022). The disassembly and recycling of solar panels is currently still challenging. The reason is that solar panels are a sandwich construction of the frame, glass, encapsulant, then the solar cells, encapsulant and plastic (for protection from moisture).

Various technologies for solar panel recycling are under development to improve process efficiency, economics, recovery and recycling rates, and environmental performance. We selected the case study of recycling of solar panels based on the above mentioned policy relevance, the expected growth of end-of-life solar panels and the importance of being prepared for large scale recycling in time. Recycling of materials is important for material preservation, recovering critical raw materials the reduction of carbon emissions, but it should also be safe for human and environmental health.

For the assessment of safety and environmental benefits and trade-offs of recycling processes, RIVM has drawn up the ‘Safe and Sustainable

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[2] https://www.government.nl/documents/reports/2023/09/27/national-circular-economy-programme-2023-2030

Material Loops' framework (SSML)(Quik, 2019; Traas, 2021). This framework can be used to compare alternative treatment options or different scenarios for processing a residual material stream compared to the current recycling process. As such, it can support decision-making processes for policy makers, but also for industry, in addition to analyses related to social, financial and economic aspects.

Environmental benefits and trade-offs range from climate change mitigation to protection of the environment in order to foster a healthy ecosystem. The assessment of safety is particularly important when applying residual or waste material streams in new applications. It is already common to include information on safety and environmental impact in decision making. However, this often is scattered information , e.g. an LCA study and technical safety data sheets. By applying the SSML framework, this information is simplified and restructured to make a fair comparison possible. The tiered approach also provides the possibility to first screen different options before delving into more data intensive assessments.

In terms of safety, the focus of this case study is on the presence of the Dutch substances of very high concern (ZZS[3]), and other substances of concern (SoC). Presence of pathogens, medicines and pesticides are part of the SSML framework but are not considered relevant for the case study.
The Dutch government takes priority action on ZZS substances as they are hazardous to people and the environment. Although the Dutch ZZS substances cover a broader range than the Substances of Very High Concern (SVHC) under REACH, they are identified based on the same hazard criteria as the SVHC substances (i.e. REACH article 57 (1907/2006). Examples include substances that are carcinogenic, impede reproduction, or bioaccumulate in food chains. ZZS may be present in waste streams as they are intentionally used in the original processes or products, or they can formed during processing. Substances of Concern do not fulfil the specific hazard criteria as mentioned above, but can be considered as toxic to humans are environment due to specific hazard properties such as acute toxicity of toxicity for aquatic organisms.

1.2 Aim of the study

The aim of this study is to explore and compare future recycling options for the product group solar panels with the SSML framework. The result of the analysis should provide insight into the advantages and disadvantages of the considered innovative processing methods with regard to circularity, environmental impact (global warming potential and land use) and safety for human health and the environment.
The main research question on the solar panel case was formulated as:
What are the environmental benefits and drawbacks of different recycling methods and what conclusions can be drawn on innovative recycling processes of end-of-life solar panels in the Netherlands?
The main research question will be answered with the following sub-questions:

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[3] ZZS: Zeer Zorgwekkende Stoffen are the Dutch Substances of Very High Concern (SVHC) which cover a broader range than the SVHC identified under REACH.

1. What is the expected quantity of end-of-life solar panels on short, mid and long term (2050) in the Netherlands?
2. What is the composition of the main types of solar panels installed in the Netherlands (which materials and which substances and critical raw materials in which quantities are present)?
3. Which ZZS or substances of concern (SoC) can hinder recycling into new products or materials from the perspective of human health and of legal requirements?
4. What processing methods are available or in development for the recycling of (Dutch) EoL solar panels?
5. Can ZZS or other substances of concern (SoC) be separated from the materials that are to be recycled, using the available processing methods? If not, what is the risk of human exposure to or leaching into the environment of these substances during processing or in the second life stage?
6. What conclusions and recommendations follow from the comparison of the recycling methods and types of panels in terms of circularity and environmental impact of recycling?
7. What is needed to ensure that panels are better recyclable in the future in the Netherlands ?

A second aim of this study is to reflect on the suitability of the SSML framework, based on the results of this case study. The SSML framework was developed and tested on residual material streams applied in recycling solutions (see Figure 1.1; Quik et al., 2019). This case study tries to use the SSML-framework to also draw conclusions on the design for recycling. This is important because measures in the design, construction and use phases of a product are likely to contribute to a circular economy, because also higher R-strategies than recycling should be considered (e.g. reduce, re-use or repair; Potting et al., 2017).

Material Safety & Sustainability Sheet for [object]
[material stream application and scenario]

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Substances of Concern
[main conclusion]
[Outcome of highest tier]
For further details see page [...]

Pharmaceutical residues
[main conclusion]
[Outcome of highest tier]
For further details see page [...]

Antibiotic Resistance
[main conclusion]
[Outcome of highest tier]
For further details see page [...]

Pathogens
[main conclusion]
[Outcome of highest tier]
For further details see page [...]

Pesticides
[main conclusion]
[Outcome of highest tier]
For further details see page [...]

Circularity
[main conclusion]
[Outcome of highest tier]
For further details see page [...]

Energy & Land Use
[main conclusion]
[Outcome of highest tier]
For further details see page [...]

This solution contributes to the SDGs:*
SUSTAINABLE DEVELOPMENT GOALS
*indicators & criteria in module text.

[Overall indication of risk, benefit and degree of uncertainty. Collor coded with green indicating no concern, addded benefit and low uncertainty; orange indicating uncertainty and red indicating concern] 🟩 🟧 🟥

Methodology described in RIVM Report 2018-xxx version xx-yy-zzzz, [contact]

Figure 1.1 Generic material safety and sustainability data sheet to present the overall outcome of the SSML framework.

1.3 Approach

This study is mostly relevant for recycling of solar panels in the Netherlands that will reach end-of-life from 2035 onwards. The size of this material flow of End-of-life (EoL) solar panels is expected to increase sharply in the coming years (TNO, 2022).

Recycling processes for solar panels are currently being developed. Based on the information in literature and from stakeholders (such as TNO, Zonnepaneel Recycling Nederland and Stichting OPEN) about solar panel recycling, we included recycling processes that can be expected to be fully operational in 2030. We focus on the processing of residual flows to widely applicable materials or a new product from secondary raw materials. This is done in the module on environmental impact and in the module on Safety of the SSML framework. Concerning indicators for circularity, we also take into account the possibility for recycling after the second use phase.

Defining scenarios for recycling, we focus on the technical possibilities and not on the business case (financial aspects). We tried to select recycling technologies that are currently being developed and expected to be available in 2030.

We performed the following steps to answer the research questions:

- Scope definition. Based on the available data on the composition and market share of different solar panel types, the scope was further defined. It was decided, among others, whether the use phase is involved, and whether we include processing up to secondary raw materials or products and if the next life phase is included.
- Interviewing of stakeholders to get insight in the current and expected future recycling technologies of solar panels. We contacted the OPEN Foundation (Stichting OPEN), responsible for the collection and recycling of solar panels in the Netherlands (in compliance with the WEEE Directive) and the Solar energy recycling Netherlands Foundation (ZRN), representing the solar energy sector. Both have a key role in the collection and organising the processing of end-of-life (EoL) solar panels.
- Future options for recycling. The current and innovative recycling technologies of solar panels were identified. TNO was contacted and a literature search was done to find out what recycling options are and will become available now and in the near future.
- Inventory of the composition of end-of-life solar panels. In particular data with respect to the presence of the Dutch ZSS and other substances of concern (SoC) were gathered.
- Data were gathered about the environmental impact and circularity of the recycling options. Because some technology is still being developed, we depended on information provided by experts or that could be found in the literature.
- Definition of scenarios. Five scenarios were defined for processing end-of-life solar panels to new raw materials and/or products.
- Applying the modules of the SSML-framework. For the five defined scenarios, an inventory was made of the data on the

environmental impact and circularity of the recycling technologies. These data were used to apply the modules circularity and environmental impact. The module on substances of concern was used to assess the potential risks of substances of concern during recycling (Quik et al., 2023).

- Integration of results and evaluation. The pros and cons of the selected recycling technologies are given. Based on the possible obstacles for processing technologies, we also analysed if design-criteria can stimulate better recycling in the future.

2 Material flows and composition of solar panels

2.1 Amount of discarded solar panels

The energy transition is going fast and solar energy is an major source. That is why it is expected that the use, and therefore the amount of waste, of solar panels will increase sharply the coming 20 years (TNO, 2022). Solar panels are covered by the Waste Electrical and Electronic Equipment (WEEE) scheme[4], which means that producers have a producer responsibility to organise the collection and recycling of their products. Within the Netherlands, this is carried out by 'Stichting OPEN'. Stichting Zonne-energie Recycling Nederland (ZRN) represents the solar energy sector and advises Stichting OPEN.

The material flow from discarded solar panels in 2023 was relatively low (40 tonnes/year) (TNO, 2022). This is due to the long lifespan of solar panels (15 to 25 years) and the relatively small amount of panels in use in the past. There is no large-scale and recycling to high-quality materials yet.
In the current -small scale- recycling process for solar panels, the aluminium frame is removed and used as a secondary raw material. The rest of the panel is ground and downcycled (see paragraph 3.2) (personal communication Stichting OPEN, 11 October 2022).

The number of EoL solar panels in the Netherlands is expected to increase considerably over the next twenty years. Therefore the OPEN Foundation will also work on improving the recovery of valuable raw materials from discarded solar panels. Commissioned by the OPEN Foundation, TNO has conducted research into the expected waste flows, recycling techniques and possible yields from the recovered raw materials (TNO, 2022). The outcomes are described below:

In 2035, the Dutch material flow of discarded panels is expected to consist of approximately 10,000 tonnes per year (middle term), which will grow strongly from then on to an expected 230,000 tonnes in 2045 (long term) (See Figure 2.1). This is a more than 1000 fold increase compared to the current level of 40 tonnes/year.

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[4] https://wetten.overheid.nl/BWBR0034782/2020-12-10

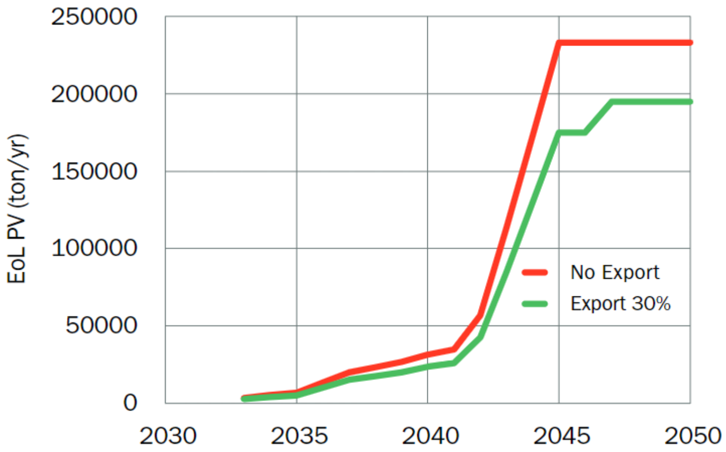

Figure 2.1 Expected material flow of end-of-life (EoL) solar panels up to 2050 in the Netherlands. The red scenario shows the total amount of EoL panels in the Netherlands. The green line shows the expected amount, taken into account export of 30% of the solar panels that can be re-used (extended use phase). (Source: TNO, 2022)

2.2 Types of solar panels and composition

There are different types of solar panels. The most common solar panels are based on crystalline silicon solar cells. Worldwide, these panels have a market share of >90% (Fraunhofer Institute, 2023[5]). The remaining 10% consists of several thin film panels: these consist of a thin layer of photovoltaic material from a few nanometers to micrometers thick on a substrate (glass, plastic, or metal). Examples are panels based on cadmium telluride (CdTe), copper indium gallium diselenide (CIGS) and amorphous thin film silicon (a-Si). Of these, CdTe panels are the most common. CdTe panels are produced exclusively by the American company First Solar, which also organizes the recycling of the panels. The recycling facility in Europe is located in Frankfurt Oder (Germany).

Panels with crystalline silicon solar cells have had the largest market share since the beginning, since the 90s[6]. This also applies for the Netherlands. Although there is development of new types of panels and solar cells, it is expected that crystalline silicon panels will remain the most widely used. In fact, the market share of thin film panels has declined over the past 10 years (Fraunhofer Institute, 2023).

2.2.1 Crystalline silicon panels

An average crystalline silicon panel is 0,99 meter wide and 1,65 meter long, with a total surface area of 1,6 m^2. The design and main components of a crystalline silicon panel is displayed in Figure 2.2.

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[5] Photovoltaics Report (fraunhofer.de)

[6] https://www.klimatosoof.nl/de-geschiedenis-van-het-gebruik-van-zonne-energie

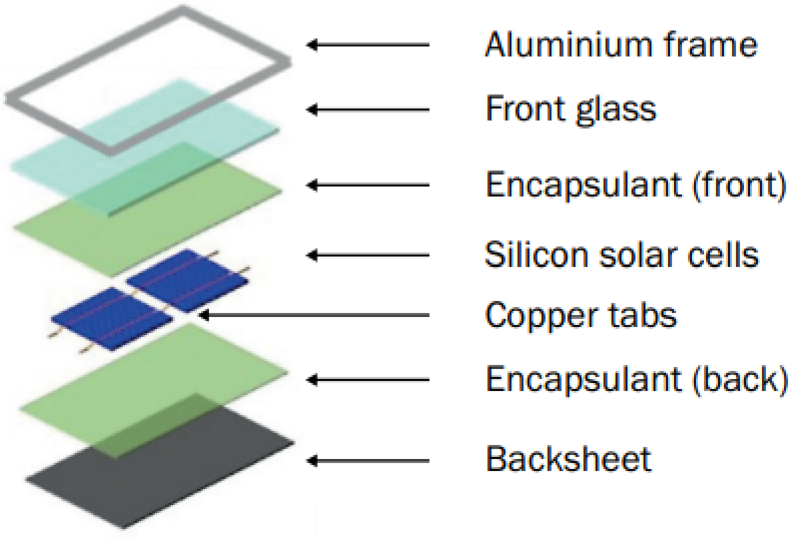

Figure 2.2 Cross section of a contemporary crystalline silicon panel (TNO, 2022).

The mass composition of the different component is given in Table 2.1. Glass makes up the largest percentage of the mass (70%). The primary purpose of the glass is to transmit as much sunlight as possible into the panel. The aluminium frame has the second highest mass percentage (18%) and the frame also includes Mg in the form of aluminium alloy (AlMg3).

The next highest percentage of mass contribution comes from the ethylene vinyl acetate (EVA) layer. The EVA is a transparent polymeric resin designed to protect the delicate solar cell regions from moisture, dirt, etc. The EVA is also used as an adhesive between the glass and the solar cells. The solar cells are made from silicon, it takes 3,65% of the mass and the solar cells are interconnected by soldering copper wires onto them. A backsheet is the last layer at the bottom and is typically made of a polymer or a combination of polymers such as polyvinyl fluoride (PVF). It protects against UV radiation, humidity, wind, dust sand and chemicals. A junction box is attached to the backside of the panel for electrical connection.

There are different techniques to connect the solar cells. The old technique is to connect the cells with tabs (90% copper and 10% silver) with silver paste. Newer techniques do not use tabs but silver adhesive or soldering lint. The soldering contains lead, tin, silver and sometimes copper (van Veen et al., 2022).

Table 2.1 Mass composition of a crystalline silicon panel and expected material streams in 2035 and 2045 (source: Latunussa et al., 2016. and estimation of the material flow based on TNO, 2022).

Material components	**weight (kg) per panel**	**percentage (%)**	**Mass composition of 1000 kg PV waste**	**Expected amounts in 2035 (ton/y)**	**Expected amounts in in 2045 (ton/y)**
Glass (containing antimony 0.01 – 1%/kg of glass)	15.4	70	700	7000	161000
Aluminium frame	3.96	18	180	1800	41400
Polymer-based adhesive (EVA) encapsulation layer	1.122	5.1	51	510	11730
Solar cell, containing silicon	0.803	3.65	36.5	365	8395
Back-sheet layer (based on polyvinyl fluoride)	0.33	1.5	15	150	3450
Cables (copper and polymers)	0.22	1	10	100	2300
Internal conductor, aluminium	0.12	0.53	5.3	53	1219
Internal conductor, copper	0.024	0.11	1.1	11	253
Silver	0.012	0.053	0.53	5.3	122
Lead	0.00115	0.0068	0.068	6.8	156
Other metals (nickel[7], tin, titanium)*	0.012	0.053	0.53	5.3	122
Total	22	100	1000	10.000	229.991

The composition is subject to change due to technological developments. The amount of silver has been reduced from about 10 grams to 5 grams per panel and will possibly be eliminated in the future (personal communication M. Spath, 2023). Alternatives for fluorinated backsheets are available in the market. Depending on when the restriction proposal for PFAS will come into force, the application of fluorine free backsheets will become (more) mainstream. With respect to the encapsulant, research is ongoing to develop an alternative for the EVA encapsulant as the plastic encapsulation not only makes the recycling of all materials more difficult but also cannot be recovered itself. A new technology being developed by TNO provides an integrated trigger mechanism that enables uncovering the solar cells during recycling.

The expected 10.000 and 230.000 tons of waste solar panels in respectively 2035 and 2045, will result in a waste stream of 7000 tons of glass in 2035 and 161.000 tons of glass in 2045. For silicon and silver, a material stream of respectively 8395 and 122 tons is expected in 2045 (See Table 2.1).

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[7] According to Maani et al. (2020) the amount of nickel is 0,163 g/m2 and therefore 0,26 g per panel

2.2.2 *Cadmiumtelluride (CdTe) panels*

The market share for cadmiumtelluride (CdTe) based panels is estimated to be 5% (Aryan et al., 2017). A standard cadmium telluride panel weighs 12 kg (Aryan et al., 2017).

In frameless CdTe panels, CdTe is the light absorber layer and it takes up 0.12% of the total mass (Maani et al., 2020). Its purpose is to absorb light and generate charge carriers (Maani et al., 2020). Frameless panels are referred to as laminates. The substrate is the material on which the CdTe solar cell layers are deposited. It is usually made of glass and occupies about 95% of the mass of the whole solar panel, see Figure 2.3 (Maani et al., 2020).

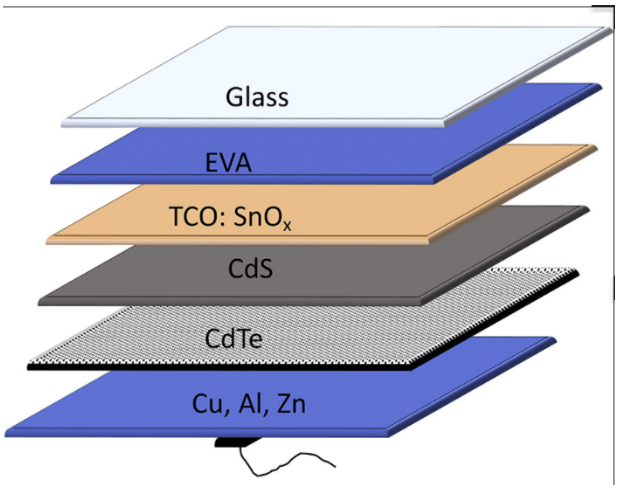
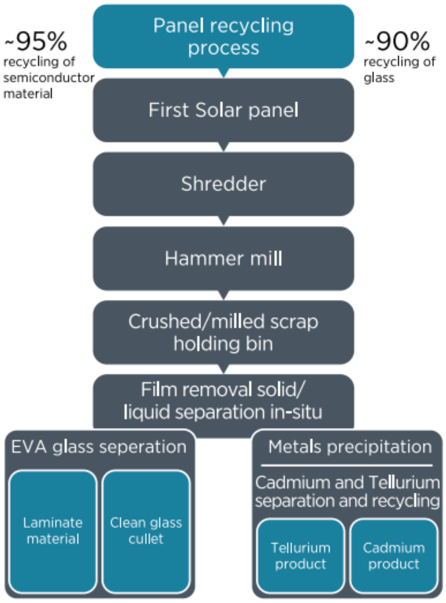


Figure 2.3 Typical structure of a CdTe PV panel. EVA: ethylene vinyl acetate. TCO: Transparent Conducting Oxide (Maani et al., 2020)

CdTe PV modules have been treated in dedicated recycling plants for several years. The producer of CdTe PV panels (First Solar) also operates recycling facilities of which one is located in Europe (in Germany). CdTe panels are currently processed and recycled using a combination of mechanical and chemical treatments (Weckend et al., 2016). A prominent example of this process includes the following steps (see Figure 2.4) which can achieve about 90% recovery of the glass and about 95% of the semiconductor material by mass:

1. Panels are shredded and crushed in a hammer mill to particles of about 5 millimetres to break the lamination bond. The dust is then collected in an aspiration system equipped with a high-efficiency particulate air filter.
2. Semiconductor layer etching is carried out with a mixture of sulphuric acid and hydrogen peroxide. The glass and larger pieces of ethylene-vinylacetate are separated in a classifier and on a vibrating screen. Finally, the glass is rinsed with water and dried on a belt filter unit.

In this study we focussed on the recycling of Si solar panels, because these are the most applied in the Netherlands. Still, comparisons with other solar panels over the whole lifecycle, including recycling are very valuable.



Based on First Solar (2015a); cadmium and tellurium separation and refining are performed by a third party

Figure 2.4 Steps in the recycling process for CdTe panels (Weckend et al., 2016).

3 Processing of End-of-life solar panels and recycling scenarios

In this chapter we describe the current recycling process of solar panels and the future recycling technologies that are currently developed. With the information on recycling technologies we defined five End-of-Life scenarios. On these scenarios we apply in the following chapters the module for circularity, the module for environmental impact (see chapter 4) and the module for Dutch substances of concern (in Dutch: ZZS) (see Chapter 5).

3.1 Scope and selection of the recycling scenarios

In Figure 3.1 the scope definition is given for all five scenarios[8] (and the recycling processes included). The scope includes the EoL- solar panels, the different steps of the recycling process and the use of the secondary (or primary) resources for producing new solar panels.

In solar panels, there is an aluminium frame which needs to be removed in the first step of the recycling process, before the sandwich layer-like structure (encapsulant with solar cells) is dismantled. This is often done manually. The junction box is also removed manually. In the comparison of environmental impact dismantling of the panels is excluded, because it is part of all recycling scenarios.

The next step for all future recycling options is the removal of the encapsulant[9] to separate the glass from the silicon cells. During this delamination stage the waste PV panels enter as a whole and by the time they leave, the (EVA[10]) encapsulant with the solar cells has been separated from the glass components. The delamination methods can be distinguished into mechanical, thermal and chemical methods.
For mechanical recycling we distinguish two different techniques: hotknife (paragraph 3.3) and waterjet (paragraph 3.4). For thermal recycling, this can be done via incineration (paragraph 3.5) or pyrolysis (paragraph 3.6).

The third step is the recycling of the separated fractions:

- Glass can be recycled into glass foam or glass fibre, or when recovered clean and/or intact, recycled as high quality solar glass
- Valuable recoverable metals are amongst others silver, copper and aluminium
- Silicon can be recovered after separation of the solar cells and the encapsulant. Two recycling grades can be distinguished for the recovered silicon: metallurgical grade silicon or solar grade silicon (highest purity). Metallurgical grade' is a lower quality compared to solar grade level due to the presence of impurities on and in the silicon. It can be used as a raw material in the metallurgical industry. Solar grade silicon can be obtained by selective chemical or mechanical treatments for stripping off the

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[8] Other scenarios may be conceivable, these five scenarios can be considered to be well chosen examples.

[9] The goal of encapsulation is to provide the mechanical support and environmental isolation required by the cells and electrical wire system to ensure their electrical performance. The most common encapsulating material used for this purpose is **EVA** (Ethylene-vinyl acetate).

[10] Ethylene vinyl acetate

antireflection coating, and the thin, highly doped silicon layers at the front and the back side of the wafers.

In the following paragraphs, the recycling scenarios are defined by combining selected technological options with specific recycling routes. The high value routes featuring recycling of solar grade glass and solar grade silicon are combined with recycling techniques that are able to generate material output that is suitable for high value recycling. Examples are:

- The full glass plate could be recovered intact from an EoL PV panel, by means of hot knife or water jet technology. Additional cleaning is required. We assume water jet is more suitable for generating clean glass as output based on an interview with TNO (TNO, 2023)
- Pyrolysis might also generate clean glass as output. This is more a theoretical assumption. During processing (due to absence of oxygen) the polymers used in PV panels leave a film of soot residue behind on the glass. To minimize soot formation the total fraction of organic material to be removed should be limited (TNO, 2022).
- Regarding recycling of solar grade silicon, this was combined with the recycling technique "pyrolysis" in the recycling scenarios as "intact solar cells" can be recovered by pyrolysis (TNO, 2022). Please note that TNO also mentions some practical and economical challenges for the implementation (TNO, 2022), thus this should also been seen as a 'theoretical option'.

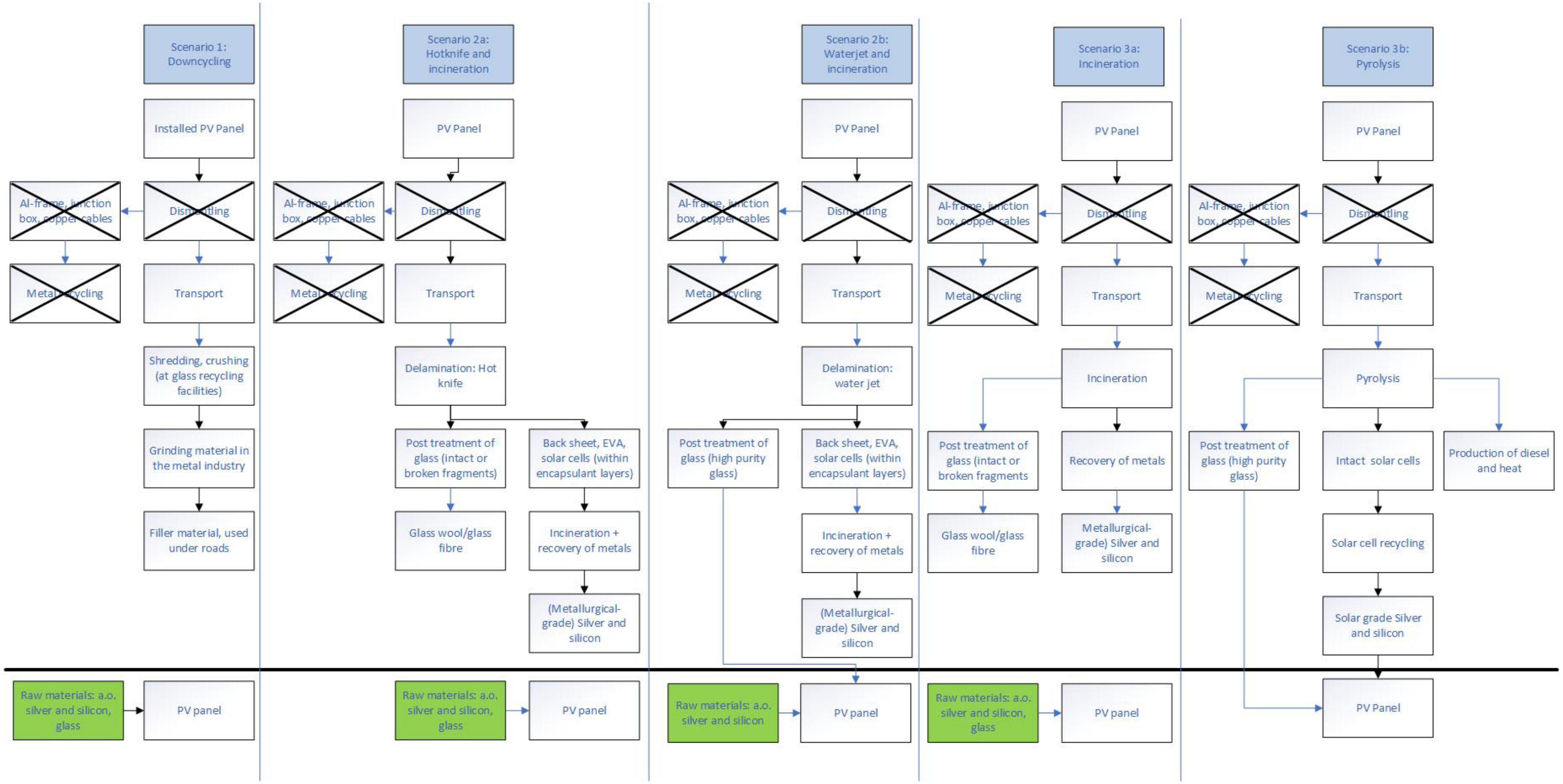

Figure 3.1 Definition of the scope of the End-of-Life scenarios of the baseline and alternative future scenarios

3.2 Baseline scenario (Scenario 1)

For this baseline scenario we use the process as currently applied by recycling facilities for the processing of Dutch solar panels. A recycling facility as described as baseline scenario is operational in Belgium. This process firstly manually removes the aluminium frame, junction box and copper cables (TNO, 2022). The metals are sent to specific recyclers. Then the solar panel is shredded in glass recycling facilities, followed by crushing and grinding and a series of manual and mechanical sorting processes. The grinded glass is used as abrasive in the metal industry (TNO, 2022). The shredded glass contains fractions of backsheet and solar cells (TNO, 2023).

After the use in the abrasion process this fraction is combined with the steel scrap and is being used in the metal production process (Stichting Open, 2023). The glass and other metals end in the metal slag that is used under roads or as filler in concrete (Stichting Open, 2023). In this scenario we assume the application under roads (see Table 3.1).

3.3 Mechanical Recycling: Hotknife and incineration (scenario 2a)

3.3.1 Delamination

Cleaving of the front side glass plate can be done with a hot knife technology. The equipment consist of a heated blade that melts and cuts the encapsulant layer between front side glass and solar cells with an operating temperature of 300°C (TNO, 2022). The Japanese company NPC offers this type of equipment for industrial use.

Their process can separate the PV cells from the glass in approximately 40 s, leaving behind a sheet of cells. The module is placed between two rollers, which move it along and hold it steady until it runs past a heated knife. The knife is a 1 m-long, 1 cm-thick steel blade that is heated and slices the cell and the glass apart (Farell et al., 2020).

The glass plate requires post-treatment for removal of the polymer residue. This can be done with a thermal process step. We assume that the glass can be recycled and used for the production of foam glass or glass fibre without an extra cleaning step. It might also be possible to recycle the glass to new solar glass. However we included the recycling to new solar glass in scenario 2b.

The incineration process of the solar cells and backsheet leads to the elimination of the polymeric encapsulant and back sheet resulting in a bottom ash containing inorganic residues from the solar cells, among others silicon and silver.

The Full Recovery End of Life Photovoltaic (FRELP) project demonstrated a pilot recycling approach that cuts apart the entire module glass sheet by a high-frequency knife at slightly elevated temperatures. This scenario is based on the FRELP process developed by an Italian company (Sasil) as part of the European ‘LIFE’ programme. An LCA analysis was performed and published by the European Commission in a JRC Technical report (Latunussa et al., 2016a). The results have been used for the purpose of this study. 98% of the glass was recovered, and the rest of the EVA/solar cell/backsheet sandwiches were sent to an incineration plant for further treatment (Deng et al., 2019).

Table 3.1 Description of the processes include in the End-of-life (recycling) scenarios

Material/ activity	**1 Downcycling Baseline scenario**	**2a Mechanical recycling with Hotknife + Incineration**	**2b Mechanical recycling with Waterjet**	**3a Thermal: incineration**	**3b Thermal: pyrolysis**
Short process description	Some fractions are recycled, such as the glass. No recycling of silicon and silver. Glass is used as abrasive in the metal industry	Hotknife[11] is a delamination technique to separate the glass from other components.	Waterjet is a delamination technique, for this scenario it assumed that the glass is recycled into new solar glass.	Incineration is a "brute force" approach leading to a bottom ash. Backsheet does not need to be removed prior to incineration.	Pyrolysis is a more "gentle" approach enabling the recovery of the solar cells intact or as larger fragments.
Backsheet	Incineration during metal production	Incineration (with scrubbers)	Incineration (with scrubbers)	Incineration (with scrubbers)	Fluoropolymer free backsheet/ recycling[12] or glass- glass panels without backsheet.
Glass	Glass cullets as abrasive in the metal sector + filler in concrete	Glass wool/ fibre	Solar glass	Glass wool /fibre	Solar glass
Silicon	Ends up in steel slag (reuse as road aggregate and filler concrete)	Metallurgical grade silicon[13]	Metallurgical grade silicon	Metallurgical grade silicon	Solar grade silicon from solar cell
Silver	Ends up in the steel slag (reuse as road aggregate and filler concrete) or other by-products from steel production	Recycling	Recycling	Recycling	Recycling
Other metals	Ends up in the steel slag (reuse as road aggregate) or other by-products from steel production	Recycling of copper and aluminium	Recycling of copper and aluminium	Recycling of copper and aluminium	Recycling of copper and aluminium

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[11] Goris et al. (2015) reported on a method of separating and recovering the glass, solar cell and backsheet layers from a c-Si module using a heated wire saw at approximately 200 C. Goris has mentioned that an advantage to this method is with the glass separated, the heating required for the cell is reduced, as the heating of the glass layer consumes a lot of energy. However, there is still EVA left on the glass and solar cells with this method. Another step would have to be employed such as pyrolysis or chemical treatment to clean and remove the leftover EVA.]

[12] Alternative backsheets without fluoropolymers are already available in the market, however not widely applied yet. As PFAS in solar panels are in scope for the restriction proposal we assume that large amounts of PV panels without fluorine backsheet will become available in 2045.

[13] Recycling of silicon on the lower 'metallurgical grade' quality level since the antireflection coating as well as the highly doped layers remain as impurities on and in the silicon.

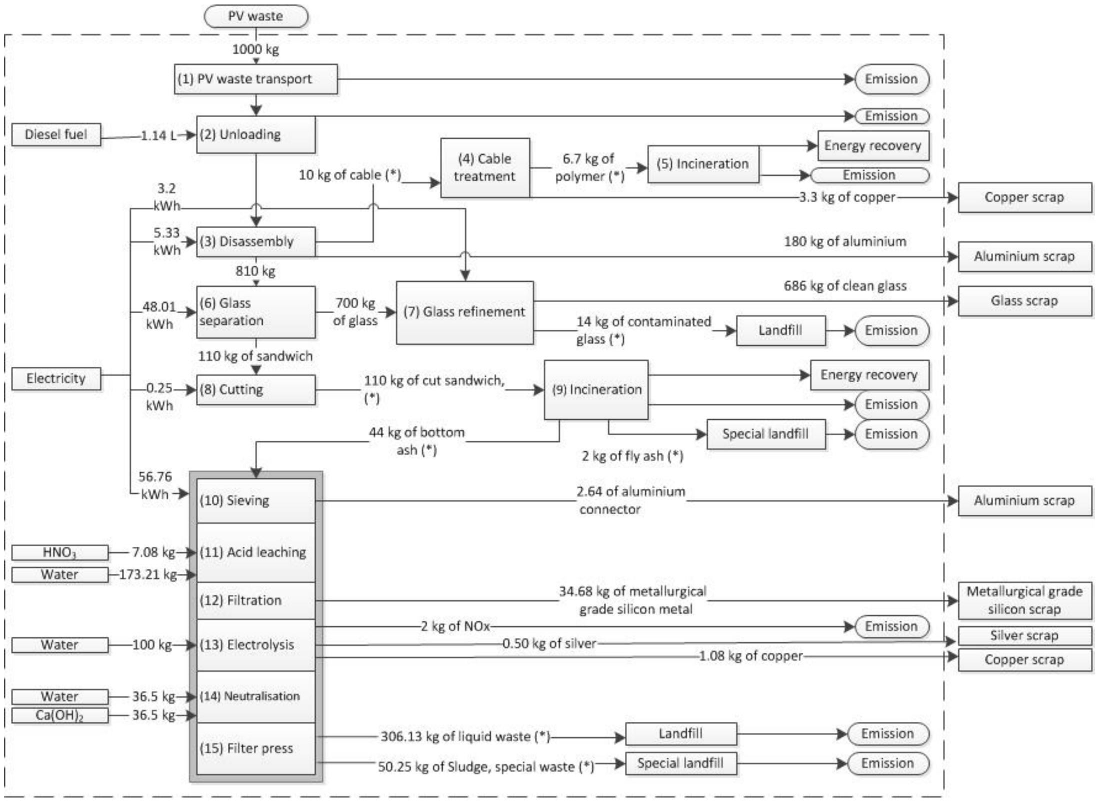

Figure 3.2 Detail of the recycling process studied (transport between the processes is indicated with an asterisk (*)) Source: Latunussa et al., 2016a.

3.3.2 *Description of the processes after delamination*

This paragraph describes the process after delamination with hotknife (scenario 2a). For delamination with waterjet (scenario 2b; see paragraph 3.4) this is identical. It is assumed that the sandwich (EVA, solar cells and backsheet) is treated in an (external authorized) incineration. After the incineration, the residual ash containing silicon and other recyclable metals is collected and treated. The description of the processes in this paragraph is retrieved from Latunussa et al. (2016a).

- Sieving:
  The ashes are treated via sieving. The objective of this process is to separate residues of aluminium connectors (originally used in the sandwich) from the ashes. The efficiency of this process in separating aluminium is approximately 50%. The residues are therefore transferred to the acid leaching phase. This process uses electricity during its operation.
- Acid leaching:
  The objective of this phase is to recover silicon metal from the ash. The silicon metal is separated using a solution of water and 65 % nitric acid ($HNO3$). During the leaching process, the ash containing metals is mixed with the solution of water and nitric acid ($HNO3$), which dissolves the metals (producing various metallic oxides) and leaves the silicon metal in the residues. This process is expected to recover silicon metal as **metallurgical grade silicon** with 95 % efficiency. Metallurgical grade means the silicon can be recycled by the metallurgical sector, but it is

not pure enough to produce new solar cells since the antireflection coating as well as the highly doped layers remain as impurities on and in the silicon. The remaining silicon and other dissolved metals in the acid solution are subsequently treated in a filtration phase.
In addition to the acid solution, this process uses electricity during its operation. However it has not been possible to be estimate the electricity consumption.

- Filtration:
  The mixture containing the dissolved metallic oxides and the silicon metal residues from the acid leaching process is transferred to a vacuum filtration process. In this phase, the silicon metal is recovered and a part of the acid solution is recirculated (around 80%).
- Electrolysis:
  The last part of the metal separation is expected to be flexible depending on the target materials to be recovered. The composition of the silicon PV panel can change over the time, especially when the lifespan of the product is very long. Therefore, the recycling processes should be adapted accordingly. According to the literature and laboratory tests conducted within the PV waste treatment project, the main recoverable metals that are present in the residuals after the leaching are silver, copper, lead and tin. In this analysis, silver and copper are expected to be recovered with an efficiency of 95%. The electrolysis process also emits NOx gases at the anode of the electrolysis (estimated at 2 kg per tonne of PV waste treated). The remaining metal residues remain in the solution to be further neutralised. Electricity is used as input energy for the electrolysis.
- Acid neutralization:
  In this process, the acid solution in output from the electrolysis is neutralised completely by the addition of calcium hydroxide — Ca(OH)2. The final output of the neutralisation process is a sludge containing calcium nitrate — Ca(NO3)2 — liquid, residual calcium hydroxide and unrecovered metals. The specific electricity consumption for sieving, acid leaching and electrolysis is approximately 1.29 kWh/kg of ash input.
- Filter press:
  In this phase, the output of the neutralisation is filtered, which mainly involves separation of the liquid waste part (constituted by water and calcium nitrate) from the sludge containing the unrecovered metals with some residual calcium hydroxide (classified as hazardous waste). These wastes are finally transported to different landfills (assumed to be 100 km away) for the final disposal.

3.4 Mechanical recycling with Waterjet technology (scenario 2b)

3.4.1 Delamination

Waterjet cutting is a well-known non-destructive dismantling technology. First attempts have been made to apply waterjet cutting for PV glass separation. This accelerated erosion process is based on water fired through a nozzle at a reduced pressure of 100 bar. The energy consumption is 20,000 Watts (TNO, 2022).

Some additional cleaning of the glass will be required, however we assume that this technology is able to result in high purity glass that can be recycled (remelted) for the production of new solar glass. It could also be used for other glass products like glass wool; we assumed that to be part of scenario 2a. The glass used in solar panels is iron free and highly transparent. An additional reason to recycle solar glass is the presence of the additive antimony in part of the PV glass manufactured today. Reportedly this element is undesired in common glass recycling, since it should not be applied in glass to be used for consumer glass based food packaging. Antimony is also an unwanted element in float glass recycling as it causes colouration of the surface and poses health risks for the workers (European Solar PV Industry, 2023).

3.4.2 Processes after delamination

After the application this delamination technologies we assume the same methods for the solar cell recycling are used as described in chapter 3.3.2. These are based in essence on acid leaching during which metallization and interconnection tabs are dissolved, most importantly, silver and copper. The undissolved silicon semiconductor can then be separated from the metals by vacuum filtration. This process results in the recycling of silicon on the ‘metallurgical grade’ quality level. It also delivers—after additional processing steps such as electrolysis—silver and copper on a level suitable for further refinement to secondary metal by metal recyclers.

3.5 Thermal recycling with incineration (scenario 3a)

Incineration can be described as a “brute force” approach leading to a bottom ash from which silicon and silver can be recovered in a subsequent step by chemical methods. The complete solar panel is incinerated, without a delamination step upfront.

The EVA begins to decompose around 350 °C, and completes its decomposition at around 520 °C, under an air atmosphere (Tammaro et. al, 2015). As consequence of the thermal treatment of PV panel, some hazardous components, as metals, can be released in the gaseous phase. It requires a good flue gas treatment section (for example with an electrostatic precipitator or fabric) to clean emissions.
Also the formation of hydrogen fluoride during thermal treatment from the backsheet, introduces severe technological difficulties to design and operate the post-combustion section.

Wang et al. (2022) used a thermal treatment to recycle the materials from silicon based solar modules. Two heating steps were performed: a first step at 330 °C to separate the backsheet from the module, and second step at 400 °C to burn the EVA and thus recover the glass plate, the cell chips and the ribbons.

For this incineration scenario we assume that glass can be recycled into glass wool and the silicon as metallurgical grade.

Recycling of the glass into foam glass or glass fibre is described in (grey) literature[14] (TNO, 2022) and mentioned by solar panel producer REC[15]. We included the production of glass wool in the recycling scenarios.

3.6 Thermal recycling with pyrolysis and recovery of solar grade silicon (scenario 3b)

Pyrolysis is defined as a process operated at moderately elevated temperatures under inert atmosphere, that is under exclusion of oxygen. In this way plastics, polymers or other organic compounds decompose leaving a mixture of smaller organic molecules that can be recovered and used as fuel or as building block for the production of chemicals.

The polymeric encapsulation layer, mostly EVA, can be either pyrolyzed into acetic acid, propane, propene, ethane, methane, and other combustible oils and gases under an inert gas environment (Deng, 2019).

The main difference between this scenario (3b) and the other scenarios (2a, 2b and 3a) is essentially the treatment of the encapsulation and back-sheet layer. The amounts of recovered aluminium, glass, silicon metal, copper and silver are assumed to be the same. However, the pyrolysis process may allow the recovery of the polymers in the encapsulation and back-sheet layer and produce diesel fuel and heat.

Table 3.2 Materials recycled and energy recovered by the treatment (including pyrolysis) of 1 000 kg of PV waste. Source: (Latunussa et al., 2016).

Material	**Estimated Quantity**	**Unit**	**Avoided Product**	**Quantity**	**Unit**
Polymer from copper cable encapsulation	6.70	kg	Electricity production	19.16	MJ
			Thermal energy	38.86	MJ
PV Encapsulation and non- fluorine backsheet layer	66	kg	Thermal energy	276.28	MJ

For the pyrolysis scenario we also assume that glass can be recovered in a pure form, enabling recycling into new solar glass.
Also we assume that silicon is being recycled in such a way that it can be used as solar grade silicon. This route differs from the ones yielding metallurgical grade silicon in the application of a more complex chemistry that is still being developed. That is the utilization of selective chemical or mechanical treatments for stripping off the antireflection coating, and the thin, highly doped silicon layers at the front and the back side of the wafers (emitter and back surface field). This procedure allows to obtain high-purity solar grade silicon. Nevertheless, it inevitably consumes more chemicals and time (TNO, 2022).

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[14] Glass fibre as potential recycling product for glass is described in TNO, 2022. REC group, a producer of solar panels is stating that recycling of glass into foam glass is being applied.
[15] https://www.recgroup.com/sites/default/files/documents/wp_-_recycling_of_solar_modules.pdf

3.7 Other developments concerning PV recycling

3.7.1 Chemical recycling

Chemical methods are generally well understood and also established in, e.g. solar cell manufacturing technology. While definitely effective, they are associated with significant amounts of chemical waste and thus environmental concerns and also related economic costs (TNO, 2022).

The purpose of chemical recycling is to dissolve the adhesive encapsulation layer to delaminate the module. Either inorganic (a) or organic solvents (b) can be used. Many academics studying chemical layering methods consider the effects of reagent type, concentration, temperature, time, solid-to-liquid ratio, and solubilisation on component separation and wafer recovery (Wang et al, 2022).
Examples of studied methods mentioned by a review paper from Deng et al, 2019 are:

- Inorganic solvent: immersing the module in nitric acid (HNO3) for 24 hours;
- Organic solvent: dissolution of EVA in trichloroethylene at 80 °C for 10 days. The chemical process can be accelerated with ultrasonic radiation. Or a dissolution of EVA in O-dichlorobenzene within 30 minutes to recover damage-free solar cells.

3.7.2 Other recycling options

Recently, there have been a number of innovations in maximising the recovery of constituents within solar panels modules. The prime example would be that of the silicon wafer where it can be recovered either intact or broken. If it is recovered intact, then certain offsets for the energy consumption and emissions of the silicon production would occur. Intact and undamaged silicon cells could potentially be remanufactured into marketable cells and modules (Bombach et al., 2006), but the value of these wafers is still highly uncertain, depending on the willingness of manufacturers to use the recycled materials in their production lines (Deng et al., 2019). Deng et al. recommends that research and development should target intact silicon wafer recovery, which can be achieved via the thermal recycling scenario and other delamination methods.

3.7.3 Future perspectives on the implementation and scaling up of recycling technologies

The TNO report "Balancing costs and revenues for recycling End-of-Life PV panels in the Netherlands (TNO, 2022) provides a comprehensive overview of the current status and perspectives of solar panel recycling. Downcycling is the main contemporary practice in the European Union leading merely to the recovery of the aluminium frame, junction box and cables, while the largest part of the panel ends up as a low value filler material after shredding. Advanced re-/upcycling, aiming at recycling of virtually all materials of the PV panel and extracting more valuable materials, is currently under development for implementation in future practice. In the case of re-/upcycling additional revenues from silicon (metallurgical or ideally even solar grade), silver and (clean) glass can be expected. But these can only be recovered by relatively complex recycling processes, many of which are still at lower TRL levels and associated with substantial additional costs. There are significant uncertainties regarding both costs and potential revenues for advanced re-/upcycling. This is due to the early development stage of the underlying technologies as well as to fluctuations in materials price levels. So, on this basis TNO concluded that recyclers today will require government subsidies or charge fees to be profitable, a conclusion that was also drawn in a recent international study (TNO, 2022).

4 Module environmental impact and circularity

4.1 Method

To determine the environmental impact of the end-of-life treatment of solar panels we use the environmental impact and circularity module of SSML (Quik et al., 2019). SSML uses a tiered approach. Each tier adds more detail to the analysis, but requires more data. For the environmental impact we apply tier 2 of SSML (there currently is no qualitative tier 1 analysis). In tier 2 a comparison is made of an alternative recycling technology or scenario with a reference (baseline) scenario on two impact categories: Greenhouse gas emissions (or energy consumption) and land use. Greenhouse gas emissions or energy consumption is used as a proxy for the overall environmental impact. Land use is relevant for products that have an organic origin. A tier 2 analysis is a comprehensive analysis to compare different scenarios. A tier 3 approach would encompass a full (multi cyclic) life cycle assessment. However, a tier 3 requires much more data. A tier 3 approach will only be needed when the results from the tier 2 analysis are inconclusive and selection is necessary.

A tier 2 analysis was performed to compare different end-of-life (EoL) scenarios of solar panels. As a functional unit we take the EoL treatment of one multi-crystalline silicon panel of 1,6 m2 being 22 kg. The inverter is left outside of the scope, because this equipment is part of the recycling of Waste of Electrical and Electronic Equipment (WEEE). The aluminium frame is outside of the scope for the environmental impact module to limit data requirements and because it is presumed to be similar in all scenarios. To determine the circularity we assume the expected waste streams in 2045 when the amount of installed of PV panels is at a steady state. The scenarios we compare are described in Table 3.1 and Figure 3.1.

Transport from the collection site to the dismantling plant is included in the analysis. It is assumed that in the baseline scenario dismantling can take place regionally (up to 50 km), whereas in the other scenarios it is assumed that the dismantling will take place in specialized recycling plants which will be more scarce on a European scale (up to 500 km). We include the different steps of the various end-of-life scenarios as well as a system expansion for the different (by-)products that are produced during recycling. The included (by-)products are glass wool, solar glass, silicon (metallurgical), silicon (solar grade) and silver.

Table 4.1 shows what data is used to compare the different end-of-life scenarios. Because part of the life-cycle inventory (LCI) refers to impact in energy usage and part to greenhouse gas emissions, a conversion factor is needed to get from kWh to kg CO_2-eq. In this study we use the greenhouse gas intensity of the Dutch electricity grid. The greenhouse gas intensity of Dutch electricity is 0,427 kg CO_2-eq/kWh (CO2emissiefactoren.nl). More details on the data used are in Appendix 1.

Table 4.1 Life cycle inventory (LCI) for the different recycling scenarios of PV panels. Data in italics are used in calculations. See Appendix 1 for more details on the data used for the calculations

Technology	**Process**	**Amount**	**Unit**	**Source**
Burning EVA, recovery of silicon by leaching, silver and copper by electrolysis #5	*Electricity consumption*	*50*	*kWh/t*	*LCI of current european pv recycling (Wambach et al., 2017)*
Burning EVA, recovery of silicon by leaching, silver and copper by electrolysis #5	Diesel	0.5	l/t	LCI of current european pv recycling (Wambach et al., 2017)
Burning EVA, recovery of silicon by leaching, silver and copper by electrolysis #5	Gas	10	m3/t	LCI of current european pv recycling (Wambach et al., 2017)
Mechanical treatment of metals #2	Electricity consumption	494	kWh/t	LCI of current european pv recycling (Wambach et al., 2017)
Thermal treatment (Delamination)	Electricity consumption	0.45	kWh/m2	Maani et al. 2020
Electrothermal heating (Delamination)	Electricity consumption	4.17	kWh/m2	Maani et al. 2020
Pyrolysis (Delamination)	*Electricity consumption*	*25*	*kWh/m2*	*Maani et al. 2020*
Shredding and Hammermilling	*Electricity consumption*	*2.2*	*kWh/m2*	*Maani et al. 2020*
Hot knife: Glass separation (6)	*Electricity consumption*	*48.01*	*kWh/t*	*Latunussa et al. 2016*
Hot knife: Cutting (8)	*Electricity consumption*	*0.25*	*kWh/t*	*Latunussa et al. 2016*
Hot knife: treatment	*Electricity consumption*	*56.76*	*kWh/t*	*Latunussa et al. 2016*
System expansion: Solar glass	Solar glass, low-iron {GLO}| market for | APOS, U	1.023165	kg CO_2-eq/kg	EcoInvent v3
System expansion: Silver	*Silver {GLO}| market for | APOS, U*	*497.7909*	*kg CO_2-eq/kg*	*EcoInvent v3.7.1*
System expansion: Silicon (m)	*Silicon, metallurgical grade {GLO}| market for | APOS, U*	*10.80895*	*kg CO_2-eq/kg*	*EcoInvent v3.7.1*
System expansion: Silicon (s)	*Silicon, solar grade {GLO}| market for | APOS, U*	*48.89594*	*kg CO_2-eq/kg*	*EcoInvent v3.7.1*
Energy recovery	*Waste incineration of glass/inert material, EU-27*	*-0.05443*	*kg CO_2-eq/kg*	*EcoInvent v3.7.1*
System expansion: Glass wool	Glass wool mat {CH}| production | APOS, U	1.270652	kg CO_2-eq/kg	EcoInvent v3

To determine the **circularity** of the end-of-life treatment of solar panels we use the circularity module of SSML. Tier 1 includes the question whether there are critical raw materials (CRM) in the waste stream and whether the demand for the resources is expected to grow in the future.

Tier two gives insight into the circularity based on three indicators:

- Recovery efficiency: The amount of useful resources that can be extracted from the residual material.
- Contribution to the market: the market share that can be supplied by recycling the material.
- Recyclability: The amount of material that can be recovered from the new application in the future.

The exact formulas can be found in Appendix Quik et al. (2019). To determine the circularity we include all the material that is used from the total solar panel:

- as grinding material/road scrap.
- the glass that ends up as glass wool.
- the recycling of solar glass.
- metallurgical Si and Ag.
- solar grade Si and Ag.
- aluminium.

4.2 Results

4.2.1 Environmental impact

In Figure 3.1 and Table 3.1 the five scenarios are described. Concerning the main material flows the scenarios can be are characterised. In all cases the aluminium frame is recycled to new aluminium.

- Scenario 1, baseline: all material, excluding the frame is shredded, used in as grinding material and ends up as road scrap.
- Scenario 2a: Glass is recycled into glass wool and metallurgical silicon and silver are recovered.
- Scenario 2b: Glass is recycled into new glass for solar panels and metallurgical silicon and silver are recovered.
- Scenario 3a: Glass is recycled into glass wool and metallurgical silicon and silver are recovered.
- Scenario 3b: Glass is recycled into new glass for solar panels and solar grade silicon and silver are recovered.

To assess the different scenarios for the environmental impact, the LCI presented in Table 4.1 was used. Details on the results can be found in Appendix 1. In Figure 4.1 and Figure 4.2 de results for the different scenarios are plotted. Figure 4.1 gives the total environmental impact (in CO_2-equivalents per panel) of each scenario, also including the impact of the production of the products not being part of the recycling process. In Figure 4.2 the impact of the recycling process and the saving of the emissions related to the saved materials are separately given, relative to scenario 1 (baseline scenario). The energy needed to make new solar glass from old solar glass was derived by using data for production of new solar glass corrected with a factor that comes from the difference of new packaging glass vs. packaging glass form recycled glass.

All recycling scenarios (scenario 2a, 2b, 3a, 3b) have a lower environmental impact compared to the baseline scenario (Figure 4.2). The pyrolysis scenario (scenario 3b) has the lowest environmental impact compared to the other recycling options. In the pyrolysis process, the solar glass is recovered and recycled to new solar glass, solar grade silicon is produced and silver is recovered.

Most important aspect of each scenario are the materials being saved in the recycling process. Products from primary (virgin) resources have a high environmental impact compared to products from recovered materials. Results show that it is environmentally sensible to try to recover solar grade silicon. There is also an environmental benefit of using glass waste for new solar glass in PV panels or for insulation material (glass wool). Based on the environmental impact recycling to solar grade glass (scenario 2b and 3b) has some advantage above recycling to glass wool.

The recycling processes themselves also have environmental impact. Recycling to glass wool (scenario 2a and 3 a) or to solar glass (scenario 2b and 3b) and pyrolysis (scenario 3b) have a relatively high environmental impact in the recycling process itself. The environmental impact of transport is in all scenarios low. This means that transport to central innovative recycling installations is sensible, because larger installations will be more efficient.

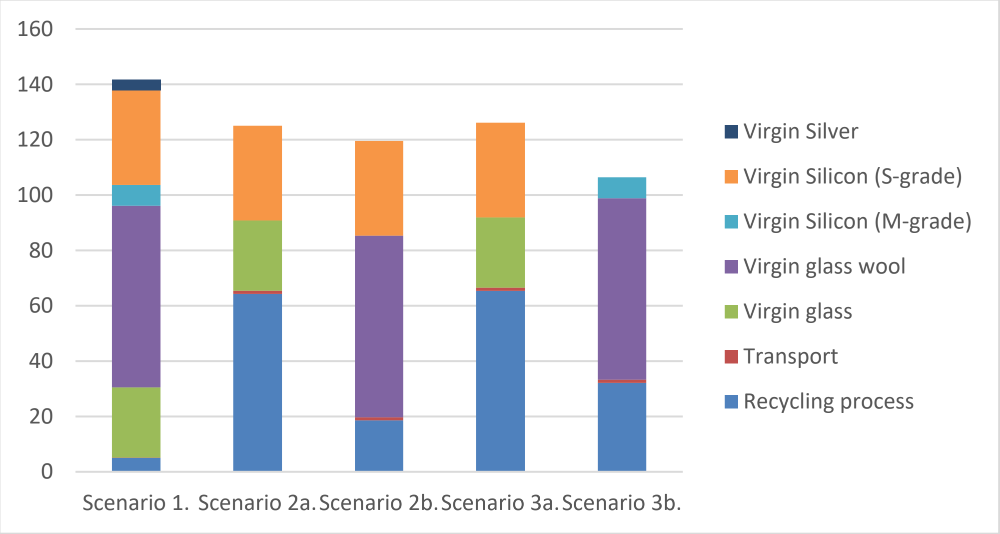

Figure 4.1 Environmental impact (kg CO_2-equivalents per solar panel of all end-of-life scenarios for solar panels. Different colours indicate the processes (transport and the recycling) and the production of products with (virgin) materials from the system expansion.

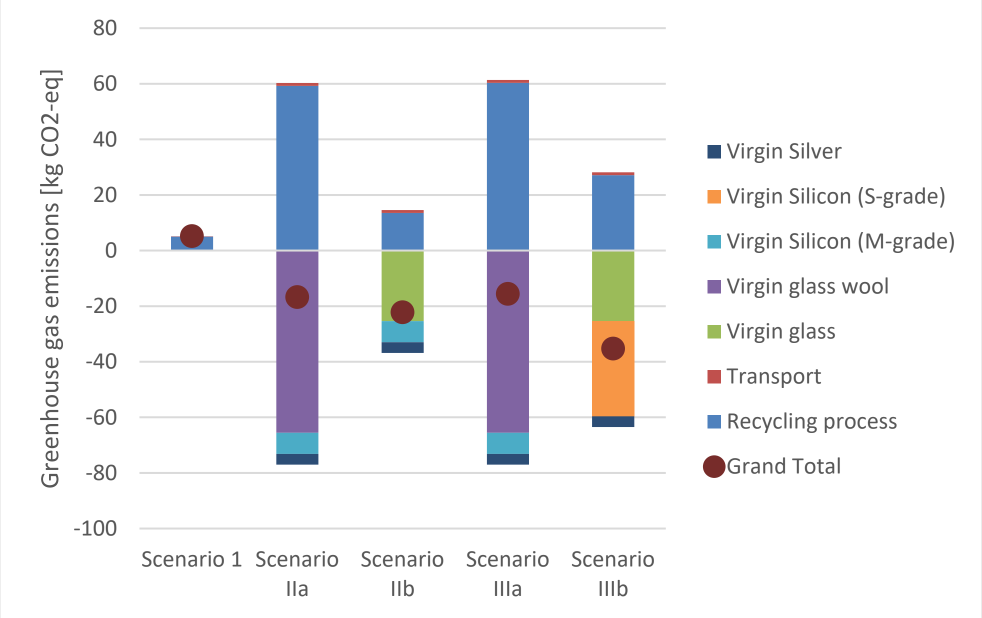

Figure 4.2 Relative environmental impact (kg CO_2-equivalents per solar panel) of different end-of-life scenarios of solar panels compared to scenario 1 (baseline scenario). Different colours indicate the different processes and products from virgin materials. The total of each scenario is indicated by brown dot.

4.2.2 *Circularity*

The module on circularity tier 1 (Quik et al, 2019) consists of two questions:

1. Does the recovered, recycled or reused material or product contain any of the EU critical raw materials (CRM)?
2. Is there a concern for material supply due to a significant increase in the demand for the source material?

The materials that can be found in the solar panels are: Silicon (Si), Silver (Ag), Copper (Cu), Tin (Sn), Lead (Pb). In the glass Antimony (Sb) can be found. Of these elements (solar grade) Silicon, Antimony and Copper are CRM in 2023 (EU, 2023)[16].
Regarding supply security, a significant increase for solar panels is expected, from 11GW installed in 2021 to 87,5GW installed in 2044 (TNO, 2022). This will have an effect on the supply security of the required resources.

To determine the tier 2 circularity indicators there are five different applications for the recovered materials that are included in the assessment:

- The aluminium frame that is recycled through aluminium recycling.
- The baseline scenario, where all other parts of the frame are used as grinding material and road scrap.
- Recycling of the glass into glass wool.
- Recycling of the glass into new solar glass.
- Metallurgical Si and Ag.
- Solar grade Si and Ag.

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[16] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023PC0160

The different recycling scenarios are a combination of these applications. Data about the composition of the solar panels is given in Table 2.1 For the recovery of silver and silicon there is need for 0.935kg of acid and caustic soda. We assume that there are no auxiliary materials needed for all other recycling processes. In appendix 2 the data on the circularity indicators are given.

The scenarios where the glass can be recycled to solar glass (scenario 2b and 3b) have the highest circularity value for the indicator efficiency and recyclability (Figure 4.3). This is caused by the fact that the glass is the heaviest part of the panel and makes up 70% of the weight. High quality recycling of solar glass to make new solar glass gives a high value to the circularity indicator **efficiency**. Aluminium recycling is assumed in all scenarios and is no distinguished feature between the different scenarios. High grade Si and Ag recycling has a low impact on the efficiency as the weight of Si and Ag present in solar panels is limited. Recycling of glass into glass wool can be done efficiently, but because it is a form of downcycling the efficiency score of this recycling technique is lower. Keeping solar glass in the same loop leads to more value retention (high transparency of the glass) and prevents the antimony in the glass to enter a product chain where its functionality is not needed.

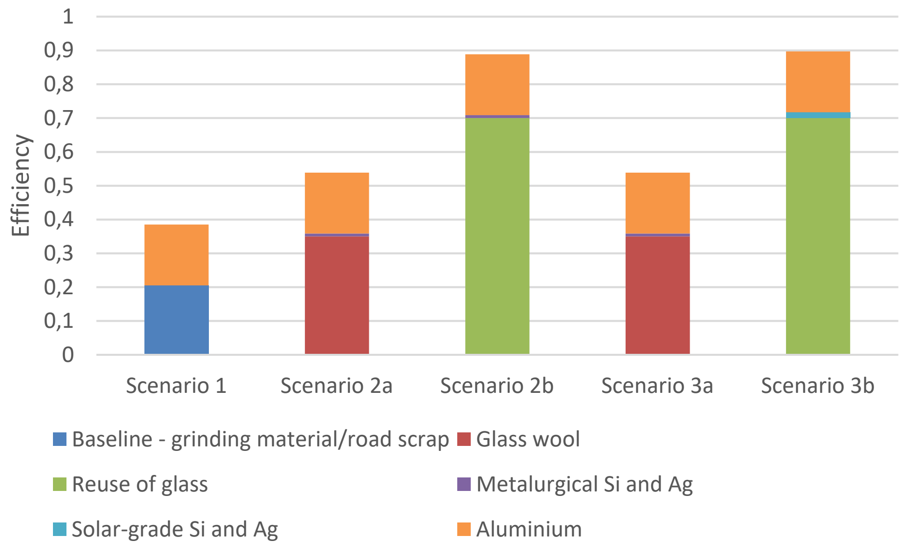


Figure 4.3 Circularity score for the indicator Efficiency for different end-of-life scenarios of solar panels, split by different materials that are recycled.

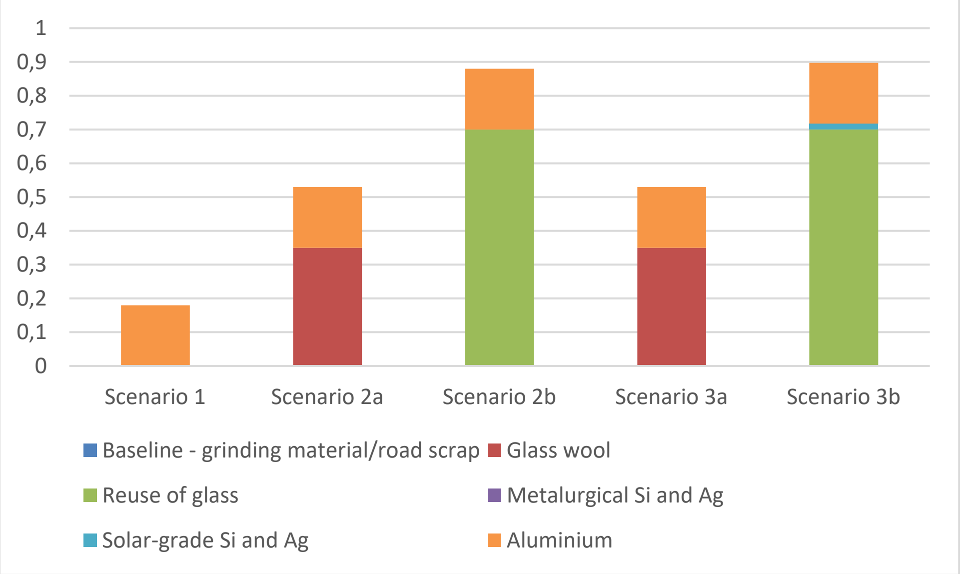


Figure 4.4 Circularity score for the indicator Recyclability for different end-of-life scenarios of solar panels, split by different materials that are recycled.

The **Recyclability** of the materials (after the second life stage) is highest in scenarios where the glass is applied in new solar panels (scenarios 2b and 3b). Recycling of old glass wool can be done, but this remains at a lower quality. We assume that the aluminium from the frame can be recycled without loss of quality in the next application as well. Recycling of old solar panels that have been shredded and end up in steel slag applied in road scrap to new products is nearly impossible, thus the recyclability of this option is lower compared to other scenarios.

The indicator **contribution** (to the market) of the different scenarios is difficult to determine due to lack of data available. Since we consider for 2045 a steady state scenario we estimate that the contribution of closed loop recycling can be close to 1 from that year onwards. To closed loop recycling options belong the reuse of the glass for new solar panels (scenario 2b and 3b) and recycling of solar-grade silicon and silver (scenario 3b). The contribution of road scrap from solar panels (scenario 1) is neglectable as many other materials are available as road scrap. The contribution to the production of glass wool is also expected to be low (scenario 2a and 2b), because of the large availability of other glass scrap.

4.3 Discussion environmental impact and circularity

We showed the applicability of the SSML framework on a case study where the data on the specific innovative recycling technologies is limited. There are some things to keep in mind when interpretating the results.

There were limited data available on the required auxiliary materials that are needed during the recycling process. As well as there was no data on material losses. This means that the circularity score is higher than when auxiliary materials and losses would be included.

All recycling techniques have a lower environmental impact compared to the baseline scenario (scenario 1). The differences in environmental impact between the innovative recycling techniques are however relatively small and there remains uncertainty about recycling specifics. The environmental impact data of recycling to metallurgic grade silicon was used for all scenarios, because no specific data are available on the recycling to solar grade silicon.
Data on the recycling of solar glass to new solar glass were derived from the production of flat glass, taking into account the lower demand of energy and resources than the primary production. For the production of glass wool data from the glass wool production from bottle glass was used. Because this is a state of the art process this bottle glass has an environmental burden. The EoL solar glass has no allocation of environmental burden, because it currently is a waste material.

SSML circularity tier 2 is a weight based calculation, this is the reason why the scenarios where glass can be applied in new PV panels score the highest. Recycling of Si and Ag have a lower impact on the circularity score because of the lower weight present in PV panels. Although the low impact on the circularity score, recovery of solar grade silicon is important due to the high environmental impact of the production of primary solar grade silicon. It is important to keep these differences in mind, when deciding what resources are important to recover.

The high environmental impact of virgin solar grade silicon shows that it is worthwhile to invest in technologies to recycle solar grade silicon. Pyrolysis combined with more complex chemistry is the only assessed technology that can recover solar grade silicon (see paragraph 3.6). Because the environmental impact seems lower than the production of virgin solar grade silicon, further development of this recycling technique is important to make it practically feasible, including the gathering of more environmental impact data to make advanced comparisons.

A tier 3 with a full LCA could be considered, because of the limited differences between the innovative recycling technologies. In particular ex ante LCA (Florin et al., 2023) can help developing new products and technologies. Still, because the limited data availability it is probably too early to perform this.

5 Module on substances of concern (ZZS)

5.1 Introduction to ZZS module and regulations

In the ZZS module of the SSML framework, safety is assessed based on the presence of the Dutch Substances of Very High Concern (ZZS). The basis for this module is the Dutch policy on hazardous chemicals, which particularly focuses on Dutch substances of very high concern: the so-called ZZS, in Dutch: Zeer Zorgwekkende Stoffen.

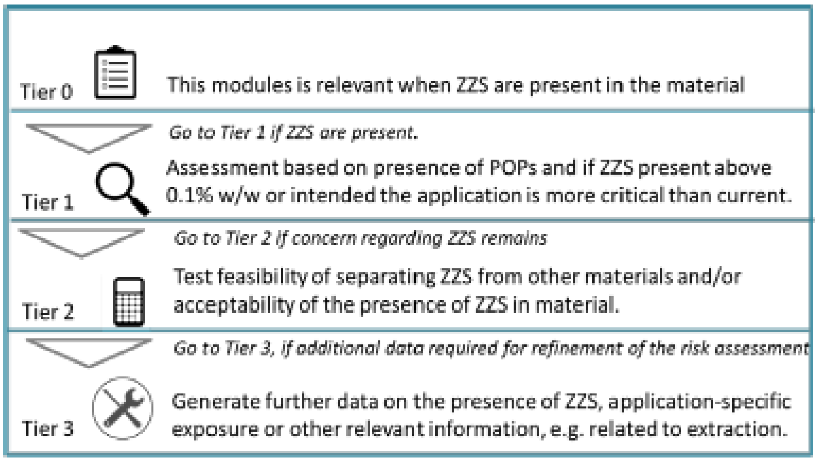
In this report the scope of the module is extended; we included also other substances of concern (SoC) in a material flow or waste stream.

The first tier assesses the material flow based on a generic ZZS limit value of 0.1% w/w, taking into account the specific regulation in place for POPs. In Tier 2, the assessment focuses in more detail on the feasibility of separation of ZZS from the material to be reused by recycling and the acceptability of the presence of ZZS in the material, taking the new application(s) into account. The third tier forms an additional step in the process, which is only needed when the feasibility or acceptability of ZZS in the material cannot be assessed yet and additional generation of data should be considered.

Within the Netherlands, national policy on hazardous chemicals is particularly focused on ZZS. These substances are of very high concern since they can seriously harm human health and the environment. The ZZS cover a much broader range than the substances of very high concern (SVHC) under REACH. ZZS are identified based on the same hazard criteria as SVHC (i.e. REACH article 57 (1907/2006)). Substances meeting one of the following criteria are considered as ZZS:

- Carcinogenic category 1A or 1B according to Regulation 1272/2008/EC.
- Mutagenic category 1A or 1B according to Regulation 1272/2008/EC.
- Toxic for reproduction category 1A or 1B according to Regulation 1272/2008/EC.
- Persistent, Bioaccumulative and Toxic in accordance with the criteria set out in REACH Annex XIII.
- Very Persistent and Very Bioaccumulative in accordance with the criteria set out in REACH Annex XIII.
- Substances for which there is scientific evidence of probable serious effects to human health or the environment which give rise to an equivalent level of concern to the criteria listed above.

For ease of reference, a non-limitative list is compiled by RIVM, which is updated twice a year. For the definition of substances of concern (SoC), CLP (Classification, Labelling and Packaging) is added. CLP is a European regulation that establishes legally binding hazard identification and classification rules, and sets requirements for the labelling of chemicals and products before placing them on the market.



This modules is relevant when ZZS are present in the material

Go to Tier 1 if ZZS are present.

Assessment based on presence of POPs and if ZZS present above 0.1% w/w or intended the application is more critical than current.

Go to Tier 2 if concern regarding ZZS remains

Test feasibility of separating ZZS from other materials and/or acceptability of the presence of ZZS in material.

Go to Tier 3, if additional data required for refinement of the risk assessment

Generate further data on the presence of ZZS, application-specific exposure or other relevant information, e.g. related to extraction.

Figure 5.1 Schematic overview of tiered workflow ZZS module (Quik et al., 2019)

The ZZS-module of SSML is largely identical to the LAP3 methodology, the current policy framework for waste in the Netherlands (IenW, 2019). LAP3 uses a risk-based approach to determine the cases in which recovery and re-use of waste containing ZZS may be permitted.
When waste materials contain ZZS substances which are already regulated within the POP- or REACH-Regulation, that policy is applicable. Otherwise a risk assessment is required to verify that materials can be recycled into new products without causing unacceptable exposure of humans and environment to harmful chemicals (ZZS) during use, after use, and in the next application. Both the ZZS module and the LAP 3 policy framework use a generic concentration limit of 0.1 mass% in case of the presence of ZZS for the risk analysis.

5.2 Results of the current module on substances of concern

5.2.1 Tier 1: presence of ZZS

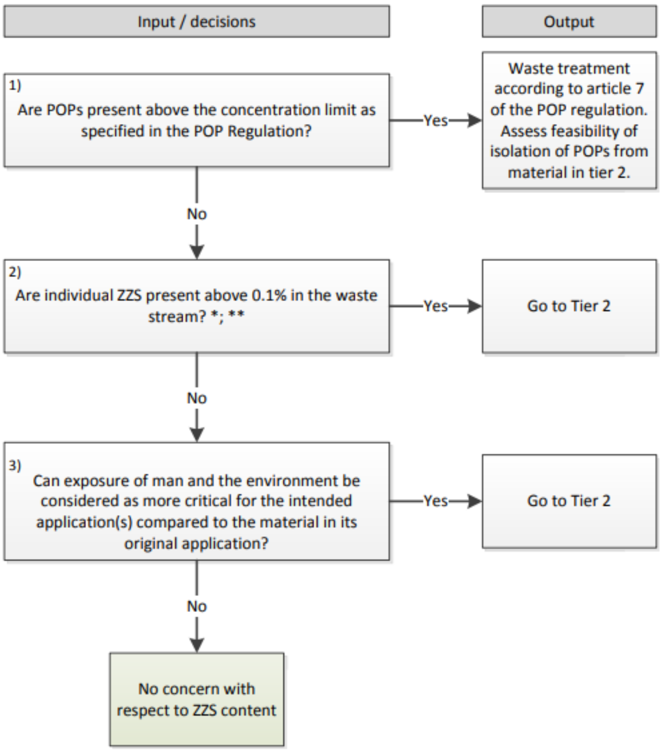


Figure 5.2 Tier 1 of the ZZS-module (Quik et al., 2019)

1) Are POPs present above the concentration limit as included in Annex IV of the POP regulation?
The first solar panels are introduced in the Dutch market in the nineties. Brominated flame retardants have been long used as additives or reactive flame retardants since the 1980s in the manufacture of Electrical and Electronic equipment (EEE), and although their application has been greatly reduced since 2009 after being listed and are thus restricted by the Stockholm Convention, they continue to be found in WEEE at high concentrations (Chaine et al., 2022)[17].
Brominated flame retardants have been used in (plastic) wire and cable insulation. As the cables are removed prior to recycling we current recycling practices apply sorting processes to remove the brominated plastics and treat these fractions according to the POP regulation.

The answer to the first question in tier 1 of the module is therefore: (possibly) “yes” for the cables and “no” for the solar panels.

2) Are individual ZZS present above 0.1% in the waste stream or above the substance specific concentration limits?
Lead (Pb) is a ZZS. Right now, most PV manufacturers use lead as soldering material. There are different techniques to connect solar cells.

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[17] https://www.mdpi.com/1660-4601/19/2/766

An old technology is to connect the tabs (90% copper and 10% silver) with silver solder. New techniques no longer use tabs, but use silver glue or soldering ribbons. Most of the ribbon is made of copper as the substrate, with 67% tin and 37% lead as the coating on it.[18] The coating melts during soldering and contacts with the silver. Alternatives for lead are available but not yet widely applied for economic reasons.
The European Union's Restriction of Hazardous Substances Directive (RoHS) restricts the use of lead in electrical and electronic equipment. However PV modules has had RoHS exempt status, since 2011.

The amount of lead in a solar panel is 12 gram (See table 2.1). This is below the concentration limit of 0.1% of lead in the complete solar panel. However, the solar panel waste is composed of different materials. If the concentration threshold would be applied to the solar cells, or the soldering material, the threshold of 0.1% is exceeded, therefore question 2 of Tier 1 is answered with “yes”.

3) Can exposure of humans and the environment be considered as more critical for the intended application(s) compared to the material in its original application?
In the crystalline solar module itself, the lead is bound so that it cannot leach into the environment under normal circumstances. In the current method of recycling, the glass and solar cells are used as abrasive and added to metal scrap. When it is applied on or in the soil (scenario 1) leaching into the environment is possible.

For the delamination recycling scenarios (2a and 2b) we do not assume crushing into smaller fragments takes place before recovery of the glass. However, if such a process would be applied, lead can enter the glass fraction and is thus contained in the recycled glass. Lead is an unwanted contaminant in food grade glass, however there are also other reasons why solar glass is not suitable for food packaging (such as antimony content). This scenario is therefore not considered as realistic and also not included in our analysis.

The technically feasible applications for recycled solar panel glass are glass wool, foam glass and new solar glass. The potential contamination of glass with lead during recycling should be researched when crushing is being considered. Whether these applications are more critical depends on specific conditions how the glass wool and foam glass will used. In case foam glass is used for construction of roads, potential exposure to soil is possible. Therefore we would recommend to measure and monitor lead concentration in recovered glass from solar panel recycling.

Fate of lead during recycling processes
During metal recycling, lead can end up in the dust, bottom ashes, fly ashes (or in the metal alloy). Environmental legislation is in place which specify the concentration at which this waste must be treated and how. In scenario (2a and 2b), the modules are delaminated by either hot knife or waterjet and after this process the solar cells, EVA encapsulant and backsheet are incinerated. The lead is essentially bound up in the

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[18] A lead-free future for solar PV – pv magazine International (pv-magazine.com)

encapsulant with the solar cells. The recycling process will need to apply filtering techniques to avoid emissions of lead during incineration.
In case of incineration of the solar cells and backsheet (scenario 2a, 2b and 4) or complete incineration (scenario 3a) lead ends up in filter residue, fly ash or bottom ash. Environmental legislation (e.g. LAP 3 amongst others) is in place which specifies the concentration at which this waste must be treated and how.

During pyrolysis, lead will either enter the gaseous, liquid or inert phase and the lead concentration should be monitored in those outputs to verify if its concentration is below the legal threshold.
In case the copper-aluminium fraction could be removed during recycling, lead can be filtered during copper recycling. However, it is questionable if removing this fraction is practically and/or economically feasible.

The lead-containing solder can in the future be replaced with alternatives materials or design solutions (to replace the soldering process) (TNO, 2023).

5.3 Other substances of concern (no ZZS)

5.3.1 *Antimony in the glass*

Antimony (Sb) has a self-classification as CMR. CMR substances are chemicals substances that are carcinogenic, mutagenic or toxic to reproduction. Antimony is self-classified as category 1A for reproductive toxicity. Self-classification aims to determine whether a chemical substance or mixture has physical, health and/or environmental hazards and to properly communicate these hazards with appropriate labelling in the supply chain when the product is placed on the market. The classification is not (yet) harmonised and therefore antimony is not considered a ZZS. Due to its environmental toxicity, environmental risk limits for water and soil are determined.[19]

Antimony is used in solar panel glass to improve stability of the solar performance of the glass upon exposure to ultraviolet radiation and/or sunlight. The concentration of antimony in textured glass is not well known and variable (European Solar Industry alliance, 2023). According to a study in which 2 samples of textured solar glass were analysed, the concentration ranges from 0.13 to 0.29%[20].
There are manufacturers which produce antimony free glass that can be used in production of PV modules. Antimony is not used in the EU glass production as it presents health risks for workers. However, the use of antimony free solar glass is not yet significant, most solar glass is produced in China (European Solar Industry alliance, 2023). As there is currently no regulation on use of solar panel glass, manufacturers can produce and market both antimony free as well as antimony containing solar panel glass. This represents a challenge for glass recyclers as antimony lead to emissions or impact the quality of the recycled products (European Solar Industry alliance, 2023).

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[19] https://rvszoeksysteem.rivm.nl/stof/detail/273
[20] https://www.eqmagpro.com/wp-content/uploads/2019/03/DraftBluePrintAntimony.pdf

It is technically feasible to reuse or recycle the glass from the PV panels; however, it is not practiced at present because of high operating costs and low profitability (TNO, 2023).
Antimony containing glass should not get mixed with normal glasses (such as food packaging and float glass) for recycling, as it may contaminate other glass waste streams. In case solar glass is used for the production of foam glass (which can applied as foundation material for roads), the leaching behaviour of antimony should be verified.

5.3.2 *Fluorinated chemicals in the backsheet*

Fluoropolymers in PV modules are largely made of PVDF (polyvinylidene fluoride) or PVF (polyvinylfluoride) also known under trade names like Kynar® and Tedlar® respectively (Aryan, 2017). The presence of these fluoropolymers makes it hardly impossible to thermally degrade (incineration or pyrolysis) or to recycle the polymeric backsheet material present in PV modules (Aryan, 2017).
Alternatives for PFAS are available such as PFAS free and recyclable backsheets or replacement of the backsheet by an extra layer of glass. These alternatives are not widely applied yet (Solar Magazine, 2021), the main reasons are the high demands and conservative solar panel industry (Solar Magazine, 2021).

Baseline scenario
In the current practice of shredding the solar panels, PFAS in the backsheet might degrade only due to high temperatures during steel recycling.
According to a literature review by RIVM (Bakker, 2021), certain by-products (short-chain PFC's) resulting from combustion of PFASs (like fluoropolymers) are thermally very stable and temperatures of 1400 degrees Celsius or higher may be required to reach a high degree of thermal degradation. This is not yet validated with measurement though. The processing temperature of steel recycling is >1500 degrees Celsius, however the formation and emission pathways of PFAS degradation products resulting from steel recycling have not been studied for this analysis. Currently relatively low amounts of End-of-Life solar panels are processed this way (Stichting Open, 2023).

Incineration
Incineration can be applied after delamination (scenario 2a and 2b) to enable the recycling of the solar cells, or incineration can be used as a technique to delaminate end-of-life solar panels (scenario 3a).

During the incineration process, PFAS are degraded to shorter chain PFAS. Thermal degradation of fluoropolymers may lead to release of toxic fluorinated compounds (e.g. hydrogen fluoride, fluoroalkanes, etc.) (Aryan, 2017). Highly potent greenhouse gases may also be formed during combustion (Bakker et al., 2021). Therefore, special care has to be taken when incinerating PV panels and/or PV backsheets containing PVF or PVDF such as treatment in dedicated incineration plants (Aryan, 2017).

In addition to the expected presence in flue gases, PFAS can occur in slag and in bottom and fly ash, the residues that remain after waste incineration (Bakker et al., 2021). Depending on the method of storage, as well as the processing of these by-products in useful applications such as building materials, there is a risk of spreading PFAS. It is important to know to what extent PFAS can be expected in bottom and fly ash and whether there is a risk of spreading to the environment.

In order to estimate the emissions to air for fluorinated backsheet, the Fraunhofer Institute conducted experimental trials. The incineration experiments show a complete release of fluorine in the gas phase measured at 750 °C. The released fluorine amounts in the gas phase equalled to the actual fluorine content measured in the ultimate analysis which was conducted prior to incineration experiments. As explained for the baseline scenario certain by-products (short-chain PFC's) resulting from combustion of PFASs (like fluoropolymers) are thermally very stable temperatures of 1400 degrees Celsius or higher may be required to reach a high degree of thermal degradation.

Pyrolysis
Pyrolysis of solar panels with fluorinated backsheet seems to be unfeasible both from an economic and the technical point-of-view in finding suitable pyrolysis product applications. The pyrolysis oil and pyrolysis char fractions obtained are also likely to contain high amounts of fluorine (in the form of halogenated hydrocarbons & aromatics), which renders their posterior application for energy recovery unsuitable due to (environmental) toxicity hazards (Aryan, 2017). The treatment of the hydrogen fluoride present in the pyrolysis gas would demand large amounts of alkaline reagent and water, as well as a large effort for treating the effluent and in handling the resultant solid waste (Calcium fluoride) (Aryan, 2017).

6 Integration and discussion

Referring to the research questions in chapter 1, the main results are described and discussed in this chapter.

6.1 Material flows

The expected quantity of residual flows of the main type of solar panel (crystalline silicon panels) in the Netherlands is expected to increase strongly after 2035 (from 10,000 to 230,000 ton in 2045). With these growing number of EoL solar panels it is highly important to have safe and sustainable recycling processes operational for the materials coming from these type of panels.

6.2 Recycling technologies and scenarios

To compare recycling processes of solar panels we first have been looking into the question what processing methods are available for the processing of (Dutch) solar panels.
Recycling methods of solar panels are under development. In the Netherlands, recycling of solar panels is currently not operational. Innovative recycling technologies, in particular thermal and mechanical delamination techniques to separate the glass and the solar cells, are still in a pilot phase and could become operational on an European scale in several years.
For these technologies we defined four future recycling scenarios with a combination on delamination and recycling technologies. Based on the results in the previous chapters the advantages and disadvantages of the five scenarios with recycling methods are presented and discussed.

Because of the lack of information we could not include chemical delamination. According to Deng et al. (2019) and Maani et al. (2020), chemical delamination is expected to have a higher environmental impact because of the chemicals that have to be used. When it is more clear which chemicals are used for the full scale techniques they could be included in the comparison of recycling scenarios.
Reuse of the whole glass pane was not defined, because it is expected that weathered glass will not be accepted. From the energetic point of view this nevertheless would be very positive.
Because currently the amount of EoL solar panels are still low, a realistic scenario would be to remove solar cells from the solar glass and first only recycle the solar glass and temporarily store the scrap with solar cells. Recycling of the solar cell could be done in a later stage when that technology is further developed.

6.3 Overview of results

Table 6.1 gives an overview of the results of the three modules that were applied for the scenarios.

Table 6.1 Outcome of the three modules for each recycling scenario. Individual outcomes

Scenario	**Substances of concern (ZZS and SoC)**	**Circularity indicators**	**Environ-mental impact [kg CO_2-eq. per panel]**	**Technical expectation**
1 Baseline scenario (downcycling)	Pb (conc<0.1%) and Sb in panels will end up in steel slag, fly ash, metal alloy or other waste stream (scrubber)	E= 0.39 C= near 0 for road scrap R=0.18	141	Current practice
2a Mechanical recycling with Hotknife + Incineration	Pb in solar cells ends in bottom ash or fly ash; Sb in glass wool	E=0.54 C= low for glass wool R=0.53	125	Realistic scenario
2b Mechanical recycling with Waterjet+ incineration	Pb in solar cells ends in bottom ash or fly ash; Sb in new solar glass	E=0.89 C= high for solar glass R=0.88	119	Realistic ambitious scenario
3a Thermal: incineration whole panel	Pb in solar cells ends in bottom ash or fly ash. Sb in glass wool	E=0.54 C= low for glass wool R=0.53	125	Realistic long term
3b Thermal: pyrolysis	Sb in new solar glass, fate of Pb not clear	E=0.90 C= high for solar glass R=0.89	106	Ambitious scenario long term (PFAS-free backsheet only)

The results show that with innovative recycling (as described in future scenarios 2a+b and 3a+b) the material circularity can be substantially improved. All recycling techniques have a lower environmental impact compared to the baseline scenario. The differences in environmental impact between the four recycling scenarios are relatively small. As stated in chapter 4.3 the amount of energy needed for recycling of solar glass to glass wool or new solar glass could be calculated (as CO_2-equivalents), but the uncertainties are not quantified. Specific information on the environmental impact of the recycling process of solar cells to solar grade silicon was not available. Nevertheless the environmental impact of scenario 3b (thermal incineration) is lower than other future recycling options, because solar grade silicon can be recovered. This costs energy, but saves the energy intensive production of virgin solar grade silicon (for which data are available).

The circularity indicators efficiency and recyclability should indicate what the preferred scenarios are. The recycling of solar glass to new solar glass has higher indicator values than recycling to glass wool (scenario 2a and 3a), because a quality factor is included. Keeping solar glass in the same loop leads to more value retention and prevents the antimony in the glass to enter a product chain where its functionality is not needed.

The recycling of silicon in solar cells to solar grade silicon (scenario 3b) only shows a small extra contribution to recycling efficiency (0.90 to 0.89), because off the higher quality of solar grade silicon compared to metallurgic silicon. Because of the lower environmental impact (CO_2-equivalents) the recycling to solar grade is strongly preferred.

As solar panels are constructed from materials that may contain ZZS and SoC, each recycling process should consider their presence and avoid emissions to the environment. It is expected that processes like crushing (baseline scenario) result in dust formation and potential release of ZZS (PFAS and Pb) and SoC (Sb), while during delamination processes (scenario 2a and 2b) dust formation can be prevented more easily. Additionally ZZS and SoC might leach to soil and groundwater when recovered glass is used as road foundation.

All the recycling scenarios, including the baseline scenario, include a thermal treatment step of the backsheet. Due to the potential presence of PFAS in the backsheet, emissions of the short chain PFAS and/or highly potent greenhouse gasses can occur depending on the incineration conditions. In the baseline scenario, crushed glass of solar panels and metal is applied in a high furnace (steel production). The process occurs at high temperature which could lead to destruction of PFAS, however this needs more research. A mass balance is needed to calculate the differences between the different techniques when it comes to the fate of the fluor atoms. Pyrolysis of solar panels (without prior delamination) is likely not feasible as long fluorinated backsheets are used, due to the high corrosivity of the reaction products and the contamination of the pyrolysis oil with fluorinated compounds. The problems with fluoropolymers in the backsheet can be circumvented if the backsheet is removed prior to the pyrolysis process, using e.g. hot-knife or water jet technology (TNO, 2022). PFAS-free backsheets are available and can be a future solution for making pyrolysis a feasible recycling process.

6.4 Substances of concern in EoL solar panels

The first question was which ZZS or substances of concern (SoC) can hinder recycling into new products or materials from the perspective of human health and of legal requirements. During recycling, emissions to air, soil and exposure to workers (occupational health) need to be controlled and managed. Lead is a ZZS and should be considered according to Dutch waste policy (LAP3). Risk analysis is obligatory for the recycling and application of recycled materials in case the (waste) materials contain a ZZS > 0.1%. Solar panels contain 12 grams of lead in a complete panel of 20 kg, which is just below the 0.1% concentration limit. The concentration of lead in the materials áfter removal of the glass, and in the homogeneous material (soldering paste) is >0.1%.

We did not identify any indication that lead can be removed mechanically during dismantling. However, chemical methods may be applied to recover (scarce) metals from the ashes after incineration of the solar cells, including lead. Lead that remains in the sludge after recovery of metals will be landfilled. In the baseline scenario the lead will end in the road foundation. A structural solution is replacing of lead-containing solder by alternative materials or a design without the soldering process.

Antimony in the solar glass is not defined as a ZZS. It is still a substance of concern, because it is (self-classified) as reproductive toxic and environmental risk limits (ERLs) have been determined to serve as scientific background to set environmental quality standards in the Netherlands.

The second and third question was: Can substances of concern (SoC) be separated from the materials using the available processing methods? And if not, what is the risk of human exposure or leaching into the environment? As most of the solar panels contain PFAS in the backsheet, emissions of PFAS to air and/or to soil (via application of bottom or fly ashes) should be monitored and controlled for each recycling technique.
The current recycling method of crushing the glass including solar cells includes no separation of the SoC of *lead* in the soldering material and *antimony* in the glass. When solar panels end up in steel slag that is applied as road aggregate, metals can leach to the subsurface.

The fate of *antimony* contained in the solar glass depends on the next application. Currently it ends up in the steel slag and emissions to the environment are possible but regulated in soil protection legislation (in Dutch: Besluit bodemkwaliteit). The amount of solar glass that is being treated is still relatively small.
Recycling solar glass into new solar glass is technically feasible. Other applications are also examined such as recycling solar glass into glass fibres, glass foam or glass wool. A risk assessment around antimony is recommended in case recycled solar glass is used for applications which may lead to environmental exposure, such as foam glass as foundation material. For other applications, additional information is required regarding potential exposure routes to determine potential exposure to human health and environment.

Depending on the incineration temperature and conditions PFAS are emitted to air during incineration and/or end up in bottom/ fly ashes.
In the baseline scenario, the processing temperature of steel recycling is >1500 degrees Celsius, which might destroy the PFAS. However the formation and emission pathways of PFAS degradation products resulting from steel recycling have not been studied for this analysis.

In the recycling scenarios (2a, 2b, 3a), it is assumed that incineration takes places in a waste incinerator specialized in treating end-of-life solar panels. According to a literature review by RIVM (Bakker, 2021), certain by-products (short-chain PFC's) resulting from combustion of PFASs (like fluoropolymers) are thermally very stable and temperatures of 1400 degrees Celsius or higher may be required to reach a high degree of thermal degradation.
As incineration of solar panel (waste) is not practiced yet, it requires more research to determine the effectiveness of the destruction of PFAS and the cleaning of the flue gases.

In the pyrolysis scenario (3b) PFAS could end up in the oil and gas phase. Because fluor from PFAS can react to corrosive hydrogen fluoride (HF), this technology can only be applied to PFAS-free backsheets. These solar panels are available, but most EoL-panels still contain PFAS backsheets.

6.5 Circularity and environmental impact

Critical Raw Materials. In the EoL flow of solar panels the critical raw materials (CRM) (solar grade) silicon, antimony and copper are present. The silicon is in the solar cells, being 3.65% of the panel. the Antimony is present in the glass with a content of 0.01-1%, copper is present in the cables and connectors with a content of almost 1%. Therefore it is important to recover these substances.

Circularity. As shown in chapter 4 there is large difference between the current recycling method and the innovative recycling technologies under development. The differences in the circularity indicator '*Recycling efficiency'* depend also on the value of the new application: when the glass is recycled to new solar glass quality, the quality factor is 1; for the production of glass wool the quality factor is set to 0.5. When solar glass is used for producing glass wool, the presence of Antimony is not needed and leads to less value retention.
The recycling of the silicon to solar grade silicon hardly contributes to a higher Efficiency indicator, because it is mass-based. This also applies for silver and silicon. Nevertheless, the environmental impact calculation shows the advantage of recycling of silicon due to the high CO_2-impact of the production of virgin solar grade silicon.

Uncertainties in energy use. The energy data are based on the available data in databases and literature. For technology still under development, data on the specific processes is hardly available. Ex ante LCA in a tier 3 analysis (Florin et al., 2023) can help develop new products and technologies. Still, because of the limited data availability that effort is probably too early. In addition, developments in the recycling processes can lead to changes in the climate impact. A source of uncertainty for the climate impact is also the energy mix used for production of new materials and for the recycling process. Still, as long as there is a shortage of green energy, the focus should be minimizing the energy use in all processes.

Results of other studies. Deng et al. (2019) refers to several studies that compared different type of recycling methods with incineration and landfilling. The results of Lunardi et al. (2018) indicated that upcycling can achieve a lower environmental impact in all categories (i.e. human health, ecosystem and resources), confirming the necessity to recycle and reuse the raw materials via high-value recycling processes. Duflou et al., (2018) presented a comparative assessment for three recycling treatments: glass recycling, thermal delamination and mechanical cutting. They showed that thermal and mechanical cutting approaches reduced global warming potential by 40% and 70%, respectively. In general, from an environment perspective, recycling is preferred over downcycling as is the current practise. Deng et al. (2019) also concludes that it is still difficult to distinguish between different recycling options.

Maani et al. (2020) also compared c-Si recycling to CdTe recycling techniques. It was revealed that delamination methods, specifically those that utilized electricity only (thermal treatments and shredding and hammermilling), results were very similar for the two technologies. However, for delamination techniques that utilize chemicals it was found that CdTe recycling produced significantly less impacts as compared to c-Si.

7 Conclusions and recommendations

7.1 Conclusions

The identified future scenarios for recycling of solar panels are more circular and have a lower environmental impact than the baseline scenario (see paragraph 3.2). Recycling of solar glass to new solar glass (scenario 2b and 3b) has a higher circularity score and prevents the substance of concern antimony in the glass to leach into the environment on the long term. Pyrolysis of the solar cells and encapsulation layer (EVA), recovering of solar grade silicon and solar glass (scenario 3b), is identified as the recycling technology with the lowest *environmental impact.* A precondition for pyrolysis though, is the use of PFAS-free backsheets. However, because of uncertainties in the estimated energy demand, differences between the future recycling technologies are relatively small compared to the difference between these options and the baseline scenario). There are still uncertainties estimated energy demand of the future recycling technologies. When these technologies are further developed (from pilot scale to full scale) it is expected that more data will be available possible for new calculations

Glass recycling to solar glass and recovery of silicon from solar cells are important innovations in recycling that contribute to *circularity* and reduce climate impact of solar panels. Delamination of solar cells from the solar glass contributes to a cleaner glass fraction and opens possibilities for high value recycling.

The *Critical raw materials (CRM)* solar grade silicon (Si), copper (Cu) and antimony (Sb) are present in solar panels and should be recovered. Silver and copper can be recovered with the technologies included in the scenarios. Lead (Pb) could also be recovered during copper recycling. but this too unsure to be part of the scenarios.

Some *substances of concern* are present in solar panels. Lead belongs to the group of ZZS and should be removed when recycling the solar panels. With respect to the total mass of the solar panel the concentrations of lead are lower than 0.1%; with respect to the solar cells it can be above 0.1%. During recycling lead might end up in the glass, dust or bottom ashes. Other substances of concern are antimony and PFAS. Antimony is not a ZZS, it is a substance of concern because it is self-classified as " known human reproductive toxicant (1A) and existing regulations for exposure to the environment. Therefore it can be concluded that glass at least needs to stay in a closed loop recycling or is has to be substituted. The PFAS in the backsheet are fluoropolymers, PVDF or PVF. From the fluorine containing backsheets, PFAS can be emitted to air during incineration of the EVA encapsulation layer and backsheet. This limits the possible recycling scenarios (pyrolysis of backsheets with PFAS-polymers is not feasible).

7.2 Recommendations

Recycling methods

First, concerning the recycling processes for EoL crystalline silicon panels we recommend to further develop and optimise delamination technology. This will make it possible to recycle clean solar glass to new solar glass.

Second, we recommend to further develop recycling technologies for the recycling of solar cells to this high quality solar grade silicon, in order to reduce the energy demand of this silicon extraction.

Concerning the current recycling of Dutch panels outside the Netherlands it should be considered to stop shredding the solar panels to glass cullet. It would be advisable to temporarily store the panels until delamination techniques will become available. This can prevent downcycling. Storage will be possible as long as the amount of panels is relatively small.

We recommend to generate more data on the energy demand of (full scale) recycling processes, e.g. the recycling of consumption glass to glass wool. On a pilots scale these data are still more uncertain.

Substances of concern

With regard to potential risks of ZZS and other substances of concern the following topics need to be considered during the development of recycling processes:

- Potential exposure to workers need to be reviewed and appropriate measures need to be taken.
- Generation of dust and emissions to the environment during dismantling and crushing need to be avoided.
- The fate of lead during recycling should be considered and potential emissions to air and soil avoided.
- Presence and risks of exposure of antimony should be further researched when determining new applications for solar glass, (i.e. recycling into foam glass for foundation material).
- More research is necessary to understand to which extent emissions of PFAS can occur as a result of (future) solar panel recycling processes.
    - More studies on the incineration of the backsheet with fluoropolymers on the destruction of PFAS is needed.
    - Standardisation of measurements of the emission concentration of PFAS in emitted flue gases of (dedicated PV waste) incineration plants is required.

Design-for-recycling

The current design of solar panels is not yet optimized for recycling. The use of EVA as encapsulant makes the separation of materials difficult. The development of other encapsulant materials is required to enable easier dismantling. It is recommend to stimulate this development.

Concerning substances of concern, substitution is the preferred way to avoid risks in the entire life cycle. For antimony, lead and PFAS-polymer containing backsheets, alternatives are already available in the market but not widely applied yet.

Policy measures (such as the review of the ROHS directive and the REACH restriction) can accelerate the transition to safer alternatives.

Regarding antimony, alternative manufacturing methods exist to replace antimony. At this moment the use of antimony containing solar glass could be considered in case of closed loop recycling. Measures to keep track of the antimony content in solar glass are recommended to ensure efficient recycling and avoid contamination of other glass waste streams.

7.3 Reflection on the methodology

The circularity tier 2 module is a weight based assessment, this means that heavier materials determine the outcome of the calculated circularity scores. However, the value of the silver and silicon is higher than the value of the glass or aluminium. It might be worthwhile to focus more on the recovery of solar grade silicon, even if this might be detrimental to the recovery of glass. This means that on one hand the environmental impact estimation has a higher value compared to circularity indicators based on weight, where on the other hand circularity indicators are more transparent and easy to calculate.

The main focus of the module on ZZS is the presence of ZZS in EoL products and the potential concentrations in secondary resources and new products. For some compounds also emissions to air and water during recycling are important pathways to take into account. It is crucial to understand the fate of substances of concern to assess potential exposure and risks. Therefore, a next step in the development of SSML could be to draft a guidance on how to verify potential exposure to chemicals during recycling. The potential PFAS emissions, originating from the incineration of fluoropolymers, and the presence of lead stress the importance to also focus on the total mass balance of ZZS in the recycling process.

Applying SSML on innovative recycling processes gives the opportunity to show the advantages and disadvantages of different future recycling scenarios in a relatively easy way. Identifying the potential (most realistic) future scenarios and data for these scenarios is crucial for the comparison. Although a complete LCA or multicyclic LCA could give more detail, SSML is a screening method making it possible to identify the most important aspects and make these transparent for recycling technology for which data are scarce because it is still in development. Still, point of attention is that information of full scale new technological developments could lead to adjusted conclusions.

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Appendix 1 Environmental impact calculation

Modelling approach

As is common for Life Cycle Assessment this rapid assessment has been performed using a mix of fore- and background data. The foreground data consists mainly of process parameters required to compile the Life Cycle Inventory for the processing options. These originate from a report by the International Energy Agency's Photovoltaics Power Systems Programme IEA-PVPS task 12 (Wambach, Heath & Libby, 2017), and two publications on solar panel recycling by Maani et al. (2020) and Latunussa et al. (2016). An overview of the aggregated data can be found in table 4.1.

The background data relies on the ecoinvent v.3.7.1. life cycle inventory database, more specifically the APOS-U (Allocation at the point of Substitution) system. Contrary to, for example, the 'cutoff' system model, this model assigns a partial environmental burden to all secondary or recycled materials from their previous life. This creates the possibility to investigate trade-offs regarding which material leads to the lowest overall environmental burden in a subsequent product, based on the origin of a recycled material. For more information on system models and their implications the reader is referred to the ecoinvent article on system models (2024).
The impact assessment of individual processes was performed using the ReCiPe 2016 midpoint (H) v1.08 impact model in SimaPro 9.5.0. The individual processes were linked and scaled in Excel for the final calculation of the scenarios.

Life cycle inventory

The data from the aforementioned sources were scaled according to the specified functional unit, which is the EoL treatment of one multi-crystalline silicon panel of 1,6 m2 with a weight of 22 kg. The table A1 shows the results of this scaling step, please note that this includes characterised inputs (e.g. post treatment of glass fragments to glass wool). These particular inputs were calculated by manipulating corresponding ecoinvent LCI datasets to represent the current product system. For both characterised inputs the manipulations consisted of replacing the existing input of secondary material by waste solar glass and transforming the functional unit from the production from ‘1kg of recovered product’ to ‘the treatment of 1kg of waste material’. The treatment of waste glass to new solar glass was modelled using the ecoinvent dataset for the production of new solar glass, which in itself is a proxy in ecoinvent 3.7.1. Using scaling factors calculated from other glass recycling inventories in ecoinvent, the material and energy inputs for this process were adapted to accommodate the replacement of primary materials (e.g. silica sand, lime) by secondary materials (solar glass culets). The simplified life cycle inventory can be found in table (Table A2).

Table A1 Aggregated LCI data per functional unit of treating 1 panel (22kg)

Stage	**Scenario 1**	**Scenario 2a**	**Scenario 2b**	**Scenario 3a**	**Scenario 3b**	**Unit**
Transport	50,00	500,00	500,00	500,00	500,00	km
Shredding, crushing, sorting	3,52					kWh
Delamination, Hot knife		1,31				kWh
Delamination, Water jet			nd			
Incineration of whole				1,10		kWh
Pyrolysis					40,00	kWh
Post treatment of glass fragments to glasswool		59,84		59,84		kg CO_2-eq
Post treatment of glass to new solar glass			13,52		13,52	kg CO_2-eq
Incineration of plastic fraction	3,51	3,51	3,51	3,51		kg CO_2-eq
Incineration of fragments	-1,20					kg CO_2-eq
Basic chemistry		1,54	1,54	1,54		kWh
Advanced chemistry					1,54	kWh

Table A2 LCI for Solar glass production from waste solar glass cullets (proxy from flat glass production, RER)

Input	**Value**	**unit**
Flat glass factory	3,92792E-10	p
Heavy fuel oil	0,120282498	kg
Hydrogen, liquid	5,86744E-06	kg
Lime, packed	0,204942134	kg
Natural gas, high pressure	0,165315383	m3
Nitrogen, liquid	0,008067729	kg
Refractory, fireclay, packed	0,001743933	kg
Silica sand	0,406897567	kg
Soda ash, light, crystalline, heptahydrate	0,161210282	kg
Steel, unalloyed	2,23289E-05	kg
Tin	1,49294E-05	kg
Electricity, medium voltage	0,156940854	kWh
Required glass cullet input from waste solar glass **(FU)**	**1**	**kg**
Output		
Solar glass sheets from recovered solar glass	1,629844911	kg

Life cycle impact assessment

In this step, all scaled inputs that are not yet expressed in carbon dioxide equivalents are characterised to allow for the calculation of the total carbon footprint of the scenarios. The allocation method for the system expansion in Table A3 is visualised in chapter 4 in two ways. The primary method is consistent with the SSML methodology as described by Quick et al. (2019) and allocates the burdens of additional primary material production to those scenarios that do not recover these materials during the recycling process. The second method allocates credits for avoided production, based on the materials that are recovered in the recycling process.

Table A3 Environmental Impact (in kg CO2-eq per solar panel)

Stage	Life cycle step	Scenario 1	Scenario 2a	Scenario 2b	Scenario 3a	Scenario 3b
Transport	Transport	0.12	1.16	1.16	1.16	1.16
Shredding, crushing, sorting	Shredding	1.50				
Delamination, Hot knife	Delamination		0.56			
Delamination, Water jet	Delamination			nd		
Incineration of whole	Delamination				0.47	
Pyrolysis	Delamination					17.1
Post treatment of glass fragments to glass wool	Glass treatment		59.8		59.8	
Post treatment of whole glass	Glass treatment			13.5		13.5
Incineration of plastic fraction	backsheet	3.51	3.51	3.51	3.51	
Incineration of fragments	energy recovery	-1.20				
Basic chemistry	Chemistry		0.66	0.66	0.66	
Advanced chemistry	Chemistry					0.66
System Expansions						
Virgin solar glass	Virgin Glass	25.4	25.4		25. 4	
Energy		n.a.	n.a	n.a	n.a	N.a
Virgin Silver	Silver	3.88				
Virgin Silicon (solar grade)	Solar grade Silicon	34.2	34.2	34.2	34.2	
Virgin silicon (Metallurgical-grade)	Metallurgical-grade Si	7.6				7.6
Grinding material			negligible	negligible	negligible	negligible
Glass wool/fibre	Glass wool	65.6		65.6		65.6
Total		140.6	125.3	118.7	125.3	105.6

Appendix 2 Circularity indicators

The following circularity indicators are quantified based on Quik et al. (2019) with addition of a quality factor for the application in the next phase as recommended in Lijzen et al. (2022)

Efficiency

The efficiency indicator shows how efficient the recycling process is. Different recycling scenarios are compared leading to different recycling products.

$$Eff = \frac{Rx * Qrx}{Rtm} * \frac{Rx}{Qxa * Maux + Rx}$$

Eff = Recovery efficiency [-];
Rx = recovered resource x [kg];
Qrx= quality of recovered resource (between 0 and 1) compared to the resource used in the source (waste) material;
Rtm = total resource in the (waste) material flow [kg];
Qxa= quality of raw materials;
Maux = raw/virgin auxiliary materials used for production of resource [kg]

Contribution

This indicator is aimed at quantifying the degree to which a recovered resource can fulfil demand within a defined geographical market (we focus here on the national level). It is based on the fraction of total applied materials in the intended application or materials cycle that can be substituted by the recovered resource. This also includes other materials required for the system to support the intended function. This can be calculated using the following equation:

$$Cont = \frac{Rx}{Rta}$$

Cont = contribution [-]
Rx = recovered resourse [kg]
Rta = Total resource required for the intended application [kg]

Recyclability

The recyclability indicator quantifies the potential for the recovered resource to be recycled or reused after the next use phase. This consists of:
1. The amount of material available after the next use phase, so after subtracting the losses, e.g. due to wear and tear and 2. The quality of the recovered materials in combination with their current application compared with the source material:

$$Rec = \left(\frac{Rret}{Rta}\right) * Qr$$

Rec = recyclability [-]
Rret = Resource returned for recycling or reuse [kg]
Qr = Quality classification factor between 0 and 1.

Circularity indicators

Efficiency	**Scenario 1**	**Scenario 2a**	**Scenario 2b**	**Scenario 3a**	**Scenario 3b**
Baseline - grinding material/road scrap	0.205				
Glass wool		0.35		0.35	
Reuse of glass			0.7		0.7
Metalurgical Si and Ag		0.0086	0.0086	0.0086	
Solar-grade Si and Ag					0.017
Aluminium	0.18	0.18	0.18	0.18	0.18
	0.39	0.54	0.89	0.54	0.90

Recyclability	**Scenario 1**	**Scenario 2a**	**Scenario 2b**	**Scenario 3a**	**Scenario 3b**
Baseline - grinding material/road scrap	0				
Glass wool		0.35		0.35	
Reuse of glass			0.7		0.7
Metalurgical Si and Ag		0	0	0	
Solar-grade Si and Ag					0.017
Aluminium	0.18	0.18	0.18	0.18	0.18
	0.18	0.53	0.88	0.53	0.90

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