Unlocking value in circular solar panel design

Comparing solar panels based on material savings and material values

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Sustainability Challenge – group 11 for Biosphere Solar
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The team

The research team for the Biosphere Solar 2025 Sustainability Challenge consists of three core members, a supervisor, and members of the Biosphere Solar team. The research team is made up of three Master's students from the Industrial Ecology programme: Emilie Cousin, Luuc Groenhart and Annemerel Klink.

The team brings together a diverse range of backgrounds, from social sciences to engineering. This interdisciplinary perspective allows them to approach the challenges faced by Biosphere Solar from multiple angles in order to find the most effective solutions. The team is also passionate about circular design and wants to help Biosphere Solar demonstrate the value and performance of their product compared to their competitors.

The team is supervised by Droovi de Zilva, a PhD candidate at the Institute of Environmental Sciences (CML), Leiden University, with expertise in energy analysis for the energy transition.

This research is conducted in collaboration with Biosphere Solar, a company originally founded by former Industrial Ecology students and since expanded with many new members. For this project, two employees from Biosphere Solar are actively involved, providing the team with data, answering questions, and facilitating contact with relevant stakeholders.

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Disclaimer

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Popular summary

Solar energy is essential for the energy transition, but today's solar panels are difficult to repair and recycle. Most panels are glued together, which means that when they break or reach the end of their life, valuable materials such as silicon and glass are often lost or downcycled. Biosphere Solar addresses this problem with its modular and circular solar panel design, the ReModule, which can be easily disassembled.

This study creates a tool to compare Biosphere Solar's ReModules with standard solar panels and analyses how much material and economic value can be recovered at the end of life of large solar parks. Using a material flow analysis of five different recycling scenarios. The study shows that ReModules enable significantly higher recovery of high-quality materials, especially solar-grade glass. This improves both circularity and potential financial returns for solar park operators. The results shows that circular design can reduce waste and save valuable resources which support a more sustainable solar energy system.

Executive summary

The rapid growth of solar energy is crucial for achieving climate targets, but it also creates a growing challenge related to environmental impact and wate of solar panels. Standard solar panels are laminated, which makes it difficult to repair and recycle. As a result, most end-of-life panels are downcycled, leading to the loss of high value and raw material intensive materials such as silicon and solar-grade glass. As large quantities of solar panels will reach the end of their service life in the coming decades, it is becoming more important to improve circularity in the design and recycling of panels.

Biosphere Solar is tackling this challenge with their modular and circular solar panel design, the ReModule. By substituting the traditional laminate layer with a removable sealing system ReModules can be easily disassembled, enabling reuse, repair and recycling of components. Previous research demonstrated the environmental benefits of the design of the ReModule through a life cycle assessment; Biosphere Solar now aims to quantify the material and economic value for their target audience: solar farms and policy makers.

This study quantifies material recovery, material value recovery and circularity at the end of life of solar panels, comparing ReModules with standard solar panels. A static Material Flow Analysis (MFA) is developed in an Excel-based tool, allowing results to be scaled to different solar park sizes. Five recycling scenarios are analysed, ranging from current recycling methods as downcycling to advanced recycling technologies such as pyrolysis.

The results show that downcycling recovers the least material and value in all cases. ReModules outperform standard solar panels in terms of material recovery quality, particularly by enabling the full recovery of solar-grade glass across all recycling scenarios. For other valuable materials, such as silicon and silver, recovery is primarily determined by the recycling technology used rather than the solar panel design. Pyrolysis is the only scenario that allows recovery of solar-grade silicon, while other advanced recycling scenarios recover silicon at metallurgical grade. Material value analysis indicates that ReModules generate higher recoverable value, although large uncertainties remain due to limited transparency in recycling market prices. The circularity results show that ReModules allow a larger share of materials to be reused within the solar industry. With pyrolysis recycling of ReModules achieving the highest overall circularity.

In conclusion, this research shows that Biosphere Solar's ReModule provides advantages over standard solar panels in terms of material recovery, value retention and circularity. The Excel-based tool developed in this study enables Biosphere

Solar to communicate these benefits to solar farm operators and policy makers. However, the results also show the importance of recycling technologies and policy frameworks in enabling fully circular solar energy systems.

1. Introduction

1.1 Background and context

Worldwide, the transition to renewable energy is accelerating, with solar energy as one of the most important technologies. Solar energy is essential for achieving the targets of the Paris Agreement. It is expected that photovoltaic systems will account for approximately a third of global electricity generation (ETIP SNET, 2017). However, the rapid scaling up of this technology presents significant challenges, particularly the large environmental footprint of solar panel manufacturing and the growing amount of waste at the end of a solar panel's lifetime.

Standard laminated photovoltaic modules are not made with circular principles, such as modularity and circularity, in mind. The core of this problem lies in the production process. Traditional photovoltaic modules have an adhesive laminate layer. This layer glues the various components of the panel into an inseparable whole. This has two big major consequences for the sustainability of the panels. First, these laminated modules are impossible to repair. When the glass sheet of the panel cracks or an internal connection fails, the panel cannot be opened or repaired. So, a defect of just a few euros leads to a total replacement of the panel. In addition, recycling of materials of the panel is difficult. Since the materials are glued together, through the lamination, high-quality recycling is difficult. These standard laminated photovoltaic panels are often shredded, with only aluminium frames and copper cables from the junction box recovered, while the rest is shredded and converted to low value road filler. The most valuable and energy-intensive materials such as silicon are lost. Despite the widespread use of solar power, only 10% of panels are recycled at the end of their lifespan (Celep et al., 2025). On average, solar panels have a lifespan of 25 years, and they are currently being installed on a massive scale. We are now in a phase of mass installation, but in 25 years, we will enter the phase of mass waste processing. Without adequate recycling solutions, photovoltaic waste is projected to reach 78 million tonnes of glass, aluminium, and rare materials by 2050 (Chowdhury et al., 2019).

1.2 Problem statement and aim

Biosphere Solar is tackling this problem by designing and building solar panels that are designed to be circular and modular, called ReModules. Instead of using the traditional laminate layer, they replace it with an innovative edge seal and liquid filler material. Thanks to this design, the solar panels are easy to disassemble, allowing components to be reused, repaired, recycled, or replaced at the end of their lifecycle. Biosphere Solar is now already at the second design generation of their “ReModule” solar panel and is getting ready to hit the market. They have already proven the environmental benefits of their solar panel design through a comparative LCA study, which compares LCA’s for different products.

As they are getting ready to enter the market, they now want to quantify the circularity their solar panel design enables, from a customer and regulator perspective. To demonstrate to their target audience why their solar panels provide greater value than other solar panels on the market. Regulators are mainly interested in a quantification of materials that can be saved from landfills through the adoption of ReModules, while customers, like big solar park operators, are mainly interested in the improved profitability that can be achieved through the use of ReModules (through improved residual value of their end-of-life assets and therefore decreased overall company capital expenditures). As different solar parks, regions and countries are analysing circularity at different scales, Biosphere Solar would like to have a practical tool that easily scales these results to the different scopes of interest. Thus, the main problem statement from Biosphere Solar is how to quantify the material and monetary value recovery made with the use of the ReModule.

1.3 Project Scope

This study focuses on quantifying the material savings and recoverable material value at the end of life of commercial solar parks, comparing Biosphere Solar’s ReModules with the current status quo of standard solar panels. The analysis is limited to end-of-life recycling at solar park level, where the largest material flows and circularity potential occur. This focus aligns with the interests of the target audience of Biosphere Solar, solar park operators and policy makers. Solar park operators primarily focused solutions on profitability, while policy makers emphasize circularity and resource efficiency.

To justify this scope, it is necessary to briefly describe current practices in the use, repair, and recycling of industrial-scale solar panels. During the initial research phase, an overview of these practices was developed in collaboration with Biosphere Solar. Solar panels used in the industrial sector, meaning large-scale solar farms, are treated as bulk products. Solar park operators purchase a surplus of panels during installation, allowing damaged panels to be replaced rather than repaired on-site. Although minor damage can occur due to environmental factors such as wind, rain, or dust, the number of damaged panels during operation remains relatively limited. When damage does occur, panels are transported to specialized facilities, where they are either repaired or recycled. These repaired solar panels are mostly resold on secondary markets and rarely ever return to big solar farms.

In practice, most solar panels do not reach end of life due to physical damage. Most solar panels reach end of life because their efficiency reduced too much, making it more profitable for a solar park to replace them rather than to keep them in operation. After approximately 20 to 25 years, continued operation becomes less economically attractive than replacement, leading to the decommissioning and recycling of entire solar parks at once. As a result, most recycling activities take place at the end of life of complete solar parks rather than during the operational phase. The repair of individual panels is highly complex, as each break is slightly different, whereas bulk recycling processes are standardized and apply the same treatment to each panel. For these reasons, material savings achieved through the repair of individual solar panels during operation are excluded from the scope of this study.

Based on this scoping, the challenge defined by Biosphere Solar has been translated into the following research question:

“How much material savings and recoverable material value can be achieved at the end of life of commercial solar parks when using Biosphere Solar ReModules instead of standard solar panels, and how can this be quantified in an Excel-based tool comparing both systems?”

The main deliverable of this research is an Excel-based tool that quantifies and compares the material recovery rates and material value of ReModules and standard solar panels at the end of life of commercial solar parks.

2. Methodological approach

To answer the research question, it was chosen to do multiple static simplified Material Flow Analyses (MFA) in Excel. The decision was made to develop the tool in Excel instead of Python or other software, because Excel allows Biosphere Solar to more easily use and adapt the tool for different scenarios, customers, and policymakers.

2. 1 Material Flow Analysis

Material Flow Analysis is a method used to quantify material flows within a system (Brunner and Rechberger 2016). It encompasses where materials come from, what they are used in, and where they end up (Brunner and Rechberger 2016). In this study, MFA is used to quantify and compare material recovery and losses at the end of life of commercial solar park using Biosphere Solar's ReModules versus standard solar panels.

The system is the place where different elements of that system interact with each other, this can be an industry, nation, etc (Brunner and Rechberger 2016). The system boundary is the time and space boundary of the system (Brunner and Rechberger 2016). In this study the system is defined as the end-of-life treatment of solar panels from commercial scale solar parks. The spatial system boundary includes all processes from removal of solar panels from the solar park to the output of recovered materials after recycling. Upstream processes such as the extraction of raw materials and the production of panels, as well as downstream processes such as the reprocessing of recovered materials, are outside the system boundaries. Because we have chosen to do a static MFA, the temporal scope is static and undefined. The undefined part is usually not done in MFA's but because the eventual tool should be focussed on a, changeable, number of solar panels going into recycling and not on a real amount of solar panels going into recycling per temporal unit, this change was made.

An MFA system has processes and flows. Processes are places where materials are used, transformed, etc, and black box processes (Brunner and Rechberger 2016), meaning that no attention is given to what happens inside the process only what goes in, out, and stays in (Brunner and Rechberger 2016). In this study processes represent recycling or treatment steps, such as manual dismantling, incineration, or hydrometallurgical recovery, and are treated as black boxes. This means that only the material inputs and outputs of each process are considered. The flows are amounts of materials going between processes, when these flows cross the system boundary they can be either import or export from the system (Brunner and Rechberger 2016).

An MFA can be either demand or supply driven (Brunner and Rechberger 2016). This means that the mass balance the total system is calculated using a single, or more, set amount(s) of material either at the demand side of the system or the supply side of the system (Brunner and Rechberger 2016). This ensures that mass balance is always achieved and that all incoming (supply) materials are used, or all outcoming materials (demand) are supplied with their ingredients. The MFA's developed in this study are supply-driven. They assume a fixed number of solar panels entering the system, and the resulting material output is calculated based on this input. This approach ensures a mass balance throughout the system and is suitable for comparing different recycling scenarios and panel designs under identical input conditions.

Transfer coefficients refer to a number that partitions a material within a process to a specific outflow (Brunner and Rechberger 2016). This is used to calculate how much of an inflow goes to a specific outflow even when the input amount changes. A mathematical representation of transfer coefficients in use can be found equations 1-3, which cannot be solved but serves to show the principle. In the equations there is the transfer coefficients (TC_1, TC_2), and flows (F_1, F_2, F_3). The F_1 flow represents an inflow to a process which is portioned into outflows F_2 and F_3 using the transfer coefficients TC_1 and TC_2 which need to add up to 1. It should be noted to actually solve these equations the inflow F_1 and one transfer coefficient should be known.

$$F_2 = TC_1 * F_1 \#1$$

$$F_3 = TC_2 * F_1 \#2$$

$$TC_1 + TC_2 = 1 \#3$$

An example of the calculations used with the values and transfer coefficients for this research is shown in equation 4-5. In the equations the transfer coefficients (TC_1 and TC_2) are the recovery and loss transfer coefficients for copper hydrometallurgy recycling which are 0.95 (TC_1: recovery) and 0.05 (TC_2: loss). As can be seen from equation 3, the transfer coefficients must add to 1, meaning that even with one transfer coefficient the other can be found through subtracting it from 1.

$$Copper_{recovered} = TC_1 * Copper_{in} \#4$$

$$Copper_{lost} = TC_2 * Copper_{in} \#5$$

If 1000 (g) of copper is put into these equations the result is as follows:

$$0.95 * 1000 = 950 \#6$$

$$0.05 * 1000 = 50 \#7$$

Resulting in 950 (g) of recovered copper, and 50 (g) of copper lost (in this case as unrecoverable metals particles in slag/ash). The full table of transfer coefficients can be found in table 4 in the recycling scenarios section of the methodological approach.

2.2 Scenarios

The recycling of solar panels is an industry that is going through many changes. This is because the first large number of first- and second-generation solar panels are currently at their end of life and going into recycling, but the recycling industry has not found a circular and sustainable way of recycling these and future panels. Instead, most solar panels are 'downcycled' at end of life. To give a good overview of both current and future recycling **five** different recycling scenarios were created which both the status quo and ReModule solar panels are put through to see differences. This is standard practice in MFA research were first a baseline scenario is created, the downcycling scenario in this case, and different other scenarios are tested to see differences in the system.

2.3 Bill of materials of ReModule and Standard Solar Panels

Before the MFA's can be calculated the input materials have to be specified. For this research the input materials are a single ReModule or a single status-quo solar panel (standard solar panel). We have chosen to use a single panel instead of more, which would better reflect the amount going from solar parks to recycling at end of life, as it could cause confusion and because scaling the calculations is extremely easy and can simply be done by multiplying the input bill of materials by the required number of solar panels. **This last point is implemented in the Excel calculator.**

The ReModule solar panel from Biosphere Solar is easy to make a bill of materials for, as Biosphere Solar can provide this. A status-quo solar panel however is harder. This is because all different solar panels have slightly different materials, and we want to provide an aggregate overview. To make this part simpler Biosphere Solar has indicated that taking the bill of materials from the ReModule and modifying this to add a lamination layer in line with normal solar panels, which often use Ethyl Vinyl Acetate (EVA) for lamination, would be the best. This ensures that the type of solar panel is the same.

In table 1 and 2 the bill of materials for the ReModule and status-quo solar panels can be seen respectively.

Table 1: Bill of Materials of ReModule and Status-Quo Solar Panels

		ReModule	Status-Quo
Part	**Material**	**Mass (g)**	**Mass (g)**
Glass Sheets	Low-iron solar Glass containing Antimony	34703.16	34703.16

Glass Sheets	Antimony	0.00	0.00
Solar Sandwich	Copper	340.66	340.66
Solar Sandwich	Tin	19.30	19.30
Solar Sandwich	Silver	5.52	5.52
Solar Sandwich	Lead	0.00	0.00
Solar Sandwich	Silicon	1620.00	1620.00
Solar Sandwich	Aluminium	48.00	48.00
Solar Sandwich	Butyl	89.96	x
Solar Sandwich	Eversolar® AB-302c	0.28	x
Solar Sandwich	Silicone Rubber	0.89	x
Solar Sandwich	Ethyl Vinyl Acetate (EVA)	x	100.00
Frame	Aluminium	1861.70	1861.70
Frame	Silicon Glue	66.00	66.00
Junction Box	Copper	72.00	72.00
Junction Box	Polyethylene	45.00	45.00
Junction Box	Polypropylene	72.25	48.25
Junction Box	Silicon Glue	24.00	24.00
Total		38968.72	38953.59

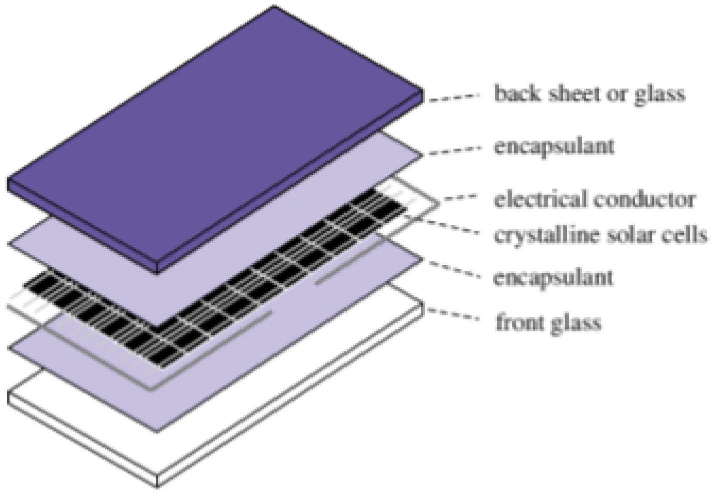

Figure SEQ Figure * ARABIC 1: Layer-by-layer overview of a standard solar panel (Naumenko and Eremeyev 2014)

In Figure 1, a simple layer-by-layer overview of a status-quo glass-glass solar panel is shown. The ReModule is very similar to this with the exception of the encapsulant (see figure 2), which is usually EVA in status-quo solar panels but is a combination of Butyl, Eversolar® AB-302c, and silicone rubber in the ReModule, making removal easier. The crystalline solar cells of a solar panel can be of different kinds. For the ReModule, and most other modern status-quo solar panels, the solar cells are monocrystalline silicon cells. This is also our assumption for the status-quo solar panel.

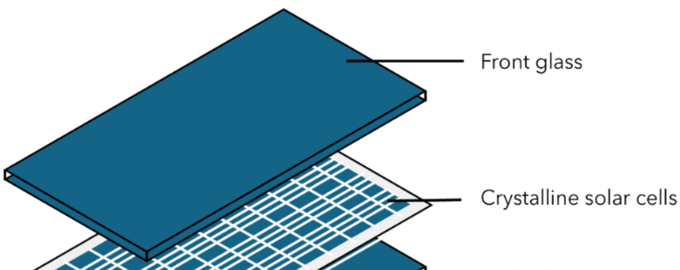

Figure 2: Layer-by-layer overview of a ReModule

2.4 Recycling Scenarios

The five different recycling scenarios can be found in Figure 3.

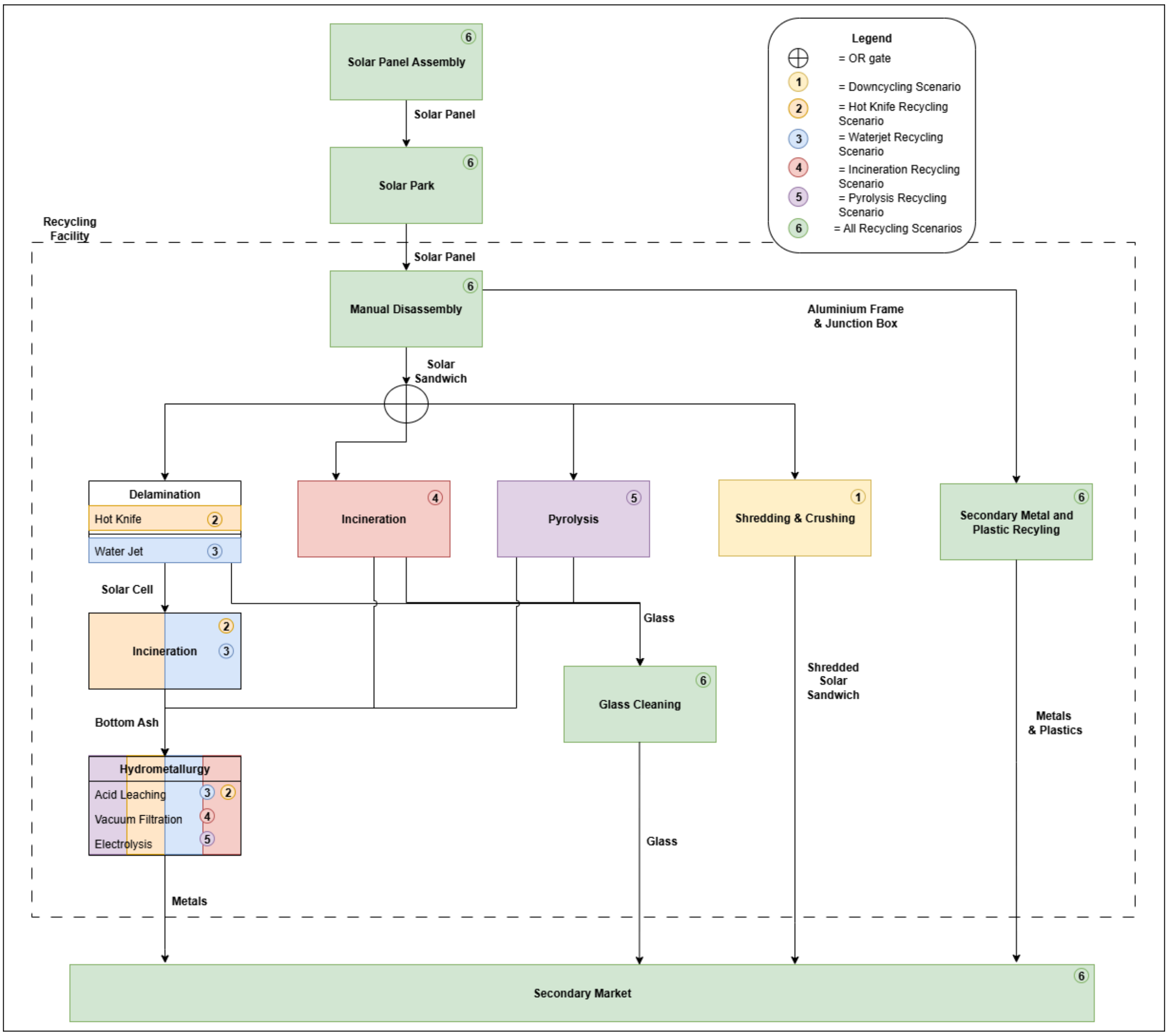

Figure 3: Solar Panel Recycling Scenarios

All scenarios have processes in common, indicated with the number six in Figure 3. All scenarios start with assembly, use in the solar park, and manual disassembly. In manual disassembly the frame and junction box are manually removed for secondary metal and plastic recycling or reuse. The solar sandwich which has the most intricate and expensive materials and components remains with the glass sheets and encapsulation. This is then recycled through the different scenarios.

Scenario 1 is the downcycling scenario. This is the most simple and common practice scenario (Späth et al. 2022). In this scenario the solar sandwich, glass and encapsulation go through a process of shredding and crushing (Späth et al. 2022). The shredded/crushed glass, metals and plastics are then used for construction purposes such as for the filling of the layer under roads (Späth et al. 2022) This is why it is called the ‘downcycling’ scenario. A very complex and expensive technology with expensive and intricate components is recycled into a very non valuable and simple material, losing all complexity and value in the process.

Scenarios 2 and 3 are very similar to each other and are the hot-knife and waterjet scenarios respectively. In these scenarios the encapsulation between the glass sheets and solar sandwich is removed through either a hot-knife or waterjet, separating the glass sheets from the solar sandwich and losing the encapsulation, fully in the process (Späth et al. 2022). But the ReModule does not have the same encapsulation as status-quo solar panels, and the ReModule can be ‘de-encapsulated’ without a hot-knife or waterjet, making these scenarios irrelevant for the ReModule. Therefore, these scenarios are only calculated for the status-quo solar panel and not the ReModule. After this the glass is cleaned. In scenarios 2 and 3 the assumption is that the glass can be removed and cleaned to remove any left-over polymer residues (Späth et al. 2022). Because hot-knife separation usually returns a more damaged glass than waterjet separation the eventual quality and possibilities for products is different (Späth et al. 2022, Lijzen et al. 2023). The hot-knife scenario can be expected to return a glass quality to produce foam glass or glass fibre, while the waterjet scenario can return glass quality for the solar panel industry (Späth et al. 2022, Lijzen et al. 2023). The solar sandwich is then incinerated into bottom-ash after which this bottom-ash goes through multiple hydrometallurgy processes such as acid leaching, vacuum filtration, and electrolysis (Späth et al. 2022). This should result in the purification and separation of metals from the bottom ash. The efficiencies and final products through this process can be found in table 2. The efficiencies noted here are used as transfer coefficients in the MFA models for scenarios 2 and 3 in the **hydrometallurgy process.** This is done by making the percentages into proportions of recovered materials.

Table 2: Hydrometallurgy Efficiencies

Material	Recovery Efficiency
Silver	95%
Silicon (metallurgical or solar grade)	95%
Copper	95%
Aluminium	50%

An important thing to notice in Table 2 is that the recovered silicon is metallurgical grade, which means that it can no longer be used in the solar panel industry as this needs solar grade silicon which has a higher purity.

Scenario 4 is a more brute force approach, pure incineration. In this scenario no delamination/de-encapsulation occurs. Thus, the glass and encapsulation remain on the solar sandwich during incineration. This means that the encapsulation is still lost but now the glass cannot be recovered in full but instead as glass wool or fibres which have much less value (Späth et al. 2022). Here a slight difference in the scenario for ReModule and status-quo solar panel occurs. Because the ReModule solar sandwich and glass is able to be removed manually, incineration with the glass still attached is not necessary. Thus, for the ReModule the glass is removed manually before incineration causing the glass to be able to be recycled at solar grade. The bottom-ash from incineration is processed through hydrometallurgical methods in the same way as in scenarios 2 and 3 with the same efficiencies.

Scenario 5 is the most ‘high-tech’ approach, pyrolysis. In this scenario the encapsulation is removed through pyrolysis, which keeps the glass intact and at solar grade (after cleaning), loses the encapsulation and provides a purer final product. This final product can then be treated through hydrometallurgical methods with the same efficiencies as in Table 2 but now retrieving solar grade silicon instead of metallurgical grade silicon. This improves the value of recovered metals, as silicon at solar grade is very valuable, and also increases circularity as the recovered solar grade silicon can be reused in the solar panel industry.

In table 3 an overview of type of recovered materials per scenario can be found.

Table 3: Quality of recovered materials per scenario

	Scenario 1: Downcycling	Scenario 2: Hot-Knife	Scenario 3: Waterjet	Scenario 4: Incineration	Scenario 5: Pyrolysis
Material	**Quality**	**Quality**	**Quality**	**Quality**	**Quality**
Aluminium (from frame)	Secondary metal	Secondary metal	Secondary metal	Secondary metal	Secondary metal
Polymers (from junction box)	Secondary plastics	Secondary plastics	Secondary plastics	Secondary plastics	Secondary plastics
Copper (from junction box)	Secondary metal (Latunussa et al. 2016 (b))	Secondary metal	Secondary metal	Secondary metal	Secondary metal
Encapsulation	-	-	-	-	-
Glass	Filler Material (Lijzen et al. 2023)	Foam glass / glass fibre (Lijzen et al. 2023, WAMBACH 2017)	Solar grade glass sheet (Lijzen et al. 2023, Latunussa et al. 2016 (b))	glass wool / glass fibre (status-quo panel) (Lijzen et al. 2023) Solar grade glass sheet (ReModule)	Solar grade glass cullets (status-quo panel) Solar grade glass sheet (ReModule)
Silver	Filler Material (Lijzen et al. 2023)	Secondary metal (Lijzen et al. 2023, Späth et al. 2022)	Secondary metal (Lijzen et al. 2023)	Secondary metal (Latunussa et al. 2016 (b), Lijzen et al. 2023)	Secondary metal (Lijzen et al. 2023)

Silicon	Filler Material (Lijzen et al. 2023)	Metallurgical grade (Lijzen et al. 2023, WAMBACH 2017)	Metallurgical grade (Lijzen et al. 2023)	Metallurgical grade (Latunussa et al. 2016 (b), Lijzen et al. 2023)	Solar grade silicon (Lijzen et al. 2023)
Copper	Filler Material	Secondary metal (Späth et al. 2022)	Secondary metal (Späth et al. 2022)	Secondary metal (Latunussa et al. 2016 (a/b))	Secondary metal
Tin	Filler Material	Secondary metal	Secondary metal	Secondary metal	Secondary metal
Aluminium	Filler Material	Secondary metal	Secondary metal	Secondary metal	Secondary metal
Lead	Filler Material	Secondary metal	Secondary metal	Secondary metal	Secondary metal

The full transfer coefficient table used for all scenarios is shown here for reference.

Table 4: Transfer Coefficients

Step	Material	TC Recovery	TC Loss	Used in Scenarios:
Manual Dismantling	Aluminium	1	0	1-5
	Copper	1	0	1-5
	Polyethylene	1	0	1-5
	Polypropylene	1	0	1-5
	Silicon glue	1	0	1-5
	Glass (ReModule)	1	0	1-5
Shredding and Crushing	Full solar sandwich and glass	1	0	1
Hot-Knife	Glass	1	0	2
	Encapsulant	0	1	2
Water Jet	Glass	1	0	3
	Encapsulant	0	1	3
Incineration	Solar sandwich	1	0	2-4
	Glass	1	0	4
	Encapsulant	0	1	4
Pyrolysis	Solar sandwich	1	0	5
	Glass	1	0	5
	Encapsulant	0	1	5

Glass cleaning	Glass	0.9	0.1	1-5
Hydrometallurgy	Silver	0.95	0.05	2-5
	Silicon	0.95	0.05	2-5
	Copper	0.95	0.05	2-5
	Aluminium	0.5	0.5	2-5
	Lead	0	1	2-5
	Tin	0.95	0.05	2-5

2.5 Material Values

The economic value of the recovered materials was estimated through literature research and interviews with recycling companies. In general, it was tried to estimate a baseline, minimum and maximum price to give flexibility to users of the calculator and to not over-or-underestimate value of materials. Due to the large size of the material value table this table is not shown in here but can be found in the calculator (Supplementary materials) material value sheet.

3. Findings

3.1 Material Flow Analysis Results

The material flow analysis results are presented with the business-as-usual (BAU) downcycling scenario as the reference case. In this scenario, standard solar panels are shredded and downcycled, resulting in limited recovery of valuable materials. All other scenarios are assessed based on the extent to which they improve material recovery rates and material quality compared to this baseline.

For multiple materials the material flow results are very similar since the bill of materials of the standard solar panel was modelled from the ReModule bill of materials. The largest differences come from differences in material quality obtained in different scenarios. Below, we will go through how much is recovered per recycling method for each material.

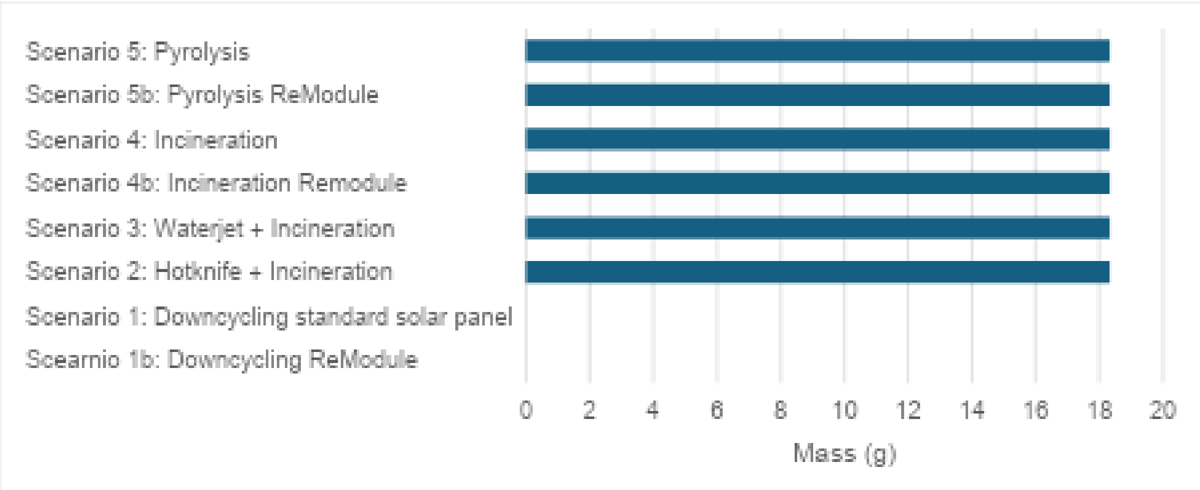

Figure 4: Tin Recovery

Tin recovery can be seen in figure 4. All tin recovered is the same quality and all scenarios have the same mass recovery except for the (BAU) downcycling scenarios which has no recovery at all.

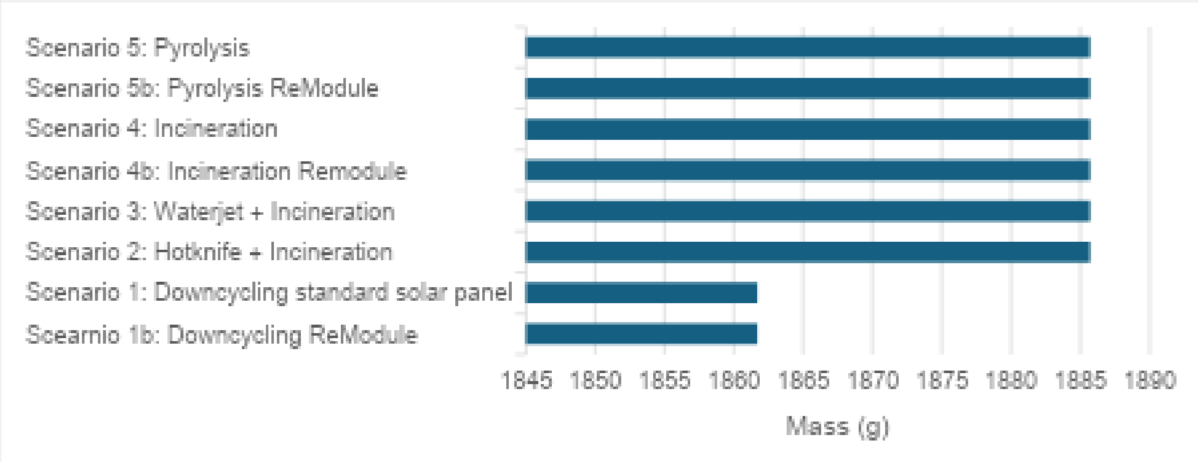

Figure 5: Aluminium Recovery

The aluminium recovered comes from the recycling of the aluminium metal frame after manual dismantling. All scenarios have the same quality of aluminium recovered and all mass recovered is the same except for the downcycling scenarios. The (BAU) downcycling scenarios still recover a large amount of aluminium as the frame of dismantled and recovered in full which makes up most of the mass of aluminium in the solar panels.

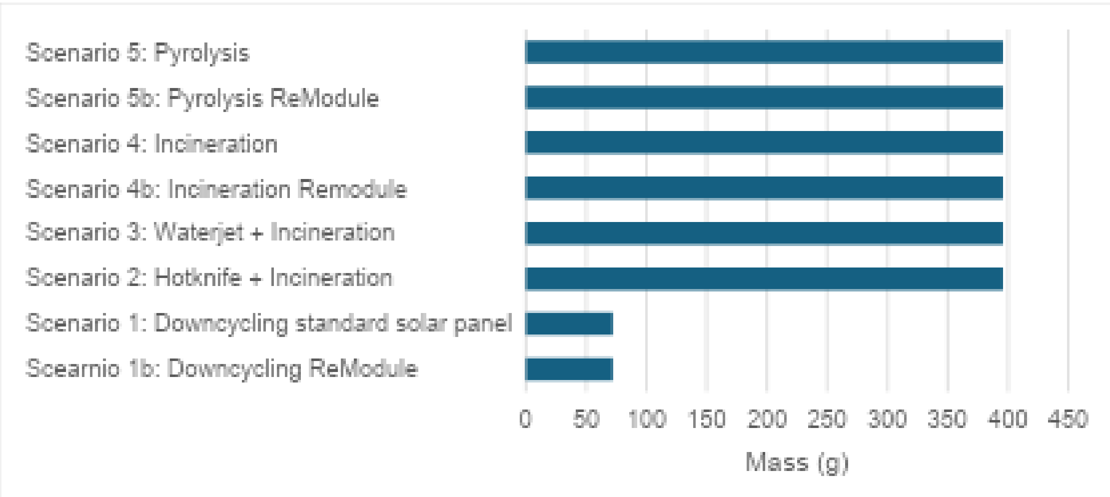

Figure 6: Copper Recovery

Copper recovery is the same as aluminium recovery but instead of the frame being recycled in the downcycling scenarios, the cables in the junction box are recovered. This is a smaller proportion of the total copper in the solar panel, meaning that little of the total copper is recovered.

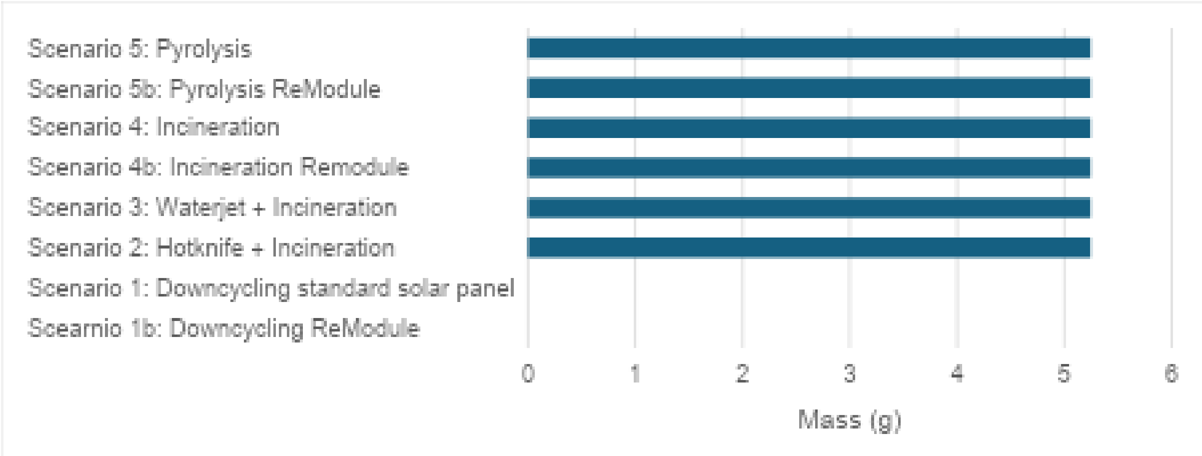

Figure 7: Silver Recovery

The silver recovery is the same for all scenarios except for the downcycling scenarios. This is because all silver, if not shredded/crushed in the downcycling scenarios, is recovered through hydrometallurgy, which has the same transfer coefficients for every scenario, and the two solar panels have the same silver mass in our bill of materials.

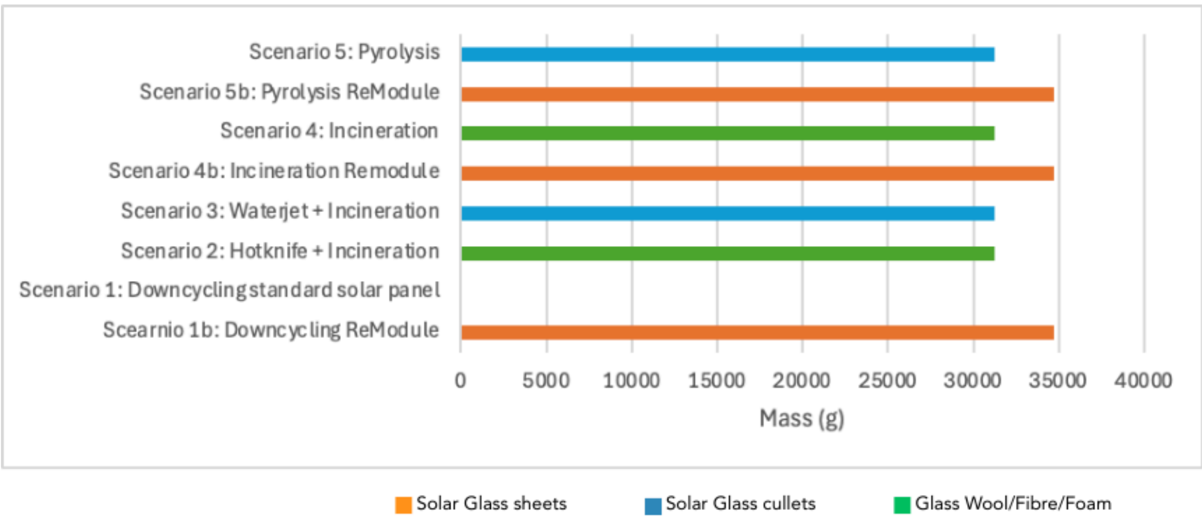

Figure 8: Glass Recovery

The glass recovery shows large differences between the different scenarios and solar panels. Because the glass sheets of the ReModule solar panel can be removed manually the recovery of solar grade glass sheets can be done at 100% for all scenarios with a ReModule. This is not the case for the standard solar panel, which can at most be recovered as solar glass cullets in scenario 5: Pyrolysis, and in scenario 3: Waterjet + Incineration. For scenario 2 and 4 the only glass that can be recovered is of a quality to create glass wool/fibre/foam. Downcycling of a standard solar panel recovers no glass as such, with all glass being downcycled to road filler material or abrasive material. It should also be noted that only the scenarios with a

ReModule solar panel recover 100% of glass mass, with all other scenarios losing some glass in cleaning and separating processes.

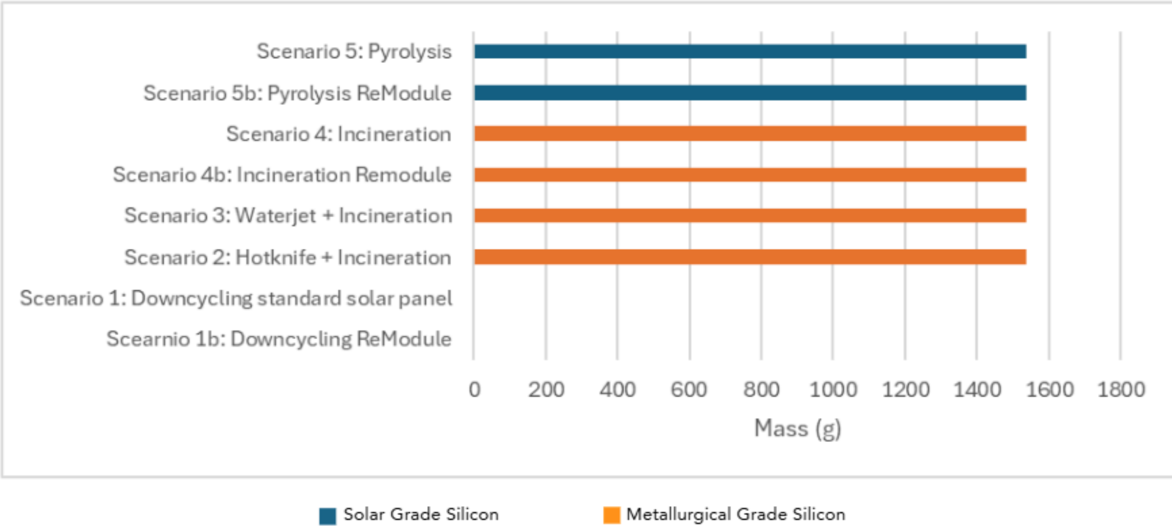

Figure 9: Silicon Recovery

The silicon recovery is simpler. Only two qualities are obtained: solar grade(4N) silicon or metallurgical grade silicon. Only the pyrolysis scenarios can recover solar grade silicon with scenario 2-4 recovering metallurgical grade silicon. All scenarios, except for downcycling which recovers no silicon, recover the same mass of silicon as all silicon is recovered by hydrometallurgy.

The material flow analysis shows three interesting findings. First that downcycling recovers by far the least mass of the mentioned materials. Second that the ReModule solar panel enables the 100% recovery of highly valuable solar grade glass. Third, that pyrolysis is the only scenario that recovers solar grade silicon with scenario 2-4 recovering metallurgical grade silicon.

3.2 Material Value Analysis Results

In figure 10 the recovered value from all materials for the different scenarios is shown. Compared to the business-as-usual downcycling scenario (scenario 1), all alternative recycling scenarios show higher recoverable material value, although the magnitude of this improvement strongly depends on both recycling technology and panel design.

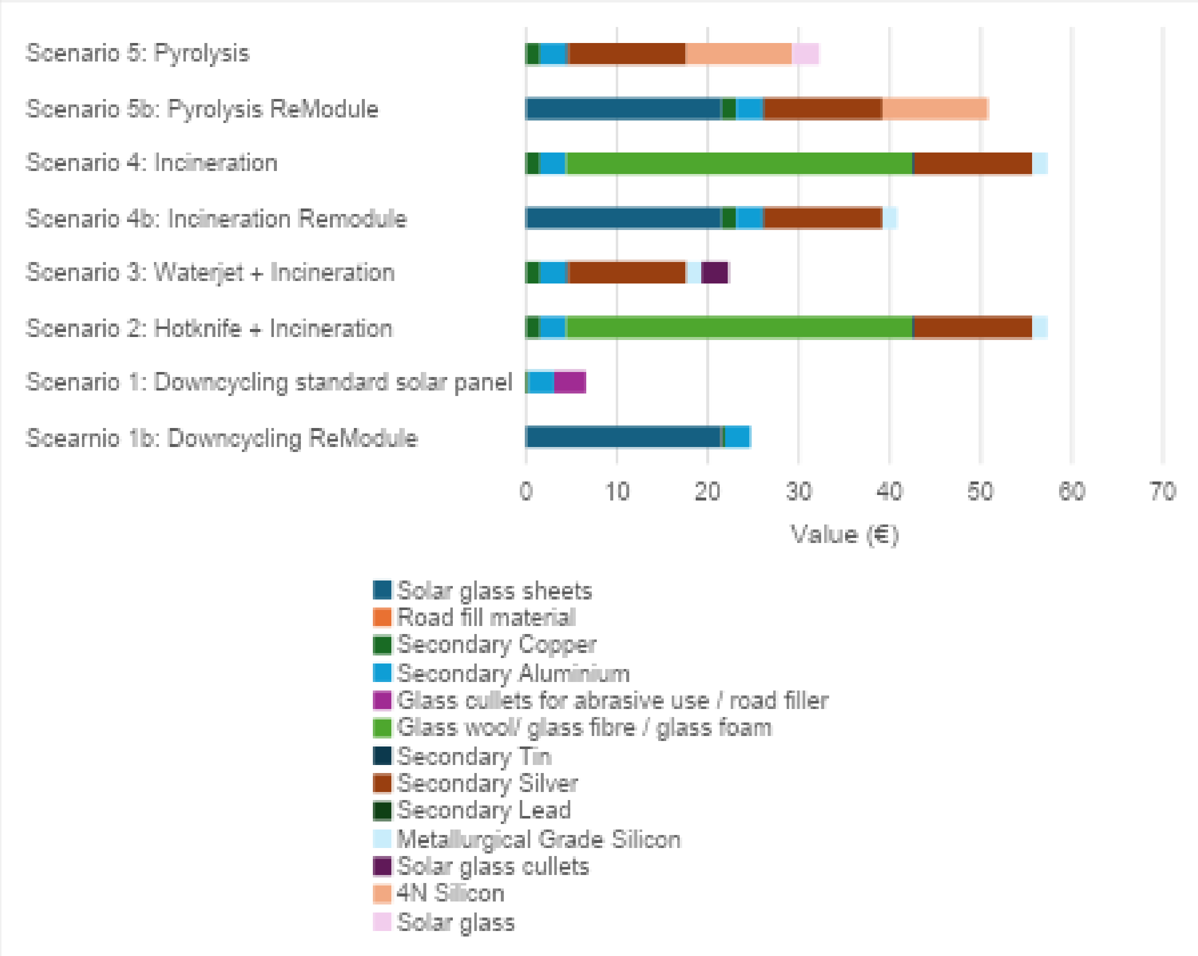

Figure 10: Material Value Recovered

Scenario 2 and 4 with the standard solar panel seem the largest in value recovered but that is unlikely to be realistic. The largest amount of value in these scenarios is by far the glass wool/fibre/foam, which is even larger than the value of the 100% mass recovered solar grade glass sheets in scenario 1b, 4b and 5b with the ReModule. This seems highly unrealistic as solar grade glass is of higher quality than glass wool/fibre/foam. While the value of glass wool/fibre/foam was confirmed through multiple sources, the disproportionate value it takes in this figure comes from multiple factors. First and foremost, it's due to a limitation of this study: remanufacturing costs are not considered. With remanufacturing of solar glass waste into glass insulating material being much more complex and cost intensive than simply reusing a recovered glass sheet on another solar panel, this makes the two numbers incomparable. Second, the glass insulating material prices used are B2C prices, which can be multiple factors higher than B2B prices.

For the sake of respecting the categories of this study, these values were assumed anyways. From the perspective of biosphere solar, we would recommend using road filler material assumptions for scenario 2 and 4 as well, as we expect this to be a more accurate depiction of the reality.

In the continuous development process of the excel calculator, we recommend biosphere solar to include remanufacturing costs in the study scope, to have more comparable and representative results.

When taking scenario 2 and 4 as data errors, scenario 5b: Pyrolysis ReModule and scenario 4b: Incineration ReModule becomes the largest value creators. The value of metallurgical grade silicon and solar grade silicon (4N Silicon) are different, but the figure shows that this does not change the total created value much. This means that incineration recycling of a ReModule might be a better recycling strategy than pyrolysis as they create similar value, but pyrolysis is more complex and further from use in production (Späth et al.. 2022).

3.3 Circularity

Instead of mass or economic value indicators of circularity can also be assessed. For this report it was chosen to indicate the circularity as the proportion of mass per material that can be reused in the solar industry

In figure 11 the percentage of input materials that can be reused in the solar industry per material per scenario can be found.

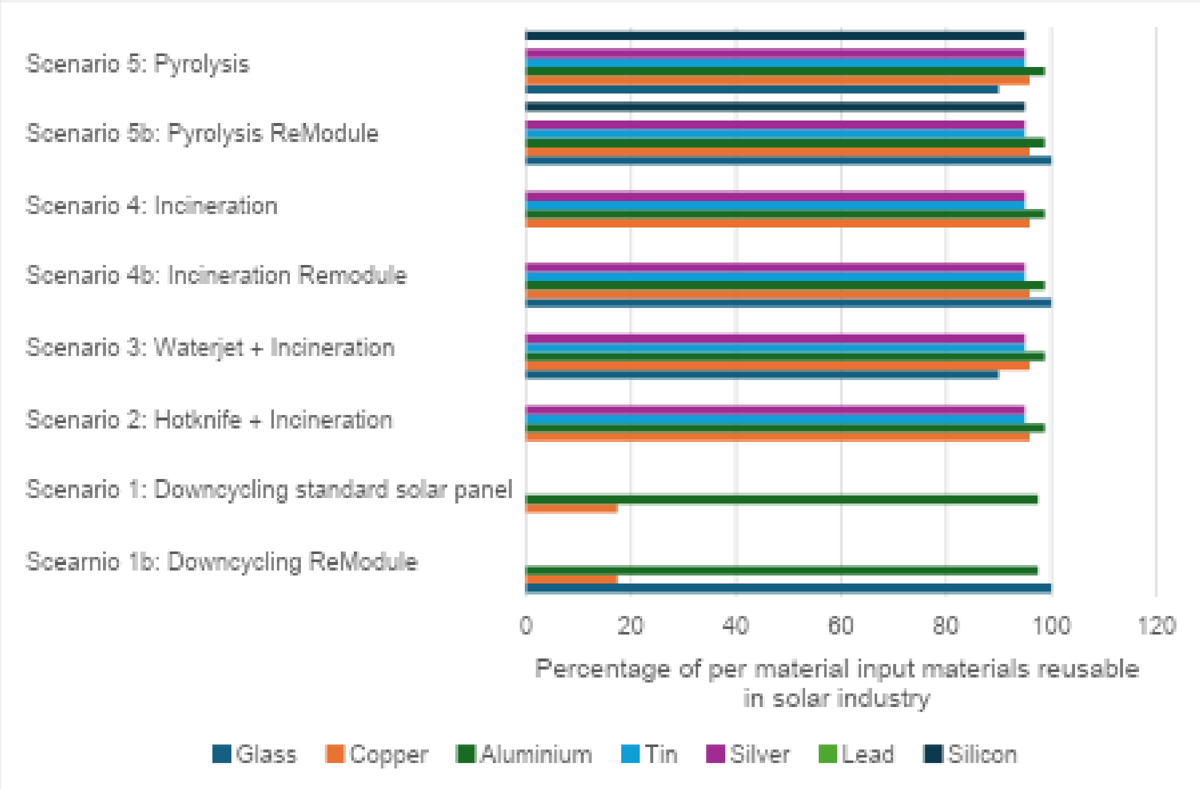

Figure 11: Percentage of input materials usable in solar industry (percentage per material input)

It shows that many metals such as copper, aluminium, tin, and silver are highly circular for many recycling scenarios, with the only scenario exception being downcycling scenarios. The business-as-usual scenario (scenario 1) performs worst across all circularity indicators, as most materials are downcycled and cannot be reused within the solar industry. Scenario 5: Pyrolysis ReModule scores the best overall when measuring circularity per material as it makes both metals, glass and silicon circular.

Figure 12 shows the total percentage of input materials reusable in the solar industry as another indicator of circularity.

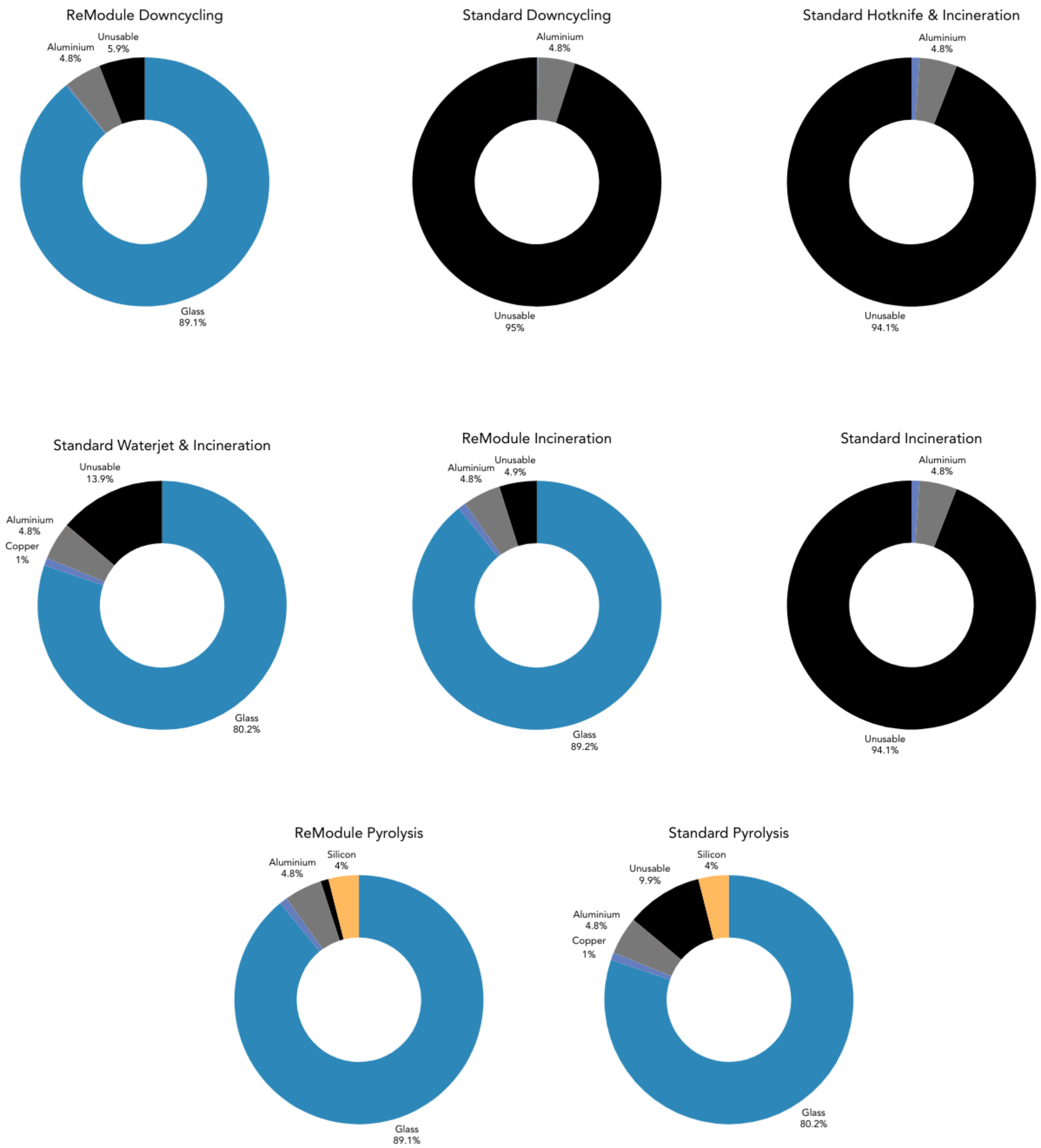

Figure 12: Percentage of Total Input Materials Reusable in Solar Industry

Here the worst scenarios in terms of circularity become obvious: scenario 1: Standard Downcycling, Scenario 2: Standard Hotknife + incineration and Scenario 4: Standard incineration. With the glass in these scenarios not being circularly recycled most of the circularity disappears. An interesting result is that scenario 5: Standard Pyrolysis performs quite well and only underperforms slightly compared to scenario 4b: Incineration ReModule (the second best overall). Scenario 5: ReModule Pyrolysis again comes out the best in this metric with only around 1% of the input material being lost and or unusable.

4. Discussion and reflection

The results of the material flow analysis, material value and circularity indicators show a large consistent pattern across all scenarios. The ReModule performs better than a standard solar panel in terms of material mass recovery, material value and circularity. These improvements are not distributed equally across all materials.

As Biosphere Solar's ReModule mainly modifies the lamination layer between the glass panels and the solar sandwich, the circularity improvements mainly come from improved glass weight and value recovery, while the recovery of other high-value materials such as silver and silicon are mainly dependent on the applied recycling process. Even here, because ReModules allow the glass to be removed prior to hydrometallurgical treatment, these processes can be applied to material streams with substantially higher concentrations of silicon and silver.

The material value recovered from the reuse of the solar glass sheets enabled through Biosphere Solar's ReModule is especially significant when compared to current industry standard recovered value. The solar recycler Solar2cycle, for example, with a process resembling scenario 2 or 3, recovers 7.50 € added value per panel. In contrast to that, the reuse of the solar glass sheet from ReModules alone recovers a material value of 21.50 €, from which only cleaning costs need to be subtracted. This shows that Biosphere Solar's circular design unlocks significant material value recovery compared to status quo recycling.

In terms of silicon recycling, achieving recovery at solar-grade purity is still one of the most challenging steps in solar panel recycling. Within the scope of this research, only pyrolysis-based recycling resulted in (close to) solar-grade purity, although all solar recyclers we interviewed expressed the clear intention to achieve solar-grade silicon recovery in the future. This shows that, while the ReModule's circular product design can improve recovery outcomes, it does not fully compensate for technological limitations in downstream recycling processes.

For Biosphere Solar, the answer to their problem statement seems clear. On all levels, material mass recovery, material value recovery, and circularity indicators, their product scores better than standard solar panels, which can be used as a clear incentive for solar park operators to choose the ReModule. At the same time, the results show that the choice of recycling method still plays a big role in determining how circular solar panels really are at the end of their life.

The Excel-based calculation tool created for this study can be used by Biosphere Solar to quantify the impact of the ReModule for buyers and policymakers. By quantifying differences in material flows, values, and circularity indicators, the tool supports a comparison between design and recycling scenarios. Large limitations exist within the data used in the tool, which are discussed later in this chapter. Therefore, the Excel calculator is designed to be adaptable, allowing changes in material masses, transfer coefficients, and material prices to be implemented easily. With this flexibility, the Excel calculation tool can be used in the future within the fast-changing context of the solar recycling industry.

4.1 Limitations

The Excel-based calculation tool and the resulting analysis have significant limitations. Although these were considered when the tool was designed, they should also be taken into account when interpreting and using the results.

One of the most significant limitations is the almost identical bill of materials of the ReModule and the standard solar panel. The bill of materials of the standard solar panel was set to be the same as the ReModule, with only slight changes made, namely the addition of encapsulation (EVA). This was done on the suggestion of Biosphere Solar, as creating an accurate average standard solar panel out of all the solar panels on the market would both be difficult and create an illusion of certainty. This difficulty arises because the materials used in solar panels and their associated masses are often owned by a specific company and cannot be traced. From this, many results for individual materials do not differ in quantity, mass, or monetary value, but rather only in quality. When the bill of materials is changed to reflect a solar panel of a specific company, the expectation is that some results would change significantly. An example of this is silver, where small changes in mass can shift the recovered material value substantially, as this material has little mass but a high value. In addition, the reference solar panel was based on the ReModule for maximum comparability. However, solar panels come in many different sizes, and many panels on the market have thinner glass than the ReModules. Nonetheless, this assumption allowed for the most comparable results.

The choice of indicators used to assess circularity also introduces limitations.

Weight-based indicators are not always suitable for representing the value recovered from solar panels, as different materials have very different values, and shredding solar panels into road filler material can hardly be considered circular, despite achieving a very high weight-based recycling ratio. To overcome this limitation, Material value was chosen as indicator as it was intended to offer a better perspective on how the ReModule's circular design enables improved circularity, despite the lack of data on remanufacturing costs. Unfortunately, this has proven to be a significant limitation for the representativeness of the results, as remanufacturing costs fluctuate significantly between recycling processes. As a result, glass insulation materials such as foam glass or fibre glass, which require lower-quality feedstock than solar glass sheets, can appear to recover higher material value. This is due to the high remanufacturing costs associated with converting contaminated solar glass cullets into insulation materials, whereas the solar glass sheets recovered from ReModules only require cleaning. This can create the impression that foam glass recovers higher material value than solar glass sheets. If this were truly the case, all glass recovered from solar panels meeting the minimum quality requirements for foam glass production would be directed toward that application.

A further important limitation concerns the uncertainty and variability of material prices. Estimating material values based on publicly available information proved to be challenging for several reasons. First, prices for key materials such as silver and copper fluctuate significantly over time making it unclear which prices are most representative to use. Second, business-to-business (B2B) prices, which are most relevant for recycling applications, are generally not disclosed publicly. As a result, material value estimates could not be derived consistently from publicly accessible sources alone.

Where available, B2B price estimates were obtained through Biosphere Solar. For materials where no such information was accessible, business-to-consumer (B2C) prices were used as a proxy. This approach introduces additional uncertainty, as B2C prices are typically multiple times higher than B2B prices and therefore do not reflect realistic transaction values in industrial recycling contexts.

To reduce this uncertainty, we contacted several solar recycling companies, including Reiling Unternehmensgruppe, Solar2cycle, and Solar-materials. However, all interviewees considered their material prices to be confidential. Some companies were willing to share indicative price ranges, but these ranges were so broad that they offered limited practical value for quantitative modeling. As a result, while all material value assumptions used in this study are methodologically grounded and transparently documented, they are not fully coherent with one another.

Beyond price uncertainty, the immaturity of end-markets and the unclear boundary between waste and product represent further limitations, particularly for solar glass and silicon.

Solar glass cullets for example do not yet have a clear recycling application. This is due to the fact that Solar glass sheet have very high and highly specific quality requirements, which are controlled through the addition of antimony with tightly controlled polarization and properties, that controls the float glas process. While this antimony is essential for producing solar glass in the first place, it poses problems at end-of-life, because it’s properties may have changed during the use phase of the solar panel or during the delamination process and can’t be controlled anymore. This makes it, in practice, impossible to recycle Solar glass cullets back into solar glas sheets according to the solar recycler Solar-materials.

As antimony is not safe for food-contact applications and tolerance levels are extremely low, recovered solar glass cullets must be heavily diluted with non-solar glass to be processed in conventional glass recycling facilities. This makes it unclear whether a truly circular handling of solar glass is currently possible, as most realistic routes remain downcycling pathways. Biosphere Solar's ReModules address this issue by enabling solar glass sheets to be reused as a whole, both through their dismantlable design and through the standardization of panel sizes, therefore solving a significant circularity challenge.

Similarly, the immaturity of end-markets affects silicon recovery. There is currently no established market for 4N-purity silicon, and the material value estimate for this quality therefore relied on a linear interpolation between metallurgical-grade (2N) silicon and 6N silicon prices.

Another limitation concerns the recycling processes and transfer coefficients used in this study. All recycling processes and most transfer coefficients were taken from a limited selection of literature sources, namely TNO (2020), Lijzen et al. (2023), and Latunussa et al. (2016a, 2016b). Although these sources can be considered reliable, they represent a small and partly outdated body of literature. Thus, there is a chance that important recycling processes/scenarios were left out, or that other literature presents different efficiencies and thus transfer coefficients.

Additionally, the different recycling scenarios, other than downcycling, used in this research are still in development and it is not known which scenario will become used at a large scale or what real efficiencies they will have. The big gap between the industry-reported net recovered material value of 7.50 €/panel for scenario 3 and our resulting (not net) material value of 22.50€/panel could also be an indicator that the recycling technologies highlighted in this study still operate far from their theoretical transfer coefficients in practice, indicating that the industry is still ramping up its industrial scale and therefore also economic efficiency.

It is therefore inherent to this research that substantial uncertainty exists regarding recycling performance.

Taken together, these limitations mean that the results of this study should be considered indicative rather than definitive. The Excel-based calculation tool is best viewed as a flexible decision-support tool that can be updated as new data, technologies, and market information become available. Its adaptability allows changes in material masses, transfer coefficients, and material prices to be implemented easily, enabling its continued use within the fast-changing context of the solar industry.

4.2 Conclusion and Recommendations

From this research, multiple challenges become clear that can be addressed either by Biosphere Solar itself or by policymakers and the solar industry at large. Although the ReModule scores well in terms of material mass recovery, material value recovery, and circularity indicators, this performance is largely driven by the recovery of intact solar glass sheets. This represents a substantial improvement compared to current recycling practices and can already be achieved even when downstream recycling relies on downcycling approaches. However, the recovery of other high-value materials, such as silver and silicon, is shown to be strongly dependent on the applied recycling method rather than on the type of solar panel used. As a result, the quantifiable improvement enabled by the ReModule can currently be demonstrated most clearly through glass recovery.

If Biosphere Solar aims to further improve the recovery of other valuable materials, such as silver and silicon, and to design future iterations of the ReModule to facilitate this recovery, we recommend working closely with recyclers to better understand which aspects of material recovery are currently difficult, costly, or inefficient. These insights could then be addressed through circular engineering, following a similar approach to the one applied in the current ReModule design.

Beyond material recovery, Biosphere Solar's ReModules appear to be particularly relevant from a repairability perspective. This represents a unique selling point that differentiates the ReModule from conventional solar recyclers, who are currently ramping up diverse technologies to recover materials at high purities despite lamination. As a next step, we recommend that Biosphere Solar assesses the potential financial benefits and material savings that could be achieved if in-field repair were implemented, either by solar park operators or by Biosphere Solar itself.

At the same time, the widespread use of downcycling represents a systemic challenge that cannot be fully addressed by Biosphere Solar alone. Downcycling is inexpensive and easy to implement, and when it is counted as recycling within policy frameworks, it can dominate end-of-life strategies. Currently, in Europe, the Waste Electrical and Electronic Equipment (WEEE) Directive is the principal policy framework governing the recycling of solar panels (The European Parliament and the Council of the European Union, 2012). The directive requires that 80% of the product mass be recycled to comply. As glass accounts for more than 80% of the total mass of a solar panel, and as downcycling is counted as recycling, this requirement can be met through the cheapest and least circular route.

To address this issue, we recommend decoupling recycling benchmarks from total input mass and excluding downcycling from being counted as recycling. Instead, setting material-specific recovery targets combined with quality-of-recovery benchmarks could incentivize both more circular product designs, such as the ReModule, and the adoption of higher-quality recycling processes across the industry.

Finally, in the continued development of the Excel-based calculation tool, we recommend expanding the study scope to include remanufacturing costs. Incorporating these costs would enable more comparable and representative results, particularly when assessing trade-offs between reuse, remanufacturing, and recycling pathways.

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Short description of task division within the group

We started the project with four of us, but soon there were only three of us left. At the start of the project, we aligned expectations and developed a joint project plan, which we presented during the delivery and presentation of the research proposal. We tracked the project's progress and task management via a shared Notion page.

Tasks were divided based on individual expertise and rotated throughout the project. Initially, Luuc focused on the MFA due to his prior knowledge, Emilie researched recycling methods, and Annemerel collected data for the Bill of Materials. While the MFA was being developed, Emilie and Annemerel prepared the presentations.

Later in the project, tasks were redistributed. Annemerel continued working on the MFA methods, while Luuc and Emilie focused on identifying data gaps in the transfer coefficients. Luuc visualized the results in nice graphs and processed them in the report, Annemerel created the poster, and Emilie gathered material price data and created the material value. The project was concluded with Luuc starting with the methods & findings section, while Annemerel and Emilie started working on the introduction and discussion part. After which all group members reviewed each other’s work, providing feedback and improving and complementing where necessary.

Statement on the use of AI

AI-based tools were used to support the writing process and to assist in identifying relevant sources for material price data in a more targeted and iterative manner than standard web searches. All sources were critically evaluated before inclusion. AI tools were not used for data generation or analysis. All scientific reasoning, interpretation, and conclusions are the responsibility of the authors.

Appendices

(see the excel attached)