BALANCING COSTS AND REVENUES FOR RECYCLING END-OF-LIFE PV PANELS IN THE NETHERLANDS

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SUMMARY

In the past decade photovoltaic (PV) solar energy in The Netherlands has become a substantial part of the total energy generation system with more than 14 gigawatt (GW) peak power installed by 2021. At the current impressive growth rate of 3.5 GW per year it is expected that the targets set for 2030 following from the climate agreements can be met even earlier. Very good news altogether, however 25 to 30 years from now the currently installed PV panels will reach the end of their useful service life and need to be discarded. The current amount of 3.5 GW of annually installed PV panels will then represent more than 200,000 ton of electronic waste to be collected and processed every year. Stichting OPEN has been made responsible for arranging collection, processing and discarding or recycling of End-of-Life (EoL) solar panels in a proper way.

The current mainstream "recycling" processes for solar panels merely leads to the recycling of the aluminum frame into raw metal feedstock, whereas the rest of the solar panel after shredding ends up as a filler material for concrete or sub base for roads mainly. It can be questioned if this practice can be sustained in future when the volumes of PV waste will be impressive compared to the amounts today. Upon request by Stichting OPEN TNO carried out a study giving an outlook towards future processes which may be used to extract all other valuable materials from discarded solar panels in addition to aluminum. Future legislation on re-use of materials or pollution prevention may be a factor to take into account as well. In this frame one could think of targets for a minimum percentage of re-use of the PV panel materials or prevention of spreading harmful substances. But whether or not a higher level of recycling will be enforced by future legislation, it is useful to look already now into alternative processes and techniques required for a more intelligent recycling, recovering not only aluminum but also silver and silicon. The latter compounds are essential for the manufacturing of new solar cells.

The study by TNO covers alternative recycling methods currently under development, for which some dedicated equipment is already commercially available (e.g. a hot knife for the separation of the front glass plate from PV panels). A key question to be answered is about the costs of advanced recycling processes compared to the potential revenues that can be generated from sales of valuable components extracted, e.g. silver. Today's PV panels production is dependent on availability of silver, which is forecasted to become a concern in future if the growth scenarios for PV develop into reality. This fact in its own should be motivation enough to start searching for and implement alternative recycling methods directed to recovery of silver as a minimum.

From the TNO study it appears that given the historical price fluctuations of the valuable materials that could be re-used, in combination with rather high and uncertain processing cost projections today it is probably difficult to make a self-sustaining business on this basis. This situation may change significantly when silver prices go up, e.g. due to a strongly increased demand by the PV industry. Also costs for advanced processing may be expected to decrease once the technology passes the development stage and is operated at an economically favorable scale. Future 'true recycling' methods for PV panels will in any case look completely different than today's common practice.

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1. INTRODUCTION

Over the next decades a growing number of photovoltaic (PV) solar panels will reach the end of their service life. This implies that large amounts of waste need to be collected and treated in an environmentally acceptable way. For the Netherlands Stichting OPEN has been appointed to make the required arrangements with regard to responsible collection and processing of End-of-Life (EoL) solar panels. In order to be able to estimate the expected future volumes of PV waste and related processing costs, Stichting OPEN has asked TNO to retrieve and report on relevant information in order to approach this issue in a proper way. This report addresses the actual request by providing an overview of current and future recycling methods for EoL PV panels. This includes estimates of potential revenues from recovered materials and processing costs. Current processes involve some re-use of materials at a very basic level, i.e. copper of cabling and the aluminium frame. These are used again as raw materials for the metallurgical industry. Apart from that all other panel components end up as low value filler materials for e.g. concrete, roads or as grinding powder. Alternative processing methods currently under development might allow to extract the more valuable materials, such as silicon and silver. Regarding the expected volume of EoL panels in the near future, recent studies suggest some 15.000 ton annually by 2030. This actually is still a very small quantity originating from the early (starting) years of PV deployment and it will grow to well above 200.000 ton/year permanently if the growth of newly built PV installations remains at the current level of 3.5 GW/year. It can be questioned if these amounts of waste materials can be responsibly re-used according to the main practice of today (filler material).

The content of this report is as follows: In section 2 an estimate of the expected future volumes of EoL panels in the Netherlands is presented. Section 3 covers an inventory of possible recycling routes aiming at recovery of useful materials. Section 4 and 5 address the estimated costs and potential revenues respectively, based on different scenarios for material price developments. Costs and revenues are compared in section 6 and section 7 finalizes with the conclusions.
A more detailed explanation of the future recycling technologies is presented in Appendix D.

2. EXPECTED VOLUME OF EOL SOLAR PANELS

Considering the future volumes of EoL PV panels to be expected, the only solid data available concerns the quantity of already installed PV installations. The total amount installed since 2015 represents a fraction more than 11 GW by 2021. The current rate of growth in 2020 and 2021 is close to 3.5 GW/yr[1]. With 20 kg per panel this amounts to 11.7 million panels per year with a total weight of 233 kton. The cumulatively installed PV panels by the end of 2021 represent 930.000 ton. All other estimates are based on scenario's and forecasts. For the Netherlands a reasonable starting point is the political ambition driven by the climate agreements to generate 7 TWh/yr by small scale PV (household) installations and another 35 TWh/yr to be generated by large scale PV parks together with wind turbines on land in 2030 [1]. If this total of 42 TWh/yr were to be generated by PV power exclusively approximately 42 GW of installed peak power would be required by 2030. This amount will be compared with the forecasted quantity of installed PV power based on a simple continuation of the current growth at a rate of 3.5 GW/yr. We assume an installation lifetime of 25 years and the growth rate of PV installations observed over the last two years to be constant from now on at 3.5 GW/yr. The maximum of all operational PV installations in this scenario would be reached in 2044 at a stable value of 87,5 GW (Figure 1). From then on, if the existing conditions prevail, the rates of building new installations and decommissioning are then in equilibrium. In this scenario 42,8 GW of installed PV could be expected in 2030, actually higher than the ambition of the Dutch government since that ambition also includes a part being covered by wind energy.

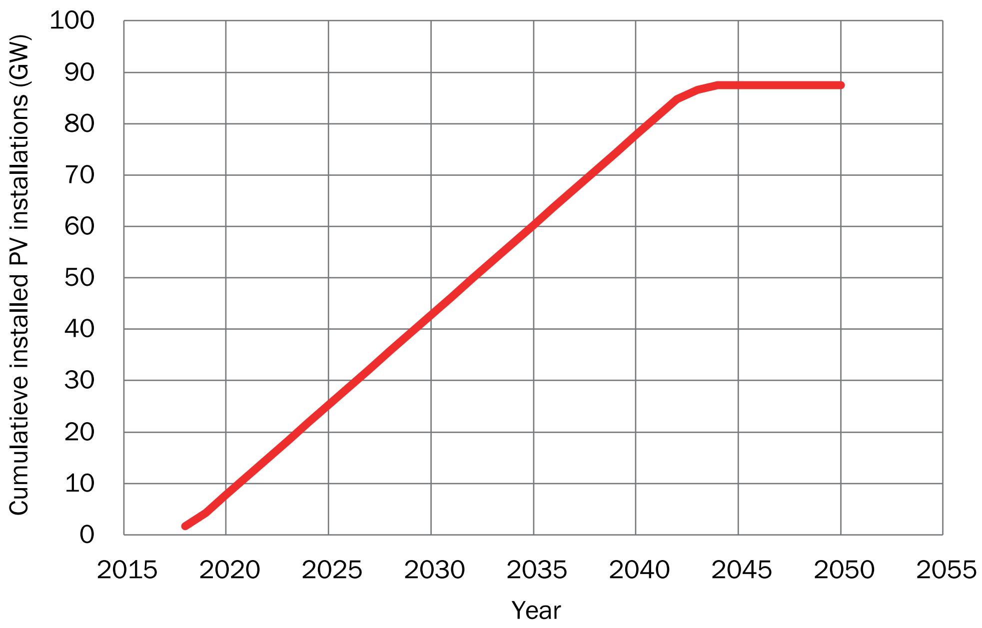

Figure 1. Growth curve based on 3,5 GW of PV installed per year from 2020 onwards and 25 year product lifetime

1. https://solarmagazine.nl/nieuws-zonne-energie/i26353/solar-trendrapport-nederland-installeerde-vorig-jaar-3-6-gigawattpiek-zonnepanelen

Whether or not the 87,5 GW of totally installed PV power would be sufficient by 2044 is dependent on multiple factors and a matter of political decisions. Looking at the targets for 2030, it can be concluded that these would be realized already earlier if the current growth rate of installed PV power is maintained at 3.5 GW/yr. Note that this current rate of 3.5 GW/yr is realistic but also higher than actually required to reach the targets for 2030. It should probably be regarded as the maximum until other plans are unveiled. Assuming 25 years lifetime and taking 2008 with a totally installed volume of 0.05 GW as a starting point, a growing annual PV waste stream may be expected from 2033 onwards. Assuming a constant growth of PV installations at 3.5 GW/yr from 2020 ahead, the projected yearly volumes of PV waste would sharply increase from 2042 as shown in Figure 2 (red curve). This is the basic scenario, to be compared with a scenario in which export of early decommissioned PV panels is taken into account (green curve). Export addresses sales of functional PV panels to other (EU) countries.

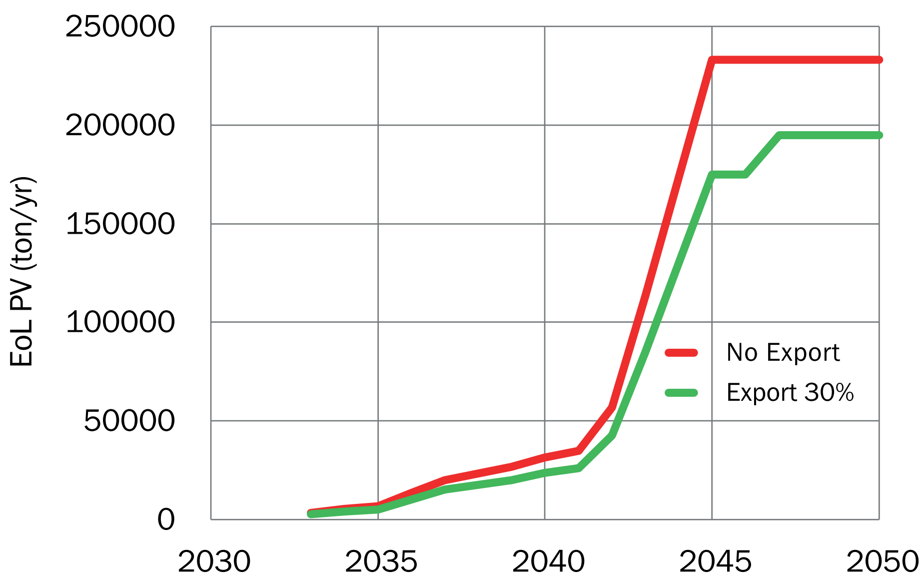

Figure 2. Projected yearly volumes of PV waste

The assumed PV panel lifetime is based on the power output warranty, which guarantees a power output of no less than 80% of the initial power after a certain period. This period is often 25 years but can also be 30 years. Technically it is reasonable to assume 25 years, in agreement with the warranty period. However, it cannot be excluded that household systems will face longer operation times, since not all PV system owners will carefully monitor the system performance and decide on replacement on an economical basis.

Although it is economically sound to keep a PV installation running for this time, it may be attractive to replace PV panels at an earlier stage (repowering), for example when higher efficient panels are introduced. This can be an economically viable option for solar park owners. If these early decommissioned panels are to be sold within the Netherlands and then used until EoL nothing changes in the expected waste volumes. Changes would only occur if these PV panels are exported, a realistic scenario in a global market with open borders and free trade. One should realize that if PV panels are exported (in particular outside EU countries) the chances are high that valuable materials are lost and PV waste is dumped illegally. Tolerating, stimulating, discouraging or prohibiting export of PV panels (waste) are all a matter of political debate, incentives and law. In case of export, the government should ensure by regulation that safety aspects are addressed by appropriate certification standards.

It is challenging to make any reasonable assumptions regarding a potential lowering of the currently expected waste volumes due to future export of PV panels. Illustrating the potential effect, a percentage of export has been used as input for calculations (green curve in Figure 2). Here it is assumed that 30 % of the PV panels installed in solar parks is decommissioned and exported after a service time of 15 years. As a side effect of export the build-up of PV power generation capacity would be slower. To compensate that slower build-up a higher growth rate of 3.9 GW/yr has been used as input for this graph. In this theoretical scenario the amount of PV waste generated would be lower. However, the targets for 2030 are still met with 49 GW operational power, actually higher than for the basic scenario. On a longer timescale the cumulatively installed power would stabilize at the same level of 87.5 GW.

3. POSSIBLE ROUTES FOR PV RECYCLING

With the estimated waste amounts derived in chapter 2 we describe the contemporary and potential future PV panel recycling technologies. Figure 3 shows an overview of the main routes for these technologies and processing steps. A common activity in all routes is "Panel collection/logistics" 1 at least in Europe, where the WEEE directive mandates that electronic waste is collected for waste treatment rather than being disposed of in landfills.

After this step Figure 3 distinguishes two main routes, namely:
- Downcycling route (= currently applied mainstream recycling technology)
- Re-/Upcycling route (= potential future recycling technologies).

The downcycling route is very basic. It involves rudimentary mechanical crushing/shredding in already existing recycling facilities for other waste streams, often together with supplementary electronic waste. Apart from the aluminium frame, junction box and copper cables, which are manually removed prior to crushing/shredding, no other materials are re-used at a higher level and end up in lower value applications instead. This can be grinding material and sub bases for roads. An example in Europe where EoL PV panel downcycling takes place is the BNE recycling facility in Belgium.

The re/upcycling routes are a lot more complex with additional processing steps required, namely:
- "Delamination" 2
- "Solar cell recycling" 3

The purpose of delamination – which occurs after the removal of aluminium frame, junction box and cables - is to separate the solar cells from the remaining PV panel components, i.e. from the glass, back sheet and encapsulant. A cross section of a contemporary standard PV panel is presented in Annex B. The "target products" resulting from this step are:
- Glass (intact or broken fragments);
- Solar cells (bottom ash, broken fragments or possibly intact).

A wide range of delamination technologies are currently under development including mechanical, thermal and chemical methods. The most advanced or promising among these methods are hot knife, waterjet, pyrolysis and incineration while chemical routes are deemed less promising, a.o. because they are slow and do not allow sufficient throughput 2 in Figure 3.

Mechanical methods, hot-knife and waterjet, are well suited to remove the solar glass from the PV panels thus enabling routes for the recovery and/or circular use of it. To achieve this, additional cleaning of encapsulant residues remaining on the glass after separation by hot-knife or waterjet is required. However, these methods don't result in access to the solar cells which remain within the encapsulant layers after the removal of the glass.

Thermal methods, pyrolysis and incineration, are effective in separating the solar cells from the encapsulant, enabling routes for the recovery of silver and silicon. 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. An incineration based PV recycling approach has been developed to prototype-scale within the EU project Life 3.0[2] and was operated for several years by Sasil in Italy. Pyrolysis is a more "gentle" approach enabling the recovery of the solar cells intact or as larger fragments. However, throughput limitations and cost are a concern. Nevertheless a recycling plant was operated for 1 year by Geltz Umwelt-Technologie. ROSI Solar, financed by Soren (the French PRO for solar panels), will establish a pyrolysis pilot installation with a throughput of 2000 ton per year.

2. LIFE 3.0 - LIFE Project Public Page (europa.eu)

Apart from the relatively high cost for pyrolysis, compared to incineration, the reasons to choose for pyrolysis over incineration are questionable. Assuming intact solar cells could be recovered in this way, the following legitimate considerations should be made in view of the practical and commercial use of these recovered solar cells:

- Compared to newly produced solar cells, efficiencies will be largely spread since the origin of the cells is variable. Measuring efficiency and binning of cells in useful ranges of efficiencies can be expected to be time consuming and expensive.
- Although part of the solar cells recovered might be still active, the design and efficiency levels at the time of recovery will be outdated making them commercially unattractive.
- Guaranteeing a lifetime of another 25 years is not feasible, given a number of different cell deterioration processes potentially occurring during field deployment of PV panels.

Considering these barriers commercial re-use of intact solar cells should be regarded as highly unlikely. Next best use of the solar cell part is the recovery of solar grade silicon. Also this is questionable considering the doping levels of the silicon. That may vary across different generations of solar cells produced and could just be regarded as ‘outdated’ in 25 year time, a period in which a lot of technological development is probably still being realized. Moreover, a guaranteed purity of recycled silicon at solar grade level will most likely pose a significant challenge.

Apart from these material quality aspects, looking at the PV growth estimates, the expected near future volume of secondary silicon recovered from PV panels is expected to be very small compared to the forecasted near future production volume of new solar cells. As a consequence recycling of silicon at solar grade level will probably be irrelevant as a source for PV industry for the coming decade(s), until an equilibrium between volumes of production and discarding is established. Nevertheless future technology development to retrieve solar grade silicon should be anticipated.

Pioneering manufacturers offering delamination equipment start to appear in the marketplace. More detailed information collected about specific delamination technologies including manufacturers, TRL (technology readiness level Appendix C), and several economic aspects can be found in Appendix D.

The purpose of solar cell recycling, is—first and foremost—to extract the economically most valuable materials from the solar cell residues obtained after the delamination step. So, the target compounds of this step are:
- Silver and Silicon

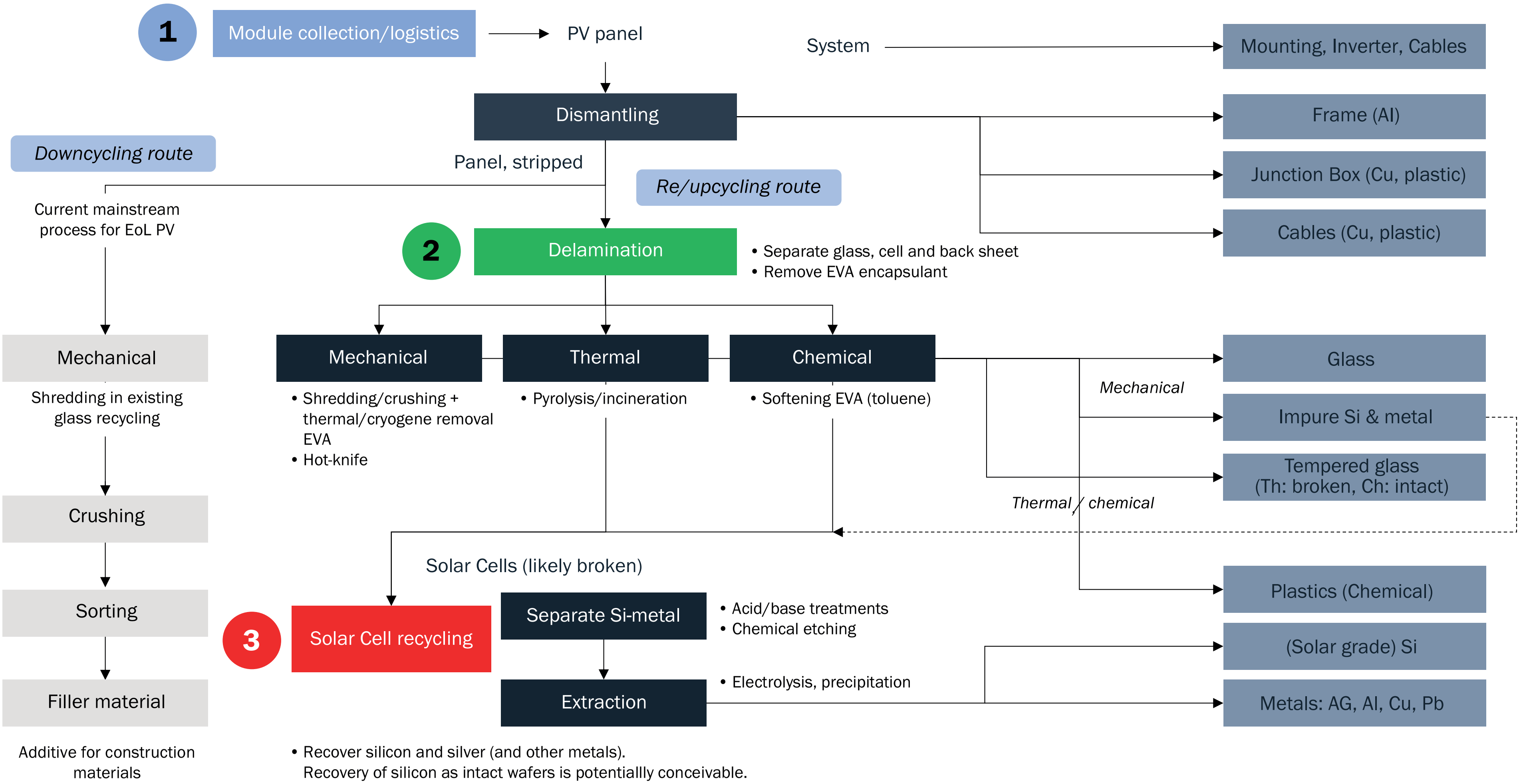

Figure 3. Current and potential future routes for PV recycling.

Despite their low mass fractions in the PV panel (see Appendix A), solar grade silicon and silver are economically interesting due to their comparatively high specific value by mass, as described in chapter 5. Furthermore, silver and solar grade silicon are listed as a 'critical raw material' in the EU RMIS (raw materials information system)[3].

Most technologies to retrieve the silver and silicon from solar cells are currently under development and are variations of wet chemical methods, such as leaching/etching and electrolysis. These technologies are well understood from contemporary extractive industries, such as hydrometallurgy and are ranking at a high TRL level (8–9). For the most valid processes, recovery rates of well above 90% of silicon and silver have been reported [3]. Next to the wet chemical methods, a notable development addresses a physical technology currently under investigation by TNO and partners. This latter method promises to avoid wet chemical waste streams achieving an environmentally superior profile compared to wet chemical methods. However, this technology is still at an early development stage (TRL level 3–4).

More detailed information collected about specific solar cell recycling technologies including TRL and several economic aspects can be found in Appendix D. Examples in Europe where EoL PV panel re-/upcycling have been developed are the Sasil facility in Italy [4] and the Veolia facility in France.

Intermediate routes between downcycling and re-/upcycling are conceivable in the near-term future. For example, recycling routes in which only some rather than all materials are recovered on a higher purity level. For instance, suitable delamination technologies could be applied to separate at least the solar glass from the PV panel enabling its high purity recovery. This would be in contrast to current approaches, where the entire PV panel is crushed/shredded and the obtained glass cullet is therefore contaminated with fragments of solar cells, encapsulant and back sheet. This type of intermediate routes might be taken by recyclers as partial and temporary solutions while waiting for more complete PV recycling technology to mature to high TRL and lower cost.

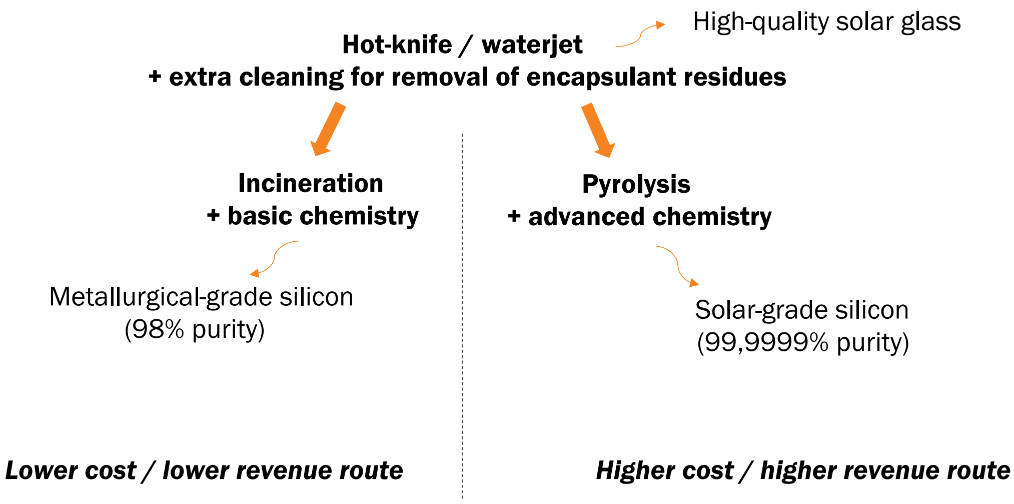

Figure 4. Recycling routes incineration and pyrolysis

3. https://rmis.jrc.ec.europa.eu/?page=crm-list-2020-e294f6

4. COST ESTIMATES

4.1 CONTEMPORARY TECHNOLOGY, THE DOWNCYCLING ROUTE

As described in section 3 contemporary PV recycling is based merely on rudimentary mechanical crushing/shredding and subsequent separation of bulk materials (first and foremost the aluminium frame). This takes place in already existing recycling facilities for other waste streams and often together with other electronic waste. So, proper delamination in the sense of separating out the solar cells from the PV panel does not occur. Solar cell recycling is therefore not feasible with contemporary technology. Instead, the crushed solar cells, along with fragments of back sheet and encapsulant remain in the low-value downcycled shreds resulting from the mechanical crushing. Cross contaminated glass-silicon material cannot be remelted and casted into transparent glass commanding a grey or black haze. This materials mixture is referred to as 'contaminated glass cullet' in the list of obtained materials below.

4.1.1 Obtained materials and costs of contemporary technology

Contemporary technology merely leads to the recovery of the aluminium frame for refinement to secondary aluminium. Copper wires are refined to secondary copper and contaminated glass cullet are applied for low value applications such as insulation and filler material. Upon request information on current processing costs can be inquired at Stichting Open.

4.2 FUTURE TECHNOLOGIES, THE RE/UPCYCLING ROUTES

In order to achieve more advanced PV recycling, i.e. recycling of economically valuable and environmentally critical materials, most notably silicon and silver, significantly more advanced technologies are required than the ones currently in use. Numerous options are being explored in current R&D projects as described in section 3. While being functionally a lot more effective in terms of extracting the mentioned materials it can generally be stated that these technologies are also associated with significantly higher costs.

Publications about re/upcycling routes in the area of PV recycling are increasing in recent years, but meaningful cost information is still scarce and uncertain due to the early development stage and low TRL levels of these technologies. Furthermore, direct comparisons between individual technologies would be rather misleading due to inconsistent TRL levels between them. The excellent recent review paper by Deng et. al. [2] addresses this complication by grouping a wide range of individual technology options into two main sub-routes, which can be distinguished by the achieved purity level of the recycled silicon:

- Sub-route 'Metallurgical grade silicon'
- Sub-route 'Solar grade silicon'.

We follow the same subdivision in this report. The costs for these two sub-routes reported in the next paragraphs are therefore directly adopted from [2] without a further breakdown into individual delamination and/or solar cell recycling technologies. The relatively wide range of the costs reflects the large data uncertainty. Note that some cost information about individual technologies is documented in Appendix D of this report, but should be seen as only indicative due to the mentioned scarcity and uncertainty of relevant data.

4.2.1 Costs of sub-route 'Metallurgical grade silicon'

After the application of any of the delamination technologies which allow the recovery of the solar cells, typically as broken fragments or bottom ash, this route involves relatively simple wet chemical methods for the solar cell recycling. 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 lower 'metallurgical grade' quality level since the antireflection coating as well as the highly doped layers remain as impurities on and in the silicon. 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.

Cost estimates of this sub-route are shown in Table 1 based on assessments by [2] from a multitude of sources and for a scale of 7000 ton (t) per year corresponding to some 350.000 panels per year. This scale is more or less representative for test facilities such as Sasil and Veolia. It is conceivable—from general economies of scale considerations—that costs for larger scale facilities may be lower.

Table 1. Costs of Sub-route 'Metallurgical Grade Silicon'

	€/t	€/panel
CAPEX	223 – 335	4 – 7
OPEX	243 – 596	5 – 12
Total Cost	466 – 931	10 – 19

Where CAPEX stands for capital expenditure of equipment and OPEX for operational expenditure for consumables and labour.
Obtained materials are:
- Aluminium from the frame (for refinement to secondary aluminium);
- Copper from wires and tabs (for refinement to secondary copper);
- Glass (for refinement to secondary glass);
- Silicon from the solar cells (**metallurgical grade**);
- Silver from the solar cells (for refinement to secondary silver).

4.2.2 Costs of sub-route 'Solar grade silicon'
This route differs from the previous one essentially in the application of a more complex chemistry. That is the utilization of selective chemical or mechanical treatments for stripping off the anti-reflection 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, time and operates at a higher cost level.

Cost estimates for this sub-route for the same capacity of 7000 t per year are shown in Table 2 [2].

Table 2. Estimated costs of Sub-Route "Solar grade Silicon"

	€/t	€/panel
CAPEX	315 – 473	6 – 9
OPEX	410 – 668	8 – 13
Total Cost	715 – 1141	14 – 23

4.2.3 Obtained materials are:
- Aluminium from the frame (for refinement to secondary aluminium);
- Copper from wires and tabs (for refinement to secondary copper);
- Glass (for refinement to secondary glass);
- Silicon from the solar cells (**solar grade**);
- Silver from the solar cells (for refinement to secondary silver).

5. POTENTIAL REVENUES

In this chapter (raw) material values related to PV panels are discussed addressing minimum and maximum material value, quantity and quality. This results in two scenarios for a potential total value of the materials present in a PV panel. It should be noted that for some of the key materials inside the panel the values have fluctuated considerably in the past, making any future price prediction unreliable.

As described in section 3, after removing frame, junction box and cabling the bare PV panel is left. For the calculation of the potential revenues it is assumed that glass, back sheet and encapsulant can be removed and separated from the solar cells, which probably will end up broken in small pieces. Once the solar cells (shreds) have been separated from the other parts they can be processed following established metallurgical extraction methods to recover silver and metallurgical grade silicon. Alternatively, when targeting solar grade silicon as a product, more complex chemical processing is required to completely remove metallization residues, antireflective coating and doping layers from the solar cell shreds.

Apart from the aluminum frame, silver and silicon as the most valuable materials contained inside a PV panel, are in principle worth extracting. Both materials are recognized as strategic by the EU policy. That is: Silver as such has a limited availability in Europe and is largely dependent on import. This provides a good argument for silver recovery from discarded PV panels but also drives efforts to decrease the silver content in cell metallization. A decrease in silver content of 50 % between 2016 and 2028 is predicted [5] [6]. On the long term the silver used for solar cells needs to be replaced or strongly reduced in quantity in any case, since the amounts that can be mined from known reserves are probably insufficient to fulfill all ambitions considering the growth of PV installations worldwide [7]. A sharp price increase as a result of shortages would drive the PV industry even faster towards developing and applying alternative metallization (e.g. based on copper). These factors are to be taken into account when estimating (future) revenues of silver sales from discarded PV panels. This value may go up, down or disappear completely. Figure 5 shows the fluctuations of the silver price in the last two decades.

Figure 5 Silver prices in the period 1999–2021

Silicon is labeled ‘strategic’ when refined up to solar grade or even higher purity (semiconductor grade, the semiconductor grade material being essential for production of computer chips). This is not related to availability of silicon from reserves as an element, but is due to the fact that virtually the majority of solar grade silicon refining industry is present outside of Europe (Asia mainly). Given the forecasted strong exponential growth in production of PV panels, the quantities of silicon potentially extracted from discarded PV panels will not keep up with the demand for solar grade silicon in the foreseeable future and likewise will not substantially relieve any shortage problem. If the labeling of high grade silicon (solar and semiconductor grade) as a strategic material is seriously implemented, the existing solar grade silicon refining industry present in Europe should be strengthened and expanded, taking quartz sand (SiO_2) as a primary resource.

Considering the large price variations for this material the market for solar grade silicon is actually far from mature. The current extremely high price levels of 30−40 euro/kg [8] are driven by a temporary shortage of production capacity and should be regarded as economically unhealthy and non-sustainable. A more realistic value is probably 5−10 euro/kg, although it should be noted that silicon purification is an energy intensive process and prone to fluctuations in the energy price.

Given the uncertainties and variations in price levels of the different valuable materials that can be recovered from PV panels, minimum and maximum values based on historical data have been determined as an input for calculating a range of potential material revenues. These values are summarized in Table 3. The figures given in the table are subject to change due to technological developments, there is a tendency to use less materials in newer generations of PV panels in particular considering silver, silicon and aluminium.

Table 3. Minimum and maximum values for most important PV panel materials

Material	Value (Euro/kg)			Quantity (kg/panel)	
	Minimum	Maximum	Ref		Ref
Silver	150	1050	[9]	0,0078	[5]
	401	650	[2]		
Metallurgical silicon	1,58	2,51	[2]	0,7	[3]
Aluminium	0,93	1,86	[2]	3,6	[3]
	1,40	2,33	[10]		
Glass (crushed)	0,037	0,16	[2]	14	[3]
Copper	4,09	6,51	[2]	0,06	[2]
	4,13	7,23	[11]		

On this basis several revenue scenarios have been established, assuming a typical standard PV panel of 60 cells, 130 mg silver/cell, aluminum frame, front glass, polymer back sheet and a total surface area of 1.6 m^2. The two most realistic scenarios are discussed in more detail: A minimum and maximum scenario assuming relatively low purity (metallurgical grade) silicon is presented in Figure 6.

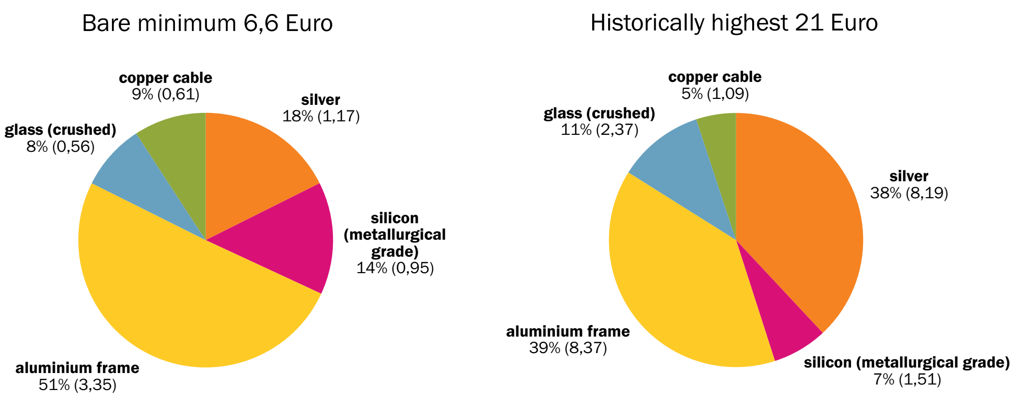

Figure 6. Minimum and maximum revenue for all valuable materials extracted, assuming metallurgical grade Si and crushed glass. Absolute material values in euro are given in brackets.

The bare minimum value of all materials involved is calculated to be just below 7 euro and the historically highest scenario with 21 euro total value is based on the highest material values from the recent past.

6. BALANCING COSTS AND REVENUES

Comparing the average material value (14 euro/panel) to the associated predicted processing costs (15 euro/panel) it can be concluded that costs for recycling are rather high compared to the revenues.

Given the rather high cost levels together with the uncertainties in the costs projected and in addition to the substantial fluctuations in material values over time it should be regarded as highly uncertain if investors would be willing to take the risk for starting up a commercial recycling business.

The value of the aluminum frame is dominant. Since this is also the component that can be recovered most easily, it is based on these revenues probably economically most attractive to just remove and recycle the aluminum frame and discard the remainder of a panel at the lowest possible cost. This is also today's practice.

In principle high quality silicon (solar grade) could be recovered when more effort is put into the purification of the material, however two aspects should be questioned:

First, can the higher material value compensate for the higher processing costs involved? These are estimated at 14–23 euro/panel, 4 euro higher than for metallurgical grade silicon (comparing costs shown in Table 1 and 2). A minimum value of around 3 euro/panel should be considered as realistic for solar grade silicon. However, this is only around 2 euro more than for metallurgical grade material, resulting in extra net costs for recovery of solar grade silicon.

Second, it is debatable if the current purity level of what is defined as 'solar grade' today would be able to meet the PV manufacturing standards in 25 years from now and if these standards could be met, it is uncertain how the purity level can be guaranteed. Based on these considerations and current costs/revenue ratio the recovery of solar grade silicon is merely left as a theoretical option. That might change when energy prices rise since production of solar grade silicon is very energy intensive, with 110 kWh energy input required for 1 kg material produced. The recent geopolitical events, resulting in a sharp increase in bulk electricity price with a factor 5, underline the necessity to carefully monitor the price and availability of energy.

To illustrate what this means for the value of silicon: Where the pre-Covid bulk trade price for electricity of 0.04–0.05 euro/kWh resulted in an energy expenditure of approximately 4–6 euro/kg of solar grade silicon, the current geopolitical situation has driven up the electricity price to 0.25 euro/kWh and higher. For the production of 1 kg solar grade silicon this would translate into more than 25 euro, a factor 5 more than a year earlier. This illustrates the close relationship between energy price and the actual value of solar grade silicon. However two aspects should be taken into account:

- The price level of around 40 euro/kg during the last few years (before the sharp increase in electricity price) is not energy related but driven by (temporary) shortages in production capacity.
- Although high energy costs are an argument to recycle silicon from discarded PV panels, one should realize that this recycling process still requires substantial amounts of energy if solar grade silicon is targeted as a product: Depending on the quality of the metallurgical silicon primarily obtained from solar cells the required energy input can still reach a level of 100 kWh/kg, hardly less than solar grade silicon directly produced from quartz sand.

Although the current state of art for recycling technology probably does not allow any grade higher than metallurgical silicon, a sustainably high price level for electricity can be a driving force to develop less energy intensive methods for recycling of silicon from discarded PV panels at solar grade level in future.

In principle the full glass plate could be recovered intact from an EoL PV panel, by means of hot knife or water jet technology. If assumed to be applicable in new PV panels it represents a relatively high value. However, it can be questioned if such a glass plate will be used again in the same application given the fact that a glass plate deteriorates in the field and product sizes for newly built panels change all the time. If, more realistically, crushed glass would be assumed. The material value would be 0.5 to 2.4 euro.

Nevertheless, it could be useful to recover the glass intact, since it results in clean iron free highly transparent glass suitable for remelting leading to new solar applications. An additional reason to do so 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. It probably means that waste solar glass needs to be processed separately anyway, providing a higher chance for re-use as solar glass and keeping it in a truly circular loop.

In conclusion, based on the current knowledge, the expected future revenues for materials extracted from EoL PV panels are relatively low and the costs associated with a higher level of materials recovery from discarded PV panels are relatively high. It can be expected that in the bare minimum scenario the costs will not be fully compensated by the revenues, i.e. this is regarded as economically non-viable.

The more optimistic historically highest scenario in principle shows feasibility of a positive business case. However, given the risk of fluctuations in material value, combined with uncertainties in costs, this does not automatically imply that investors would be keen to start a commercial recycling business based on that scenario. Even more important, the aluminum frame representing a substantial part of the total material value, is also the component being most easily removed and recycled, leaving a low value frameless PV panel. This further increases the pressure on the uncertain balance between potential revenues and costs of recycling for the remaining materials in a PV panel. It follows that replacement of the currently applied waste processing by a more advanced recycling technology is not likely to happen. This may change if material values increase sustainably and/or processing costs for advanced recycling decrease as a result of further development or larger scale processing. Glass and in particular solar grade silicon are energy intensive materials. This means that a future rise in energy price may affect the revenue/cost balance for advanced recycling in a positive way. Legislation can also influence the replacement of the present waste processing technology. If environmental factors around the current EoL processing practice would become a concern, additional legislation would be a political way to discourage or even prohibit todays practice. If advanced recycling methods were to be enforced by law today, the costs would probably be higher than for the current (downcycling) processes.

7. CONCLUSIONS

This report provides a comprehensive overview of the current status and perspectives of EoL solar panel recycling. It distinguishes between two main routes. Downcycling is the main contemporary practice in the EU 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.

Cost estimates and potential revenues for the re-/upcycling processes have been documented, based on information available in the relevant scientific literature, public reports and by expert interviews. 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.

When making up the balance the report concludes that the costs typically outweigh the revenues significantly, based on different scenario's studied. The reason for this is, most importantly, the relatively low and uncertain potential revenue from recycling owing to the limited economic value of materials in the solar panels. In the case of downcycling this revenue results mostly from the aluminium frame and is outweighed by the processing costs for the remainder of the PV panel. 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. So, on this basis it can be 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 [12].

In the future, profitable recycling without subsidies or fees is not ruled out, but can only be achieved when relatively high sales prices for the recycled materials are achieved on the revenue side and/or costs of PV recycling technologies decrease. A perspective for the future is that costs may indeed decrease as PV recycling technologies reach higher TRL levels and economies of scale. So, in the longer run, the balance between costs and revenues could improve. Since glass and solar grade silicon production are energy intensive, an increase in energy price will result in a higher value of those materials. Silver resources are limited and the expected growth of PV installations in its own could lead to a substantial price increase or even lack of silver availability. In such a situation one could typically expect advanced recycling to take off, just for the recovery of silver to start with. On the other hand if silver is replaced by lower costs materials the embedded materials value of PV panels will decrease even further, hampering advanced recycling. Finally, also future legislation considering waste treatment may substantially affect the options for recycling processes.

These considerations underline the fact that the figures discussed in this report are subject to changes and should be reviewed from time to time.

RECOMMENDATIONS

Based on the current state of the art and knowledge of available recycling technologies, we conclude that the costs for advanced recycling methods are uncertain while the potential revenues fluctuate considerably and are also uncertain in future. More technological developments are required to decrease processing costs. It is recommended to follow these developments, in particular the pilot projects considering pyrolysis and incineration based processes for treatment of PV waste. For now it means that responsible recycling of PV panels needs to be financed. Similar to the regulation for household electronic equipment a fee could be levied on newly purchased PV panels to cover the costs of waste processing or recycling.

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APPENDICES

A. ASSUMED MATERIALS COMPOSITION OF EOL SOLAR PANELS

The following composition is representative for an industry average of the recent past and was therefore assumed for most of the calculations carried out in this report [3]. The figures given in the table are subject to change due to technological developments.

Table 4. Mass composition of 1000 kg of PV waste as input to the recycling process

Mass composition of 1000 kg of PV waste as input to the recycling process.

Component	Quantity	Unit	Percentage (%)
Glass, containing antimony (0.01–1%/kg of glass)	700	kg	70
PV frame, made of aluminium	180	kg	18
Polymer-based adhesive (EVA) encapsulation layer	51	kg	5.1
Solar cell, containing silicon metal	36.5	kg	3.65
Back-sheet layer (based on Polyvinyl Fluoride)	15	kg	1.5
Cables (containing copper and polymers)	10	kg	1
Internal conductor, aluminium	5.3	kg	0.53
Internal conductor, copper	1.14	kg	0.11
Silver	0.53	kg	0.053
Other metals (tin, lead)	0.53	kg	0.053
Total	**1000**	**kg**	**100**

B. CROSS SECTION OF STANDARD PV PANEL

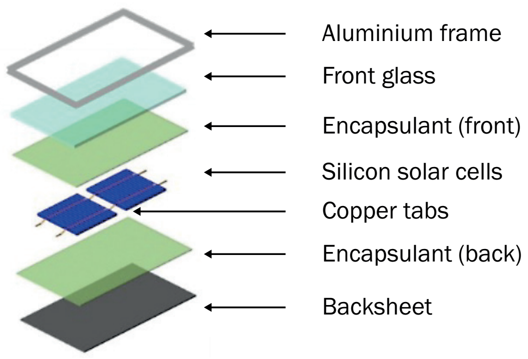

Figure 7. Cross section of a contemporary standard PV panel

C. TECHNOLOGY READINESS LEVEL (TRL)

Technology readiness levels (TRLs) are helpful for estimating the maturity of technologies. They are also increasingly used and referred to by the European Commission, e.g. in the EU Horizon 2020 program for R&D funding. They are based on a scale from 1 to 9 with 9 being the most mature technology.

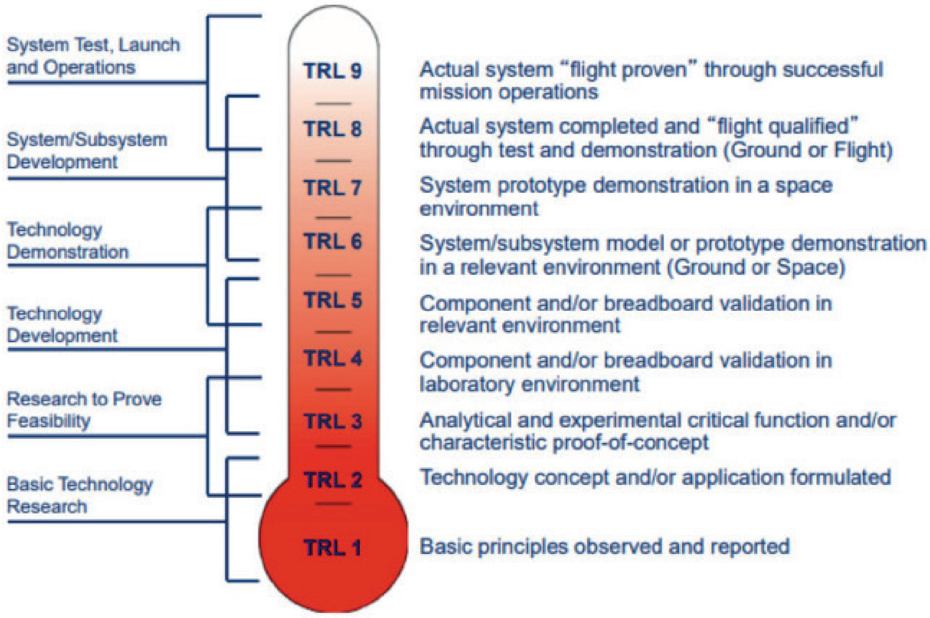

Figure 8. Technology readiness levels

D. INFORMATION SHEETS PER RECYCLING TECHNOLOGY

This appendix provides information on individual delamination and solar cell recycling technologies, i.e., the ones listed in the table below.

Table 5. TRL overview of recycling technologies

Technology overview	TLR levels
Delamination technologies	
Hot knife	7 – 8
Waterjet cutting	9
Flash pulse	6 – 7
Super critical CO_2	2 – 3
Solar cell recycling technologies	
Traditional chemical methods	9
Innovative chemical methods (e.g. MSA)	8
Physical methods	3 – 4
Pyrolysis	4 – 5

D.1 DELAMINATION TECHNOLOGIES

PYROLYSIS

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 in principle be reprocessed into building blocks for production of new polymers.

Since the typical temperatures in the range of 400–600 °C used in a pyrolysis process are much lower than for incineration processes, such a process is in principle suitable for recovery of intact solar cells from a PV panel.

There are drawbacks of application of a pyrolysis process to PV panels:

- Under strict exclusion of oxygen the polymers used in PV panels leave a film of soot residue behind on the glass and solar cells. To minimize soot formation the total fraction of organic material to be removed should be limited, the consequence is that the process throughput is inherently low compared to incineration. In addition small amounts of oxygen need to be added during the processing to gently burn off this soot residue. These factors make the process more complex and more time consuming than simple incineration.
- The fluoropolymer containing back sheet may pose a challenge regarding waste gas treatment that is required to scrub fluor containing compounds.

The problems with the fluoropolymers in the back sheet can be circumvented if the back sheet is removed prior to the pyrolysis process, using e.g. hot-knife or water jet technology. The relatively long processing time and low throughput however seem to be unavoidable. Based on our own preliminary estimates considering commercially available equipment for pyrolysis the minimum costs for this process would amount to 4 euro per PV panel.

HOT KNIFE

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. The Japanese company NPC offers this type of equipment for industrial use. A hot knife installation consists of an automated Alu frame and junction box separator in line with an automated glass separator. Purchase price of such an installation is at €1,3 million with k€ 579 for the hot knife part. The processing time is at approximately 90 sec/panel for PV panel with back sheet and unbroken / broken glass. Applicable panel sizes are 960 mm × 1,620 mm and 1,000 mm × 2,000 mm. The glass thickness range is between 2,8 to 4 mm. Annual throughput is estimated to approx. 115,000 panels/year recovering 1600 ton of glass and 230 ton of waste polymers. Metal scrap consisting of Alu frame, cables and encapsulant are at an amount of 460 ton. At present 4 of these installations are in operation solely in Japan.

A drawback of the technology is present by the wear of the knife against the glass plate and local overheating of the polymer causing stickiness complicating the process. The glass plate requires post-treatment for removal of the polymer residue. This can be done with a thermal process step.

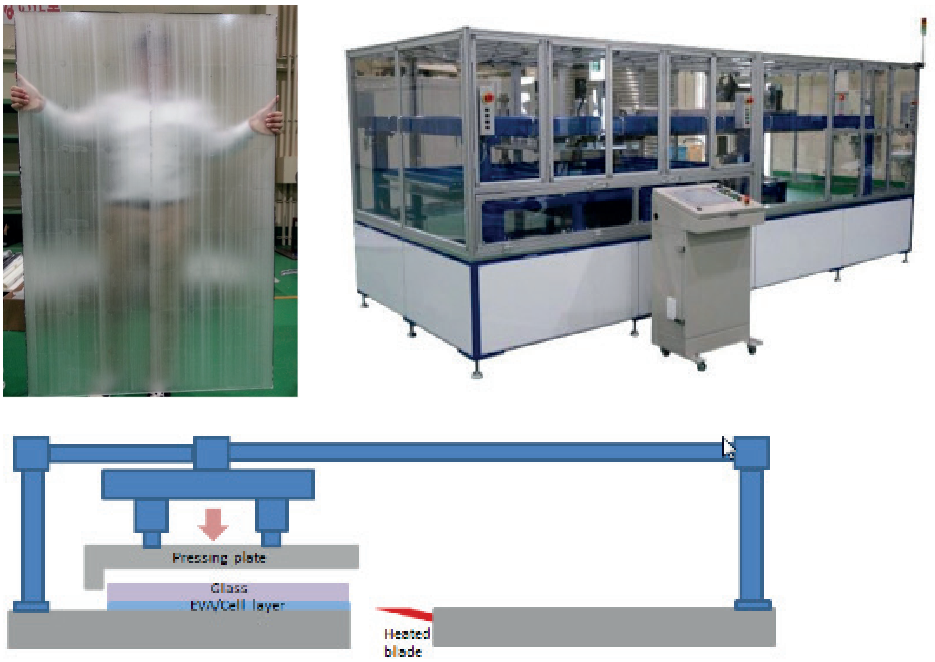

Figure 9. Left, PV glass plate after separation with polymer residue. Right, NPC Japan hot knife glass separator installation. Below working principle of the hot knife installation

WATERJET CUTTING

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. For the process front glass condition should be unscathed. At present only one company offers waterjet cutting services mainly for thin film panels. Lately tests have focused on the separation of the glass plates from EoL Si PV panels (see Figure 10). Two axis industrial robotic waterjet systems for metal cutting are available for an estimated cost price of 95k€. The energy consumption is at 20,000 Watts and one operator is required. Processing costs and revenues are not available at present.

Figure 10. Displays a recycled glass plate from an EoL Si standard PV panel

FLASH PULSE

FLAXRES Germany developed the Flashlamp process for Veolia. The technology comprises a millisecond flash pulse of a certain wavelength to interact with a substrate interface therefore release of the polymer layer. This high-intensity and low-energy light pulses are able to separate the glass plate of a PV panel where stack components are separated layer by layer. The process was developed for thin film PV and is recently used for standard Si panels. A drawback of the technology is that Si panels have to be sorted as each type requires an adjusted lamp setting. The process is quite fast especially with lamp arrays in parallel. This process allows for fractioning of an entire module into a clear frontside glass, and if applicable a clear backside glass, polymers, bus bars and light absorbing materials like silicon wafers in less than one second. Thin-film modules can be treated in a similar way as wafer-based modules by changing exposure time and light intensity. Thermal simulations have shown that temperatures of several hundred degrees Celsius inside thin films or even silicon wafers can be reached by low heating energies on glass substrates that stay close to room temperature during the whole process. The construction of a pilot line, dedicated to dismantling modules with a size up to 2 m × 1 m is in progress. Its light source is going to enable the exposure of an entire photovoltaic module at once. Since the equipment fits into a standard sea container, it can easily be transported to any production site for solar modules, photovoltaic power stations or places for end-of-life module collection to minimize transportation routes, especially for glass. At present only FLAXRES is selling the flashlamp system. Cost structures are unknown. [13]

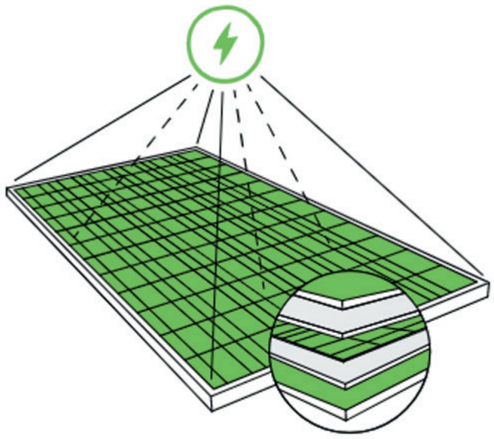

Figure 11. Schematic of FLAXRES / lamp process

SUPER CRITICAL CO_2

Supercritical CO_2 is an excellent alternative to solvents for cleaning a wide range of materials. Practiced for over a century, the process entails bringing carbon dioxide to a temperature above 31°C and pressure to above 74 bar simultaneously. Under such conditions, carbon-dioxide behaves in a "supercritical" phase, displaying properties of both a gas and a liquid. The properties of Supercritical CO_2 are similar to those of a solvent, and may be used as a substitute for solvents in full or in part. Supercritical CO_2 is a harmless cleaning and particle-removing agent; there is no risk of oxidation or other damage to the material undergoing treatment.

Separated from the contaminants, Supercritical CO_2 can be recycled indefinitely while its properties remain unchanged. Supercritical CO_2 avoids use of solvents or detergents which represent a significant cost reduction both for their consumption and elimination. First attempts are made to use Supercritical CO_2 for removal of EVA encapsulant on glass plate and solar cell surfaces. The technology ranges at a low TRL at present and is for the particular case of PV panel recycling in its infancy.

D.2 SOLAR CELL RECYCLING TECHNOLOGIES

TRADITIONAL AND INNOVATIVE CHEMICAL METHODS

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.

Other, more innovative methods aim at reducing chemical waste. A good example is the Methanesulfonic acid (MSA) technology. MSA is safer and environmentally more friendly than the mineral acids (HCl, H_2SO_4, HNO3) currently employed for leaching metals from primary and secondary sources. The promise of MSA is that it can be reused for multiple cycles i.e. it acts as a 'chemical shuttle' thereby reducing chemicals consumption and waste. Not necessarily more expensive compared to 'traditional chemistry', e.g. acid leaching by HNO3 (65%). Rationale, higher costs for MSA is compensated by reduced consumption and waste of chemicals.

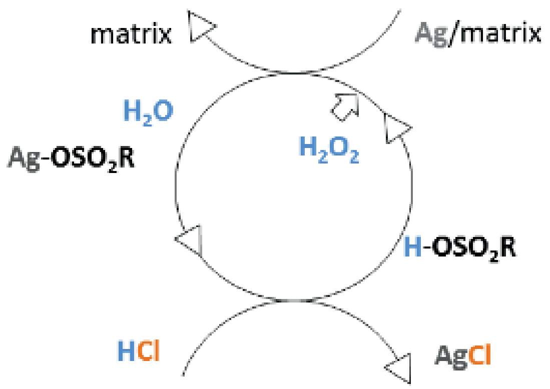

Figure 12

PHYSICAL SOLAR CELL SILICON RECYCLING TECHNOLOGY

Silicon, represents a valuable material given its purity and the amount of energy put into it with its manufacturing. The aim is to reuse this material at a higher level than today's common practice and ultimately again into solar cells. Presently the PV silicon industry is rather conservative and making any changes to the existing production materials and processes meets serious barriers. That is for good reasons and linked to product quality. Related to this it is difficult to introduce recyclate silicon of unknown source and purity in the production process. Given the relatively small volumes of today's available recycle PV silicon it is difficult to invest in purification of this material up to solar grade silicon. This makes the barrier for reuse in PV production currently too high, rendering it difficult to find a business case. To overcome this barrier, two applications of high grade silicon (other than solar cells) have been identified as potential market launching opportunities: silicon-aluminum alloy and improved lithium battery silicon-anodes.

These applications enable for a gradual growth and improvement of the recycling processes to ultimately render it suitable for solar cell production. Silicon scrap harvested from EoL PV panels contains several impurities originating from the cell metallization and dopants. To render the silicon suitable for the novel TNO physical solar cell recycling technology a purification step is required. The technology necessitates pre-processing to separate solar cells from panel stack either complete or in pieces. Recyclate production of silicon with physical technology saves 65% in energy consumption. Recovery of Si and Ag is feasible with this technology. Minimal amount of aluminium, part of the solar cell, is destructed in the process including the semiconductor dopants. Silicon production price based on this novel technology can be estimated to €2,55/kg. The production process depends strongly on the actual electricity price level.

Currently about 7,000,000 metric ton (MT) of silicon is being produced on global scale. Of that total silicon, about 500,000 MT is polysilicon, 90 % of this Poly-silicon is used for solar cells (solar grade silicon) and 10 % for Semiconductor grade silicon. The 6 largest producers of poly-silicon at the moment are: Tongwei - 96,000 MT (China), GCL Poly - 90,000 MT (China), Wacker - 84,000 MT (Germany and USA), Daqo New Energy - 80,000 MT (China), Xinte - 80,000 MT (China) and East Hope - 40,000 MT (China). Four out of these five Chinese producers, have most of their production capacity located in Xingjiang. Silicon is a 'critical' material since it is essential for Europe and Europe produces far less than it requires. The silicon world market revenue is at present 4,24 billion US$ growing to 8,67 billion US$ in 2027 with a solar and semiconductor part of 7% (see table).

Table 6. Market revenues of silicon 2020 to 2027

Market size value in 2020	USD 4.24 billion
Revenue forecast in 2027	USD 8.67 billion
Growth Rate	CAGR of 4.6% from 2020 to 2027

Near future economic perspective is based on the assumption, that the EU is in the process of establishing the carbon border adjustment mechanism (CBAM) potentially starting from 2025. Companies from outside the EU would then have to pay a tax on the CO_2 they emitted when producing in their country. In time the CBAM mechanism would be beneficial for a European manufacturer which is not affected by this tax.

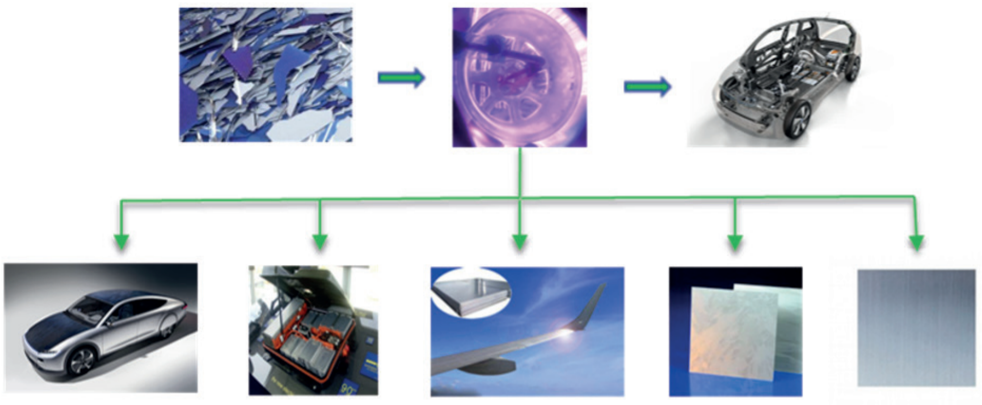

Figure 13. Silicon solar cell waste, physical process, lower grade 99,6% purity for low weight high strength materials and e-car battery silicon-anodes. Final goal production of new solar cells with solar grade (9N) silicon

D.3 EXAMPLE OF AN ENTIRE PV RECYCLING PROCESS

FULL RECOVERY END-OF-LIFE PHOTOVOLTAIC, FRELP

The EU project FRELP developed an entire PV recycling process including delamination and solar cell recycling technologies. This process has the following main characteristics in terms of delamination and solar cell recycling technologies:

For delamination a combination of hot-knife and incineration is used. The hot-knife technology leads to the separation of the glass from the PV panel. The incineration process 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 bottom ash is treated by an acid leaching process, the goal of which is to separate the silicon from the other metals in the ash. This is achieved because the metals are dissolved in the leaching solution while the silicon remains and can be recovered by filtration. The recovery efficiency for silicon is reported to be 95% at metallurgical grade purity. The dissolved metals are treated by electrolysis for which a recovery rate of 95% is reported as well, both for silver and copper at a purity level that is suitable for secondary metal refinement. More details of the FRELP process are described in [3] in conjunction with a life-cycle assessment of this process.

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