

THE USE OF RECYCLED SEMICONDUCTOR MATERIAL IN CRYSTALLINE SILICON PHOTOVOLTAIC MODULES PRODUCTION - A LIFE CYCLE ASSESSMENT OF ENVIRONMENTAL IMPACTS

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Abstract

To offset the negative impact of photovoltaic modules on the environment, it is necessary to introduce a long-term strategy that includes a complete lifecycle assessment of all system components from the production phase through installation and operation to disposal. Recycling of waste products and worn-out systems is an important element of this strategy.

As the conclusions from the previous studies have shown, thermal treatment provides an efficient first step in the recycling process, while chemical treatment was more advantageous in the second step.

This study aims to assess the environmental impact of recovering and recycling the valuable semiconductor silicon wafer material from photovoltaic solar cells. A comparison was made between producing new solar cells with or without recycled silicon material.

The analysis of the photovoltaic cell life cycle scenario including material recycling presented in this article was performed using SimaPro software and data combined and extended from different LCI databases. The idea is that the use of recycled materials, which were energy-consuming in the primary production stage, allows to meaningfully reduce the energy input in the secondary life cycle.

All stages of the silicon cell life cycle contribute to the Global Warming Potential (GWP) and greenhouse gas emissions reductions through the use of recycled silicon material represented 42%. The total environmental impact of photovoltaic production can be reduced by as much as 58%, mainly through reduced energy consumption in the production process of high purity crystalline silicon.

Keywords: photovoltaic solar cells, recycling, life cycle analysis, silicon, metals and glass recovery

30 Introduction

31 Photovoltaic (PV) technology is considered an energy source responsible for relatively small
32 amounts of waste, as none is generated during the lifetime of PV modules. We should not
33 however, ignore the waste stream generated at the end of the exploitation phase of PV
34 installations. A small stream of waste is also created at the production stage of products that
35 are rejected by quality control, as well as during operation in the case of damaged modules,
36 which show reduced efficiency (e.g., anti-reflective coating defects).

37 In the European Union, photovoltaic modules are defined as e-waste in the WEEE Directive
38 (Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on
39 waste electrical and electronic equipment). The term ‘electrical and electronic equipment’ or
40 EEE is defined as equipment designed for use with a voltage rating not exceeding 1,000 V for
41 alternating current and 1,500 V for direct current, equipment dependent on electric currents or
42 electromagnetic fields in order to work properly, equipment for the generation of such
43 currents, equipment for the transfer of such currents, or equipment for the measurement of
44 such currents.

45 Reviews of PV life cycle assessment (LCA) have been published [1–4]. However, they do not
46 take into account the stage involving recycling and re-use of the silicon material, the
47 production of which, due to the high purity required, significantly impacts the environment.
48 The reason why scrap silicon from electronic-grade silicon production has not been taken into
49 account is because its share in the market in 2005 was only 5% [5]. In this calculations silicon
50 from PV modules recycling was not considered as scrap from production. Some researchers
51 have included the end of life (EoL) phase of PV modules by burying the waste in landfills or
52 recycling them [6], but recycling covers only the glass, plastic, metal components, and other
53 waste materials without recovery of the valuable semiconductor material.

54 Life cycle inventory (LCI) databases for silicon photovoltaic modules are generated with data
55 from eleven European and American (US) photovoltaic companies participating in the
56 European Commission’s Crystal Clear project [5]. Many researchers focused on the energy
57 payback time (EPBT) [1, 7-21]. The EPBT is between 3.5 and 5 years, depending on ambient
58 irradiance, and for systems installed in desert areas that use crystalline silicon (c-Si) modules
59 the EPBT is 2.5 years [22]. Most of the energy consumption of PVs is linked to the module

60 production step [4]. However, it is worth noting that EPBT is an index dependent on
61 insolation (localization) [23], and therefore cannot be universally applied to comparisons.

62 On the other hand, the environmental impacts of a polycrystalline PV module and a wind
63 turbine using the LCA method were compared [6]. This study modelled landfill disposal and
64 recycling scenarios for decommissioned PV modules and wind turbines, and compares their
65 impacts to those of the other stages in the life cycles. In contrast to this analysis, another LCA
66 was based on the recycling step focusing mainly on the glass (74.16% recycled) and
67 aluminium frame (10.30% recycled) with the assumption that the energy input for these
68 processes was calculated as 26% of the total energy required in the manufacturing process
69 [24].

70 Some articles [e.g., 25] discuss the application of LCA methodology to the innovative process
71 of only recycling PV waste panels. They conclude that the majority of the impacts for the
72 recycling process are related to the transport of PV waste to the site, the plastic incineration
73 processes, and further treatments (including sieving, acid leaching, electrolysis, and
74 neutralization) for the recovery of metals (including silver) from the bottom ash.
75 Environmental benefits of recycling are related not limited to the space in landfills, but also to
76 energy savings, avoided raw materials extraction, and emissions reductions.

77 The operational life of photovoltaic modules guaranteed by manufacturers is typically 25
78 years, though there is a tendency to extend this period as their production technology
79 improves. However, practice shows that many users exchange their PV installations before
80 the theoretical end of life, after an average 17 years of use, in order to obtain better energy
81 yields resulting from continuous technology improvements [26]. At the stage of manufacture
82 and assembly, the level of waste is about 2 per cent. On the basis of the installed power in
83 Europe and assumed life expectancy of modules (17 years), the amount of PV waste is
84 estimated to rise to 5,500,000 tons by 2026 [27].

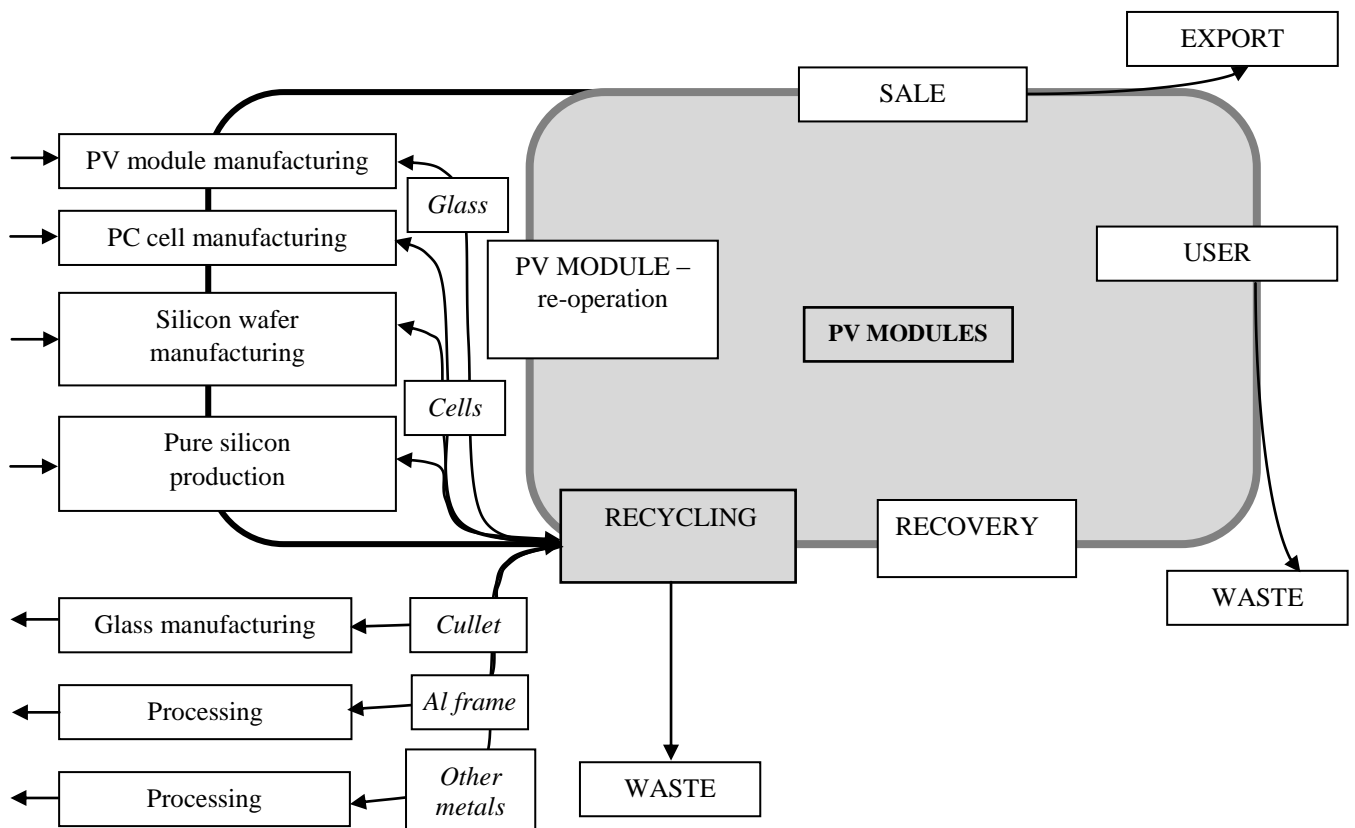
85 Crystalline PV modules have been the most desirable choice for years and accounted for
86 approximately 85–90% of the global PV market. Si-wafer based PV technology accounted for
87 about 95% of the total production in 2017 [28].

88 The ecological impact of silicon is high because the metallurgical process for silicon
89 purification has a high energy demand and because of the use of submerged arc and induction

90 furnaces. Some toxic compounds such as chlorine can be emitted in the process [29]. The use
 91 of highly harmful substances such as hydrogen fluoride (HF) and hydrogen chloride (HCl) is
 92 reduced in PV production. For example, in the US photovoltaic industry the quantity of these
 93 chemicals still being used is less than 0.1% of the total amount of chemicals used [5]. Adding
 94 pure silicon from the recycling process can decrease the high cost of solar grade silicon
 95 production and limit unfavourable impacts to the environment.

96 Silicon is the most important material recoverable from classic c-Si solar cells [30], though
 97 the value of silver increases the profitability of the recycling process [31–32].

98 The flow of materials in the recycling system for PV modules is shown in Figure 1.



99
 100 **Figure 1.** Material flow in the PV module recycling system [26].

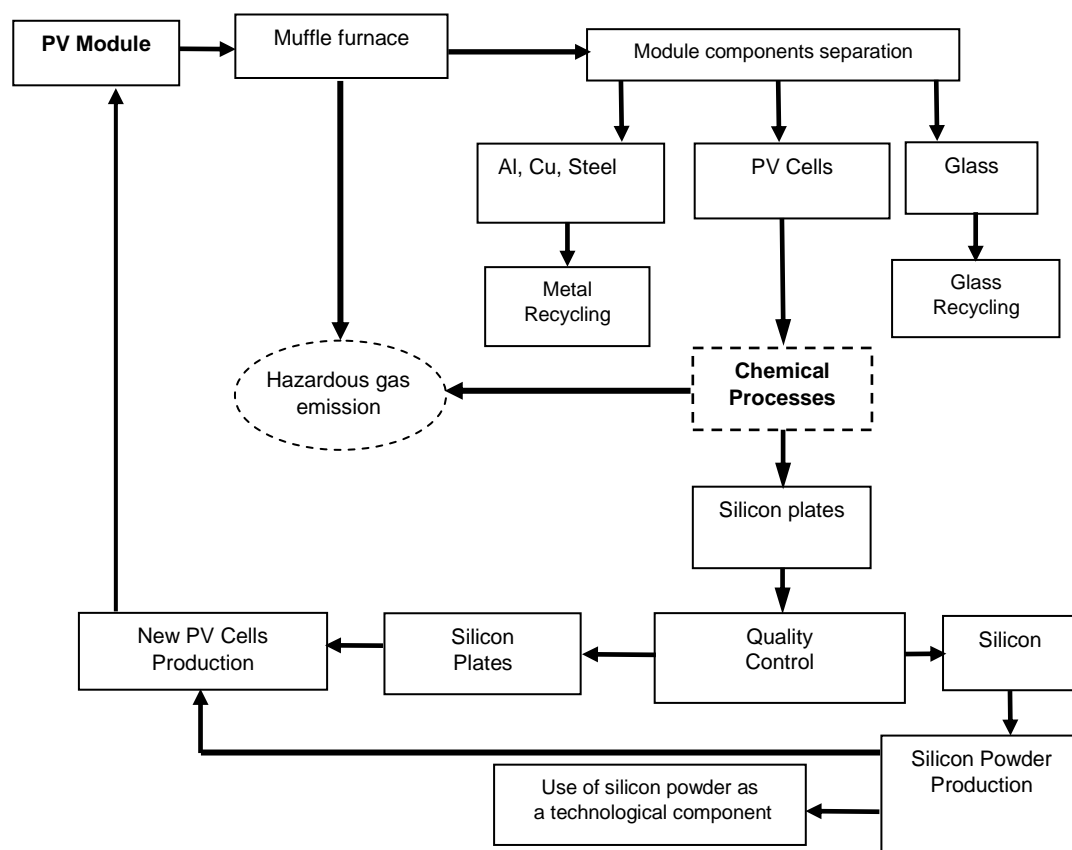
101 Recovered materials, such as aluminium and glass, can be used in PV module manufacturing
 102 and also in any other process. Pure silicon is a valuable material and reuse in new cell
 103 production would lower the cost and environmental impact of production. This is the reason

104 why the aim of this study is to include the environmental impact of recovering and recycling
105 the semiconductor material from photovoltaic solar cells. Authors compare process of new
106 solar cells production with or without recycled silicon material to confirm this assumption.

107 For test purposes, spent silicon solar cells made according to different standards were
108 selected. Originally, the PV cells had dimensions of $125 \times 125 \text{ mm}^2$.

109 The PV recycling process requires two main stages (Figure 2):

- 110 • PV solar cell separation: in thermal delamination, the EVA (Ethylene Vinyl Acetate)
111 is removed and materials such as glass, Tedlar[®], aluminium frame, steel, copper and
112 plastics are separated;
- 113 • cleansing the surface of PV solar cells: unwanted layers (antireflection layer, metal
114 coating and p-n semiconductor) are removed from the silicon solar cells separated
115 from the PV modules; as a result, the silicon substrate, suitable for re-use, can be
116 recovered.



127 **Figure 2.** Thermal and chemical processes in PV crystalline cell and PV module recycling [30]

128 In order to separate silicon photovoltaic cells from a damaged PV module, the module was
129 placed on a SiO₂ bed, which then was heated. After the cells have been separated from PV
130 modules, the various layers of material applied in the production process must be removed in
131 a specific order: front metal coating, bottom metal coating, anti-reflective coating and n-p
132 junction. The chemical process of removing the different layers so that the silicon base could
133 be recovered was optimised and examined.

134 With the recovered silicon wafers, several processes were used for preparing new silicon solar
135 cells. Before processing, each wafer was laser-cut to dimensions of 50 mm×50 mm; this
136 technique guarantees the quality of the edges.

137 The suggested technology enables the production of photovoltaic solar cells with conversion
138 efficiencies of 16% for monocrystalline silicon wafers and 13% for multicrystalline silicon.
139 Each of the seven basic steps of the technological process, described in detail below, was
140 carried out with particular emphasis on the physical parameters of the base material and the
141 finished solar cell. The cell manufacturing sequence consists of the following main steps:
142 texturisation, emitter formation, parasitic junction removal, passivation, antireflection coating
143 deposition, front and back contact formation.

144 Measurements of illuminated current-voltage characteristics for the cells produced were
145 conducted under Standard Test Conditions: AM1.5, irradiance 1000 W/m², temperature 25°C.
146 Series and shunt resistance and temperature coefficients were specified as well. The new cells,
147 despite the fact that they have no SiN_x antireflective coating, have a very good efficiency of
148 13-15% [40].

149 **Methodology**

150 Life cycle analysis (LCA) is a technique to assess environmental aspects and potential
151 impacts associated with all stages of life of products and technologies including: mining and
152 processing of mineral resources, production process, distribution, transport, use, recycling,
153 and final disposal of waste. In the presented analysis, the actual methodology was used,
154 normalization was performed, and the result was obtained according to LCA international
155 standards and the ILCD handbook [33].

156 The basic standard associated with the assessment of the product life cycle is the ISO standard
157 14040 Environmental management - Life cycle assessment - Principles and framework. ISO

14040:2006 describes the principles and framework for life cycle assessment, including definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements.

The following standards are included under the 14040 series: ISO 14040 – General Principles and Framework, ISO 14041 – Goal and Scope Definition and Inventory Analysis, ISO 14042 – Life Cycle Impact Assessment (LCIA), ISO 14043 – Life Cycle Interpretation, ISO 14047 – Technical Report, ISO 14048 – LCA Data Documentation Format, and ISO 14049 – Technical Report. ISO 14040 form International Organization for Standardization, 2006, divides LCA into four stages: goal and scope definition, LCI, LCIA, and interpretation (Figure 3).

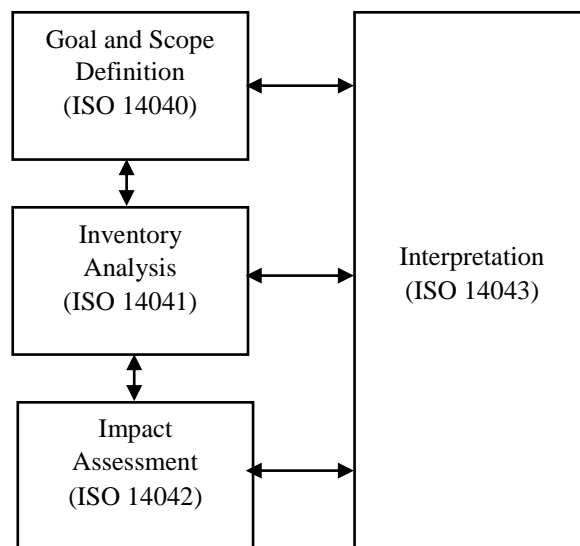


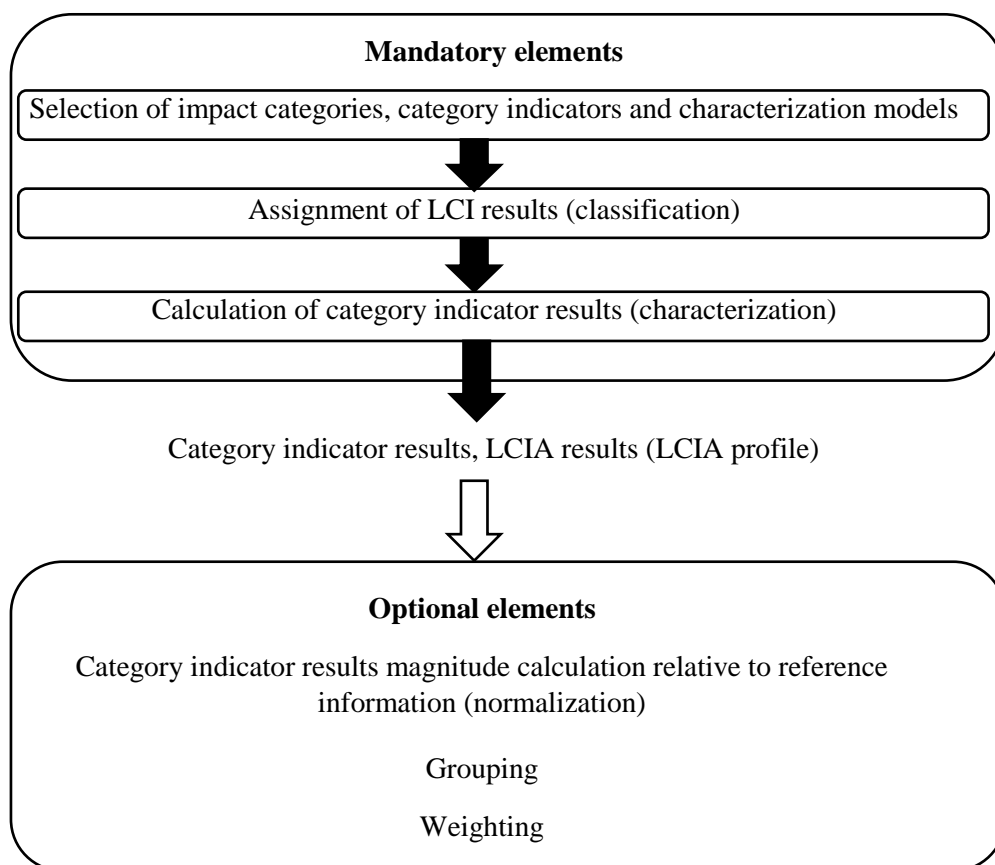
Figure 3. Relationships among LCA stages according to ISO 14040.

A LCIA consists of several elements, the classification, characterization, normalization, and weighting. Classification and characterization are mandatory elements within a LCIA, the normalization and weighting are optional elements (Figure 4).

The third phase of the LCA (characterization) is carried out using various methods, for example, Eco-indicator'99 or ReCiPe, most often implemented with LCA research software (SimaPro, GaBi). The number of available methods for LCA analyses indicates continuous

184 development of the LCA methodology, however, in Europe the most frequently chosen
 185 method is Eco-indicator'99. Eco-indicator'99 is an end-point method, originally developed in
 186 1995 to provide design engineers with environmental information in a simple single value
 187 format and is intended for internal use.

188 ReCiPe is a more recent end-point method that transforms inventory results into eighteen mid-
 189 point indicators and three end-point indicators that are weighted into a single score.



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200 **Figure 4.** Elements of the LCIA phase (ISO 14040, 2006).

201 Assessment models of the temporal perspective of ecological effects are presented in Table 1.

202 **Table 1.** Archetypes of the temporal perspective of ecological effects [34–35].

Model	Time perspective	Management possibilities	Evidence
Individual (I)	Short-term	Technology helps avoid many problems	Only verified
Egalitarian (E)	Long-term	Problems may cause a disaster	All

Hierarchical (H)	Balance between long- and short-term	Good politics help avoid many problems	Consensus between verified and non-verified
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203 The type of model chosen has a large influence on the results (Table 1). The egalitarian
204 method has a long-time perspective and includes even very preliminary scientific knowledge
205 about the environmental impact. This approach is supersensitive to any effect - future or
206 present. This method assumes that nature is fragile and unstable, and provides the worst
207 possible scenario.
208 A short-term perspective, based on very strong proves and judgment of the environmental
209 consequences, is presented in the individual model. This approach assumes that nature is
210 stable and able to recover from almost any damage, and emphasises the present situation over
211 future gains or losses. Balance between these two types of model is achieved with the
212 hierarchical approach, which assumes that nature is in balance and any damage can be
213 avoided with proper management. These three archetypes are based on an anthropological
214 approach to the human nature of environmental decision-making. To make results comparable
215 to other Europe countries Eco-indicator'99 method was chosen and very often used SimaPro
216 software. The chosen model was hierarchical because of its balanced approach giving the
217 view for long and short term perspective. Because of the silicon recovered from the recycling
218 process usage in manufacturing comparison this approach seems to be the most reasonable.

219 Assumptions

220 The preparation of inventory tables for LCA requires the preparation of universal (from the
221 point of view of different producers) data on the consumption of materials and energy during
222 the production of solar modules without taking into account recycling processes and also
223 including the material recycling.

224 Currently, the dominant semiconductor material used for the production of photovoltaic cells
225 is silicon in the form of mono- or poly- crystalline tiles. By weight, typical c-Si PV panels
226 contain about 76% glass (panel surface), 10% polymer (encapsulant and backsheet foil), 8%
227 aluminium (mostly the frame), 5% silicon (solar cells), 1% copper (interconnectors), and less
228 than 0.1% silver (contact lines) and other metals (mostly tin and lead) [36]. For each type of
229 silicon module production the quantity of particular material is different (Table 2).

230 **Table 2.** Inputs in the production of 1m² of PV module in 2006 (frameless) [5]

Input	Material	Ribbon-Si	p-Si	m-Si
Components [kg]	Cell material	0.9	1.6	1.5
	Glass	9.1	9.1	9.1
	EVA	1.0	1.0	1.0
	Others	1.8	1.8	1.8
Consumables [kg]	Gases	6.1	2.2	7.8
	Liquid	2.2	6.8	6.6
	Others	0.01	4.3	4.3
Energy media	Electricity [kWh]	182	248	282
	Oil [l]	0.05	0.05	0.05
	Natural gas [MJ]	166	308	361

231 Also, the energy consumption in 1m² production varies according to the type of silicon used,
 232 but for mono- and polycrystalline silicon the difference is almost negligible. From the
 233 perspective of the recycling process, monocrystalline silicon cells are easier to reuse.

234 In the production process, solar cells are encapsulated for protection against climatic
 235 conditions and mechanical damage. An ethylene-co-vinyl acetate (EVA) copolymer material
 236 covers both sides of the cells, while Tedlar® is used on the rear side. The front of PV modules
 237 are covered with glass.

238 **Table 3.** Material share and recovery rate in the recycling process of silicon solar module [37]

	Glass	Aluminium frame	Solar cells	EVA, Tedlar	Ribbons	Other
Weight [kg]	10.0	1.39	0.47	1.37	0.10	0.16
Share [%]	74.16	10.3	3.48	10.15	0.75	1.16
Recovery rate [%]	90	100	90	-	95	-

239 An example of innovative recycling process of silicon solar cells is presented in the Figure 5.
 240 Amount of chemicals and energy is presented as help to understand importance of recycling
 241 process development and used techniques. Table 3 presents typical recovery rate for crystalline
 242 silicon module. Both (Table 3 and Figure 5) they give an idea about material and energy
 243 consumption and recovery rate in today used techniques.

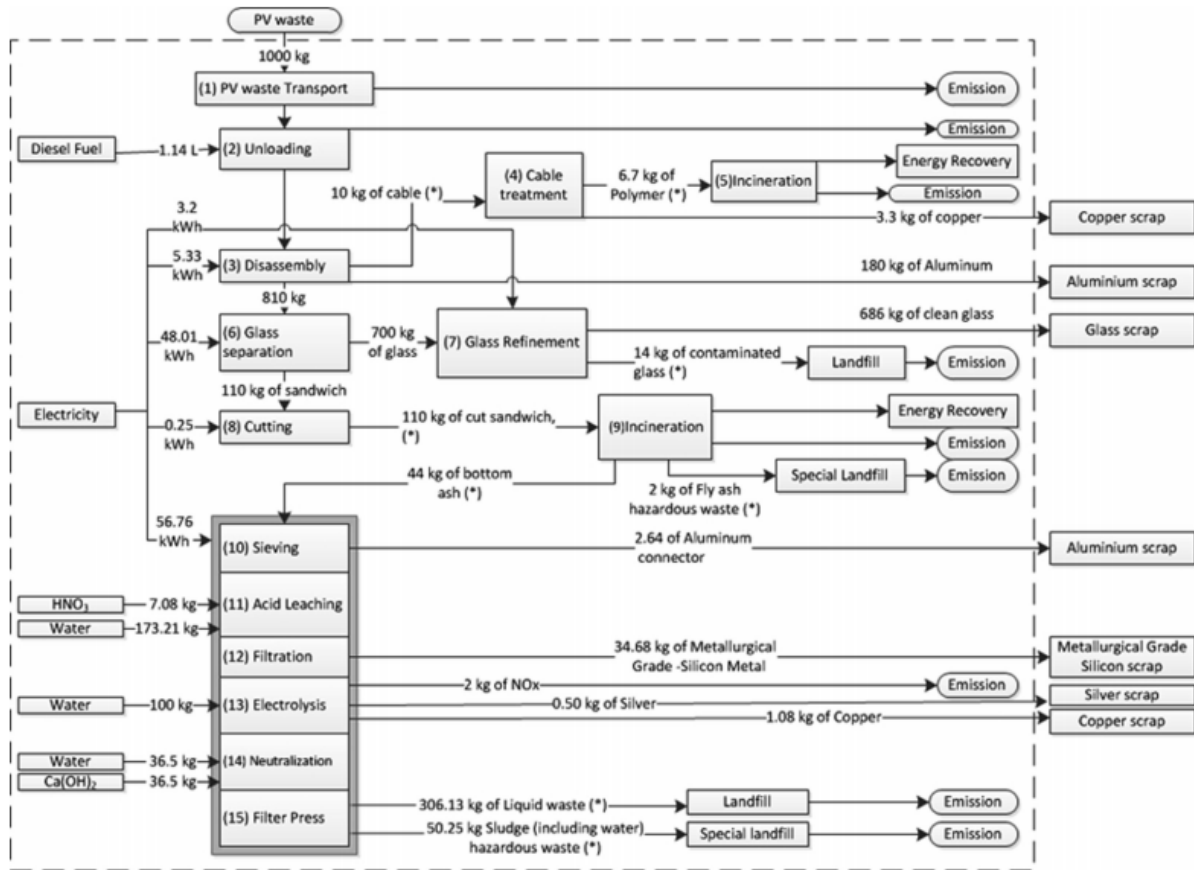


Figure 5. An example of innovative recycling process for crystalline silicon photovoltaic panels [25]

In order to recover silicon as a ‘wafer’ suitable for use as a substrate in the production of new cells, the aluminium frame and junction box should be dismantled manually and the EVA poly laminate layer must first be removed from the module by thermal or chemical processes. Then, with a mixture of alkalis or acids, the anti-reflective layer, the metallization of the front and rear surface of cell, and p-n junction have to be removed. To separate the individual cells, a thermal method was chosen. A thermal process enabling quick, simple, and economically-efficient disassembly of the module is the first stage in PV module recycling. First, the EVA-laminated cells are separated. This recycling process is energy consuming, but since up to 85 % of the recycled cells are reused, energy consumption when manufacturing new PV modules is reduced up to 70 % [38].

Optimal compositions of the mixtures and the design of technological lines for recycling of silicon photovoltaic cells have been registered in the Republic of Poland Patent Office under Patent No. 215 770 [39].

260 The proposed recycling process aims at separating PV wafers for their potential reuse in new
261 panels [30]. Recovering pure silicon from damaged or end-of-life PV modules can lead to
262 economic and environmental benefits. Cells manufactured from recycled silicon wafers had
263 efficiencies between 15-12% [40]. With reference to cells manufactured with the same
264 technique, in literature efficiency is 16% for monocrystalline and 13% for polycrystalline. It
265 can be state that lost of the efficiency is almost negligible if thickness of recovered wafers is
266 suitable. If not, silicon can be reused as pure powder in monocrystal forming process.

267 To enable recycling of the silicon base from PV cells, a universal chemical process for
268 removing different layers from the cell surface has been developed. Because of the high
269 quality requirement for the recovered silicon, chemical processing is the most important stage
270 of the recycling process. Etching should be continued until the relevant layers have been
271 removed, although it is essential to avoid too great a loss of silicon. For the silicon base to be
272 suitable for incorporation into new cells, it must not be too thin. A loss of mechanical strength
273 may cause the base to break during the processes performed on its surface. It was assumed
274 that photovoltaic silicon cells have a standard size of $156 \times 156 \text{ mm}^2$ and a thickness of 270-
275 300 μm .

276 The metal coating should be removed through an etching sequence. The universal recycling
277 procedure for all Si solar cells includes the three main steps: removing metal coatings, e.g. Al
278 and Ag coatings, anti-reflective coatings (ARC), and n-p junctions. During this step, the silver
279 is dissolved. Silver is recovered from the waste acids by electrolysis. From a value standpoint,
280 silver is an expensive component per unit of mass for a c-Si panel – consuming today about
281 15% (including losses) of the global silver production. The amount of silver that can be
282 recovered from the etching solution is up to $1.6 \text{ g} \cdot \text{kg}^{-1}$ of broken solar cells [32].



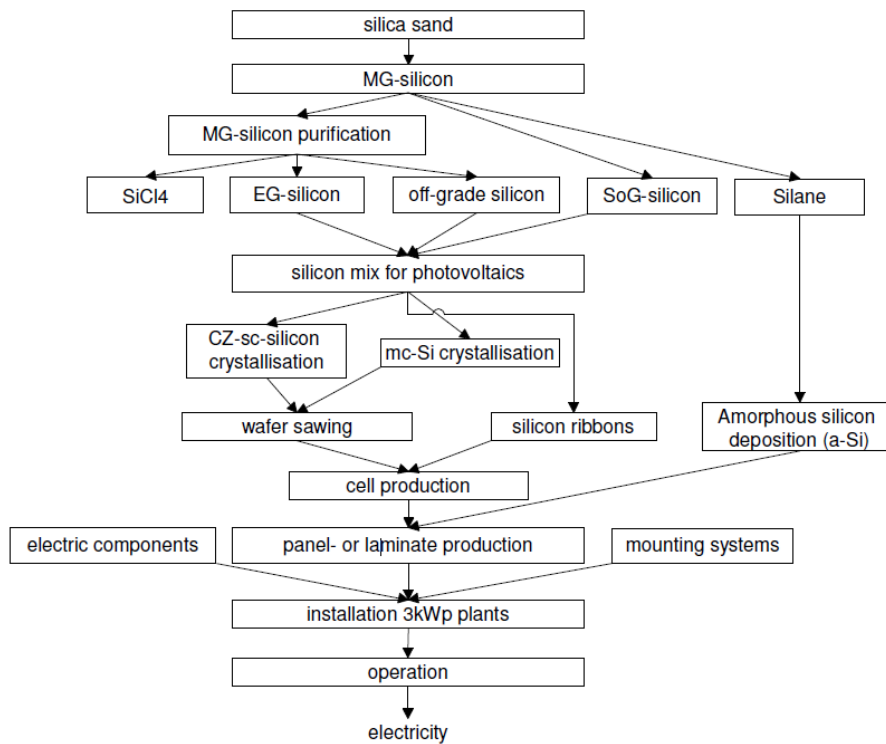


Figure 6 Supply chain of silicon based photovoltaic electricity production. MG-silicon: metallurgical grade silicon; EG-silicon: electronic grade silicon; SoG-silicon: solar-grade silicon; a-Si: amorphous silicon; CZ: Czochralsky; kWp: kilowatt peak [41]

The models proposed for analysis by different authors present in fact a similar approach to the production chain of solar modules, including recycling.

Lunardi et al. presented a process flow diagram for c-Si possible EoL scenarios and the description of each process as a compilation of the best results found by the authors [42].

Development of new material-saving technologies is expected in the coming years. By 2030 the glass content of c-Si panels is predicted to increase by 4% to a total of 80% of a panel's weight. The main material savings will include a reduction in silicon from 5% down to 3%, a 1% decrease in aluminium, and a very slight reduction of 0.01% in other metals. A reduction in the quantity of silver used is a clear target [43]. Specifically, silver consumption is expected to further decrease through adoption of improved metallization processes [44]. However, at present and for the next two decades, recycling will include solar modules produced in recent years.

300 The basic environmental benefits of the proposed photovoltaic module recycling technology
 301 result from the use of recycled semiconductor material. The repeated use of silicon, which has
 302 been purified in the previous cycle of cell production (Figure 6.), will significantly reduce
 303 energy consumption. The quantities of energy required in various processes during the
 304 fabrication of PV modules are listed in the Table 4. Additionally etching solutions can be
 305 reused to decrease environmental impact of recycling process. New etching methods without
 306 solvents are studied to make recovery of materials environmental friendly as much as
 307 possible. Benefits for the environment are major compared to the alternative solutions such as
 308 PV waste incineration.

309 SimaPro was used for the LCA. SimaPro is a professional tool for collecting, analysing, and
 310 monitoring sustainability performance data of products and services.

311 **Table 4.** Energy requirement in different processes during the production of PV modules [45].

Process	Energy requirements
Silicon purification and processing	
- Czochralski Silicon (Cz-Si) production from EG-Si	290 kWh kg ⁻¹ of EG-Si
- Electronic grade silicon (EG-Si) production form MG-Si	100 kWh kg ⁻¹ of EG-Si
- Metallurgical grade silicon (MG-Si) production from silicon dioxide (quartz, sand)	20 kWh kg ⁻¹ of MG-Si
Fabrication of solar cell	120 kWh m ⁻² of silicon cell
Assembly of PV module	190 kWh m ⁻² of PV module
Roof top integrated PV system	200 kWh m ⁻² of PV module

312 However, the data from Ecoinvent base all reflects European averages, except for the end of
 313 life waste treatment, which was based on the situation in Switzerland.

314 Results

315 This section dissects the environmental impacts calculated in the LCA carried out here. The
 316 main environmental impacts of two possible end-of-life scenarios were analysed: i) disposal
 317 and ii) recycling of a panel with the recycled semiconductor base reused.

318 The environmental impacts associated with the production steps of PV modules remain the
 319 same for both scenarios, and therefore this study mainly focused on analyzing traditional cell
 320 production with new raw materials versus production that incorporates recycled silicon

321 material. Other differences of installations, such as building integrated vs. free-standing
 322 systems, as well as those associated with PV module orientation, direction, and performance
 323 of the balance of system (the balance of system (BOS) encompasses all components of a
 324 photovoltaic system other than the photovoltaic panels) all have notable effects on the LCA
 325 results.

326 Table 5 presents results of the comparative analysis of environmental impacts for
 327 characterisation per impact category carried out using Eco-indicator'99 method.

328 **Table 5.** LCA characterisation results for impact category

Impact category	Unit	c-Si cells at plant	c-Si cells using recycled materials
Carcinogens	DALY	4.2E-5	6.55E-6
Respiratory organics	DALY	1.04E-7	8.02E-8
Respiratory inorganics	DALY	8.9E-5	3.6E-5
Climate Change	DALY	5.25E-5	3.1E-5
Radiation	DALY	1.88E-6	1.72E-7
Ozone layer	DALY	3.33E-8	2.86E-8
Ecotoxicity	PAFm ² year	31.4	5.96
Acidification/Eutrophication	PDFm ² year	2.0	1.56
Land use	PDFm ² year	1.39	0.823
Minerals	MJ surplus	1.44	0.71
Fossil Fuels	MJ surplus	272	185

329 The results of the comparative analysis of environmental impacts of electronic grade silicon
 330 production with and without the use of recycled material are presented in the Figure 7. This
 331 figure presents the normalization results.

332 Table 6. presents the final LCA analysis results in points after weighting for producing 1 kg of
 333 c-Si with all new material in comparison to using recycled material.

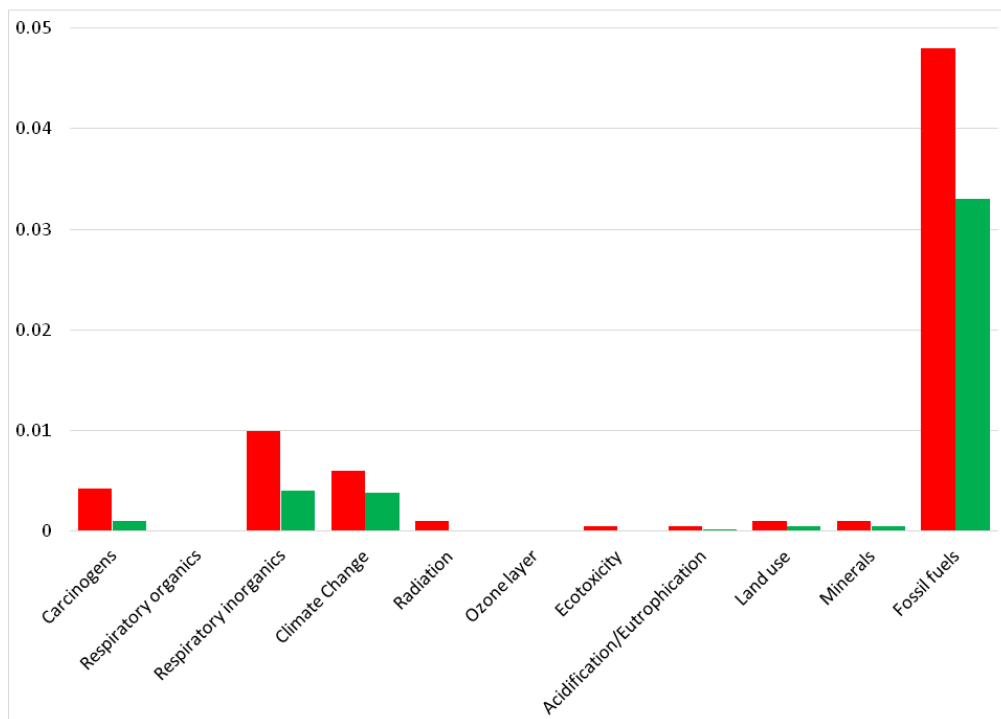


Figure 7. The results of the normalization for the production of silicon solar cell without (red bars) and with the use of recycled silicon (green bars).

Table 6. LCA results for producing 1 kg of c-Si at plant in comparison to the use of recycled material.

Impact category	c-Si cells at plant (Pt)	c-Si cells using recycled materials (Pt)
Carcinogens	0.0757	0.0636
Respiratory organics	0.00165	0.000674
Respiratory inorganics	0.66	0.339
Climate Change	0.603	0.242
Radiation	0.0016	0.00148
Ozone layer	0.000611	0.000406
Ecotoxicity	0.0226	0.0183
Acidification/Eutrophication	0.0829	0.037
Land use	0.0421	0.03
Minerals	0.0139	0.0107
Fossil fuels	3.82	1.49
Total	5.33	2.23

339 To achieve environmental benefits, the environmental impact of the recycling process must be
340 smaller than the environmental impact of the material production process. Others have
341 demonstrated that the environmental impact (expressed in environmental points – Pt) of
342 transportation and recycling stages are of little significance in terms of the whole lifecycle
343 [45].

344 **Conclusions**

345 Recycling helps to reduce the consumption of valuable raw materials, production costs, and
346 environmental impacts. An important argument for the recycling of photovoltaic modules is
347 the reduced energy consumption at the production stage through the use of existing purified
348 material. All stages of the silicon cell life cycle contribute to the GWP and reduction of
349 greenhouse gas emissions through the use of recycled silicon material represents 42%. The
350 total environmental impact of PV production can be reduced by as much as 58%, primarily
351 due to reduced energy consumption during the production of high purity crystalline silicon.

352 In the analysed recycling process, after separation of the cells from the PV module, several
353 processes were carried out that led to the recovery of the base material, i.e., silicon wafers.
354 These silicon wafers were examined to determine whether any inclusions remained.
355 Following the appropriate preparation, new photovoltaic cells were produced from the
356 recovered wafers. This approach allows for a maximum reduction of photovoltaic panel
357 impacts on the environment through re-use of all valuable materials, including silicon
358 substrates.

359 To achieve environmental benefits, the environmental impact of the recycling process must be
360 smaller than the environmental impact of the material production process. Although the cost
361 of storage module landfill is smaller, recycling must be economically viable. The LCA of c-Si
362 PV cell production with and without recycling of spent semiconductor material demonstrates
363 that the negative environmental impact of photovoltaic cell production with recycled material
364 was nearly two times lower than the environmental impact associated with producing cells
365 from primary materials.

366 The biggest difference was seen in the fossil fuels category and a relatively small difference
367 was observed in the radiation category. Photovoltaic panel production involves the use of
368 many chemical substances and emissions, which are not environmentally neutral. We cannot



369 consider photovoltaics as a zero-emission technology. It must be emphasized that the coal-
370 based energy sector is one of the least environmentally friendly. That is why the comparative
371 analysis with clean energy mixes may indicate even lower environmental efficiency of PV
372 cells.

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