LIFE CYCLE ANALYSIS OF A SOLAR MODULE RECYCLING PROCESS

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ABSTRACT: Photovoltaic solar energy is an environmentally friendly technology. Therefore the environmental impacts of photovoltaic modules during their complete life cycle have to be investigated and reduced further. Life cycle assessments were performed in the past without consideration of the end-of-life phase. This gap is filled by the presented work, which analyses the environmental impacts of a recycling process for crystalline silicon modules. The data were based on a process that is presently in operation at Deutsche Solar. The results show that even if the environment is essentially burdened by the inputs and outputs of a recycling process, recycling can be justified. This applies if: (1) the recycling process has a much lower environmental effect than other end-of-life scenarios, and (2) the environmental burden during the production phase of reusable components is higher than the burden due to the recycling process. Concerning a module with crystalline cells, the recycling process of Deutsche Solar makes good ecological sense, because the environment is disburdened due to the reuse of the recovered wafers.
Keywords: Environmental Effect, Recycling

1 INTRODUCTION

The production and installation of photovoltaic modules is increasing rapidly. At the same time the amount of end-of-life photovoltaic modules is relatively small. In the near future a vast increase in PV modules as waste is anticipated. For Europe, the emergence of end-of-life modules in 2040 is estimated to rise to 33.500 tons from 290 tons in 2010 [1]. Until now neither the photovoltaic industry nor the European legislators have decided about the disposal of end-of-life modules. In the near future a European regulation can be expected [2]. If the sustainability of the photovoltaic technology has to be asserted, then disposal has to be considered. Therefore the end-of-life phase has to be included in life cycle assessments (LCA). A LCA is an evaluation of products regarding their ecological impact during all life phases. It can be used as an analysis of flaws of processes or products or for a comparison between different products, components, materials or processes. This paper focuses on the environmental evaluation of the recycling process of Deutsche Solar (DS). The burden of the process is compared to the disburden caused by the reuse of the recovered wafers and the material of other components. Moreover, alternative waste treatment methods, such as a shredder process or the incineration in a municipal waste incineration plant, are compared to the recycling process of Deutsche Solar.

2 RECYCLING PROCESS OF DEUTSCHE SOLAR AG

The recycling process of Deutsche Solar in Freiberg enables, at a pilot plant scale, the recovery of wafers from crystalline solar modules. By burning off the laminate, solar cells are first removed from the module compound structure. Subsequently the metallization, anti-reflection coating and pn-junction of the cell are removed in an etching line. The clean wafer, which is the final product of the recycling process, can be processed again in a standard solar cell production line and integrated into a PV module. The process is described further in [3].

During the thermal treatment, energy is consumed by the furnace, afterburner and washer. In addition, the washer consumes water and chemicals. Important outputs are air emissions and the different waste streams. Metals, mainly from the frame, glass and cells are separated. The metals and the glass are given to recycling partners for integration in the adequate material loops. The recovered cells are treated in a chemical process. During the chemical process different chemicals are required. Moreover, water and energy are consumed in the line and the exhaust gas washer. The chemicals used for the etching are treated chemically and physically. The resulting sludge is disposed of. Resulting water can delivered to a sewage treatment plant. Important in- and outputs are summarised in figure 1.

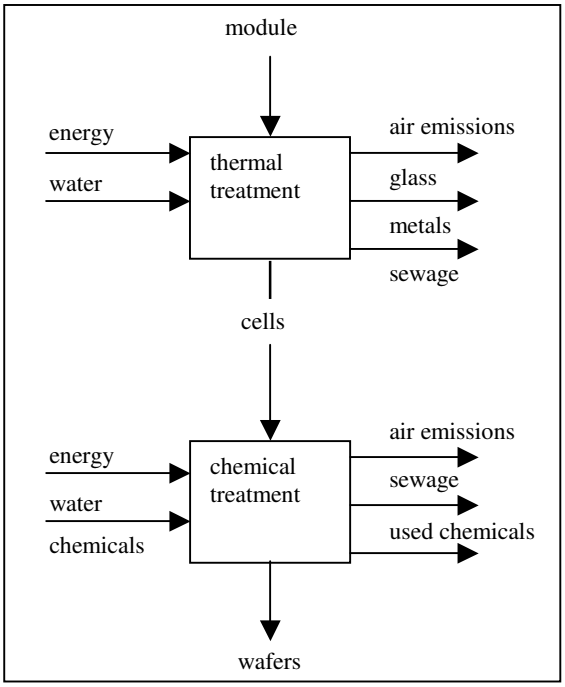

Figure 1: important in- and outputs during the recycling process of DS

3 ENERGY CONSUMPTION

The energy consumption of the recycling process is substantial. It is composed of the consumption of natural gas by the furnace and the afterburner and the electrical energy demand of the exhaust gas cleaning and the etching line. An assessment of the total energy demand during the recycling process gives a first insight on the environmental effects of the process. For this purpose the amount of primary energy was converted to electrical energy with an assumed effiency of 35%. In table I, the energy consumption during production of a module with new wafers and a module with recycled wafers is compared. For the use-phase, a Middle-European location (irradiation 1000 kWh/m²/yr, performance ration 0,75) and a lifetime of 20 years are assumed. Due to the recycling process, two thirds of the necessary energy for wafer production can be saved. As a result the Energy Pay-Back Time (EPBT) of a module with recycled wafers is much lower. With the aforementioned assumptions, EPBT amounts to 1.6 years, compared to 3.8 years for a standard module.

	Module A	Module B
wafer production	355	
recycling process		92
cell processing	66	66
module assembly	38	38
total	**459**	**196**

Table I: energy consumption of a module (160 Wp) with new wafers (A) and a module with recycled wafers (B) in kWh_{el}/module (energy consumption during production based on [4])

4 LCA

In the presented LCA a standard module was investigated with 72 cells (125mm × 125mm), Tedlar as backside foil and an aluminium frame. For the evaluation of the environmental impacts, the CML Baseline-2000 method of the Institute of Environmental Science in Leiden (CML) was implemented. The analysis was performed with the software Simapro 6.0. Calculations are based on own data as well as data from the ecoinvent 2000 database [5]. In the following we present the results of the characterisation.

In the impact assessment step of an LCA all the inflows and outflows of the considered system (enclosing the product life cycle) are evaluated in terms of specific environmental impacts, for example “climate change” For each impact category an specific indicator is calculated as the weighted sum of individual emissions For climate change this indicator is the Global Warming Potential, expressed in kg CO_2-equivalent [6].

Figure 2 shows the contribution from the thermal and chemical processes, the recycling of glass and aluminium as well as of reuse of recovered wafers to different impact categories. The sum of the positive contribution (environmental burden) and negative contribution (environmental disburden) is always scaled to 100%. The reason is that each category is evaluated by a different indicator with its own unit. The absolute impact values are shown in Table II. Due to the avoidance of new wafers and recycling of glass and metals the recycling of a standard module by the investigated process reduces the environmental burden for each impact category.

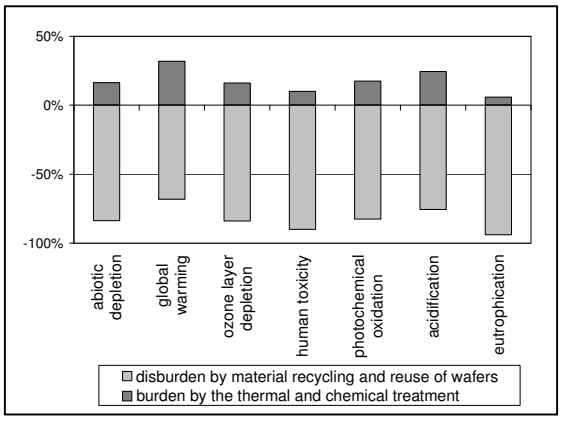

Figure 2: Contributions to the environmental impact of the DS recycling process. Environmental burdens are positive in the figure, while disburdens are depicted as negative.

The highest contribution to the disburden of the environment is related to the avoidance of new wafer production. Glass recycling is of minor importance. The burden of the environment is mainly related to the energy consumption during the thermal treatment and the use of chemicals in the etching line.
The results also show that is important to decrease the energy consumption of the thermal treatment process and to save on the consumption of chemicals in the etching line.

	recycling DS	unit
abiotic depletion	- $6.1 * 10^{-8}$	kg Sb $_{eq}$
global warming	- 59.2	kg CO_2 $_{eq}$
ozone layer depletion	- $1.2 * 10^{-5}$	kg CFC-11$_{eq}$
photchem. Oxidation	- $1.9 * 10^{-2}$	kgC_2H_2 $_{eq}$
acidification	- 0.4	kg SO_2 $_{eq}$
eutrophication	- 0.4	kg PO_4 $_{eq}$

Table II: result of the characterisation, treatment of one module by the recycling process of DS

5 COMPARISON WITH ALTERNATIVE PROCESSES

Conventional photovoltaic modules have a mass portion of organic material higher than 3%. According to the criteria and procedures for the acceptance of waste at landfill sites, end-of-life modules can not be deposited in landfills without pre-treatment [7].

A possible scenario is a treatment in a municipal waste incineration and a subsequent disposal at a landfill for inert waste. Due to the high material value of aluminium frames, it is assumed that the frame is removed before such a thermal pre-treatment. The energy consumption of a municipal incineration plant per kilogram is substantially lower than of the plant of Deutsche Solar. Main reason is that a incineration plant

is a large scale plant unlike the furnace of DS. Even if the environmental impact of the described waste treatment scenario is minor compared to the process of DS, there is no environmentally positive effect due to the reuse of wafers and glass. In figure 3, the characterisation results of a frameless module treatment with the two different processes are compared – the DS process and the incineration-landfill process. The negative contribution (disburden) of the incineration scenario results only from recycling the aluminium frame. For each considered categorie the recycling process of DS is favourable.

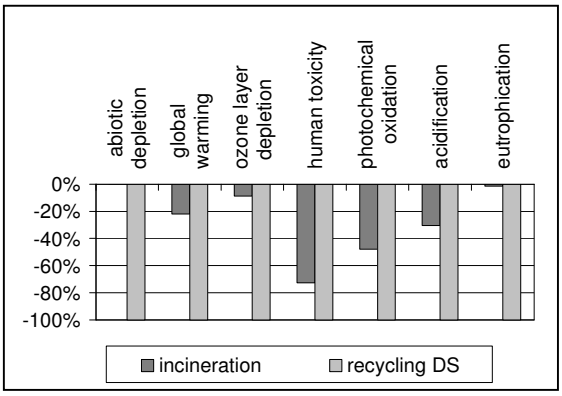

Figure 3: comparison of the characterisation results of the recycling process of DS and a treatment in a municipal incineration plant with subsequent landfill.

Another scenario is a shredder process with subsequent sorting. It is expected that the aluminium frame is removed before the shredder process. The recovered glass fraction can be put back into glass production. The second fraction consists of organic material, metals and crushed solar cells. Due to its high organic content, it has to be thermally pre-treated before it can be deposited on a landfill. The energy consumption of a shredder process is two orders of magnitudes lower than the recycling process. But the recycled fractions alltogether have a lower value compared to the seperated fraction of the process of DS. That justifies the operation of the process of DS even with a higher energy consumption. In general high grade recycling solution are preferable to low grade solutions. In consideration of the scarcity of silicium for the PV industry the reuse of wafers is reasonable further.

6 SUMMARY AND FORECAST

Concerning environmental aspects recycling of PV modules by dismantling the modules and a chemical treatment of the recovered cells is favourable. The principle reasen is the lower environmental damage by the process of Deutsche Solar AG compared with wafer production. To decrease the environmental impact in the short term, the energy and chemicals demand per recovered wafer has to be reduced further. Together with research partners DS works on an improved etching control, that can lead to a longer use of etching baths [8]. In the long term it is favourable to develop an encapsulation, that enables to dismantle modules without much effort [9], [10]. Which recycling process will be applied in the future depends on the legeslation and on the initiative of the PV industrie [11].

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