RECYCLING OF THIN-FILM SOLAR MODULES
LIFE CYCLE ASSESSMENT CASE STUDY

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ABSTRACT:
The economic relevance of thin film solar cells has increased recently, but recycling or disposal options for used modules (End-of-Life) has not been considered and developed sufficiently yet. In the future an increase of mass flows of the used thin film solar modules is expected, as well as possible directives, which could enforce the PV-module producers and users to recycle the PV-modules, even for the young thin film PV-technologies, as consequence recycling options must be researched in advance.
The EU-funded project "SENSE" has worked on the research and development of the recycling technology for thin film PV-modules. The accompanying Life Cycle Assessment (LCA) study enables the analysis of environmental impacts caused by the entire life cycle of thin film PV-systems including the recycling technology, developed in the SENSE project.
This paper reports on the developed End-of-Life strategies and the results of the LCA studies, in which a comparison to conventional energy supply system is carried out.
The LCA results show significant environmental advantages of thin film PV-modules compared to conventional energy supplying systems e.g. UCTE.

Keywords: CIGS, a-Si, CdTe, Thin film, Recycling, Life Cycle Assessment

1 INTRODUCTION

The demand of society and politics for sustainable energy sources is higher than ever. Photovoltaic (PV) energy is meanwhile seen as one of such auspicious "sustainable" candidates. At the beginning of PV-system history, due to laboratory scale or small scale production, the required energy for a PV-module production was relatively high. This disadvantageous prejudice of PV-systems has basically changed in recent years along with its rapid market growth and the technological improvement [1].

Besides wafer based crystalline silicon PV-modules, thin film PV-modules are alternative mass production oriented PV-systems. Although their worldwide market share in 2004 was with relatively small (7 %), growth is expected. This tendency can already be seen in the growing production capacity of thin film PV-modules [2]. Recent development and optimization of thin film production systems along with the increasing production capacity lead to an improvement in environmental performance of thin film PV-systems. Therefore, analyses are important in order to examine the actual environmental performance of thin film PV-systems.

A further important aspect must be followed in the same time: concerning "End of Life" of thin film PV-systems a recycling strategy is still missing. Today´s legal situation and its tendency show the importance of being prepared for future environmental legislation. E.g. for electric and electronic products the WEEE ("Waste Electrical and Electronic Equipment Directive" [3]) regulates the recycling and reuse rate by weight, and the RoHS ("Restriction of Hazardous Substances Directive" [4]) bans the use of certain hazardous materials. As one of the products which could be affected by these directives once PV-modules were under discussion. Although finally it has resulted that PV-modules do not fall into the scope of the WEEE and RoHS until today, efforts should be made in order to establish a recycling strategy in advance.

The project "Sustainability Evaluation of Solar Energy Systems (SENSE)" (ENK5-CT-2002-00639) funded within the 5th Framework program of EC aimed at reaching both, an Life Cycle Assessment (LCA) analysis as well as the development of recycling strategies for CIGS, a-Si and CdTe PV-systems. A consortium consisting of Ambiente Italia, Free Energy Europe, Fraunhofer ICT, Gaiker, University of Stuttgart, Würth Solar and Zentrum fuer Sonnenenergie- und Wasserstoff-Forschung (ZSW), coordinated by University of Stuttgart, had worked on SENSE from 1st January 2003 to 30th June 2006.

2 RECYCLING

2.1 Analysis of recycling options

The institutes Gaiker, Fraunhofer ICT and ZSW worked on the development of recycling strategies by carrying out a series of laboratory experiments on sample thin film PV-modules, which were provided by the PV-producers. This development was accompanied by LCA studies.

The following figure shows an overview of the main techniques and approaches followed under the SENSE-project in order to recover and recycle the PV-modules parts. The approaches can be divided into three main stages, i.e. processes for module delamination, removal of the EVA (Ethylene-Vinyl Acetate) layer, and removal and recovery of the metals.

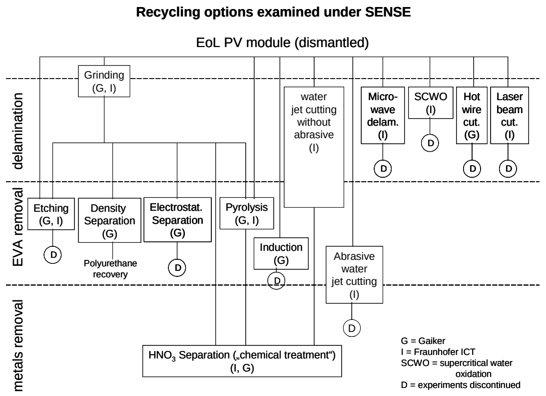

Figure 1: Recycling options of thin film solar cells

2.2 Recycling strategy for thin film PV-modules

According to the results obtained in each test, a few processes have been judged as technically feasible and suitable, i.e. providing an interesting yield both in terms of quantity and quality of recovered materials and cost. Consequently, three different recycling strategies have been designed and identified as appropriate to carry out an integral recycling of the thin film PV-modules. The three strategies have been optimized depending on the specific thin film PV type, i.e.:

- Recycling strategy 1: Waterjet cutting & Chemical treatment for CIGS solar modules
- Recycling strategy 2: Thermal treatment (pyrolysis) & Chemical treatment for CIGS and CdTe solar modules
- Recycling strategy 3: Grinding & pneumatic separation of polymer frame for a-Si solar modules

3 LIFE CYCLE ASSESSMENT

The evaluation of environmental impact of thin film PV-modules in the project SENSE is carried out by implementing the method of Life Cycle Assessment (LCA). An LCA analysis considers the environmental burdens caused during the entire life cycle of a product [5]:

- Production phase,
- Use phase and
- End of Life phase.

One of the main advantage due to the consideration of the entire life cycle is, that shifting of environmental burdens from one life phase to another does not influence the total environmental impact of the considered system.
The choice of the impact categories bases on a preliminary study carried out in the first stage of the project SENSE. This study enabled the determination of relevant impact categories as follows:

- Global Warming Potential (GWP)
- Photochemical Oxidation Potential (POCP)
- Acidification Potential (AP)
- Eutrophication Potential (EP)
- Ozone Depletion Potential (ODP)
- Human Toxicity Potential (HTP)

The characterization of environmental burdens by the above mentioned impacts were carried out according to CML 2001 [6].
In addition, the “primary energy use” was also regarded, which is no an “impact category” but an important aspect to be considered, as it reflects e.g. the “voice of the engineer”. Primary Energy Use reflects the use of non renewable energy resources.
In this report the presentation of results will concentrate on above mentioned impact categories and primary energy use except for HTP.

3.1 System description

Three types of thin film PV-technologies with following specifications are considered:

- CIGS (copper indium gallium selenide thin-film)
- a-Si (amorphous silicon thin-film) and
- CdTe (Cadmium Telluride thin-film).

For all three PV-technologies three types of applications are considered:

- Ground mounted power module
- Building integrated (solar roof)
- Mobile application

The location of the PV systems can influence the solar energy harvesting, the transports, the take back aspects etc. and therefore have to be clearly defined.
The following regions for all thin film PV-modules (Power Plant, solar roof and mobile modules) have been used in SENSE:

- Central Europe (Germany)
- Mediterranean areas
- Solar belt region

3.2 Production phase

For an LCA analysis every relevant process has to be considered. The actual data of the current PV modules production lines were collected by project partners. Furthermore data related to the manufacturing of required materials or energy in the production line must not be neglected; the data have been provided by GaBi database. Besides the thin film PV-modules other components have been included in the analysis. The Balance of systems (BOS), which refers to all accessories in PV-systems, are essential for the functionality of PV modules. BOS includes electric cable, frames, electronics such as inverters etc. Depending on the module and application types, different BOS systems are required. The data for BOS were provided by project partners or estimated on the base of literature data, including the results of the EU-project ECLIPSE [7]. Besides the manufacturing data for PV modules, BOS data, e.g. inverters, were as well collected with the support of industry (see chapter 2.2.1.2).
The LCA analysis was carried out using LCA Software GaBi 4.

3.3 Use phase

PV-modules have basically no environmental burdens during the use phase since no direct energy is consumed or direct emissions are produced during PV modules operation. Furthermore the efforts for maintenance are negligible, beside the inverters whose lifetime is assumed to be 10 years (respectively 2 inverters are required in

one module lifetime).
The modeling of the use phase consists in the calculation of the electrical output of PV systems over their typical lifetime of 20 years. The results are strongly influenced, as previously detailed in chapter 3.1 by the PV-technology, the types of application and the location.
The amount of energy gained by the PV-modules within their whole life cycle is the reference amount. Dimension: kWh/m*2
The values for irradiation and BOS efficiency have been calculated on the base of the results of the ECLIPSE project[7]. The used irradiation data (at the optimal angle) are:

- Frankfurt: 1200 kWh/m^2y
- Rome: 1700 kWh/m^2y
- Solar Belt: 2200 kWh/m^2y

The following PV module solar efficiencies were used:

- a-Si: 5,5 % (14,3 m^2/kWp)
- CdTe: 10 % (11 m^2/kWp)
- CIGS: 11,5 % (8,7 m^2/kWp)

The PV-systems results have been compared to the conventional electricity systems Depending on the type of solar cell and its typical application, the counterpart for the comparison was a UCTE (Union for the Co-ordination of Transmission of Electricity) power grid-mix for grid-connected applications or a diesel power generator for stand-alone installation.
For grid-connected installations the UCTE power grid mix is used. This power grid mix represents an average electricity grid in the UCTE countries, considering the absolute power production in the countries and the composition of different power sources (e.g. oil, gas, nuclear, water etc.) and the origin of the respective energy carriers, including all transports.

3.4 End of Life
The environmental impacts and benefits due to the recycling phase have been calculated including all the processes from the dismantling of the PV-plant to the disposal of the final waste and taking into account all the “credits” associated to the recycled materials, i.e. recovered semiconductors and recycled BOS materials.

3.5 Results of LCA analysis
In the following figures, the results of the LCA analysis for considered thin film PV-modules are presented. Since the aim of this study is not the comparison between the different thin film PV-technologies, the results of each thin film PV-technology are aggregated to an average result in order to make easier the comparison to the conventional energy supply, More specifically Figure 2 shows the comparison of the electricity produced by thin film PV modules, as a ground mounted power plant, installed in Central Europe, to an average European electricity mix (UCTE), latter one containing the environmental impacts of the average power supply with coal, oil, nuclear and other energy sources. The environmental burdens, are associated to the provision of 1 GJ electricity by PV-modules and by conventional electricity, considering all above mentioned aspects including module lifetime.

Considering the whole lifetime of PV-modules, all impact potentials are referred to each potential caused in whole Europe (normalization to Europe). The aim of the normalization is to understand better the relative magnitude for each indicator.

In figure 2, the impacts are referred to 1 GJ of produced electricity, in order to make an average of three thin film PV-technologies. In all regarded impact categories the thin film solar cell modules have significantly less environmental impact than UCTE-mix. Especially in the category GWP but also in the other categories the significant advantage of solar module is evident.
Analyses for other scenarios show that these significant advantages are for all regarded location and application types as well.

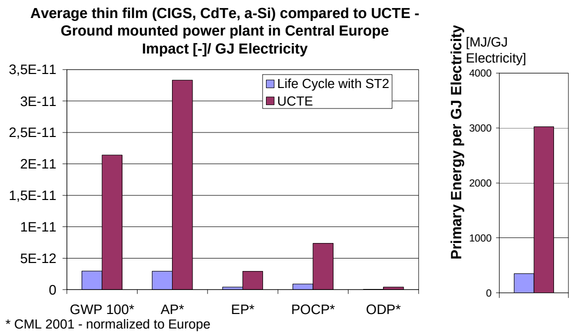

Figure 2: comparison average thin film PV-module with UCTE – normalized to Europe; referred to 1 GJ of provided electricity

The recycling has influences on the life cycle of thin film PV-modules, however does not change nor influence the basic statement (see Figure 3).
The technical effort (material and energy use) for the recycling, are nearly compensated by the environmental credits, gained by the recycled materials.

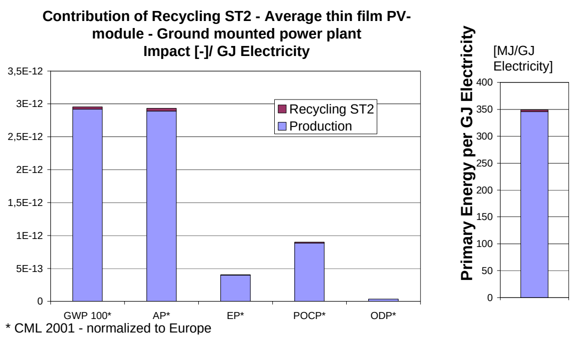

Figure 3: Contribution of recycling for average thin film PV-module normalized to Europe; referred to 1 GJ of provided electricity

4 CONCLUSION

The LCA analysis shows the environmental impacts caused by thin film PV-systems compared to conventional energy systems,. Although the results differ depending on the mentioned circumstances, the qualitative statements remain the same: thin film PV-systems are environmentally significantly advantageous

compared to conventional energy systems.
Although recycling of such complex products is seen as feasible but implying not negligible amount of energy and material use, the environmental burdens of the developed recycling system have a relatively small contribution, 4 %, in the environmental burdens of the whole life cycle. The environmental “credits” due to gained metals after recycling are considered hereby.
During the project, especially for CIGS modules, technical optimization in the production line was put into practice. Together with an increase of production capacity the optimization led to an improvement of environmental performance of this thin film PV-system. Depending on the technology, application and location (Location: Central Europe, Mediterranean Area, Solar belt) the EPBT has been reduced by about 30 % e.g. for roof integrated application in Mediterranean Area to 1,3 years, for ground mounted power plant in the same region to 1,5 years. Further development and improvement are expected for the near future [8].

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