LIFE CYCLE ASSESSMENT OF CdTe MODULE RECYCLING

Michael Held
University of Stuttgart, Chair for Building Physics (LBP), Department Life Cycle Engineering (GaBi)
Hauptstraße 113, 70771 Leinfelden-Echterdingen, Germany

ABSTRACT: The photovoltaic industry considerably increased in the last years. Thin film technologies have grown at an even more significant rate than conventional silicon solar technologies. A market share of about 20 % for thin film solar modules is forecasted for the year 2020 and worldwide measures to increase the production capacities of photovoltaic manufacturers are recognized. Besides the increasing implementation of photovoltaic's on the market it is strongly important not to lose sight of possible end-of-life strategies for used PV modules, like take back systems and recycling options. Due to the long life expectancy, today's returns of used PV modules are relatively low, but it is expected that there will be a significant increase from the year 2020. PV manufacturers already identified the need for research on further treatment options of used PV modules and to develop technology specific recycling processes. Based on advanced recycling procedures, most materials used in PV modules can be returned on the market as valuable materials, or in case of plastics, energetically recovered. Regarding thin film technologies, the recycling of used modules could also provide an additional source of rare metals like tellurium or indium to satisfy the increasing demand of these materials on the market. For ecological purposes, the recycling of modules can furthermore contribute to a reduction of the environmental profile of the whole module life cycle. Using the method of Life Cycle Assessment (LCA), these environmental benefits due to the recycling of PV modules can be quantified.

At Chair of Building Physics (LBP) a Life Cycle Assessment study was carried out to evaluate the environmental profile of the recycling of CdTe modules. Based on latest industry data, the study presents LCA result of an already applied recycling process of CdTe solar modules. Within this study a detailed LCA model of the recycling is built up including the processing of used modules, the recycling and energy recovery of materials as well as the further treatment and disposal of solid and liquid wastes. The study showed that the recycling of materials would contribute to a significant reduction of the environmental profile of end-of-life of CdTe modules. In total, the recycling of outgoing materials would reduce the Primary Energy demand in the End-of-Life from 81 MJ/m² to -12MJ/m² (reduction from around -93MJ/m²) and in terms of the Global Warming Potential from 6kg CO_2-equiv./m² to -2,5 CO_2-equiv./m² (reduction from around -8,5 kg CO_2-equiv./m²).

The paper gives an overview on the approach of the study, discusses the main outcomes and analyses the significance of recycling in relation to the environmental profile of the production and total life cycle of CdTe modules.

Keywords: Life Cycle Assessment (LCA), CdTe, thin film, recycling

1 INTRODUCTION

There are several drivers why producers decide to apply recycling strategies on spent products. Main reasons are policy requirements, public demands, marketing issues, or environmental requirements.

In terms of environmental aspects there are different criteria why product recycling could lead to an improvement of product life cycles. On the one hand, the recycling of product leads to a reduction of wastes and related emissions, avoiding uncontrolled disposal or conservation of landfill capacities. On the other hand, the use of recycled materials could contribute to energy savings and emission reductions in production processes. This is especially the case for raw materials with high impurities which often require energy intensive pre-treatments, or in case of the glass production where the carbon content of primary materials is released as CO_2 emissions in the melting processes.

The most significant aspect is that recycled materials substitute primary materials, which allows conserving materials, energy and land resources. Especially for rare materials like precious metals, these benefits are from high importance as the extraction processes of raw materials are often associated with high energy and auxiliary demands and related emissions.

Furthermore the conservation of resources also could preserve ecosystems as the material extraction (e.g. mining) is generally a land consuming processing.

This shows that an assessment on the environmental benefits of material recycling requires a comprehensive investigation on the impacts due to the recycling processes of materials as well as avoided impacts by returning materials to the value chain.

Based on life cycle thinking the method of Life Cycle Assessment is a suitable tool for quantifying the environmental performance of product recycling.

A LCA study on the life cycle of current CdTe modules was carried out at the LBP, dept. Life Cycle Engineering in cooperation with the Brookhaven National Laboratory.

The goal of the project is to quantify the environmental performance of a CdTe module over its whole life cycle by using the method of Life Cycle Assessment (LCA) according to ISO 14040 series [1], [2]. The main aim is to receive representative LCA results regarding the environmental profile of a typical CdTe module life cycle, therefore the used data for the study is based on current available industry data.

In the framework of the study a detailed environmental analysis on currently applied module recycling processes is carried out. The main outcomes are presented in this paper.

3 METHODOLOGICAL APPROACH OF END-OF-LIFE IN LCA

There are different options available to handle products or systems reaching their end-of-life:

- Reuse of products or components in further applications,

- Refurbishment of components for reuse in similar applications,
- Recycling of materials for further utilization,
- Incineration of materials,
- Disposal of material as wastes (e.g. land filling of solid and liquid fractions)

The methodological approach of the end-of-life consideration in LCA is similar to the all other life cycle phases. This means that all required energies and auxiliary materials flows as well as emissions due to the different end-of-life treatments are accounted for.
However, in addition to the caused environmental impacts of end-of-life treatments there is also the challenge to account for the environmental benefit due to the recycling of materials or energy recovery correctly.

There are several methods available to reflect environmental benefits from material recycling or energy recovery in LCA. A commonly used approach is to account recycling benefits (e.g. by substituting the production of respective materials) as credits. To do this, it is necessary to account all caused emissions related to the whole recycling process of materials, e.g. for the remelting, as these are applied to produce the recycled materials. This assumes is based on the assumption that there are no changes in the inherent properties of the recycled materials (see. ISO 14044 [2], chapter 4.3.4.3).

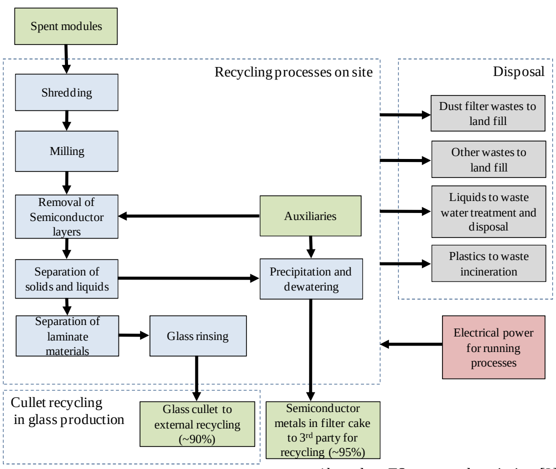
In terms of waste incineration processes, the recovered energy from materials (e.g. plastics) is accounted as credit by substituting energy production from conventional energy production systems.

4. RECYCLING PROCESS OF SPENT CdTe MODULES

The recycling of spent CdTe modules includes mechanical and hydrometallurgical processing, divided into five main process steps which are subsequently briefly described.

1. Shredding and milling
2. Extraction (film removal)
3. Solid/Liquid separation
4. Glass- Laminate separation and glass rinsing
5. Precipitation and dewatering

Figure 1 illustrates a simplified process flow chart of the recycling process of CdTe modules.



**based on FS process description [3]*

Figure 1: Flow chart of CdTe module recycling processes

Shredding and milling: The collected modules are first reduced in a shredder to large pieces and crushed in a hammer mill into desired piece size from around ~4-5 mm. This ensures that the lamination bond is broken for exposing the cadmium telluride to be dissolved in the following extraction process. Due to the screen size of the milling crusher, the bulk of glass is separated, starting from larger pieces of the laminate foil.

Film removal (Extraction): The film removal process physically removes the semiconductor films in a rotating leach drum. Sulphuric acid is added. Afterwards hydrogen peroxide is added throughout the leach cycle to form the tellurium into tellurous acid.

Solid-Liquid separation: After extracting the semiconductor materials, the liquids are separated from solid materials. This is done in a spiral classifier using an Archimedean screw. This allows a separation of the glass pieces from the liquid. The glass pieces are further treated to separate the laminate foil from the glass whereas the extracted liquor leaves to precipitation and filtration.

Laminate foil/glass separation and rinsing: Due to the screen size in the milling and crushing process most of the laminate foil is already separated in large pieces from the glass. In a vibrating screen the remaining laminate foil parts are separated from the glass cullet. The separated glass is then discharged and washed and ends up to recycling.

Precipitation and filtration: The metal compound containing extraction liquor is further treated by a three stage precipitation process with an increasing pH using sodium hydroxide for pH control. A certain pH value is aspired where the cadmium and tellurium are least soluble. The precipitated solution is thickened, so the solids settle and increase in a solids loading. The thickened slurry is filtered and ends up in a semiconductor material enriched filter cake and a liquid solution. The filter cake is stocked for further processing by third party companies to recover the containing metals. The liquid solution is transferred to waste water treatment.

5. LCA APPROACH ON THE END-OF-LIFE OF CdTe MODULES

The end-of-life phase of CdTe PV modules is reflected by material and system specific end-of-life treatments, which are divided into four main end-of-life routes: recycling of materials, waste incineration land filling and waste water treatment.

All specific data on the CdTe module recycling process was collected and provided by industry. The data includes a detailed description of recycling process steps as well as a statement of required auxiliary materials, energy demand and additional treatment of wastes and recycled materials.
Based on this data a Life Cycle Inventory (LCI) model was set up in the GaBi 4 software [4]. The recycling and further treatment of outgoing materials and wastes is represented by material and system specific datasets based on the GaBi 4 databases.

5.1 Boundary conditions of the end-of-life assessment

Functional unit: The functional unit for the LCA is 1m² of spent CdTe modules.

Geographical scope: The recycling plant is considered to be in Germany. Therefore all datasets of used auxiliaries, energies and end-of-life processes like material recycling or disposal on landfill are country representative datasets.

Impact categories: Potential contributions to Acidification (AP), Eutrophication (EP), Global Warming (GWP), Photochemical Ozone Creation (POCP) and the use of fossil energy resources represented by the Primary Energy demand from resources (net. cal. value) (PE) are considered in the quantitative assessment. The used impact assessment methodology is based on CML2001 [4]. These categories are widely accepted and on a comparable basis.

Data origin: All primary data - data that is directly related to the recycling, like energy demand, use of auxiliary materials, material and waste outputs - are based on industry data. Secondary data, e.g. on the production of used auxiliary materials, energies as well as the consideration of further waste treatments or recovered materials are based on available GaBi 4 datasets and recycling models

5.2 Main assumption on the module recycling

The end-of-life consideration in this study is carried out based on two main approaches:

- Module specific end-of-life treatment based on the data provided by the project partners (PV module recycling strategy)

- Average end-of-life treatments for external components and assemblies (e.g. lead wire, connection box) are considered by material or component specific end-of-life processes available in the GaBi 4 databases.

5.3 Recycling and further treatment of outgoing materials and wastes from the recycling site

Clean glass cullet: The clean glass cullet leaves to recycling by the glass industry. The environmental benefits due to the cullet recycling are reflected by the following three main aspects:

1. The cullet is used for **substituting primary material** in the glass. Therefore the avoided environmental impacts and primary energy demand due to the substitution of the primary material mix is considered as credit.

2. **Reduction of CO_2 emissions in the melting process.** The primary material mix for the glass production consists of carbonate containing materials, like limestone, dolomite, soda/soda ash. The carbon content of these materials is reduced during the melting process and emitted as CO_2 emissions during the melting process. The caused CO_2 emissions related to the carbon released from the primary materials is depending on the used material mix, around 30% of the total CO_2 emissions in the melting process of the German flat glass mix [6]. Avoided CO_2 emissions in the melting process due to the use of glass cullet instead of primary materials are considered as credit.

3. **Energy reduction in the melting process.**

The lower melting point of glass cullet compared to the primary material mix leads to a lower energy demand in the glass melting process. The energy reduction potential of cullet glass in the melting process is in the range of around 3% per 10% glass cullet [6] - [10]. These benefits are considered as credits by the reduction of required fuels and related emissions in the glass melting process.

Filter cake: The semiconductor material containing filter cake from the recycling process is currently sent to a 3rd party for processing into CdTe for use in new solar modules. Around 95% [3] of input semiconductor materials are recovered in the filter cake. . As there is no representative data on the filter cake recycling available yet, it is not further considered in this study. However, we expect that the recovery of the metals to provide a positive benefit.

Lamination wastes:

Laminate wastes are burned for energy recovery. Data on caused emissions during the thermal treatment and the material specific energy output (thermal and electrical energy) related to the energy content of the plastic are taken from the GaBi 4 databases. Recovered energy is further used and therefore considered as credit by substituting the production of electricity and thermal energy from fossil fuels.

Glass fines, dust filters and other waste: The further treatment of filters, glass fines and other wastes is represented by material specific land filling processes.

Liquid wastes: The treatment of the sodium sulphate solution in a waste water plant is represented by material specific waste water treatment processes including further treatment of solid residues.

5.3 Recycling of junction boxes and lead wires

There is no specific data on the end-of-life treatment of the junction boxes or lead wires available. Therefore the end-of-life of these assemblies is represented by material specific end-of-life treatments.

It is assumed that all plastic materials are burned in a waste incineration plant. Material specific emissions in the incineration process are accounted. The recovered energy according to the energy content of the plastics is reflected as credit for the substitution of electrical power and thermal energy.

The recycling of metal parts which is mainly cooper from connectors and cables is represented by a copper specific recycling process. The recycling process reflects the processing of copper scrap to secondary copper metal. Environmental benefits of secondary copper due to the substitution of primary copper are accounted as credit.

6. IMPACT ASSESSMENT OF CdTe MODULE RECYCLING

In the following the LCIA results of the end-of-life phase CdTe modules are presented. The evaluation is done for two cases: including and excluding environmental credits from material recycling. This provides a range of the environmental profile of the end-of-life phase.

A comprehensive overview of all LCIA results is given in Table 1 at the end of this chapter.

6.1 Impact assessment of end-of-life phase without accounting for the material recycling credits

Figure 2 presents the LCIA results of the end-of-life of CdTe modules. Environmental benefits of material recycling are not accounted as credits:

The environmental credits, which are given for the energy recovery from waste incineration (e.g. of plastics) are presented as negative values.

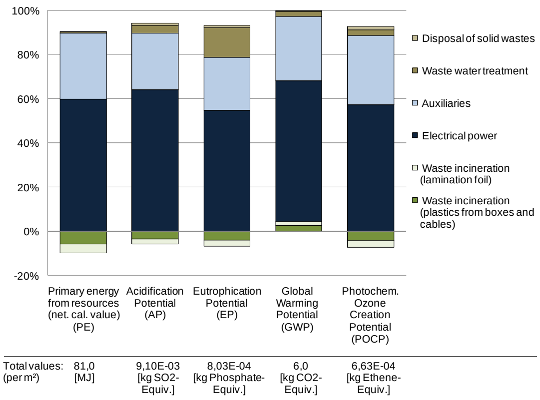


Figure 2: End-of-life phase, w/o material recycling credits (relative shares)

The analysis shows that the required energy and auxiliaries of the module recycling process are the main contributors in all considered environmental impact categories. The environmental benefits due to the energy recovery of incinerated plastic wastes (laminate and plastics from junction boxes and wires) could lead to a reduction from ~6 to ~8% of considered impact categories excluding GWP. The contribution of the incineration of plastic wastes to the GWP is due to caused CO_2 emissions in the incineration which overweight the benefits of associated energy recovery. In terms of the Primary Energy demand the energy recovery from plastics wastes leads to a reduction of ~12%. Regarding the disposal of wastes, most significant contributions are identified for the waste water treatment to the EP. These contributions are mainly related to nitrogen oxide emissions and COD (chemical oxygen demand) in the processing.

6.2 Impact assessment of end-of-life phase including material recycling credits

In the following the main contributors to environmental impact categories including credits from material recycling, with the exception of metals recovery from the filter cake, are investigated. The results are exemplary illustrated for the Acidification Potential, Global Warming Potential and Primary Energy demand in Figure 3- Figure 5. A comprehensive presentation of the LCIA results is given in Table 1.

The environmental assessment of the end-of-life of CdTe modules including environmental benefits from material recycling shows that for all considered impact categories the benefits due to material recycling and energetic recovery outweigh the impacts of the recycling process and therefore would lead to a reduction of the environmental profile of the overall CdTe PV module life cycle, to around -2,5 kg CO_2-equiv./m² in the GWP and ~12,5 MJ/m² in the Primary Energy demand.

These benefits are mainly due to the recycling of the glass cullet and the copper recycling from the junction boxes and wires, whereas the environmental benefits from glass cullet recycling are significantly higher.

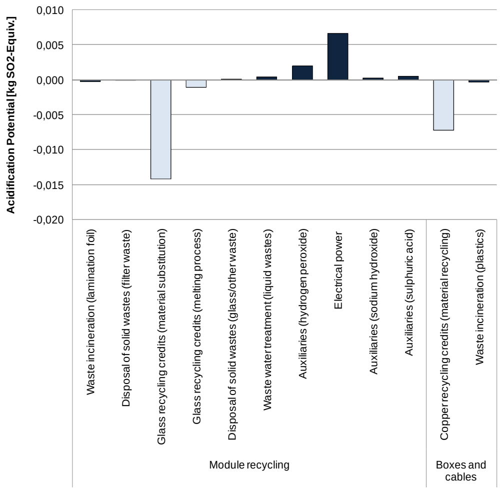


Figure 3: Acidification Potential of the end-of-life phase

The assessment also shows the contribution of required auxiliaries, mainly hydrogen peroxide, and energy demand for running the recycling processes of CdTe modules, which are mainly significant in the Primary Energy demand and Global Warming Potential (Figure 3, 4). For the hydrogen peroxide these impacts are mainly due to required energies in the production process.

In terms of the **glass cullet recycling,** the main environmental benefits in all considered environmental impact categories are due to the substitution of the primary material mix in the glass production.

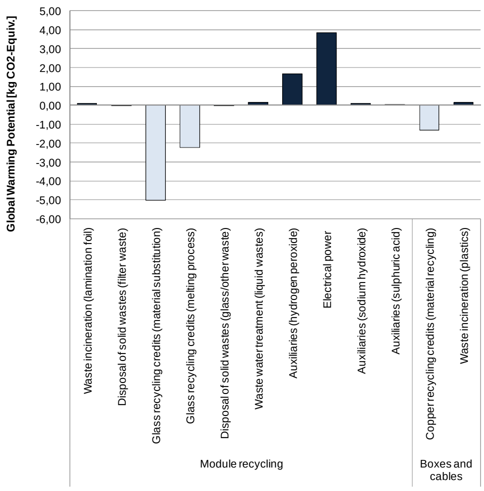


Figure 3: Global Warming Potential of the end-of-life phase

Regarding the **Global Warming Potential,** an additional benefit of the glass cullet recycling is investigated for the glass melting process, where the substitution of primary materials also avoids CO_2-emissions related to the carbon reduction of used raw materials like limestone, dolomite or soda ash.

The benefits of the glass recycling on the **Primary Energy demand** (Figure 4) are divided into benefits from substituting primary materials and energy reduction in the glass melting process, where the cullet leads to a reduction of the melting point of the material batch and hence to a reduction of the energy demand in the melting process.

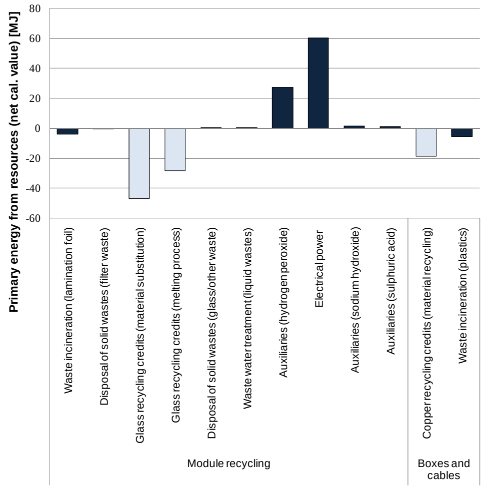


Figure 4: Primary Energy demand of the end of life phase

Depending on applied furnace technology the blend of cullet in the glass material mix leads to a reduced energy demand of around 3% per 10% mass share of the cullet in the glass melting process.

6.3 Recycling of precious metal containing filter cake

Currently the outgoing filter cake from the module recycling is send to a 3rd party for recycling into compounded CdTe for use in new solar modules. However, data on this process was not available for this study and it is therefore not reflected in this study.

Since around 95% of the semiconductor materials are recovered for further treatment, it is assumed that the filter cake recycling also contributes to a reduction of the environmental profile of end-of-life phase of the CdTe modules.

Table 1: Life Cycle Impact assessment results of CdTe module recycling (per m²)

CdTe Module recycling per m²		Primary energy from resources (net cal. value) [MJ]	AP [kg SO2-Equiv.]	EP [kg Phosphate-Equiv.]	GWP [kg CO2-Equiv.]	POCP [kg Ethene-Equiv.]
CdTe module recycling	Auxiliaries (recycling process)	29,86	2,64E-03	2,24E-04	1,76E+00	2,43E-04
	Electrical power (recycling process)	60,12	6,59E-03	5,07E-04	3,84E+00	4,45E-04
	Glass cullet recycling	*-74,87*	*-1,53E-02*	*-2,16E-03*	*-7,23E+00*	*-1,63E-03*
	Waste incineration and energetic recovery, lamination foil	-3,98	-2,45E-04	-2,58E-05	9,54E-02	-2,34E-05
	Disposal of wastes (glass fines, filter wastes, others)	0,18	9,38E-05	1,08E-05	1,22E-02	1,19E-05
	Waste water treatment, liquid solutions	0,49	3,60E-04	1,23E-04	1,51E-01	1,96E-05
Junction box and lead wires	Waste incineration, plastic materials	-5,64	-3,41E-04	-3,52E-05	1,72E-01	-3,26E-05
	Copper recycling	*-18,64*	*-7,20E-03*	*-4,28E-04*	*-1,30E+00*	*-4,88E-04*
Total* (incl. material recycling credits)		***-12,49***	***-1,34E-02***	***-1,80E-03***	***-2,50E+00***	***-1,45E-03***
Total* (without material recycling credits)		**81,03**	**9,10E-03**	**8,03E-04**	**6,03E+00**	**6,63E-04**

** negative values describe environmental benefits accounted as credit within the life cycle assessment*

6.4 Significance of end-of-life phase to product life cycle

Figure 5 presents the LCIA results of the life cycle of CdTe modules. Impacts due to the production phase are set to 100%. The use phase is not listed as it is assumed that there are no maintenance measures during the useful lifetime.

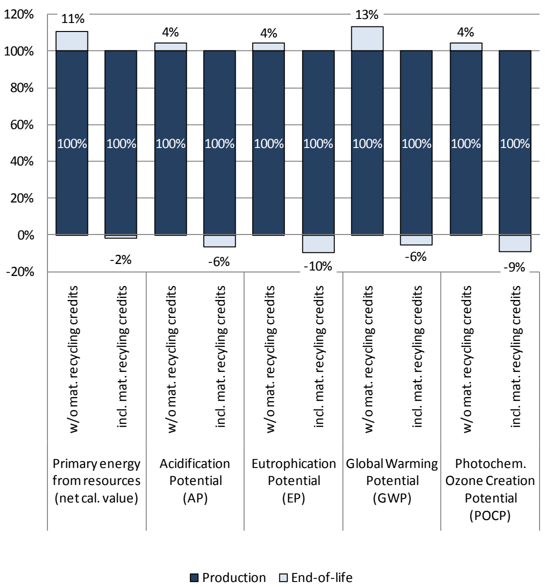


Figure 5: Life cycle phases (relative shares)

The analysis shows that, compared to the production phase, the relative contribution of the end-of-life phase of CdTe modules ranges between 4-13% in considered environmental impact categories and ~11% in the primary energy demand from resources.

Furthermore Figure 5 shows that the recycling of outgoing valuable materials in the end-of-life, the environmental impacts of the CdTe module life cycle could be further reduced by around 6-10% in respective impact categories and demand by around 2% in terms of the primary energy demand.

7. CONCLUSION

The paper presented the environmental profile of currently applied recycling processes and end-of-life treatments of spent CdTe PV modules. In addition, optional environmental benefits due to the recycling of outgoing materials were investigated.

It showed that the main contributors to considered environmental impact categories are due to required chemicals and energy within the processing of CdTe modules. Especially the primary energy demand and contribution to the GWP of required el. power and hydrogen peroxide has significant effect on the environmental profile of the module recycling.

Furthermore it was investigated, that a recycling of outgoing valuable materials would lead to a significant reduction of the overall environmental profile of CdTe PV module. The outgoing semiconductor material containing filter cake from the current module recycling is currently being sent to a 3rd party recycler; however, data was not available for this analysis. However, the recovery of tellurium will result in further reduction of the environmental profile of CdTe module recycling in addition to providing a source of tellurium.

8. REFERENCES

[1] ISO 14040: Environmental management – Life Cycle Assessment – Principles and framework, 2006

[2] ISO 14044: Environmental management – Life Cycle Assessment – Requirements and guidelines, 2006

[3] First Solar, 'Modulrücknahme- und Recycling-Programm', Recycle_MD-5-501-Rev2-Nov2008_DE-WEB.pdf , 2008

[4] GaBi 4, Software-System and Databases for Life Cycle Engineering: University of Stuttgart, Chair of Building Physics in cooperation with PE international, Stuttgart, Echterdingen, 2007

[5] Centre of Environmental Science - Leiden University (CML): Characterization and normalization factors; Leiden, The Netherlands; 2001

[6] Nachhaltige rohstoffnahe Produktion, Fraunhofer ICT, 2007.

[7] Gitzhofer, Karlheinz, 'BVT-Festlegung in ausgewählten industriellen Bereichen als Beitrag zur Erfüllung der Klimaschutzziele und weiterer Immissions-schutzrechtlicher Anforderungen' - Teilvorhaben 02: Erarbeitung eines deutschen Beitrages zur Revision des BVT Merkblattes für die Glas- und Mineralfaser-industrie, Forschungsprojekt im Auftrag des Umweltbundesamtes FuE-Vorhaben 205 44 324/02; February 2007

[8] Integrated Pollution Prevention and Control (IPPC), Reference Document on Best Available Techniques in the Glass Manufacturing Industry, December 2001

[9] Ullmann's Encyclopedia of Industrial Chemistry, 'Glass', Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, 2005

[10] Rue, M. D., 'Industrial Glass Bandwidth Analysis', Gas technology institute, Energy Utilization Center, 2007

[11] Held, M.; Ilg, R.; 'Life Cycle Assessment (LCA) of CdTe thin film modules and Material Flow Analysis of cadmium within EU27', 23rd European Photovoltaic Solar Energy Conference, 2008, Spain