SENSE

Sustainability Evaluation of Solar Energy Systems

LCA Analysis

SENSE
Sustainability EvaluatioN of Solar Energy systems

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Project Partners	Wuerth Solar GmbH & Co.KG.
	Free Energy Europe SA
	Zentrum fuer Sonnenenergie- und Wasserstoff-Forschung
	Fraunhofer-Gesellschaft zur Foerderung der Angewandten Forschung e.V.
	Ambiente Italia srl
	Fundacion Gaiker

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Energy systems

Funded by the European Community under the 5th Framework Programme (1998-2002)

Contents

Glossary

a-Si	Amorphous silicon
AP	Acidification Potential
BIPV	Building Integrated Photovoltaic
BOS	Balance of Systems
CdTe	Cadmium telluride
CIGS	Copper indium diselenide
ECLIPSE	Environmental and ecological Life Cycle Inventories for present and future Power Systems in Europe
EoL	End of Life
EP	Eutrification Potential
EPBT	Energy Payback Time
EVA	Ethylene vinyl acetate
GWP	Greenhouse warming potential
IPCC	Intergovernmental Panel on Climate Change
LBP	Chair for Building Physics
LCA	Life Cycle Assessment
NMVOC	Non-methane Volatile Organic Compounds
POCP	Photochemical oxidant creation potential
PV	Photovoltaic
SENSE	Sustainability Evaluation of Solar Energy Systems
UCTE	Union for the Co-ordination of Transmission of Electricity

Executive Summary

This paper reports on the Life Cycle Assessment results of the project “Sustainability Evaluation of Solar Energy Systems (SENSE)” (CONTRACT N°: ENK5-CT-2002-00639). The project was co-funded by the EC during 2001 to 2006. Within the project two objectives were achieved: the identification of possible **recycling strategies** for thin film Photovoltaic (PV) modules (CIGS, CdTe and a-Si) and the analysis of **environmental performance** of these PV modules.

A consortium of manufactures, recyclers and scientists developed a practical applicable recycling system and assessed the environmental impact of production and utilization of thin film PV modules as well as of the developed recycling system.

Concerning recycling strategies for PV modules, many experiments on different possible recycling routes for each PV technology were carried out. After a large series of careful analyses, a few processes turned out to be practically applicable and economic meaningful, i.e. providing an interesting yield both in terms of quantity and quality of recovered materials. The most auspicious route for CIGS and CdTe modules is the delamination of modules by thermal treatment, with a following chemical solving process and recovery of deposited metals. A survey showed that metal producers are willing to pay for such metal containing solutions, which can be inserted in a metal production line. For a-Si modules the most practical and meaningful recycling system consists of delivering the PV modules without separating the a-Si layer from the glass, and recycling the plastic frames. Especially for CIGS analyses showed the potential of recycling of manufacturing waste.

The environmental assessment was carried out by using the method of Life Cycle Assessment (LCA), which showed the environmental impacts of thin film solar modules through their entire life cycle – from manufacturing to End of Life –. Both the impacts caused by stationary and mobile PV application systems were regarded, each compared to respective appropriate alternative energy sources: the electricity generation mix and diesel generators.

A comparison of environmental burdens was carried out by considering the specific PV technology, the type of application (including BOS[1]), and the location of installation. The results show that present thin film PV modules cause significantly less environmental burdens compared to conventional energy carriers. The result of the comparison remains the same independently of the different technology (CIGS, a-Si, CdTe) types of application (Power Plant, BIPV[2], mobile for stand-alone systems).

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[1] Balance of System, i.e. mounting structures and electric auxiliary systems

[2] Building-Integrated PV

1 Introduction

The demand of the society for sustainable energy sources is higher than ever. Photovoltaic (PV) energy is meanwhile seen as one of the auspicious “sustainable” candidates. At the beginning of PV system history, due to laboratory scale or small scale production, the required energy for the production of a PV module was relatively high. This disadvantageous character of PV modules has basically changed in recent years along with its rapid market growth and technological improvement. However the actual potential environmental impacts and benefits of PV systems and of renewable energy sources in general must be analysed carefully, since depending on the nature of the specific energy carrier (solar, water, wood, biogas etc.) and the application region the environmental impact can differ significantly (also compared to non-renewable energy carriers).

Beside wafer based crystalline silicon PV modules, thin film PV modules are alternative mass production oriented PV technologies. Although their worldwide market share in 2004 was with 7 % relatively small, significant growth is expected in the coming years and decades. This tendency can already be seen in the growing production capacity of thin film PV-modules [Jäger 2006]. 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, updated analyses are important in order to examine the actual environmental performance of thin film PV-systems.

A further important aspect must be followed at the same time: concerning “End of Life” of thin film PV-systems a recycling strategy or technology is still missing. The present legal situation and its tendency show the importance of being prepared for future environmental legislation. For example, the WEEE[3] regulates the recycling and reuse rate of electric and electronic products by weight, and the RoHS[4] bans the use of certain hazardous materials. As one product category, which could be affected by these directives, once PV-modules were under discussion. Although finally it resulted that PV-modules do not fall into the scope of the WEEE and RoHS until today, effort should be made in advance, in order to establish a recycling strategy for PV systems. While this is not an important issue today because of the small absolute values of the world PV market, it will become a significant one, as market grows exponentially.

Although “recycling” is due to its resource saving and waste reducing character per se understood as being environmentally friendly, this is not always the case. Depending on the scope of the recycling system, including logistical aspects and the required effort, recycling can increase the environmental impacts of a product over its life cycle, instead of reducing them. To avoid such potential environmentally disadvantageous effects, the development of a recycling system should be accompanied by an environmental impact assessment. This is an effective decision-making supporting tool for (technology) designers, and policy-makers.

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[3] Waste Electrical and Electronic Equipment Directive

[4] Restriction of Hazardous Substances Directive

Of course, also economic aspects should be addressed in the development phase of a recycling system. Recycling is not naturally more expensive than alternatives, as far as conventional ways of End of Life (EoL) are accompanied with costs (e.g. for final disposal of hazardous waste).

These challenges are covered in the project “Sustainability Evaluation of Solar Energy Systems (SENSE)” (ENK5-CT-2002-00639) co-funded by the European Commission (EC) within the 5th Framework Programme. This project combines both the development of recycling techniques and strategies for PV-modules with a Life Cycle Assessment (LCA), the latter covering the production, use phase and End of Life phase of a PV-system. The project specifically focused on thin film technologies, i.e. a recycling strategy for Copper-Indium-Gallium-Diselenide (CIGS), amorphous silicon (a-Si) and Cadmium-telluride (CdTe) PV-systems was developed and assessed. 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, worked on SENSE from 1st January 2003 to 30th June 2006.

2 PV Technologies

The following three types of thin film photovoltaic technologies were examined, each in its different application types (power plant, BIPV, mobile)

- Copper Indium Gallium Selenide (CIGS)
- Amorphous silicon (a-Si)
- Cadmium telluride (CdTe)

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

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

Table 1 shows the characterization of considered thin film PV-modules. The efficiency of the modules varies, e.g. in case of CdTe from 9 to 12 %. For the LCA study the average value is implemented. From these data the numbers of modules per kWp is calculated.

In the analysis the infrastructures of solar modules such as cable, inverter module, frames etc. are considered.

	ground mounted power plant			
	CIGS	**a-Si**	**CdTe**	**Data source**
Efficiency [%]	11,5	5,5	10,0	Industry data
Module size [m2]	0,72	0,27	0,72	Industry data
Power per module [Wp]	80[2]	14,8[1]	65[2]	[1]Calculated, [2]Industry data
Module weight [kg]	11,5	3,5	14,0	Industry data
Frame weight (aluminium) [kg]	1,3	-	1,3**	Industry data
Frame weight (PUR) [kg]	-	0,5	-	Industry data
BOS* weight [kg]	18,4	6,9	18,4	[ECLIPSE]
Electric cable* weight [kg]	0,117	0,040	0,117**	Industry data
Inverter* weight [kg]	29,9	29,9	29,9	Industry data
Total weight per module	**61,1**	**40,9**	**63,7**	

*per module and life time; **expected to be the same as CIGS

	roof integrated			
	CIGS	**a-Si**	**CdTe**	**Data source**
Efficiency [%]	11,5	5,5	10,0	Industry data
Module size [m2]	0,72	0,27	0,72	Industry data
Power per module [Wp]	80	14,8[1]	65	[1]Calculated
Module weight [kg]	11,5	3,5	14,0	Industry data
Frame weight (aluminium) [kg]	-	-	-	[ECLIPSE]
Frame weight (PUR) [kg]	-	-	-	[ECLIPSE]
BOS weight [kg]	1,2	0,4	1,2	[ECLIPSE]
Electric cable weight [kg]	0,117	0,040	0,117**	Industry data
Inverter weight [kg]	29,9	29,9	29,9	Industry data
Total weight per module	**42,7**	**33,9**	**45,2**	

*per module and life time; **expected to be the same as CIGS

	mobile			
	CIGS	**a-Si**	**CdTe**	**Data source**
Efficiency [%]	11,5	5,5	10,0	Industry data
Module size [m2]	0,72	0,27	0,72	Industry data
Power per module [Wp]	80	14,8[1]	65	[1]Calculated
Module weight [kg]	11,5	3,5	14,0	Industry data
Frame weight (aluminium) [kg]	-	-	-	[ECLIPSE]
Frame weight (PUR) [kg]	-	-	-	[ECLIPSE]
BOS weight [kg]	1,2	0,5	1,2	[ECLIPSE]
Electric cable weight [kg]	0,117	0,040	0,117**	Industry data
Inverter weight [kg]	29,9	29,9	29,9	Industry data
Total weight per module	**42,7**	**33,9**	**45,3**	

*per module and life time; **expected to be the same as CIGS

Table 1 Basic specification of different PV-modules

3 Life Cycle Assessment

A LCA analysis considers the environmental burdens caused during the entire life cycle of a product production phase, use phase and End of Life phase [ISO 14040]. This is a suitable tool for analysing and assessing the environmental impacts which are caused through production, use and disposal or recycling of product systems for specific applications. With this approach the environmental burdens shifting from one life cycle phase to another can be avoided.

As a rule LCA does not produce clear-cut straightforward assertions but gives diverse and complex results. It supports the process of decision-making by making complex issues transparent.

The LCA analysis enables the determination of the environmental performance of thin film PV modules considered in this project. Within the SENSE project the LCA analyses were carried out by applying the LCA software “GaBi 4”, with its background data.

3.1 Goal and scope of the study

The LCA analysis in the SENSE project aims at the determination of environmental performance of the current three thin film PV modules and the comparison to the conventional energy supplying systems. For this purpose, an LCA analysis for a-Si, CIGS and CdTe PV modules concerning their production, installation and developed recycling systems were carried out.

A comparison among the different PV-technologies is not intended in this project. The PV systems are considered each solitary. Therefore the results shown in this report present the LCA results for each technology type separately.

The production line of PV modules were analyzed as detailed as possible (CIGS and a-Si). For CdTe the production data were provided as aggregated form. For those processes, which were still under development, the LCA analysis was continuously accompanied in order to present the most up-dated development status.

3.2 Functional Unit

A LCA analysis takes a reference value – “functional unit” – as a basis. As functional unit for the purpose of SENSE, either 1 kWp (Kilowatt peak) or 1 MJ provided electricity can be chosen. 1 kWp presents the power output of a PV module at the standard test condition (1000 W/m^2 solarisation by 25 °C cell temperature and solar spectrum at Air Mass AM = 1,5). 1 MJ take the PV as system and thus its utilization phase into account in addition to the production phase.

The general scope of products is restricted by the product portfolios of the module manufacturing project partners Würth Solar and Free Energy Europe as well as by Antec Solar for CdTe. The restriction gives more reliable results of the LCA, because only consolidated data from these manufacturers are necessary. Although the basically applied module types are today as the following shows, within the project the application types which are not commonly used are analyzed as well (e.g. for CdTe mobile modules, for a-Si power plant modules and roof integrated BIPV)

The amount of gained energy by a PV-module depends on:

- Peak power or efficiency of the module (to be separately considered for the three technologies CdTe, a-Si and CIGS and the three product types)
- Site of installation (latitude, climate): possible scenarios to consider in SENSE: Central Europe, Mediterranean Area, Solar belt
- Installation type: possible scenarios to consider in SENSE: Ground mounted, sloped roof, mobile
- Lifetime: expected lifetime 20 years

3.3 System Description

According to the product portfolios of the three module manufacturers a scope of products was defined. Every process step with its material and energy use can have a significant influence on the environmental burdens. The choice of production, installation and recycling location has significant influences on the transport and primary energy use, which must be defined in the project.

The environmental performance of PV-systems was evaluated in a life cycle perspective, including the manufacturing, the operation and the end-of-life phases.

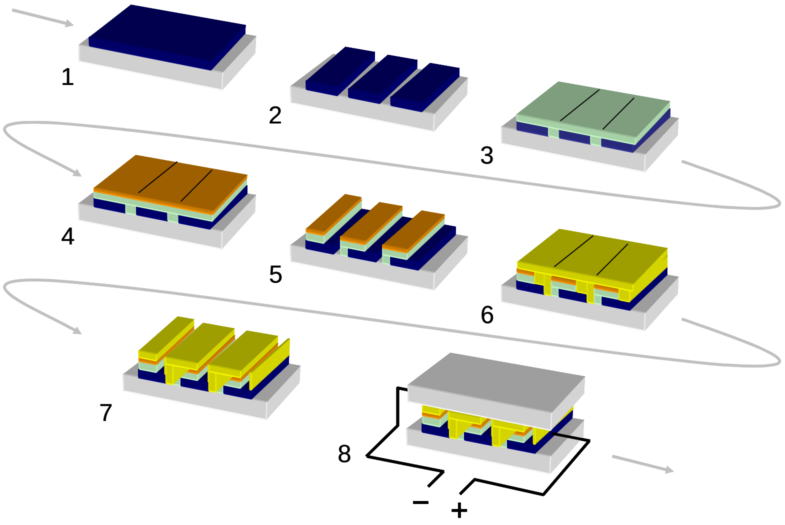
3.4 Production of PV-modules

The contribution of thin film PV-producers in the SENSE-project enabled a detailed data collection of the module production lines, as well as necessary accessories for the proper operation of PV systems, (e.g. mechanical/structural Balance of System (BOS), inverters, frames etc.). Furthermore, specific primary data related to the developed recycling strategies have been collected. These data, as well as the auxiliary product samples provided by producers (e.g. an inverter) ensured a high quality of the LCA analysis.

The data collection concerning CIGS and a-Si manufacturing were carried out with the direct support of manufactures, therefore the quality of these data are very high.

CIGS (Cu, In, Ga, Se)

The data for the production of CIGS solar module were provided from the project partner “Würth Solar”. Glass serves as substrate of a CIGS solar cell module, which is washed in the first manufacturing step. Sputtering of molybdenum aims the coating of “back contact”. The substrate is structured by laser technique. In a flow process the light-absorbing layer (copper, indium, gallium and selenium) is co-evaporated. The buffering layer of CdS (cadmium sulphide) is put on the substrate by dip coating. A mechanical structuring follows. The front electrode is deposited by sputtering of zinc oxide, which is doped with Al_2O_3. After the following mechanical structuring, the module is semifinished. A functional test identifies the defective products. The installation of infrastructures as well as the front glass follows to complete the manufacturing.



1. sheet glass; rear contact Mo; cathode sputtering
2. Laser structuring of rear contact
3. absorber Cu (In, Ga) Se2; simultaneous vaporisation
4. intermediate layer CdS; chemical soaking bath
5. mechanical structuring of absorber
6. front contact ZnO; cathode sputtering
7. mechanical structuring of front contact
8. final contacts; sealing with cover slip and adhesive foil

Fig. 1 Production of PV-module

a-Si

Amorphous silicon cells are made by applying plasma technique. For this solar cell the industry partner Free Energy Europe provided inventory data. The cut and washed glass sheet is prepared in a furnace and are preheated and deposited in a metal chamber with gaseous substances (plasma deposition). Afterwards the substances are evaporated with aluminium. Laser structuring follows. To fill the data gaps, data based on assumptions are used in this stage of the project. The installation of infrastructures and the assembly of the backside glass sheet complete the manufacturing of the a-Si module.

CdTe

Concerning CdTe the manufacturing data was provided as black-box data by a module producer. Due to confidentiality agreement this report dispense on further details.

At the beginning of the manufacturing of CdTe solar cell modules, float glass is fed into a standard glass washing machine and preheated at atmospheric pressure in order to remover adsorbed water and to preheat the substrates for the first deposition step.

The deposition of the transparent front electrode and the first scribing step follow. On a thermalised precision table the film is cut into stripes by means of a laser system, which number is determined by the desired system voltage. After being fed horizontally into the next in-line vacuum system the glass plates are heated. The semiconductor materials (CdS and CdTe) are deposited by close space sublimation from a number of graphite crucibles held at about 700°C. Finally, the coated plates are dynamically annealed and cooled.

Mechanical scribing is then applied to structure the semiconductor film.

Following a dynamic wet etch station, the metallic back contact is deposited in a system similar to the TCO coating by sputtering in a vertical in-line system. The final scribing step of the back contact is then done again by mechanical scribing.

Isolation from environmental conditions and the high voltage integrity finally requires the removal of the materials at the edge of the cell that is done automatically by sand blasting. In lamination line, first a function test of the solar cells is done. Contact and current busses are applied to the cell.

BOS and Frames

Balance of Systems (BOS) refers to all accessories in PV-systems which are essential for their functionality. BOS includes electric cable, frames, electronics such as inverters etc. The data for BOS were provided by project partners as well as by the EU-project ECLIPSE[5].

Depending on the module and application types, different BOS systems are required. These are considered in the LCA analysis of the SENSE-project.

Due to Industry data from project partners, for CIGS and a-Si specification of BOS systems including frame and inverter could be determined (see chapter 3.3).

According to [Alsema 2000] the size of frames depends on the size of the modules.

As inverter one model is assumed to be used for all types of PV-modules, which has a capacity of 1200 Wp as Input power. The lifetime of an inverter is discussed to be different. In this project, the lifetime is set to 10 years, i.e. two inverters are necessary for a lifetime of a PV-module. The inverter was provided by a project partner – this enabled a detailed analysis of the inverter.

Location for PV-module production

Two different options are relevant for the choice of the energy-mix:

- For the LCA model of the production site in SENSE with the goal of an environmental optimisation respectively weak point analysis, the country-specific energy-mixes are used according to the country the production plant is actually located (Germany for CdTe and CIGS, France for a-Si).
- For an overall evaluation of solar technologies among each other, a consistent power mix will be used. In this project UCTE mix is considered as a basis.

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[5] ECLIPSE: **E**nvironmental and e**C**ological **L**ife Cycle inventories for present and future **P**ower **S**ystems in **E**urope Contract; No. ENG2-CT-2001-00520

3.5 Use Phase of CIGS, a-Si and CdTe

PV modules have basically no use phase in respect of environmental burdens, since the efforts for maintenance are usually neglected. However the use phase defines the amount of supplied energy during a lifetime of a PV module. For the purpose of the results presentation, in which the environmental burdens are referred to 1 GJ of supplied energy, the use phase is essential.

In order to evaluate the use phase the irradiation of each location and modules as well as their efficiency of the entire system are considered. For the use phase the irradiation data were provided by the EU funded project "ECLIPSE".

For the three considered PV-types, the life cycle of the PV-modules will be compared to the conventional electricity in a typical lifetime of 20 years. Several scenarios have been calculated, namely an installation in central Europe (Frankfurt), southern Europe (Rome) and in the solar belt.

In order to enable a comparison to conventional energy systems, the amount of energy gained by the PV modules within their whole life cycle are the reference amount. **Dimension: kWh/m*2**

The values for irradiation and BOS efficiency have been calculated out of the results of the "ECLIPSE" project. Following assumptions for irradiation (at an optimal angle) have been made:

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

The following BOS efficiency has been used:

- Power modules: Frankfurt: 93,1%, Rome 91,20%, Solar Belt: 89,30%
- BIPV: Frankfurt: 90,3%, Rome 88,46%, Solar Belt: 86,62%
- Mobile modules: Frankfurt 87,5%, Rome 85,74%, Solar Belt: 83,83%

The following solar cell efficiencies were chosen:

- a-Si: 5,5 % (18,2 m^2/kWp)
- CdTe: 10 % (11 m^2/kWp)
- CIGS: 11,5 % (8,7 m^2/kWp)

Depending on the type of solar cell and its typical application, the counterpart for the comparison was a UCTE power grid-mix for grid-connected applications or a diesel power generator for stand-alone installation.

CIGS	**kWh/(m^2*y)**		
Installation	**Power plant**	**roof integrated**	**mobile**
Central Europe	128,5	124,6	120,8
Mediterranean	178,3	172,9	167,6
Solar belt	225,9	219,2	212,3

a-Si	**kWh/(m^2*y)**		
Installation	**Power plant**	**roof integrated**	**mobile**
Central Europe	61,4	59,6	57,8
Mediterranean	85,3	82,7	80,2
Solar belt	108,1	104,8	101,6

CdTe	**kWh/(m^2*y)**		
Installation	**Power plant**	**roof integrated**	**mobile**
Central Europe	111,7	108,4	105,1
Mediterranean	155	150,4	145,8
Solar belt	196,5	190,6	184,7

Table 2 Annual electricity provision [kWh] of considered modules and installations

The electricity provided by 1 m^2 module in 20 years is as following:

CIGS	**20 Years [MJ/m^2]**		
Installation	**Power plant**	**roof integrated**	**mobile**
Central Europe	9252	8971	8698
Mediterranean Area	12838	12449	12067
Solar Belt	16265	15782	15286

a-Si	**20 Years [MJ/m^2]**		
Installation	**Power plant**	**roof integrated**	**mobile**
Central Europe	4421	4291	4162
Mediterranean Area	6142	5954	5774
Solar Belt	7783	7546	7315

CdTe	**20 Years [MJ/m^2]**		
Installation	**Power plant**	**roof integrated**	**Mobile**
Central Europe	8042	7805	7567
Mediterranean Area	11160	10829	10498
Solar Belt	14148	13723	13298

Table 3 Provided electricity per 1 m^2 module after 20 years [MJ]

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.

3.6 Recycling of CIGS, a-Si and CdTe

The partner institutes Gaiker, ICT Fraunhofer 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 in the consortium as well as by non-partners.

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[6] layer, and dissolution of the semiconductor and recovery of the metals.

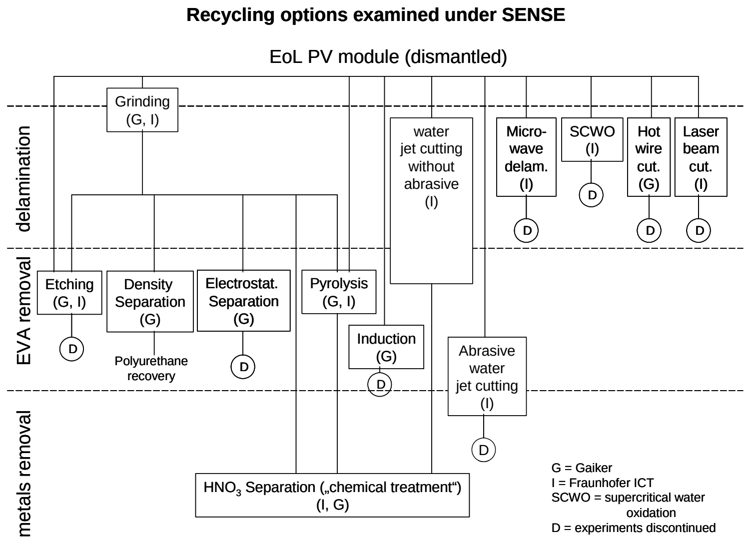

Fig. 2 Recycling options of thin film solar cells

According to the results obtained in each test, only 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. 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 most auspicious route for CIGS and CdTe modules is the delamination of the modules by thermal treatment, with a following solving process of the deposited metals. A survey showed that metal producers are willing to pay for such metal containing solutions, which can be inserted in a metal production line. For a-Si modules the most practical and meaningful recycling system consists of delivering the glasses with a-Si layer without separating to glass recyclers and of recycling the plastic frames.

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[6] EVA = Ethylene Vinyl Acetate is a transparent polymeric dielectric insulation material used to encapsulate the semiconductor layer between the substrate and glass (or double-glass) sheets.

The three strategies are different/ optimized depending on the specific thin film PV type, i.e.:

Recycling strategy 1:	Water jet cutting & chemical treatment for CIGS PV modules
Recycling strategy 2:	Thermal treatment (pyrolysis) & chemical treatment for CIGS and CdTe PV modules
Recycling strategy 3:	Grinding & Pneumatic separation of PUR[7] for a-SI solar modules

The economic assessment of these recycling routes was satisfactory. In fact, despite of small scale experiments, in which the processes can usually not be designed optimally, the economic effort is already close to break-even. An increase in profitability can be expected if the recycling system will run in industrialized scale with optimized parameters.

Location for Recycling of PV-modules

The places where the recycling activities will take place may have a certain influence on results, as e.g. the electricity-mix may highly differ among each and therefore the eco-profile and primary energy consumption for the use of electricity are different. For the calculations in SENSE, Central Europe is assumed to be the location of recycling.

4 LCA Results

The choice of the impact categories bases on a preliminary study carried out in the first stage of the project SENSE. The most important impact categories are identified and implemented in SENSE. In SENSE the following categories are taken into consideration according to the characterisation factors CML 2001:

• Global Warming Potential (GWP)	[kg CO_2-equivalent]
• Photochemical oxidation Potential (POCP)	[kg Ethylene-equivalent]
• Acidification Potential (AP)	[kg SO_2-equivalent]
• Eutrophication Potential (EP)	[kg Phosphate-equivalent]
• Primary Energy Use	[MJ]

The “primary energy use” is considered as well, which is strictly speaking not an “impact category” but an important aspect to be considered, because it is an indirect indicator of primary (e.g. fossil and nuclear) resources consumption.

The results of the LCA study for the manufacturing phase are presented in this chapter. For each PV-module type (CdTe, CIGS and a-Si) the environmental impacts as well as the primary energy use are presented in their equivalent units.

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[7] Polyurethane contained in the module frames

For the environmental burdens the entire life cycle is considered, i.e. production as well as the developed recycling. As recycling system for CIGS, the Strategy 2 (ST2) is selected for the comparison, which is the more auspicious recycling option. For CdTe strategy 2 is as well selected. For a-Si strategy 3 is selected as the only practically applicable recycling system, therefore these are considered in the comparison scenarios. Beside the chosen impact categories (GWP, AP, EP and POCP) the use of non renewable primary energy is considered.

An additional "normalization by Europe" of the impact potentials shows the ratio to the total impact of each category caused in Europe. The normalized impact potentials are presented in one diagram for each PV-module; however the normalisation and this form of presentation do not aim the comparison of the impact categories among each other. The implementation of a "weighting factor" would enable the comparison of the importance of each impact category. Anyway, as this weighting step is always subjective (what is "worse" a contribution to Global Warming or a toxic emission), it is not applied for the presentation of result here.

CIGS

In this chapter, the LCA results for a CIGS solar module is taken at. For this PV module, detailed material data were available. As a result, a detailed analysis is possible.

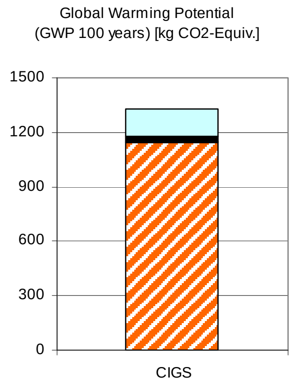

Fig. 3 Global Warming Potential (GWP) per kWp

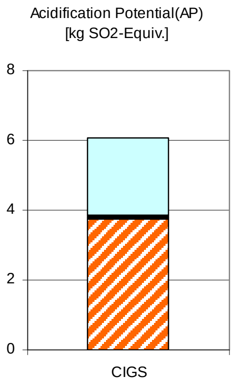

Fig. 4 Acidification Potential (AP) per kWp

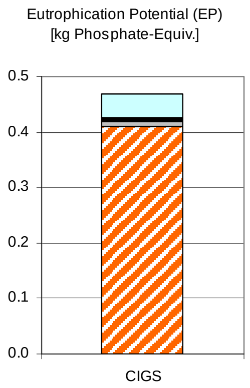

Fig. 5 Eutriphication Potential (EP) per kWp

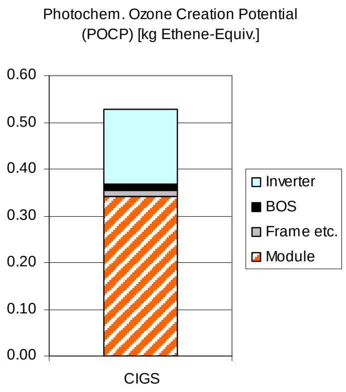

Fig. 6 Photochemical oxidant potential (POCP) per kWp

The environmental burdens caused by 1kWp CIGS module are as following:

In case of the CIGS solar module, a significant part of the total **GWP** is caused by the power generation used for the absorber simultaneous evaporation, An also significant part of GWP comes from the production of BOS; including inverter, electric cable and aluminium-based frame, which is also mainly caused by CO_2. The air conditioning and lightning system for the building has

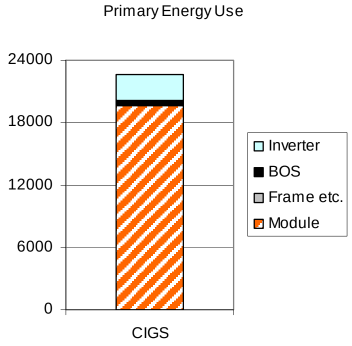

Fig. 7 Primary energy use [MJ] – CIGS per kWp

also a significant share of total GWP.

In **EP** both the power generation for the process “absorber simultaneous deposition” and the production of the metal frame and other BOS parts such as inverter and electric cables take a significant part. Both are mainly caused by NO_2 emissions in the air. Both processes have similar contribution to **AP**. About half of AP is caused by the manufacturing of frame, cables and connection box. Absorber simultaneous deposition and building air conditioning and lightening have as well a great share of AP.

Most of **POCP** is caused by the manufacturing of BOS (frame, cables and connection box), a lower part by absorber simultaneous deposition. Further contributions are caused by the glass production and by building air conditioner and lightening. Due to the emission of hydrocarbons in oil exploration, the EVA contributes with a quite low part.

Fig. 7 presents the non-renewable primary energy use in the manufacturing stage of a CIGS solar module. With its energy consumption the process “absorber simultaneous vapour-deposition” is the most primary energy consuming process. Also the frame, cables and connection box production requires a significant amount of non-renewable primary energy.

a-Si

This session describes the LCA results of an a-Si solar module for 1kWp. The same environmental impact categories as in the chapters before are considered: GWP, AP, EP and POCP. Also for this solar cell type the non-renewable energy use is considered as an additional evaluation category.

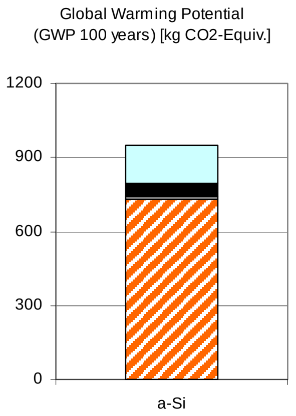

Fig. 8 Global Warming Potential (GWP) per kWp

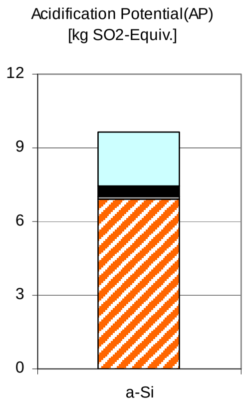

Fig. 9 Acidification Potential (AP) per kWp

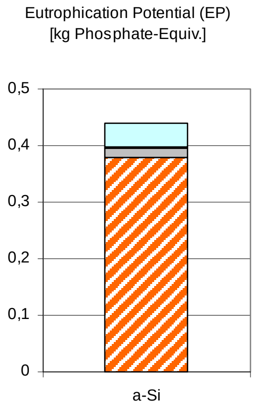

Fig. 10 Eutriphication Potential (EP) per kWp

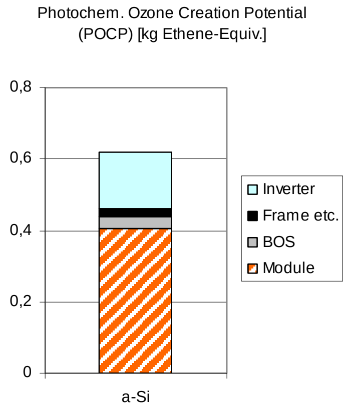

Fig. 11 Photochemical oxidant potential (POCP) per kWp

The manufacture of 1 kWp a-Si solar modules causes about 950 kg CO_2-eqv GWP. For the panel production these are mainly caused by the energy intensive “PE-CVD” process.

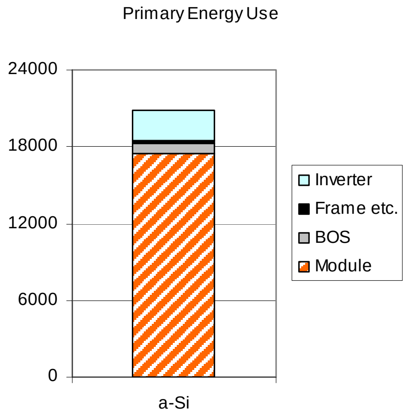

Fig. 12 Primary energy use [MJ] – a-Si module per kWp

The CO_2 emissions of the silane manufacturing used in the "PE-CVD[8]" process causes a significant part of total GWP. The whole process including power generation for this process contributes to a great extent of the total GWP.

EP and AP are mainly caused by BOS production. PE-CVD process has a significant share in EP and an even greater share in AP. The contribution of glass production is not negligible.

NO_2 emission is the main contributor for EP. For AP the SO_2 is the main contributor, but NO_2 has also a significant influence.

More than half of the POCP is caused in the production of BOS. But PE-CVD contributes also significantly. NMVOC emissions are the main contributor of POCP in this process.

The primary energy use in the manufacturing of a-Si solar module amounts about 21000 MJ /kWp, whereas the process "PE-CVD" is the main causer.

CdTe

In this chapter, the LCA results of the manufacturing of CdTe solar cell module are presented. All presented potentials are referred to 1 kWp output.

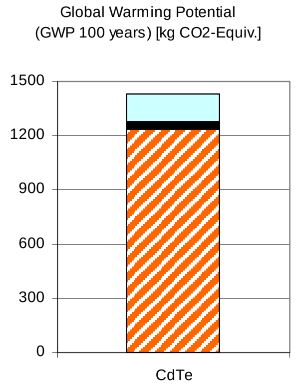

Fig. 13 Global Warming Potential (GWP) per kWp

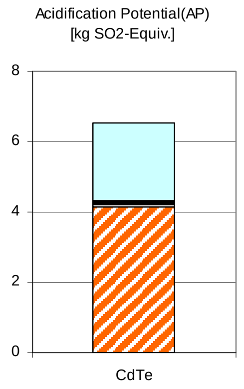

Fig. 14 Acidification Potential (AP) per kWp

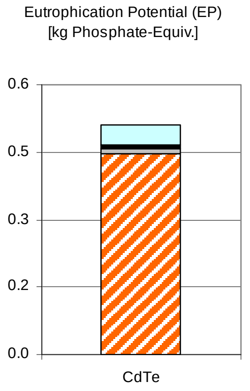

Fig. 15 Eutrification Potential (EP) per kWp

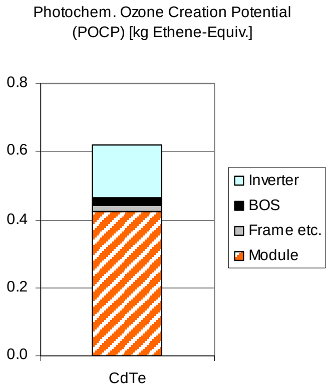

Fig. 16 Photochemical oxidant potential (POCP) per kWp

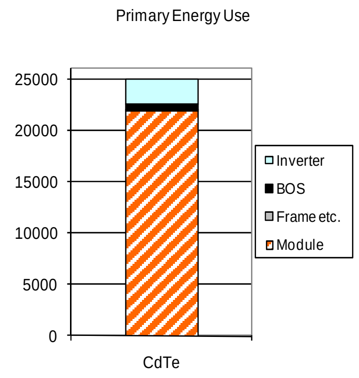

Fig. 17 Primary energy use [MJ] – CdTe per kWp

One significant part of the **GWP** is caused by CO_2 emissions of the process “power generation”, which is required for the manufacturing of the solar module. Another significant part comes from CO_2 of the production of BOS including inverter and frames. Which production stage actually causes the highest GWP within the manufacturing line is not identifiable as the energy use of the manufacturing was available as aggregated data for the entire process line only.

The major part of the Acidification Potential (**AP**) is attributed to sulphur dioxide emissions caused by the production of inverter, whereas the production of BOS (excluding frame and inverter) and their raw materials, and power generation for the production line have as well high contribution. For AP the glass manufacturing has another high contribution, which is caused by nitrogen oxide emissions.

The main causer of eutriphication potential (**EP**) is the glass sheet manufacturing with a contribution due to nitrogen oxide emission. Another part is caused by BOS including frame, inverter and connection box etc. and by the process energy. Also in this impact category the NO_2 emission is the main causer. A great extent of **POCP** is caused due to BOS including frame and electric cable production (Sulphur oxides, NMVOC[8] into air etc.).The production of the glass and EVA co-polymer has also a significant contribution. Power generation for the manufacture line causes relatively high potential due to emissions of heavy metals. The use of **primary energy**[9] is presented in Fig. 17. The most primary energy is consumed in “power generation” for the manufacture line. A lower share is consumed in the manufacturing process of frame, cables and connection box excluding the actual energy use.

4.1 Comparison to alternative energy supply

The comparison in this chapter shows the environmental advantages of present thin film PV-modules. Independent of the technologies (CIGS, a-Si and CdTe), locations (central Europe/Frankfurt, Mediterranean Area/Roma and Solar belt) and application type (ground mounted power plant, solar roof and mobile) the PV-systems come off well against the conventional energy mix (UCTE and diesel generator).

In the following figures, 1GJ power output of **1 m^2** of the respective kind of solar module, installation and region is compared to the generation of the respective amount of power using conventional sources. The absolute potentials differ in every scenario, but the amount of electrical power is the same for PV-systems and conventional power sources. In the following the comparison is presented for ground mounted power plant installation exemplary:

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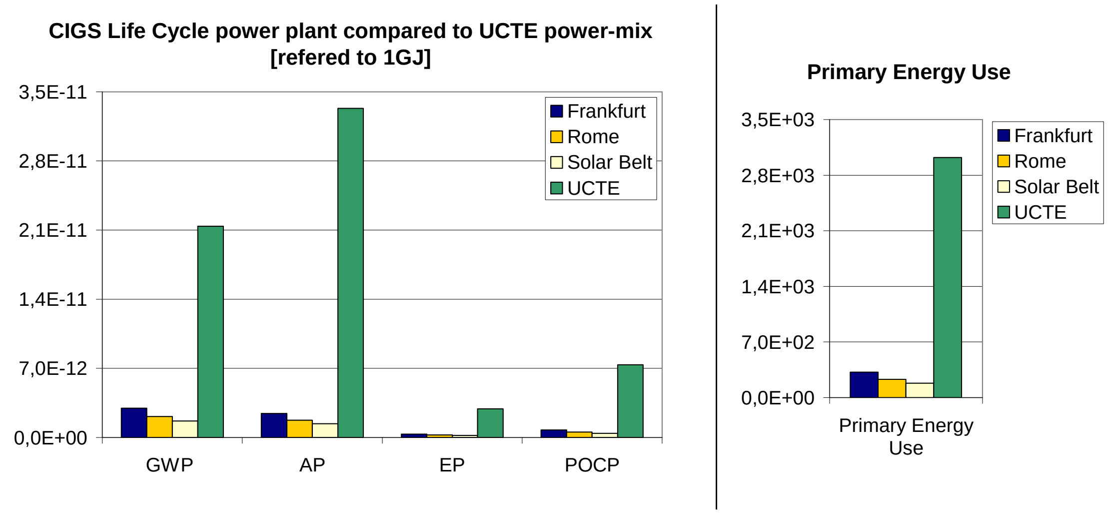
[8] Non-methan Volatile Organic Compounds

[9] non renewable resources, such as crude oil, natural gas, brown coal, hard coal etc.

CIGS

CIGS power module installations compared to UCTE power mix



** normalized to Europe CML 2001*

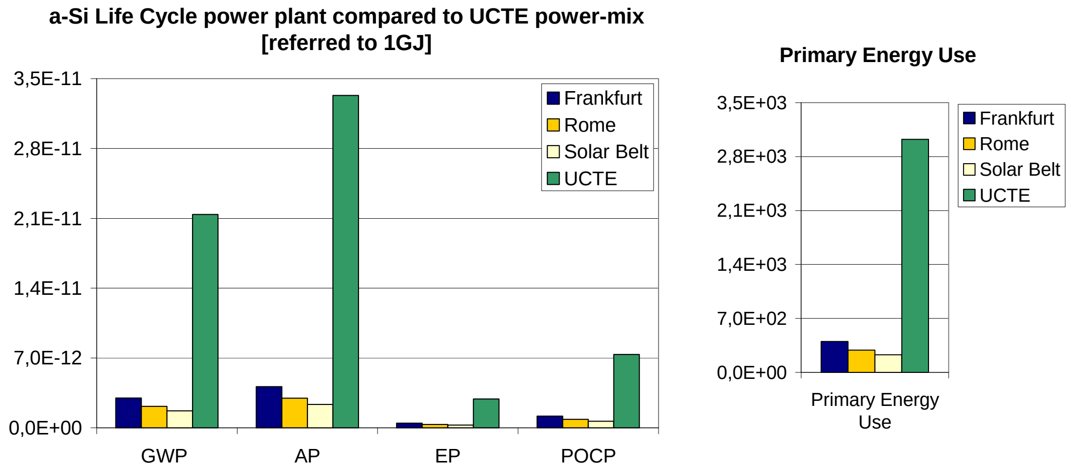
Fig. 18 CIGS power module installations compared to UCTE, normalized

CIGS	GWP [kg CO2-Equiv.]	AP [kg SO2-Equiv.]	EP [kg Phosphate-Equiv.]	POCP [kg Ethene-Equiv.]	Primary Energy Use [MJ]
Frankfurt	2,96E-12	2,44E-12	3,49E-13	7,56E-13	3,22E+02
Rome	2,14E-12	1,76E-12	2,51E-13	5,45E-13	2,32E+02
Solar Belt	1,69E-12	1,39E-12	1,98E-13	4,30E-13	1,83E+02
UCTE	2,14E-11	3,33E-11	2,90E-12	7,36E-12	3,02E+03

Table 4 CIGS installation, power modules, compared to UCTE, normalized

a-Si

A-Si power module installations compared to UCTE power mix



** normalized to Europe CML 2001*

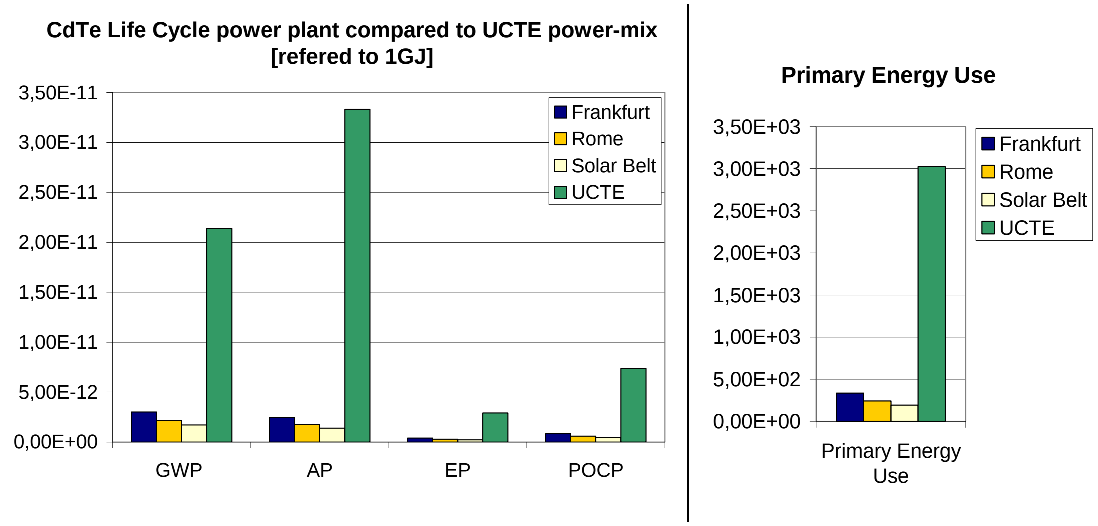
Fig. 19: a-Si power module installations compared to UCTE, normalized

a-Si	GWP [kg CO2-Equiv.]	AP [kg SO2-Equiv.]	EP [kg Phosphate-Equiv.]	POCP [kg Ethene-Equiv.]	Primary Energy Use [MJ]
Frankfurt	3,00E-12	4,15E-12	4,77E-13	1,18E-12	4,01E+02
Rome	2,16E-12	2,98E-12	3,43E-13	8,48E-13	2,89E+02
Solar Belt	1,70E-12	2,35E-12	2,71E-13	6,69E-13	2,28E+02
UCTE	2,14E-11	3,33E-11	2,90E-12	7,36E-12	3,02E+03

Table 5 A-Si installation, power modules, compared to UCTE, normalized

CdTe

CdTe power module installations compared to UCTE power mix



** normalized to Europe CML 2001*

Fig. 20: CdTe installation, power modules, compared to UCTE, normalized

CdTe	GWP [kg CO2-Equiv.]	AP [kg SO2-Equiv.]	EP [kg Phosphate-Equiv.]	POCP [kg Ethene-Equiv.]	Primary Energy Use [MJ]
Frankfurt	3,01E-12	2,46E-12	3,93E-13	8,24E-13	3,35E+02
Rome	2,17E-12	1,77E-12	2,83E-13	5,94E-13	2,41E+02
Solar Belt	1,71E-12	1,40E-12	2,23E-13	4,68E-13	1,90E+02
UCTE	2,14E-11	3,33E-11	2,90E-12	7,36E-12	3,02E+03

Table 6 CdTe installations, power modules, compared to UCTE, normalized

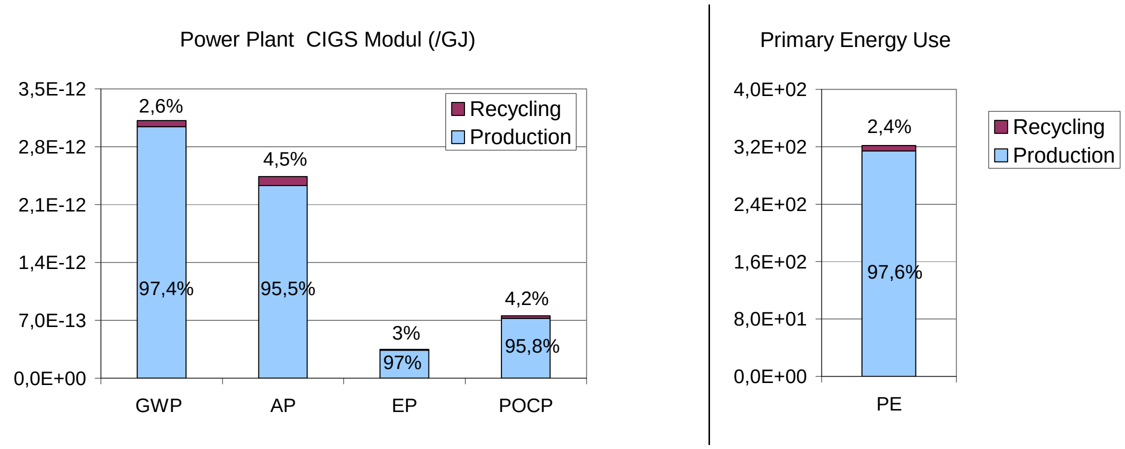
As a whole, the environmental burdens caused by thin film PV-modules are definitely considerably less than those caused by conventional energy supply systems. The environmental performance of a PV-module depends basically on its application type (power plant, mobile, building integrated/ solar roof etc.) and the location. In case of a comparison to conventional energy systems and the calculation of Energy Payback time (EPBT) the choice of location, type of installed PV-system and comparing systems have high influence on the results.

Although the results differ depending on the technology, installation type and installed location, the qualitative statements remain the same: thin film PV-systems are environmentally significantly advantageous compared to conventional energy systems.

4.2 Recycling

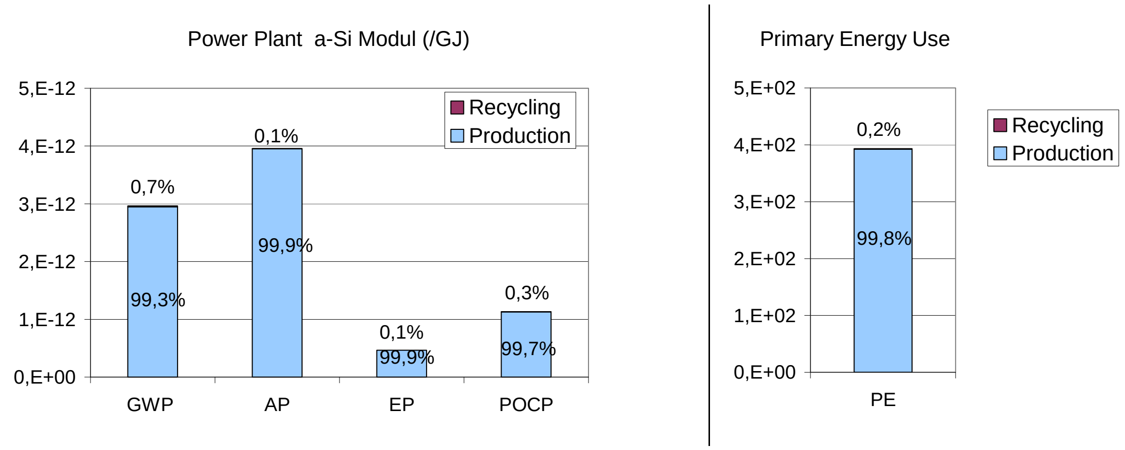
Moreover the question was addressed to what extent the developed recycling strategies influence and change the LCA results of the studied PV systems.

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.



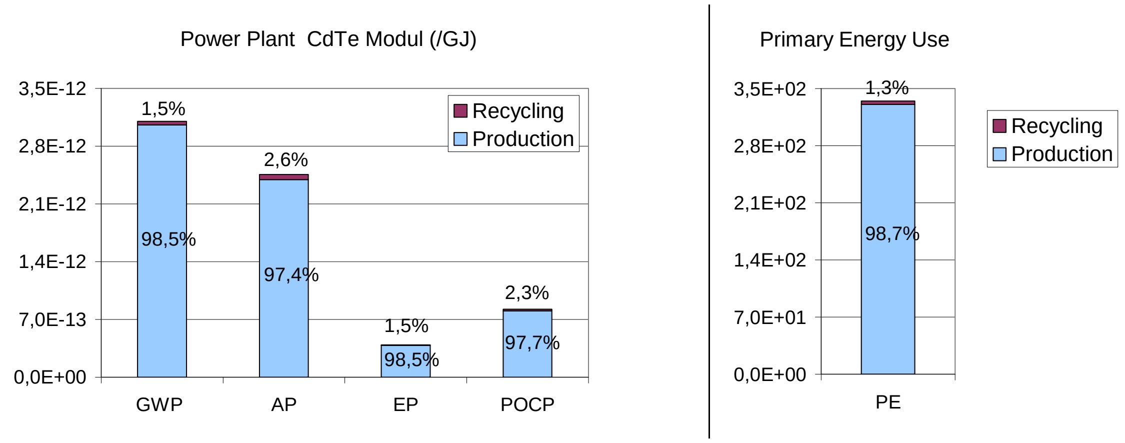
** normalized to Europe CML 2001*

Fig. 21: CICS, power modules, normalized



** normalized to Europe CML 2001*

Fig. 22: a-Si, power modules, normalized



** normalized to Europe CML 2001*

Fig. 23: CdTe, power modules, normalized

The results show, that – although the experiments were carried out on laboratory scale or small scale experiment plants, which have in general worse environmental profile than those of industrialized plants – the environmental burdens of the developed recycling processes have just a relatively small contribution over the whole life cycle of PV systems. The non negligible amount of energy consumption and material use for the recycling of such complex product, the potential environmental benefit due to recycled materials can almost compensate the potential burdens. As other works for PV recycling show, the implementation of a industrialized plant as recycling system can lead finally to a environmental credit of the recycling system and thus to a reduction of environmental potential impacts. Therefore it is expected, that an industrialization of the recycling system leads to further improvement of environmental performance.

4.3 Energy Payback Time

For PV-systems a further evaluation criteria is the “Energy Payback Time (EPBT)”, which is a standard evaluation key for PV-systems. The EPBT is defined as the time necessary for a PV-panel to generate the energy equivalent to that used to produce it [Wisconsin 2000]. The EPBT is therefore naturally depending on parameters such as the solar irradiation and the position and orientation of the modules, lifetime, as well as the location where the PV-modules are produced.

What exactly is to be understood by “Energy” is not defined unitary in different literatures and publications, if ever. Since however the aim of PV-modules is to replace “fossil” conventional energy supply, in this project the non-renewable primary energy resources are considered as base for EPBT calculation. As comparing energy supply system for the use phase UCTE[10] will be used, for the production and recycling the power mix for the country where production/ recycling is conducted is used.

In the case of comparison to conventional energy systems and calculation of Energy Payback time (EPBT) - the latter is a standard performance indicator in the PV sector - the choice of location, type of installed PV-system and reference conventional system for comparison have high influence on the results.

For the calculation of EPBT the non renewable primary energy are considered. Considering Europe as the location of PV-module installation, the EPBT for thin film PV-modules as following:

	Location	**Application**	**EPBT**		
			CIGS	**a-Si**	**CdTe**
1a	Central Europe (Frankfurt)	Power modules (UCTE*)	2,1	2,6	2,2
1b		BIPV roof integrated (UCTE*)	1,9	1,8	1,9
1c		Mobile (Diesel Generator*)	2,4	2,3	2,5
2a	Mediterranean area (Rome)	Power modules (UCTE*)	1,5	1,9	1,6
2b		BIPV roof integrated (UCTE*)	1,3	1,3	1,4
2c		Mobile (Diesel Generator*)	1,7	1,6	1,8
3a	Solar belt	Power modules (UCTE*)	1,2	1,5	1,2
3b		BIPV roof integrated (UCTE*)	1,1	1,0	1,1
3c		Mobile (Diesel Generator*)	1,4	1,3	1,4

*=substituting system

Table 7 EPBT for different scenarios for CIGS, a-Si and CdTe

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[10] UCTE: Union for the Co-ordination of Transmission of Electricity [GaBi 4]

4.4 Scale up to mass production at the example CIGS

During this project technological development and optimization were put into practice for the manufacturing of thin film PV-modules. Especially for CIGS modules, technical optimization in the production line was put into practice, so it was fortunately possible to track the environmental improvement of technical development within the project. 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; Application: Ground mounted power plant, roof integrated PV, mobile application) 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. An approaching increase of production capacity will lead to further EPBT improvement. For roof integrated application in Mediterranean Area 1,0 year and for ground mounted power plant in the same region 1,2 years are expected. This shows that along with further development and increase of production capacity from today's under 20 MJ/a to future's 100~200 MW, there is still great potential for improvement of EPBT and the environmental performance. A pre-calculation of the LCA analysis leads to the following results the following LCA results.

Fig. 24 shows exemplary the development of EPBT for CIGS in which the actual and future but realistic numbers are presented.

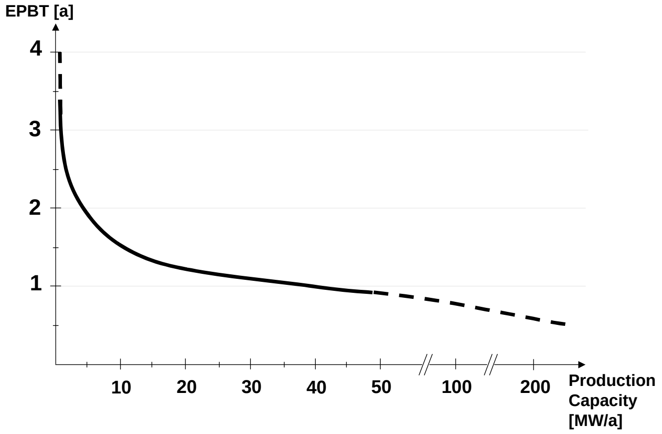

Fig. 24 Exemplary development of EPBT for CIGS according to development in productions capacity with future prediction

5 Conclusion

The LCA results show for each solar module type the main causer of the environmental impacts and primary energy use.

In case of CIGS solar module production, the main causer of the environmental impacts is obvious. The power use in the process “absorber simultaneous deposition” and the production of metal frame contribute to all environmental impact categories. Thus a technical development in this processes or the use of another materials for the frame could affect the LCA result of the manufacturing phase significantly.

The results for the manufacturing of CdTe solar modules show that the energy use, glass production and the production of metal frame are the main causer of environmental impacts, considering the manufacturing of solar module. The energy requirement of each stage of the manufacturing line should be specified to enable a more detailed analysis.

The metal frame has a relatively high impact for both solar module types.

The main causers for the environmental impacts of the a-Si module production are spread. The silane production, which is required for the PE-CVD process contributes visible in GWP, AP and EP. With the electric power use, the PE-CVD process contributes also highly to the primary energy use. The plastic productions, required for the sealing process (frame), are also contributing in the impact categories GWP and POCP, as well as in the primary energy use. The primary energy use is attributed to MDI production and the rest of the impact categories to polyether polyole production. But also other use of materials such as hydrogen and copper leads to higher environmental impact in POCP (by hydrogen production).

Looking at the results of the environmental assessment, as a whole the environmental burdens caused by thin film PV-modules are definitely lower than those caused by conventional energy supply systems (UCTE[11] - average electricity generation mix of main European countries, diesel generator etc.). The environmental performance of a PV-system depends basically on its application type (power plant, mobile, building integrated etc.) and the location.

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[11] Union for the Co-ordination of Transmission of Electricity

6 Outlook

The results of SENSE prove both – the recyclability of thin film PV-modules with adequate effort as well as the environmental advantages of thin film PV modules compared to conventional power generation.

The developed recycling strategies are auspicious. Even though the developed recycling strategies are examined and analyzed in small scale and laboratory scale, the contribution of environmental impacts are low. So in spite of the complexity and difficulty in separation of layers of these PV modules, the recycling do not significantly influence the advantageous environmental performance of thin film PV-modules, but contributes to a saving of resources.

The environmental results calculated in SENSE are drawing an encouraging image of solar energy and the sustainability of electricity produced by solar panels. In all relevant impact categories like e.g. Global Warming, Acidification, Eutrophication, Summer Smog the electrical power produced by thin film solar cells is clearly advantageous compared to conventional power grid mixes. The environmental payback time for the mentioned environmental impact categories is in between 1 and 5 years, in the most relevant categories even between 1 and 2 years. As it is to expect that solar installations will last for at least 20 years, the reduction of environmental impacts is significant and considerable.

The EPBT as well as the above mentioned environmental payback times proves that the thin-film photovoltaic systems regain the environmental loads caused by their production in a – compared to the typical installation timeframe – very short time.

“Towards a more sustainable future” – the project results of SENSE prove that thin-film PV modules can and should be a part of a tomorrows energy supply. With an excellent environmental behaviour – proven for the whole life cycle of these products including all necessary “add-ons” like cables, inverter etc. – and a good recyclability solar modules offer an excellent potential for future energy supply. As the technical development is ongoing, it is to expect and partly already foreseeable that the performance will increase continuously.

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