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STUDY ON PHOTOVOLTAIC PANELS SUPPLEMENTING THE IMPACT ASSESSMENT FOR A RECAST OF THE WEEE DIRECTIVE

FINAL REPORT

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1.1. CONTEXT

The European Commission has in December 2008 proposed to recast the Directive 2002/96/EC on waste electrical and electronic equipment (WEEE). As concerns the scope of the Directive within the recast procedure, the Commission intended to clarify the scope without changing it. A potential extension of the Directive to include photovoltaic panels was for that reason not addressed by the supporting impact assessment SEC(2008)2934. The discussions in the co-decision procedure and the negative evaluation of an environmental agreement submitted by the photovoltaic industry have shown that the option of including photovoltaic panels in the scope of the WEEE Directive should be analysed, in order to provide a solid ground for the ongoing discussions between the legislators on this specific issue.

Photovoltaic panels represent a renewable source of energy by enabling the direct conversion of solar radiation into current electricity. Several types of photovoltaic panels exist, representing three generations of technology and characterised by differentiated material composition. The photovoltaic industry can be described as a very dynamic industry with increasing competition; utilisation of solar energy is anticipated to increase exponentially in the future.

The amount of photovoltaic panels placed on the EU market has been rising sharply in the recent years and is expected to strongly grow in the coming years. While current volumes of photovoltaic panel waste are negligible, assuming a 25 year life time for panels, mentionable quantities will occur around 2025 or 2030. Total quantities of end-of-life photovoltaic panels in 2050 are anticipated to amount to 9.57 million tonnes.[1] The main environmental problems linked with photovoltaic panels, if not properly disposed of are: leaching of lead, leaching of cadmium, loss of conventional resources (primarily aluminium and glass) and loss of rare metals (silver, indium, gallium and germanium).

1.2. OBJECTIVES OF THE STUDY

The objectives of this study are, in line with the objectives of the general impact assessment SEC(2008)2934 which this study supplements:

- To identify the most relevant environmental impacts of end-of-life photovoltaic panels;
- To describe the basic policy options that can ensure a diversion of this stream of WEEE from mixed waste streams, and that create sustainable conditions for the proper treatment of this specific WEEE stream;
- To compare the environmental, economic and social costs and benefits of these policy options to the baseline scenarios.

[1] Waste quantities total to about 9.2 million tonnes when emerging technology photovoltaic panels are not considered; throughout the study, due to a lack of compositional information, emerging technology PV panels have not been considered.

1.3. RECYCLING OF PHOTOVOLTAIC PANELS

Photovoltaic panel recycling is currently not economically viable because waste volumes generated are too small; significant volumes of end-of-life photovoltaic panels will only begin to appear in 2025 or 2030. While a number of treatment and recycling processes are under development globally for photovoltaic panels, there are only two treatment and recycling methods tailored to PV panels which have been tested and put into operation: Deutsche Solar's treatment and recycling process for crystalline silicon panels and First Solar's treatment and recycling process for cadmium telluride panels. PV Cycle, founded by the photovoltaic industry as an association to put in place a take back and recycling programme, also offers recycling services in Europe.

Treatment and recycling procedures for photovoltaic panels are similar to recycling for LCDs, screen glass, mirrors, windscreens, other laminated glass, and gas discharge lamps, due to their large portion of glass. Current recycling options, other than specialised techniques developed by Deutsche Solar and First Solar, centre around glass recycling, as glass composes the largest percentage of photovoltaic panels. Existing options for those photovoltaic panel producers wishing to apply a simple material recycling process to their production waste are either float glass or fibre glass recycling.

Future outcomes of current research, development and testing efforts of photovoltaic panels and new recycling techniques are difficult to assess. A challenge in recycling of photovoltaic panels is their long life time which is estimated at 25 years. However, technical lifetime could be as long as 30 to 40 years. Not enough time has elapsed to be able to differentiate technical lifetimes between photovoltaic technologies.

In December 2010, PV Cycle submitted an 'Environmental Agreement on the separate collection and recycling of photovoltaic panels', proposing a voluntary collection and recycling scheme for the photovoltaic industry, whose validity was dependant on acceptance by the European Commission. The Commission evaluated the agreement and did not acknowledge or recommend it due to a number of specific concerns including financing and target setting. The voluntary agreement proposed by PV Cycle is not considered in this report as it is not currently a valid legally binding document.

1.4. SCENARIOS ASSESSED

Two potential baseline scenarios ('no policy action', 'Photovoltaic panels are outside the scope of the WEEE Directive') are considered: one which involves improper disposal ('worst case') and the other which involves the continuation of current recycling and treatment practices ('voluntary action'). Two potential policy options ('policy action', 'inclusion of photovoltaic panels in the scope of the WEEE Directive') are considered: one which involves the inclusion of only residential photovoltaic panels within the scope of the WEEE Directive ('Residential PVs in the scope of the WEEE Directive') and the other which involves the inclusion of all photovoltaic panels (both residential and commercial) within the scope of the WEEE Directive ('All PVs in the scope of the WEEE Directive '). Throughout the study, proper disposal has been used to refer to pre-treatment (physical separation and sometimes thermal separation too) and recycling (material recycling) including the contained disposal of hazardous substances in line WEEE Directive and Waste Framework Directive provisions.

Due to the current rapid development and evolution of photovoltaic technologies and recycling techniques and a lack of concrete data on many aspects of photovoltaic recycling in the future, assumptions, based on information currently available, were applied in order to estimate what a potential reality may look like for photovoltaic recycling in the future.

1.5. CONCLUSIONS

Assessment of the four scenarios considered leads to the conclusion that including photovoltaic panels in the WEEE Directive reduces the potential negative environmental impacts of improper disposal and generates economic benefits. Limiting the quantity of photovoltaic panels improperly disposed of has positive environmental impacts of avoiding lead and cadmium leaching and avoiding potential resource loss due to non-recovery of valuable conventional resources and rare metals in photovoltaic panels which are improperly disposed of.

Environmental impacts are reduced by a factor of 4 when comparing the inclusion of residential photovoltaic panels in the WEEE Directive (Policy option A) to a baseline scenario involving no pre-treatment or recycling of photovoltaic panels (Baseline A). This increases to a factor of 6 when comparing inclusion of all photovoltaic panels in the WEEE Directive (Policy option B) to a baseline scenario involving no pre-treatment or recycling of photovoltaic panels (Baseline A). Simple recycling, as considered in Baseline Scenario B, does not lead to an offset of material recycling costs by recycling revenues; however, when considering high yield recycling in the two policy options involving WEEE inclusion, revenues of recycling more than offset logistics, pre-treatment recycling costs. Job creation potential increases with the quantity of end-of-life panels generated and the quality of recycling applied to waste panels.

Policy Option B ('All PVs in the scope of the WEEE Directive') has been identified as the recommended policy option. Taking into account the benefits and costs of collection, proper treatment and recycling based on current knowledge and the assumptions described, Policy Option B yields the highest net benefits. In 2050, these net benefits would annually amount to about 16.6 billion Euros compared to Baseline Scenario A, 16.5 billion Euros compared to Baseline Scenario B, and 1.67 billion Euros compared to Policy Option A. The net benefits of Policy Option A ('Residential PVs in the scope of the WEEE Directive') are also clearly positive, and would in 2050 amount annually to about 14.9 billion Euros compared to Baseline Scenario A, and nearly 14.8 billion Euros compared to Baseline Scenario B.

For the recommended policy option B, the benefits identified stem to a very high share from the gain of resources through recycling.

2. PRELIMINARY INTRODUCTION

2.1. DEFINITION AND TECHNOLOGIES

Photovoltaic panels (or photovoltaic abbreviated as PV) represent a renewable source of energy by enabling the direct conversion of solar radiation into current electricity. The solar cell is the elementary building block of the photovoltaic technology. Solar cells are made of semiconductor materials, such as silicon, exhibiting the photovoltaic effect.

There are several types of solar cells. However, more than 90% of the solar cells currently produced worldwide consist of wafer-based crystalline silicon cells. The second most utilised solar cell material, with an increasing market share, is cadmium telluride. It enables the production of thin-film cells which can be manufactured at lower costs than silicon based solar cells. Cadmium-based solar cells have however a lower efficiency than silicon-based cells, requiring therefore a bigger exposure surface for a similar performance.[2]

The broad categories of technologies are classified as 1st, 2nd and 3rd generation technology (see below). Crystalline silicon cells represent the 1st generation, while cadmium telluride cells are part of the 2nd generation (next to other thin film technologies). Third generation includes technologies that have not yet been commercialised on a large scale.

Types of photovoltaic panels[3,4,5]:

1st generation: **Crystalline Silicon** (c-Si)

i. Monocrystalline (very efficient, but expensive, highest purity silicon, sophisticated manufacturing process)
ii. Multicrystalline (or polycrystalline, solar cells cut from multifaceted silicon crystals, most common type, cheaper than monocrystalline)

2nd generation: Thin Film (one or more thin layers of photovoltaic material on surface, e.g. glass, stainless steel or plastic)

i. Amorphous silicon (non-crystalline form of silicon, uses less scarce materials)
ii. **Cadmium telluride** (CdTe, semi-conductor compound formed of cadmium and tellurium, cost-effective but not as efficient as crystalline silicon, high toxicity of cadmium)
iii. Copper indium gallium selenide (CIS or CIGS, newer technology, highest efficiencies of thin film technologies, higher manufacturing costs because of more complex process)

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[2] EC (2009) Photovoltaic solar energy – Development and current research http://etc.europa.eu/energy/publicaions/doc/2009_report-solar-energy.pdf

[3] NTSA (2009) An overview of photovoltaic technologies

[4] EPIA & Greenpeace (2011) Solar Generation 6: Solar photovoltaic electricity empowering the world

[5] Larsen, Kari (3 August 2009) 'End of life PV: then what? Recycling solar PV panels,' Renewable energy focus http://www.renewableenergyfocus.com/view/3005/endoflife-pv-then-what-recycling-solar-pv-panels/

3rd generation: Concentrator photovoltaics (CPV) and emerging technologies

i. CPV utilises lenses to focus sunlight on to solar cells. The cells are made from very small amounts of highly efficient, but expensive, semi-conducting PV material. CPV cells can be based on silicon or III-V compounds (generally gallium arsenide or GaA).
ii. Dye-sensitised solar cells are lower-cost and release electrons from, for example, titanium dioxide covered in a light-absorbing pigment.
iii. Organic solar cells are composed of biodegradable materials such as organic polymers or small organic molecules; while lower cost they can present a risk of material degradation and instability.
iv. Hybrid cells involve the combination of current technologies on the market and the combination of organic and inorganic semiconductors.

The terms photovoltaic panel, photovoltaic module, solar panel and solar module all refer to the same unit, that is to say, a unit composed of individual photovoltaic or solar cells. Throughout the report the term 'photovoltaic panel' has been used. Further detail on terms used through the report can be found in Section 9: Annex B.

Watt-peak (**Wp**) is the measure of the nominal power of a photovoltaic installation under defined illumination (a light intensity of 1000W/m^2 at a temperature of 25°C). This unit allows a comparison of different panels. Standard crystalline silicon panels have a nominal power ranging from 120 to 300 Wp depending on size and efficiency. Standard thin film panels have lower nominal power (60 to 120 Wp) and their size is generally smaller.[6]

The panel size depends on the technology: the typical size of a crystalline silicon panel is 1.4 to 1.7 m^2 although larger panels are also manufactured (up to 2.5 m^2). For CdTe and CIGS, the size ranges from 0.6 to 1.0 m^2 and for silicon-based thin films from 1.4 to 5.7 m^2.[6] The weight also varies with the type of technology, e.g. around 15kg for 1m^2 of a typical CdTe panel or between 17-20kg for 1 m^2 of a CIGS panel.

Table 1 below summarises typical weight and size specifications for photovoltaic panels. Table 2 details sample of panel compositions by type of technology; additional information on photovoltaic panel specifications and composition can be found in Section 14.1: Annex G.

	Crystalline Silicon Modules	Thin Film Modules		
		a-Si	*CdTe*	*CIS/CIGS*
Total weight per module	5-28 kg	11.7-20 kg	9-15 kg	10.2-20 kg
Normal capacity	120-300 Wp	60-120 Wp		
Size range	Typically 1.4 to 1.7 m^2, can be up to 2.5 m^2	1.4 to 5.7 m^2	0.6 to 1.0 m^2	

Table 1: Photovoltaic panel specifications by technology[6,7]

[6] EPIA & Greenpeace (2011) Solar Generation 6: Solar photovoltaic electricity empowering the world

[7] Ökopol et. al. (2007) Study on the development of a take back and recovery system for photovoltaic products

Material	Crystalline Silicon Modules	Thin Film Modules		
		a-Si	*CdTe*	*CIS/CIGS*
Glass	74%	86%	95%	84%
Aluminium	10%*	<1%	<1%	12%
Other components (including rare metals)	16%	14%	4%	4%
Other key materials (representing over 1% of composition)	EVA, Tedlar backing film, silicon, adhesive	Polyol, MDI	EVA	EVA
Rare metals included	Silver	Indium, Germanium		Indium, Gallium
Presence of Cadmium (Cd) and Lead (Pb)	Pb		Cd	Cd

*Represents the frame, which is primarily aluminium

Table 2: Examples of average PV composition[8,9]

As the distribution of solar irradiation is different for varied geographical latitudes and the intensity of the light determines the amount of electrical power each cell generates, the power of a photovoltaic system will vary depending on the geographical location. Hence, in a region with less sunlight, a bigger surface covered by photovoltaic panels will be needed to provide the same amount of solar electricity as in a sunny region.

The cost of a PV system is usually measured in price-per-peak-watt (€/Wp or US$/Wp for example). Over the past years, the prices have strongly decreased. Information on current prices depends very much on the source, as well as on the size (small rooftop installations, large PV systems...). An order of magnitude would be €2.9/Wp or €1.67/1.35€/€0.95 per panel (lowest prices for mono-c-Si, multi-C-Si and thin film respectively).[10] Prices are expected to further decrease: by 2030 they could drop to between €0.70/Wp and €0.93/Wp. By 2050, the price could even decrease to €0.56/Wp.[11]

2.2. THE PHOTOVOLTAIC INDUSTRY AND MARKET

The photovoltaic industry can be described as a very dynamic industry with increasing competition. In 2009, China was the main producer of photovoltaic panels for the second year in a row (see Figure 1 below). Together, **China and Taiwan accounted for 49 percent of all photovoltaic manufacturing**. The

[8] Ökopol et. al. (2007) Study on the development of a take back and recovery system for photovoltaic products

[9] BIO Intelligence Service for ADEME (2010) Etude de potentiel de recyclage de certains métaux rares: Partie 2

[10] Solarbuzz (2011) Panel pricing http://www.solarbuzz.com/facts-and-figures/retail-price-environment/panel-prices

[11] EPIA & Greenpeace (2011) Solar Generation 6: Solar photovoltaic electricity empowering the world

former industry leaders Japan, Germany and the United States have lost significant market shares to ascending China and Taiwan.

95% of the Chinese production is exported, mainly to **Germany**, who is the **leader in European photovoltaic panel use**, where almost two thirds of the total EU-27 photovoltaic installations (15 861,204 MWp) are located (please see Section 11: Annex D).[12] Germany is followed, however in striking distance, by Spain, Italy, Czech Republic, Belgium, France and Portugal.

In the whole European Union, approximately 70,000 people are employed by the photovoltaic sector.[13]

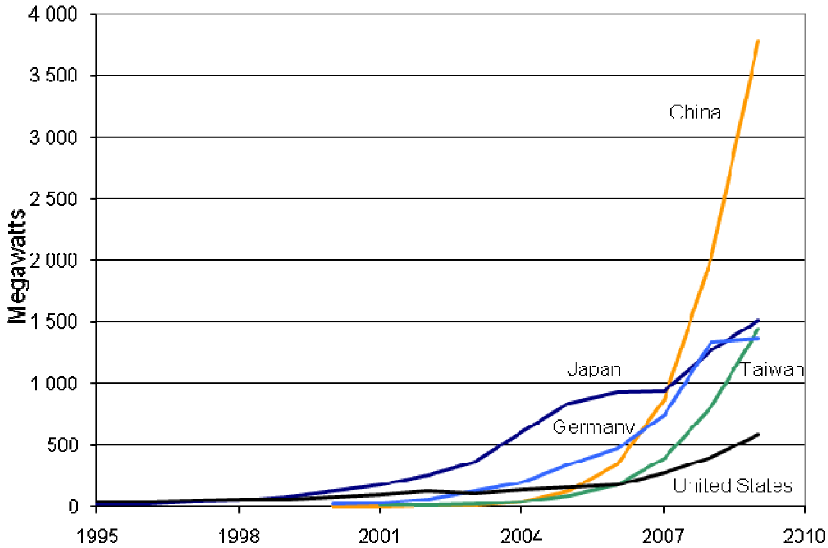


Figure 1: Annual photovoltaic photovoltaic production in selected countries, 1995-2009[12]

2.3. CURRENT RECYCLING PRACTICES

According to experts, **recycling is currently not economically viable because waste volumes generated are too small**; significant volumes of end-of-life photovoltaic panels will only begin to appear in 2025 or 2030 (See Section 12: Annex E for additional information on quantities of end-of-life photovoltaic panels). Despite their higher energy intensity for production, it is cheaper to use virgin raw materials in photovoltaic panel production. While this remains true for silicon-based panels due to the abundant supply of silicon as a raw material, more potential economic incentives exist for CIS, CIGS, and CdTe panels due to the rarity of indium, tellurium, and other rare metals, particularly in comparison to expected future growth in the photovoltaic industry and the resulting exponential increase in raw material demand.

While a number of treatment and recycling processes are under development globally for photovoltaic panels[14], there are currently only two treatment and recycling methods developed specifically for PV panels which have been tested and put into operation: **Deutsche Solar's process** (previously operational

[12] Earth Policy Institute (2009) Solar cell production climbs to another record in 2009 http://www.earth-policy.org/index.php?/indicators/C47/

[13] EC (2009) Photovoltaic solar energy – Development and current research http://ec.europa.eu/energy/publications/doc/2009_report-solar-energy.pdf

[14] A number of different types of recycling and treatment options are under development, which vary by producer and type of photovoltaic technology considered. Table 42 in Section 14: Annex G profiles some known recycling activities, which are currently in development and have completed the majority of laboratory tests required.

in **Germany**) which is predominantly used for **crystalline silicon panels**[15], and **First Solar's process** (currently operational in the **United States, Germany, and Malaysia**) which is primarily used for **CdTe panels**. **PV Cycle**, founded by the photovoltaic industry as an association to put in place a take back and recycling programme, also **offers recycling services in Europe**.

Treatment and recycling procedures for photovoltaic panels are similar to recycling for LCDs, screen glass, mirrors, windscreens, other laminated glass, and gas discharge lamps, due to their large portion of glass. Deutsche Solar and First Solar's processes, as well as the voluntary take back and recycling scheme proposed by PV Cycle are described in more detail below.

Deutsche Solar's crystalline silicon PV panel treatment process

- **Start date:** 2003
- **Current status:** Deutsche Solar's pilot has recently halted because of its costliness, due to the low quantities of photovoltaic panel waste at the current time; however, the organisation is considering a demo plant at some point in the future.
- **Locations operating:** Germany (previously)
- **Capacity available and type of waste:** None currently, if exist would be only for production waste, due to limited amount of end of life photovoltaic panels.
- **Technologies concerned:** 1st generation photovoltaic panels representing crystalline silicon panels. The technology has been used for a variety of types and sizes of silicon-based photovoltaic panels.

First Solar's CdTe PV panel treatment process

- **Start date:** 2003
- **Current status:** Recycling takes place at each of First Solar's manufacturing locations; primarily production waste is treated. First Solar includes contact information for recycling on the back of each photovoltaic panel sold; collection and recycling are free for consumers. First Solar provides packaging material and customers ship used photovoltaic panels to the nearest First Solar manufacturing location. The programme is prefunded by placing money in a custodial trust account at the time of sale of each panel, equal to the estimated cost of collection, transportation and recycling of a panel; since the first commercial recycling operations in 2003 up through 2009, First Solar has set aside 86 million dollars to fund panel collection and recycling.
- **Locations operating:** United States, Germany, Malaysia
- **Capacity available and type of waste:** Currently capacity available is for production waste from each factory location; managing end-of-life panels would require a large increase in capacity.
- **Technologies concerned:** 2nd generation photovoltaic panels, representing CdTe. First Solar shares technical knowledge with other producers and has tested their processes on other CdTe panels and is completing testing on CIS and CIGS technologies.

[15] Deutsche Solar's treatment process, launched in 2003, has since halted because of its costliness, due to the low quantities of photovoltaic panel waste at the current time; however, the organisation is considering a demo plant at some point in the future.

Current recycling options, other than the specialised techniques developed by Deutsche Solar and First Solar, centre around glass recycling, as glass composes the largest percentage of photovoltaic panels. Existing options for those photovoltaic panel producers wishing to apply a simple material recycling process to their production waste are either float glass recycling or fibre glass recycling. Float glass recycling results in high quality glass cullet which can be reused by a number of sectors and in a variety of products; fibre glass recycling results in lower quality glass cullet which is used for insulation or for other uses by the construction sector. While Deutsche Solar and First Solar's high yield recycling involves both physical and thermal separation and leads to recovery of lead and cadmium for reuse, simple glass recycling only involves physical separation and leads to the recovery of glass as well as the controlled disposal but not the recovery of lead and cadmium; additional information on recycling processes considered in the current study can be found in Annex H: Section 15.1.

The future outcomes of current research, development and testing efforts on photovoltaic panels and new recycling techniques are difficult to project. Emerging technologies may allow for a lower content of hazardous substances, and will require new types of recycling processes. For example, hybrid cells, combining various technologies currently on the market, could be treated by similar recycling techniques to those currently on the market, while dye-sensitised solar cells may involved other chemicals, and organic solar cells will most likely necessitate a fundamentally different recycling technique. A challenge in recycling of photovoltaic panels is their long life time, which is estimated at 25 years. However, this represents the warranty lifetime; technical lifetime could be as long as 30 or 40 years. Not enough time has elapsed to be able to differentiate technical lifetimes between photovoltaic technologies.

PV Cycle's voluntary take back and recycling programme for end-of-life panels

- **Start date:** 2007
- **Current status:** As of 2011, PV Cycle reported 91 certified collection points for photovoltaic panel recycling across Europe and counts over 180 member companies. Companies pay an annual fee to join PV Cycle, in part based on the weight of the panels they produce, which covers transport and recycling costs. In 2010 PV Cycle collected 80 tonnes of end-of-life photovoltaic panels and anticipates collection of 1500 tonnes in 2011; PV Cycle does not cover production waste.
- **Locations operating:** Recycling in Germany, headquarters in Brussels, collection through the EU-27
- **Capacity available and type of waste:** PV Cycle estimates the current recycling capacity for end-of-life photovoltaic panels in Europe at 60,000 tonnes.
- **Technologies concerned:** PV Cycle collects all photovoltaic technologies, separating silicon-based technologies from thin film technologies.

Additional information on current recycling practices can be found in Section 14: Annex G.

In December 2010, PV Cycle submitted an 'Environmental Agreement on the separate collection and recycling of photovoltaic panels', proposing a voluntary collection and recycling scheme for the photovoltaic industry, whose validity was dependant on acceptance by the European Commission.[16] The

[16] PV Cycle (2010) Environmental agreement on the separate collection and recycling of photovoltaic panels http://www.pvcycle.org/uploads/media/ENVI_Agreement__final_2010.pdf

Commission evaluated the agreement and did not acknowledge or recommend it due to a number of specific concerns including financing and target setting[17]. The voluntary agreement proposed by PV Cycle is not considered in this report as it is not currently a valid legally binding document.

2.4. POLICY BACKGROUND

The European Commission has in December 2008 proposed to recast the Directive 2002/96/EC on waste electrical and electronic equipment (WEEE). As concerns the scope of the Directive within the recast procedure, the Commission intended to clarify the scope without changing it. A potential extension of the Directive to include photovoltaic panels was for that reason not addressed by the supporting impact assessment SEC(2008)2934. The discussions in the co-decision procedure and the negative evaluation of an environmental agreement submitted by the photovoltaic industry have shown that the option of including photovoltaic panels in the scope of the WEEE Directive should be analysed, in order to provide a solid ground for the ongoing discussions between the legislators on this specific issue.

[17] EC (2011) Evaluation by the Commission services concerning an Environmental Agreement submitted by PV Cycle to the Commission on 03 December 2010
http://ec.europa.eu/environment/waste/weee/pdf/Evaluation%20PV%20Cycle%20Environmental%20Agreement.pdf

3. PROBLEM DEFINITION AND OBJECTIVES OF THIS STUDY

3.1. PROBLEM DEFINITION

The amount of photovoltaic panels placed on the EU market has been rising sharply in the last years, and is expected to strongly grow in the coming years. Assuming an average life time of 25 years for such panels, the waste generated for this equipment is projected as follows (Section 12: Annex E provides details on estimations and calculations made).

Please note that the figure, as well as all other figures and tables throughout the report, shows annual values and not values for time periods longer than one year.[18]

The quantities of end-of-life PV are negligible today. The first mentionable quantities will occur around 2025/2030 (188 and 2,033 MW respectively), reaching about 68,000 MW in 2050.

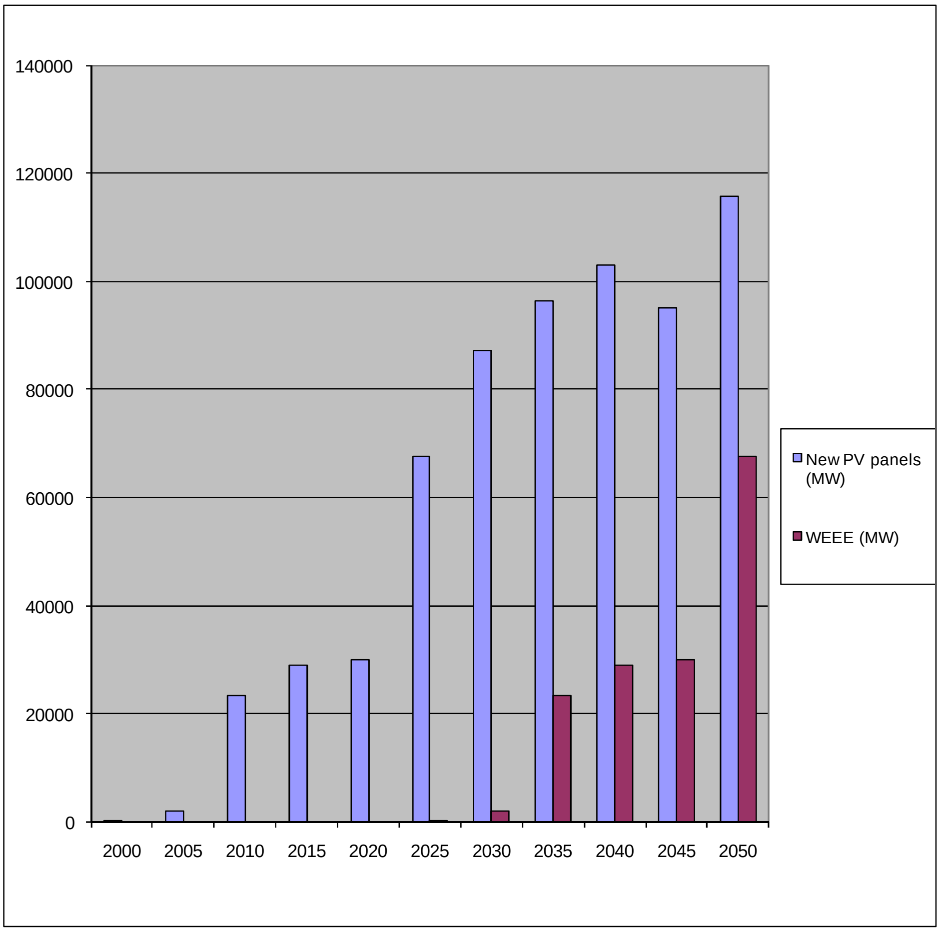


Figure 2: PV placed on the market and e-waste generated annually in the EU27 (in MW)[19]

Divided by technology, the PV waste quantities as shown in the graph below can be expected in the next decades. The total quantity of **end-of-life photovoltaic panels to be expected in 2050 amounts to about 9.5 million tonnes**. The most important end-of-life panels in the waste stream will be c-Si (1st generation) panels (more than 40%), followed by 2nd generation panels (a-Si, CdT, CIGS) which will be increasing

[18] e.g. the value for 2035 is the value for the year 2035 and not the value for the period 2030 to 2035.

[19] Calculated by BIO Intelligence Service

steadily over the years. The end-of-life quantities of 3rd generation panels (emerging technologies and CPV) will only play a minor role by 2050.[20]

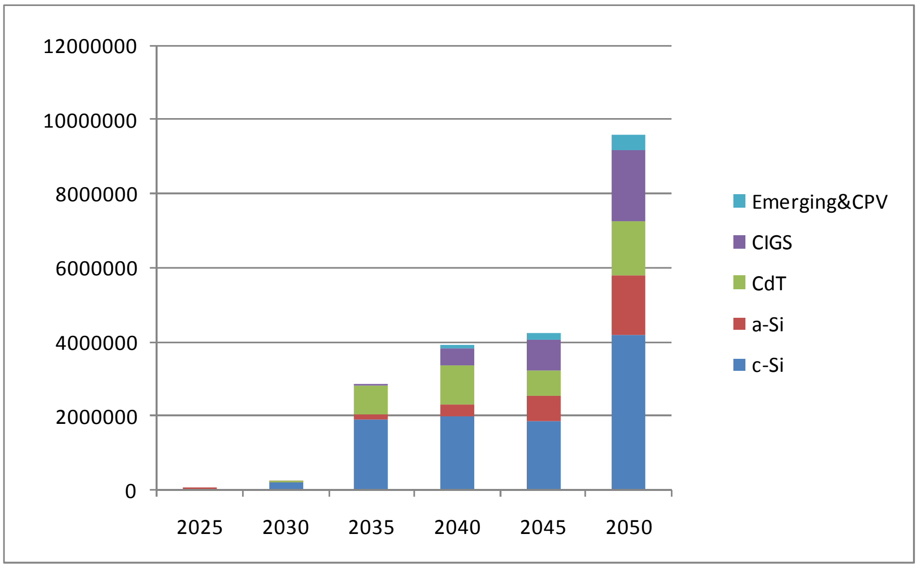


Figure 3: PV e-waste generated by technology annually in the EU27 (in tonnes)[21]

Another approach is used by Ökopol in their 2007 study in order to derive tonnes from MWs. This methodology only uses one conversion factor (not broken down by technology), which results in a lower quantity of tonnes; for additional detail, see Section 12: Annex E.

The main problem of these quantities of waste photovoltaic panels is, according to the existing literature available, that if not disposed of properly, they can cause the following negative impacts on the environment and human health:

a) Leaching of lead

b) Leaching of cadmium

c) Loss of conventional resources, primarily glass and aluminium

d) Loss of rare metals, notably silver, indium, gallium and germanium

3.2. OBJECTIVES

The objectives of this study are, in line with the objectives of the general impact assessment SEC(2008)2934 which this study supplements:

- To identify the most relevant environmental impacts of end-of-life photovoltaic panels;
- To describe the basic policy options that can ensure a diversion of this stream of WEEE from mixed waste streams, and that create sustainable conditions for the proper treatment of this specific WEEE stream;
- To compare the environmental, economic and social costs and benefits of these policy options to

[20] Due to limited waste quantities and uncertainty on composition of emerging technology PV panels and development of recycling technologies, emerging technology PV panels have not been assessed in the context of the current study.

[21] Calculated by BIO Intelligence Service

the baseline scenario.

4. ENVIRONMENTAL IMPACTS OF END-OF-LIFE PHOTOVOLTAIC PANELS

According to the existing literature available, waste photovoltaic panels, if not disposed of properly, can cause the following negative impacts on the environment and human health:

a) Leaching of lead

b) Leaching of cadmium

c) Loss of conventional resources, primarily glass and aluminium

d) Loss of rare metals, notably silver, indium, gallium and germanium

4.1. SOIL AND AIR POLLUTION

Lead is a heavy metal with a high potential for accumulation in humans and the environment. Once taken into the body, lead distributes throughout the body in the blood and accumulates in the bones. Dependant on the level of exposure, lead can adversely impact the nervous system, kidney function, immune system, reproductive and developmental systems, and the cardiovascular system. Ecosystems near sources of lead demonstrate a range of adverse effects including losses in biodiversity, decreased growth and reproductive rates in plants and animals and neurological effects in vertebrates.

Lead leaching is primarily linked to 1st generation crystalline silicon (c-Si) photovoltaic panels. While lead leaching is negligible if the lead contained in a c-Si photovoltaic panels remains at the same pH as the panel itself, exposure to low pH, such as nitric acid or rain incite leaching of between 13% up to 90% of the quantity of lead found in an average c-Si photovoltaic panel. Approximately 12.67 g of lead is contained in an average c-Si panel (which weight about 22 kg), hence representing the potential for lead leaching into the environment of **between 1.64 g and 11.4 g per panel or 75 g and 518 g per t of panel disposed of**.

Cadmium is a heavy metal which accumulates in living organisms, with a biological half-life of 30 years; severe illnesses associated with low-level cadmium poisoning can have a latency of up to 10 years. Cadmium has high acute toxicity as well as a high accumulation potential in humans. An established carcinogen, cadmium can cause serious pathophysiological changes under conditions of repeat exposure.

Cadmium leaching is a risk specific to 2nd generation thin film photovoltaic panels (particularly CdTe and CIGS technologies). Cadmium leaching for CdTe PV is on average at 7% of the volume of cadmium contained in a photovoltaic panel if kept at the pH of the panel itself. However, exposure to a lower pH, such as nitric acid or rain, for example in a landfill setting, increases cadmium leaching to between 29% and 40%. Approximately 4.60 g of cadmium is contained in an average CdTe panel (which weigh about 12 kg), hence representing the potential for cadmium leaching into the environment of **between 0.32 g to 1.84 g per panel or 27 g and 153 g per t of panel disposed of**.

The **external cost** of pollution linked to lead and cadmium leakages respectively are assumed to be **1.174 €/g of lead released and 0.046 €/g of cadmium released**. While overall costs of leaching to soil and air emissions of cadmium and lead may be higher, in the current study only human health damages could be monetised. See Section 13: Annex F for additional information.

4.2. RESOURCES LOSS

Aluminium and glass make up the majority of the materials for photovoltaic panels (see Section 13: Annex F for detailed composition of PV), indicating that the **loss of potentially reusable resources occurs across all types of photovoltaic panels**. For example crystalline silicon photovoltaic panels (1st generation) are composed 74.16% of glass and another 10.30% is made up of the frame, which is primarily aluminium. Expressed in terms of weight, this represents 16.6 kg of glass and 2.3 kg of aluminium per panel (total weight: 22 kg) which could be potentially recycled in an average c-Si photovoltaic panel. A standard CIS model (2nd generation) contains up to 84% glass and 12% of aluminium, representing approximately 8 to 9 kg of glass and 1.4 kg of aluminium per panel (total weight: 11.7 kg) which could also potentially be recycled. The market price of glass has remained relatively stable over the period 2000 to 2009, with a price of around 50€ per tonne. As of February 2011, the market price of aluminium is approximately 1200€ per tonne[22]. A study completed by the FORWAST project, which assessed the environmental impacts of a variety of waste streams and treatment options, cited recycling of aluminium and glass waste as having one of the largest potentials for reducing the environmental impacts of waste.[23]

Loss of rare metals, particularly silver, indium, gallium and germanium is another impact of lack of recycling of photovoltaic panels. Each of the rare metals is found across a range of photovoltaic panels. While these rare metals combined typically **only represent 1% of the mass of a photovoltaic panel, their value is significant**. Table 3 shows current values for key rare metals included in photovoltaic panels.

Rare metals	Price per kilogram	Types of photovoltaic panels in which present
Silver (Ag)	650€	Crystalline Silicon
Indium (In)	442€	Amorphous Silicon, CIS, CIGS
Gallium (Ga)	515€	CIGS, CPV and emerging technologies
Germanium (Ge)	957€	Amorphous Silicon, CPV and emerging technologies

Table 3: Rare metals in PV panels with market price information (Current – February 2011)[24]

Over time, the cost of the loss of conventional resources and rare metals found in photovoltaic panels could further increase, due to an increase in resource prices. Future market price variations for aluminium, glass and rare metals are dependent on the level of depletion of natural stocks, future demand and availability of recycling technologies to provision reused materials. Based on market prices as of February 2011, the loss of conventional and rare resources could lead to an economic loss of up to 146 Euros / panel for crystalline silicon PV panels and 123 Euros / panel for thin film PV panels, corresponding to a recycling of 100% of materials found in both types of panels. However, to take into

[22] The market price of aluminium gradually increased over the period 2001 to 2005, experienced high price volatility over the 2006 to 2008 period, which was followed by a sharp drop in 2009, and a relatively rapid climb, which continues today.

[23] FORWAST (2010) Documentation of the contribution analysis and uncertainty assessment. Results interpretation identifying priority material flows and wastes for waste prevention, recycling and choice of waste treatment options. Policy recommendations. http://forwast.brgm.fr/Documents/Deliverables/Forwast_D63.pdf

[24] BIO Intelligence Service for ADEME (2010) Etude de potentiel de recyclage de certains métaux rares: Partie 2

account realistic recycling efficiencies, recycling output is for this study assumed to be **100% for aluminium, 95% for glass and 30% for rare metals.** [25]

When considering those **realistic current material recovery rates** by material, which will be done throughout the study, the economic loss due to lost materials decreases to **46 Euros / panel for crystalline silicon PV panels** and **37 Euros / panel for thin film PV panels**.[26,27] This figure can also be expressed as **2105 Euros / tonne of crystalline silicon PV panels and 2349 Euros / tonne** of thin film PV panels. Additional information on current recycling practices and potential economic loss due to lack of proper treatment and recycling of end-of-life photovoltaic panels can be found in Annex G: Section 14.2 and Annex H: Section 15, respectively. Detail is provided on the partial material recovery hypothesis, which is applied when calculating both potential economic loss and potential revenues from recycling, in Annex H: Section 15.2.

			Crystalline Silicon (1st generation)		a-Si model (2nd generation)	
Material	*Price (per kg)*	*Recovery rate*	*Mass (kg/Wp)*	*Price per Wp*	*Mass (kg/Wp)*	*Price per Wp*
Glass	0,05 €	95%	0,0734	0,0037 €	0,2371	0,0119 €
Aluminium	1,20 €	100%	0,0107	0,0128 €	0,0001	0,0001 €
Rare metals	Variable*	30%	0,0003	0,1989 €	0,0009	0,6086 €
Total				**0,22 €**		**0,62 €**
Per Average Module				**46,31 €**		**37,23 €**
Per Tonne				**2 105 €**		**2 349 €**

* Estimated at €650 for c-Si panels (contain Silver), €700 for a-Si panels (contain Indium and Germanium), based on market pricing as of February 2011

Table 4: Estimated economic value lost at the current time (February 2011) through lack of proper treatment and recycling of PV (per panel) – high yield recycling, variable recovery rate for all materials[28]

4.3. SUMMARY OF ENVIRONMENTAL IMPACTS

Table 5, Table 6, Table 7 hereafter summarise the environmental impacts per panel that will be used to assess the policy options in Section 6.

[25] 100% recovery of aluminium, 95% of glass and 30% of rare metals; based on information from PVCycle and Ökopol 2007 study.

[26] PV Cycle (2010) Making the photovoltaic industry 'double green' http://www.pvcycle.eu/fileadmin/pvcycle_docs/documents/membership/PVCYCLE_11_2010.pdf

[27] Ökopol et. al. (2007) Study on the development of a take back and recovery system for photovoltaic products

[28] Calculated by BIO Intelligence Service

	Impact per unit of PV modules disposed of
Soil and Air Pollution	
Lead leaching from c-Si PV modules	75-518 g/t
Cadmium leaching from CdTe PV modules	27-153 g/t
Resource Loss	
Glass	
Glass in c-Si PV modules	0.0734 kg/Wp
Glass in thin film PV modules	0.2371 kg/WP
Aluminium	
Aluminium in c-Si PV modules	0.0107 kg/Wp
Aluminium in thin film PV modules	0.0001 kg/Wp
Rare metals (Rm)	
Rm in c-Si PV modules	0.0009 kg/Wp
Rm in thin film PV modules	0.0025 kg/Wp

Table 5: Impact per unit of PV panels disposed of[28]

	External cost per tonne of Cd/Pb	External cost per tonne of PV panels
External cost of air and soil pollution		
Lead leaching from c-Si PV modules	1 174 000 €	348 k€/t
Cadmium leaching from CdTe PV modules	46 000 €	12 €/t

Table 6: External cost per unit of PV panel disposed of (external cost of soil pollution)[28]

	Economic loss per t of PV modules disposed of
Economic loss due to resource loss	
For c-Si PV modules	2105 €/t
For thin film PV modules	2349 €/t

Table 7: Economic loss per unit of PV panel disposed of applied in analysis, assuming high yield recycling and varying recovery of all materials (February 2011)[28,29]

[29] 100% for aluminium, 95% for glass, and 30% for rare metals; these hypotheses are applied to Policy Option A and Policy Option B, please refer to Section 13.4 in Annex F.

It should be noted that economic loss has been calculated using compositional information available in Ökopol's 2007 study,[30] with c-Si PV panels as representative of the family of crystalline silicon PV panels and a-Si PV panels as representative of the family of thin film PV panels. Amorphous silicon (a-Si) PV panels have been used to represent the family of thin film PV panels due to a lack of detailed compositional data available for all types of thin film PV panels. However, their larger percentage composition of glass and their use of rare metals (indium and germanium) as compared to crystalline silicon PV panels effectively represent the material composition of other thin film PV panels (CdTe and CIGS/CIS).

When calculating economic loss, high yield recycling was assumed, with recovery rates at 100% for aluminium, 95% for glass and 30% for rare metals. Pricing used is based on current (as of February 2011) market pricing and assumes the sale of recovered materials for the same price as virgin materials. When assessing estimated recycling revenues, hypotheses of variable recovery by material were applied; more information can be found in Annex H: Section 15.2.

Remark: Inflation has not been taken into account when using current market pricing of conventional resource and rare metals; however, inflation can be estimated in the EU-27 at approximately 2% per year, which could incrementally increase estimated future market prices. Market prices could also be impacted by fluctuations due to demand, depletion of natural stocks and the availability of recycling technologies to provision reused materials.

[30] Ökopol et. al. (2007) Study on the development of a take back and recovery system for photovoltaic products

5. DESCRIPTION OF SCENARIOS AND POLICY OPTIONS

The negative impacts of end-of-life photovoltaic panels can largely be mitigated, and the valuable materials contained can be recycled, if an appropriate infrastructure for collection, pre-treatment and recycling is in place, and if it is supported by a sustainable financing mechanism. Such conditions can be expected to vary as a function of the following policy options.

Two potential baseline scenarios ('no policy action', 'Photovoltaic panels are outside the scope of the WEEE Directive') are considered: one which involves improper disposal with no treatment and recycling of end-of-life PV panels ('worst case') and the other which involves the continuation of current recycling and pre-treatment practices ('voluntary action'). Two potential policy options ('policy action', 'inclusion of photovoltaic panels in the scope of the WEEE Directive') are considered: one which involves the inclusion of only residential photovoltaic panels within the scope of the WEEE Directive ('Residential PVs in the scope of the WEEE Directive ') and the other which involves the inclusion of all photovoltaic panels (both residential and commercial) within the scope of the WEEE Directive ('All PVs in the scope of the WEEE Directive ').

Remark: As quantities of 3rd generation (emerging technologies) PV panels are minimal up through 2050 compared with other photovoltaic panel technologies[31] and in light of the absence of compositional information, uncertainty on the materials to be used in emerging technology photovoltaic panels, and the no current availability of recycling techniques for emerging technologies, quantities of end-of-life emerging technology PV panels have not been considered in the current study. Information on estimated quantities of end-of-life emerging technology PV panels can be found in Section 12: Annex E; quantities total to 406,304 tonnes in 2050.

Remark: it is difficult to precisely establish Baseline Scenario B ('voluntary action') due to the low quantity of panels currently becoming waste, the limited economic incentives to recycle with such low waste quantities, the limited amount of specific techniques for applying material recycling to photovoltaic panels, and the varying amounts of installations and recycling facilities between MS. Assumptions made were based on 20-30% recycling rate over the 2030 to 2050 period examined, with no-recycling of CIGS/CIS technologies, due to a lack of current recycling processes for these types of models and the uncertainty of the direction of technical recycling development for these types of photovoltaic panels up to 2050 (those are thus considered as being disposed of without any treatment and recycling as in Baseline A). Additional information on the assumptions used in building Baseline Scenario B can be found in Annex I: Section 16.2.

5.1. BASELINE SCENARIO A: 'WORST CASE'

Baseline scenario A ('no policy action', 'improper waste treatment') implies that end-of-life PVs are not covered by legislation, and that existing technical proper waste collection, proper treatment and recycling options are not voluntarily applied by the relevant actors. The volume of waste which would not be treated and recycled is estimated at just over 9 million tonnes in 2050. Additional information on Baseline Scenario A can be found in Annex I: Section 16.1.

[31] End-of-life emerging technology PV panels only account for just over 4% of end-of-life PV modules in 2050.

Photovoltaic technology	a Amount of waste generated (in million tonnes)			b Collection rate (percentage)			c Properly treated and sent for recycling (in million tonnes) c = a x b			d Not properly treated and not sent for recycling (in million tonnes) d = a - c		
	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
c-Si	0,20	2,00	4,21	0%	0%	0%	0,00	0,00	0,00	0,20	2,00	4,21
a-Si	0,02	0,33	1,57	0%	0%	0%	0,00	0,00	0,00	0,02	0,33	1,57
CdTe	0,01	0,79	1,49	0%	0%	0%	0,00	0,00	0,00	0,01	0,79	1,49
CIGS/CIS	0,00	0,05	1,89	0%	0%	0%	0,00	0,00	0,00	0,00	0,05	1,89
Total	0,22	3,18	9,16	0%	0%	0%	0,00	0,00	0,00	0,22	3,18	9,16

Table 8: Photovoltaic panel quantities annually in the EU27 - Baseline Scenario A

5.2. BASELINE SCENARIO B: 'VOLUNTARY ACTION'

Baseline scenario B ('no policy action'): Photovoltaic panels are outside the scope of the WEEE Directive. Where systems for the collection, treatment and recycling are already operating today (current legislation or current practice), these are presumed to continue functioning in the future, covering an equal share of WEEE generated as today.

Current collection of end-of-life photovoltaic panels has been estimated at approximately 20-30% by Knut Sander, of Ökopol, the main author of Ökopol's 2007 'Study on the development of a take back and recovery system for photovoltaic products'.[32] Of the amount collected, nearly 100% enter a recycling facility; this collection and recycling hypothesis covers current recycling practices run by First Solar and other photovoltaic manufacturers. Therefore, a recycling rate of 20% has been applied for 2020, 25% for 2040, and 30% for 2050. The recycling rates have been applied to c-Si, a-Si and CdTe technologies due to the current existence of recycling techniques for these technologies; recycling rates for CIGS/CIS technologies have been estimated at 0% up to 2050 due to a lack of current technologies for treatment and recycling and uncertainty about their development in the future.

The volume of waste which would remain untreated and unrecycled is estimated at just under 7 million tonnes in 2050. Additional information on Baseline Scenario B can be found in Annex I: Section 16.2.

[32] Interview 3 March 2011.

Photovoltaic technology	a Amount of waste generated (in million tonnes)			b Collection rate (percentage)			c Properly treated and sent for recycling (in million tonnes) c = a x b			d Not properly treated and not sent for recycling (in million tonnes) d = a - c		
	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
c-Si	0,20	2,00	4,21	20%	25%	30%	0,04	0,50	1,26	0,16	1,50	2,95
a-Si	0,02	0,33	1,57	20%	25%	30%	0,00	0,08	0,47	0,01	0,25	1,10
CdTe	0,01	0,79	1,49	20%	25%	30%	0,00	0,20	0,45	0,01	0,59	1,04
CIGS/CIS	0,00	0,05	1,89	0%	0%	0%	0,00	0,00	0,00	0,00	0,05	1,89
Total	0,22	3,18	9,16	18%	25%	24%	0,04	0,78	2,18	0,18	2,39	6,98

Table 9: Photovoltaic panel quantities annually in the EU27 - Baseline Scenario B[33]

5.3. POLICY OPTION A: 'RESIDENTIAL PVS INCLUDED IN THE SCOPE OF THE WEEE DIRECTIVE'

Policy option A ('inclusion of residential photovoltaic panels in the scope of the recast WEEE Directive'): Photovoltaic panels sold to private households and installed on private homes ('residential'), and all residential end-of-life photovoltaic panels, are included in the scope of the WEEE Directive with provisions similar to those applying for other e-waste streams under the Directive. As a consequence, a collection rate of 85% of waste from residential photovoltaic panels is assumed with nearly 100% of quantities collected entering a recycling facility, to avoid negative impacts on the environment and human health. While the assumption of a 100% recycling rate of those quantities of photovoltaic panels may at first sight appear high, currently 100% of photovoltaic panels collected are recycled, a trend which is likely to continue with the introduction of photovoltaic panels into the WEEE Directive. Due to the valuable materials which can be recovered from photovoltaic panels through high yield recycling, there is an economic motivation to recycle those panels which would be collected.

Based on market share reporting and trending, as of 2014, residential photovoltaic panels are assumed to account for 86% of the photovoltaic panel market, with commercial (non residential) installations representing the remaining 14%.[34,35]

The 86% of residential photovoltaic panels are assumed to be recycled based on an 85% collection rate (of waste generated) across all technologies (c-Si, a-Si, CdTe, and CIGS/CIS). The 14% of commercial photovoltaic panels are assumed to be recycled in line with Baseline Scenario B (between 20-30% collection and recycling rate, applied only to c-Si, a-Si, and CdTe technologies).Additional information on the application of a 85% collection and recycling rate in Policy Option A to residential photovoltaic panels covered under WEEE can be found in Annex I: Section 16.3.

[33] Total recycling rates for 2030, 2040 and 2050 represent the percentage of total quantity of end-of-life panels recycled; it should be noted that in 2050 this percentage is lower than in 2040 due to the entry onto the market of large quantities of CIGS/CISpanels to which a 0% recycling rate hypothesis has been applied.

[34] WinterGreen Research Inc. (2008) Solar residential panel market shares, forecasts and strategies, 2008-2014 http://www.researchandmarkets.com/reports/650926/solar_residential_panel_market_shares_forecasts

[35] WinterGreen Research Inc. (2008) The enterprise goes green: worldwide commercial solar panel market shares, strategies and forecasts 2008-2014 http://www.marketresearch.com/product/display.asp?productid=1912877

The volume of waste which would remain being improperly treated and not sent for pre-treatment and recycling is estimated at approximately 2 million tonnes in 2050. Additional information on Policy Option A can be found in Annex I: Section 16.3.

Photovoltaic technology	a Amount of waste generated from residential photovoltaic module installations (in million tonnes)			b Collection rate (percentage)			c Properly treated and sent for recycling (in million tonnes) c = a x b			d Not properly treated and not sent for recycling (in million tonnes) d = a - c		
	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
c-Si	0,17	1,72	3,62	85%	85%	85%	0,14	1,46	3,08	0,03	0,26	0,54
a-Si	0,02	0,29	1,35	85%	85%	85%	0,01	0,24	1,15	0,002	0,04	0,20
CdTe	0,01	0,68	1,28	85%	85%	85%	0,01	0,58	1,09	0,001	0,10	0,19
CIGS/CIS	0,00	0,04	1,63	85%	85%	85%	0,00	0,03	1,39	0,00	0,01	0,24
Total	0,19	2,73	7,88	85%	85%	85%	0,16	2,32	6,70	0,03	0,41	1,18

Table 10: Residential photovoltaic panel quantities annually in the EU27 – Policy Option A

Photovoltaic technology	a Amount of waste generated from commercial photovoltaic module installations (in million tonnes)			b Collection rate (percentage)			c Properly treated and sent for recycling (in million tonnes) c = a x b			d Not properly treated and not sent for recycling (in million tonnes) d = a - c		
	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
c-Si	0,03	0,28	0,59	20%	25%	30%	0,01	0,07	0,18	0,02	0,21	0,41
a-Si	0,002	0,05	0,22	20%	25%	30%	0,0005	0,01	0,07	0,002	0,04	0,15
CdTe	0,001	0,11	0,21	20%	25%	30%	0,0002	0,03	0,06	0,001	0,08	0,15
CIGS/CIS	0,00	0,01	0,27	0%	0%	0%	0,00	0,00	0,00	0,00	0,01	0,27
Total	0,03	0,44	1,28	20%	25%	24%	0,006	0,11	0,31	0,02	0,34	0,98

Table 11: Commercial photovoltaic panel quantities annually in the EU27 – Policy Option A

Photovoltaic technology	Amount of waste generated from all (residential and commercial) photovoltaic module installations (in million tonnes)			Quantity collected (in million tonnes)			Quantity not properly treated and not sent for recycling (in million tonnes)		
	2030	2040	2050	2030	2040	2050	2030	2040	2050
c-Si	0,20	2,00	4,21	0,15	1,53	3,25	0,05	0,47	0,96
a-Si	0,02	0,33	1,57	0,01	0,26	1,21	0,004	0,08	0,36
CdTe	0,01	0,79	1,49	0,01	0,61	1,15	0,002	0,19	0,34
CIGS/CIS	0,00	0,05	1,89	0,00	0,03	1,39	0,00	0,01	0,51
Total	0,22	3,18	9,16	0,17	2,43	7,00	0,05	0,74	2,16

Table 12: Total (residential and commercial) photovoltaic panel quantities annually in the EU27 – Policy Option A

5.4. POLICY OPTION B: 'ALL PVS INCLUDED IN THE SCOPE OF THE WEEE DIRECTIVE'

Policy option B ('inclusion of all photovoltaic panels in the scope of the recast WEEE Directive, residential and non-residential'): All photovoltaic panels sold to private households and for commercial installations, are included in the scope of the WEEE Directive with provisions similar to those applying for other e-waste streams under the Directive. As a consequence, a collection rate of 85% of waste from all photovoltaic panels is assumed with 100% of volumes collected sent to proper pre-treatment and recycling, to avoid negative impacts on environment and human health.

In 2050, slightly under 8 million tonnes would be recycled, leaving about 1.4 million tonnes not treated and not recycled. Additional information on Policy Option B can be found in Annex I: Section 16.4.

Photovoltaic technology	a Amount of waste generated (in million tonnes)			b Collection rate (percentage)			c Properly treated and sent for recycling (in million tonnes) c = a x b			d Not properly treated and not sent for recycling (in million tonnes) d = a - c		
	2030	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
c-Si	0,20	2,00	4,21	85%	85%	85%	0,17	1,70	3,58	0,03	0,30	0,63
a-Si	0,02	0,33	1,57	85%	85%	85%	0,02	0,28	1,33	0,003	0,05	0,24
CdTe	0,01	0,79	1,49	85%	85%	85%	0,01	0,67	1,27	0,001	0,12	0,22
CIGS/CIS	0,00	0,05	1,89	85%	85%	85%	0,00	0,04	1,61	0,00	0,01	0,28
Total	0,22	3,18	9,16	85%	85%	85%	0,19	2,70	7,79	0,03	0,48	1,37

Table 13: Photovoltaic panel quantities annually in the EU27 – Policy Option B.

6. EVALUATION OF POLICY OPTIONS

6.1. MAIN ASSUMPTIONS

Due to the current rapid development and evolution of photovoltaic technologies and recycling techniques and a lack of concrete data on many aspects of photovoltaic recycling in the future, assumptions, based on information currently available, were applied in order to estimate what a potential reality may look like for photovoltaic recycling in the future. Below, assumptions made on end-of-life photovoltaic panel quantities, environmental impacts, economic impacts and social impacts of the four scenarios examined for end-of-life photovoltaic panel recycling are presented in detail.

All impacts assessed in this section are for 2050. **Please note that the figures shown in this section and throughout the report, shows annual values and not values for time periods longer than one year.**[36]

Remark: Inflation has not been taken into account for economic loss, logistics and recycling cost, or recycling revenues; however, inflation can be estimated in the EU-27 at approximately 2% per year, which could incrementally increase estimated future costs and revenues.

- **Quantities**

Annual quantities of end-of-life photovoltaic panels generated have been estimated at 9.16 million tonnes for all scenarios assessed; the percentage of these panels properly collected, treated and recycled, versus incorrectly disposed of varies by scenario. Quantities are summarised in Chapter 5 – Definition of policy options. Additional information on calculations of end-of-life photovoltaic panel quantities can be found in Section 12: Annex E.

- **Environmental impacts**

Environmental impacts assessed in relation to improper disposal of photovoltaic panels assume no collection or pre-treatment or recycling of such panels; environmental impacts of improper disposal are based on leaving end-of-life photovoltaic panels in nature (see Chapter 4 – Environmental Impacts of end-of-life photovoltaic panels). Lead and cadmium leaching analysis are based on current estimates of lead and cadmium quantities found in photovoltaic panels. External cost of such leaching and the economic loss of conventional and rare materials not recovered has been monetised based on data available in 2011 and does not take into account inflation. It should be noted that quantities of hazardous substances such as lead and cadmium could reduce in photovoltaic panels in the future; this has not been considered in the current analysis, due to uncertainty on the extent of this trend. The external costs of leaching could also evolve in the future, but it is not possible to estimate the direction or extent of such evolutions.

The external cost per kg of cadmium is 46 Euros (or 46,000 Euros / tonne); improper disposal of one tonne of CdTe PV panels links with 12.04 Euros of external cost. The external cost of lead is 1174 Euros / kg (or 1 174 000 Euros / tonne); improper disposal of one tonne of c-Si PV panels leads to 348 255 Euros of external damage. Both values capture damage to human health. The amount of lead found in c-Si PV panels (1.64 to 11.4 g per panel) is higher than the amount of cadmium found in CdTe PV panels (0.32 g

[36] e.g. the value for 2050 is the value for the year 2050 and not the value for the period 2011 to 2050.

to 11.4 g per panel) and leaching of lead in lower pH conditions can reach much higher values (13% to 90%) than expected leaching for cadmium (29% to 40%). Due the lower quantities of cadmium found in CdTe PV panels as compared to c-Si PV panels, the potentially lower leaching of cadmium in comparison to lead, and the lower external cost of cadmium compared to lead, it should be noted that external costs of cadmium in PV panels remain limited compared to lead.

While the International Agency for Research on Cancer (IARC) lists cadmium as Group 1 (Carcinogenic to humans) and lead as Group 2B (Possibly carcinogenic to humans), lead has historically been estimated as having a higher external cost, specifically due to its higher likelihood of entering the human body.[37] Lead is not necessarily less dangerous than cadmium, but is more likely to enter into the human body through a wider set of channels than cadmium, notably through pollution in the atmosphere; also, the effects of lead are difficult to control. While overall costs of leaching to soil and air emissions of cadmium and lead may be higher, in the current study only human health damages could be monetised.

Additional information on calculations for external cost can be found in Annex F: Section 13.2.

- **Economic impacts**

Assumptions made on the costs of logistics and recycling for end-of-life photovoltaic panels are based on current recycling prices of photovoltaic panels as assessed by experts including Deutsche Solar and Ökopol. It should be noted that logistics as well as pre-treatment and recycling costs for end-of-life photovoltaic panels could be expected to decrease with an increase in volumes of photovoltaic waste quantities, and hence the achievement of economies of scale. However, due to uncertainty on the extent of this trend and limited information on anticipated future recycling costs for photovoltaic recycling (due largely to potential technology shifts), logistics and recycling costs have been based on data available for 2011.

Logistics costs have been uniformly applied to all scenarios where collection and recycling takes place at 150 Euros / tonne, based on PV Cycle's reported experiences in their 2010 collection and recycling activities.[38] It should be noted that logistics costs can vary based on the collection and transport system chosen and the distance between the collection point and the recycling centre. Recycling costs applied vary by technology, in line with the recycling cost estimates presented in Ökopol's 2007 study, as summarised in Table 14 below.

When assessing revenues achievable through the recycling of photovoltaic panels, assumptions applied in Baseline Scenario B and in Policy Options A and B differ. In Baseline Scenario B recycling through a float glass plant is assumed, costing a total of 25 Euros / tonne and resulting in 15 Euros / tonne in revenues; this type of simple recycling assumes only the recycling of glass. While in the future, net revenues could become positive, it is not currently possible to assess this trend. In Policy Option A and Policy Option B, due to the high quantities of end-of-life photovoltaic panels and the economies of scale achievable when recycling with such quantities, high yield material recycling has been assumed, resulting in the recovery of 100% of aluminium, 95% of glass and 30% of rare metals.

Revenues calculated assume the sale of recovered materials at the current market price (as of February 2011) for virgin raw materials. These assumptions have been used in light of the lack of reliable

[37] International Agency for Research on Cancer (2010) Agents classified by the IARC Monographs, Volume 1-100 http://monographs.iarc.fr/ENG/Classification/ClassificationsAlphaOrder.pdf

[38] As reported by Dr. Karsten Wambach of Sunicon; Interview 3 March 2011, Interview 16 March 2011

information price trending for raw materials up through 2050, although a tentative has been made to analyse potential trends; detail can be found in Annex F: Section 13.3.

In Baseline B the logistics, pre-treatment and recycling costs total to €175 for each tonne of photovoltaic panels collected, treated and recycled, without distinction by technology. These costs represent collection, transportation, pre-treatment, and float glass recycling. In this situation, no attempt is made to recover aluminium and rare metals in end-of-life photovoltaic modules; recycling centres on glass crushing and resale of glass cullet. Revenues per tonne for this type of recycling total to €15. While this type of simple glass recycling is not profitable for producers, it is assumed to take place due to branding and extended producer responsibility concerns on the part of photovoltaic panel producers, especially since solar energy is considered a 'green' form of energy.

In Policy Options A and B, the logistics, pre-treatment and recycling costs vary by technology, due to varying requirements for material recycling which are differentiated by technology type; costs range between €210 and €290. High yield recycling in these scenarios involves the separation and material recovery of at least aluminium, glass and rare metals contained in end-of-life photovoltaic panels. Revenues resulting from such recycling range between €2105 and €2349 per tonne. Additional information on costs of logistics and recycling for photovoltaic panels applied in the current study can be found in Annex H: Section 15.1.

BASELINE B

	*Logistics unit cost****	*Treatment and recycling unit cost **	*Total unit cost (euros per tonne collected)*
c-Si	150,00 €	25,00 €	175,00 €
a-Si	150,00 €	25,00 €	175,00 €
CdTe	150,00 €	25,00 €	175,00 €
CIGS/CIS	150,00 €	25,00 €	175,00 €

POLICY OPTIONS A AND B

	*Logistics unit cost****	*Treatment and recycling unit cost***	*Total unit cost (euros per tonne collected)*
c-Si	150,00 €	140,00 €	290,00 €
a-Si	150,00 €	60,00 €	210,00 €
CdTe	150,00 €	119,00 €	269,00 €
CIGS/CIS	150,00 €	120,00 €	270,00 €

Table 14: Logistics, treatment and recycling unit costs for Baseline B and Policy Options A and B

It should be noted that logistics and recycling costs are of a similar order of magnitude, although recycling costs vary by technology. Recycling costs considered remain uniform at 175 Euros per tonne of end-of-life photovoltaic panels in Baseline Scenario B, whereas in Policy Options A and B total logistics and recycling costs range between 210 Euros / tonne and 290 Euros / tonne based on estimated differences in recycling techniques and pre-treatment required. Revenues are 15 Euros / tonne in Baseline Scenario B, but vary between 2105 Euros / tonne and 2349 Euros / tonne for Policy Options A and B. Assuming resale of recovered materials at current market prices (as of February 2011) for raw virgin materials, revenues for c-Si photovoltaic panels are 7 to 10 times higher than recycling and logistics costs. For thin film panels, revenues of material recycling range from 8 to 11 times higher than recycling and logistics costs depending on the technology.

While it should be understood that these types of revenues may not be immediately achievable, due to technical limitations and limited current volumes of photovoltaic waste, these assumptions have been taken as the best possible estimate representing revenues achievable in 2050.

- **Social impacts**

Social impacts considered are job creation potential, which are based on expert input. Job creation varies based on the type of recycling applied to photovoltaic panels. In Baseline Scenario A, with no recycling of photovoltaic panels, no job creation takes place, while in Baseline Scenario B when proper treatment and simple recycling is applied to photovoltaic panels, some job creation occurs. In Policy Options A and B the application of proper treatment and high yield material recycling techniques to end-of-life photovoltaic panels leads to even higher job creation potential due to the usage of specialised techniques and, most likely, the creation of new pre-treatment and recycling facilities to execute such techniques. Additional information on social impact assessment can be found in Annex I: Section 16.6.

Table 15 below provides a summary of the environmental, economic and social impacts of the 2 Baseline scenarios and 2 Policy options examined. Impacts are examined in more detail below.

2050 (annually)	**Baseline Scenario A** *"Worst Case"*	**Baseline Scenario B** *"Voluntary Action"*	**Policy Option A** *"Residential PV in WEEE"*	**Policy Option B** *"All PV in WEEE"*
Quantities				
Amount of PV waste generated (in million tonnes)	9,16	9,16	9,16	9,16
Amount of PV modules collected, properly treated and sent to recycling (in million tonnes)	0,00	2,18	7,00	7,79
Amount of PV waste improperly disposed of (in million tonnes)	9,16	6,98	2,16	1,37
Environmental benefits of policy action				
Soil and air pollution (in tonnes)				
Lead leaching from c-Si PV modules	316-2181	221-1527	72-495	47-327
Cadmium leaching from CdTe PV modules	40-228	28-159	9-52	6-34
Soil and air pollution (average external cost, in billion Euros)				
Lead leaching from c-Si PV modules	-1,47	-1,03	-0,33	-0,22
Cadmium leaching from CdTe PV modules	-0,01	-0,004	-0,001	-0,001
Total external cost *(in billion Euros)*	-1,47	-1,03	-0,33	-0,22
Gain of resources (recycling input, in million tonnes)				
Glass in c-Si PV modules and Thin film* modules	0,00	1,82	6,00	6,68
Aluminium in c-Si PV modules and Thin film* modules	0,00	0,13	0,34	0,38
Rare metals in c-Si PV modules and Thin film* modules	0,00	0,02	0,07	0,08
Gain of resources (recycling output, in million tonnes)				
Glass in c-Si PV modules and Thin film* modules	0,00	1,73	5,70	6,35
Aluminium in c-Si PV modules and Thin film* modules	0,00	0,00	0,34	0,38
Rare metals in c-Si PV modules and Thin film* modules	0,00	0,00	0,022	0,025
Gain of resources (recycling output, in billion Euros)				
Glass in c-Si PV modules and Thin film* modules	0,00	0,03	0,29	0,32
Aluminium in c-Si PV modules and Thin film* modules	0,00	0,00	0,41	0,45
Rare metals in c-Si PV modules and Thin film* modules	0,00	0,00	14,96	16,65
Total gain of resources *(in billion Euros)*	0,00	0,03	15,66	17,42

Economic cost of policy action				
Costs				
Logistics cost (in billion Euros)	0,00	-0,33	-1,05	-1,17
Proper treatment and recycling cost (in billion Euros)	0,00	-0,05	-0,83	-0,92
Total costs *(in billion Euros)*	0,00	-0,38	-1,88	-2,09
Social impacts				
Impact on employment (number of jobs created)				
Job creation	0	400	13 000	20 000
Net benefits				
Net benefits stand-alone (in billion Euros)	-1,47	-1,39	13,44	15,11
Net benefits vs. Baseline A (in billion Euros)	N/A	0,09	14,91	16,58
Net benefits vs. Baseline B (in billion Euros)	N/A	N/A	14,83	16,49

*Thin film refers to the sum of a-Si, CdTe, CIGS/CIS technologies.

Table 15: Summary table of scenario and policy options evaluation - 2050

6.2. BASELINE SCENARIO A: 'WORST CASE'

- **Quantities**

In Baseline Scenario A, when no policy action is taken and photovoltaic panels are assumed to be improperly treated, 0 tonnes of PV panels are recycled and just under 9 million tonnes of end-of-life photovoltaic panels are improperly disposed of; recycling rate as compared to the overall quantity of waste generated in this scenario is 0%.

- **Environmental impacts**

In 2050, environmental impacts associated with the improper disposal of nearly million tonnes of end-of-life photovoltaic panels are leaching of between approximately 320 and 2200 tonnes of lead and between 40 and 230 tonnes of cadmium into the environment, resulting in between approximately 1.5 billion Euros of average external costs due to soil and air pollution. Resource gain associated with Baseline Scenario A totals to 0 Euros, as all quantities of end-of-life PV panels are not pre-treated or recycled, leading to the recovery of 0 tonnes of glass, aluminium and rare metals.

- **Economic impacts**

Due to the non-collection and non-pre-treatment and recycling of photovoltaic panels in Baseline Scenario A, the costs for logistics and recycling are assumed at zero, with resulting revenues from recycling of photovoltaic panels at zero.

- **Social impacts**

As there is no impact on the recycling industry linked to photovoltaic panel recycling, there is no impact on job creation in Baseline Scenario A.

6.3. BASELINE SCENARIO B: 'VOLUNTARY ACTION'

- **Quantities**

In Baseline Scenario B, in which current levels of recycling of photovoltaic panels are expected to continue, just over 2 million tonnes of PV panels are recycled and just under 7 million tonnes of end-of-life photovoltaic panels are improperly disposed of; the recycling rate (i.e. entering a recycling facility) as compared to the overall quantity of waste generated in this scenario is 24%.

- **Environmental impacts**

Environmental impacts are less in comparison to Baseline Scenario A, however leaching of lead into the environment is estimated between approximately 220 and 1,500 tonnes and leaching of cadmium is estimated between approximately 30 and 160 tonnes. These volumes produce average external cost impacts of just over 1 billion Euros. Recycling input in Baseline Scenario B totals to 1.82 million tonnes of glass, 0.13 million tonnes of aluminium and 0.02 million tonnes of rare metals. As simple recycling is applied in Baseline Scenario B, recycling output is only glass, which totals to 1.73 million tonnes; this leads to a total resource gain of 0.03 billion Euros.

- **Economic impacts**

Recycling which is undertaken is assumed to be centred around pre-treatment and recycling of end-of-life photovoltaic panels in a float glass recycling plant, leading to pre-treatment/recycling costs of 175 Euros per tonne and recycling revenues of 15 Euros / tonne. Logistics, pre-treatment and recycling costs in Baseline Scenario B total to 0.38 million Euros.

- **Social impacts**

Due to the pre-treatment and recycling of photovoltaic panel waste in glass recycling plants, some job creation is anticipated to augment current capacity to handle large volumes of photovoltaic waste. Total job creation is estimated at 400 jobs in 2050 for this scenario.

6.4. POLICY OPTION A: ‘RESIDENTIAL PVS INCLUDED IN THE SCOPE OF THE WEEE DIRECTIVE’

- **Quantities**

In Policy Option A, when residential photovoltaic panels (accounting for 86% of waste generated) are recycled under the WEEE Directive, 7 million tonnes of photovoltaic panels are recycled while just over 2 million tonnes of end-of-life panels are improperly disposed of. This represents a 76% recycling rate (i.e. entering a recycling facility) as compared to the overall quantity of waste generated.

- **Environmental impacts**

Environmental impacts of Policy Option A are reduced in comparison with Baseline Scenarios A and B. Lead leaching in the environment totals to between approximately 70 and 500 tonnes and cadmium leaching totals to between approximately 10 and 50 tonnes. The resulting average external cost of leaching is assessed at approximately 0.33 billion Euros. Resource input in Policy Option A totals to 6.0 million tonnes of glass, 0.34 million tonnes of aluminium and 0.07 tonnes of rare metals, leading to a total resource gain of 15.66 billion Euros.

- **Economic impacts**

The total cost of collecting, pre-treating and recycling residential PVs as assumed in this option are estimated annually at just under 2 billion Euros in 2050. The high yield recycling assumed to be realistic for these high volumes, of 100% recovery of aluminium, 95% of glass and 30% of rare metals, is projected to yield revenues in the order of just over 15 billion Euros annually in 2050, due to the sale of recovered materials at market prices. In other words, with these high volumes the recycling becomes highly profitable. The economic benefits could increase further if improved recycling technologies become available, especially for rare metals.

As regards Small and Medium Enterprises (SMEs), positive impacts are expected, although they cannot be quantified based on the available data. The waste management obligations incurred on producers by the WEEE Directive typically are executed on the ground through the cooperation of a number of actors in an interlinked value chain. Final recycling and disposal operations are often taken over by large capital-intensive recycling plants, while collection and pre-treatment operations are typically carried out by SMEs. In the case of PVs, it can be expected that tasks related to de-installation, collection and pre-treatment would most likely be carried out by the same SMEs that are also active in the installation of the panels. Hence, a prolongation of the value chain into waste management would create additional demand for the services of these SMEs. It should be mentioned in addition that the setting up of collection systems on a large scale is practically impossible for a small company alone, while the costs per unit decrease rapidly with the size and use of the system to be set up. Therefore, small producers of photovoltaic panels should benefit disproportionately by participating in a collective compliance scheme, as foreseen as one option under the WEEE Directive.

- **Social impacts**

Due to an increase in high yield recycling capacity available, job creation for the photovoltaic recycling industry is estimated at 13,000 jobs in 2050.

6.5. POLICY OPTION B: 'ALL PVS INCLUDED IN THE SCOPE OF THE WEEE DIRECTIVE'

- **Quantities**

In Policy Option B, when all photovoltaic panels are recycled under the WEEE Directive, just under 8 million tonnes of photovoltaic panels are recycled while approximately 1.4 million tonnes of end-of-life panels are improperly disposed of. This represents an 85% recycling rate (i.e. entering a recycling facility) as compared to the overall quantity of waste generated.

- **Environmental impacts**

Environmental impacts in the Policy Option B are lower than those found in Policy Option A, with lead leaching between approximately 50 and 330 tonnes and cadmium leaching between 5 and 35 tonnes, resulting in a total external cost of approximately 0.22 billion Euros. Recycling input totals to 6.68 million tonnes of glass, 0.38 million tonnes of aluminium, and 0.08 million tonnes of rare metals, resulting in gain of 17.42 billion Euros.

- **Economic impacts**

The total cost of collecting, pre-treating and recycling residential PVs as assumed in this option are estimated annually at just over 2 billion Euros in 2050. The high yield recycling assumed to be realistic for these high volumes, of100% recovery of aluminium, 95% of glass and 30% of rare metals, is projected to yield revenues in the order of nearly 17.5 billion Euros annually in 2050, due to the sale of recovered materials at market prices. In other words, with these high volumes the recycling becomes highly profitable. The economic benefits could increase further if improved recycling technologies become available, especially for rare metals.

As regards Small and Medium Enterprises (SMEs), positive impacts are expected, as described above for Policy Option A.

- **Social impacts**

Due to an increase in high yield recycling capacity available, job creation for the photovoltaic recycling industry is estimated at 20,000 jobs in 2050.

6.6. COMPARISON OF POLICY OPTIONS

When comparing Policy Options A and B to Baseline Scenarios A and B, as represented above in Table 15, benefits achievable represent a large gap between the Baseline Scenarios considered and the Policy Options considered. Recycling of photovoltaic panels increases by 76% when comparing Policy Option A to Baseline Scenario A and by 85% when comparing Policy Option B to Baseline Scenario A. When comparing Policy Option A and Baseline Scenario B, net benefits attainable are approximately 10 times higher than those achieved in Baseline Scenario B; the same comparison between Policy Option B and Baseline Scenario B demonstrate that benefits attainable in Policy Option B are approximately 11 times higher compared to Baseline Scenario B.

When comparing the Policy Options A and B to the Baseline Scenarios A and B, negative environmental impacts decrease in line with the achievement of higher recycling rates. For example, when comparing Policy Option A with Baseline A, external cost of leaching is reduced by 1.14 billion Euros; when comparing Policy Option B with Baseline A, external cost of leaching is reduced by 1.25 billion Euros.

In comparing Policy Option A and Policy Option B, benefits attained in Policy Option B are visibly above those obtained in Policy Option A. While in Policy Option A the percentage of overall end-of-life photovoltaic panels recycled is 76%, in Policy Option B this percentage increases to 85%, leading to reduced negative environmental impacts, reduced economic loss and external costs. Net benefits of both Policy Options are positive, with resource gains from recycling outweighing the costs of recycling and with job creation potential elevated. Overall benefits achieved are approximately 6% higher across all categories assessed in Policy Option B as compared to Policy Option A. In terms of social impacts, large gains are anticipated in job creation when comparing Policy Options A and B with Baseline Scenarios A and B.

Despite the above, some arguments could be brought forward in favour of maintaining the status quo with photovoltaic panels outside the scope of the WEEE Directive. They mainly relate to the probability for voluntary action as represented by Baseline Scenario B, and to the question of subsidiarity.

Regarding voluntary action as represented by Baseline Scenario B and beyond, it is certainly realistic to assume that some voluntary action would be taken, as assumed in this study. Producers of PVs are aware of their environmental responsibility and their public image, and the materials contained in PVs can make the recycling process profitable over time. However, in order for the recycling process to become profitable, large volumes of e-waste are needed, on a reliable basis over a long planning period. And raw materials prices, as well market conditions for new PVs, can fluctuate strongly. Therefore, significant long term finance mechanisms have to be agreed upon between producers, in order to ensure a sustainable collection, pre-treatment and recycling operation even in periods when raw materials prices are low, and even for those steps of the process that are not profitable. As the attempt by industry to establish a voluntary agreement on photovoltaic panels shows, establishing such mechanisms with foresight and under the condition of uncertainty as regards the market and prices is a very significant challenge. Hence, it cannot be expected that Baseline Scenario B can come close to the environmental and resource benefits provided by Policy Options A and B.

As regards the principle of subsidiarity, the issue has been analysed and decided on a general level when the original WEEE Directive was adopted in 2003, and its logic applies equally to end-of-life PVs. Recital 8 of the current Directive 2002/96/EC states:

"The objective of improving the management of WEEE cannot be achieved effectively by Member States acting individually. In particular, different national applications of the producer responsibility principle may lead to substantial disparities in the financial burden on economic operators. Having different national policies on the management of WEEE hampers the effectiveness of recycling policies. For that reason the essential criteria should be laid down at Community level."

Net benefits have been calculated taking into account external costs avoided and resource gain as benefits, and subtracting total costs for logistics, collection, proper treatment and recycling.

The equation for calculating net benefits is the following:

(External costs avoided + resource gain) – (total logistics, proper treatment and recycling cost) = net benefits

Additional information on the analysis completed can be found in Section 16: Annex I.

7. CONCLUSIONS

Including photovoltaic panels in the WEEE Directive reduces the potential negative environmental impacts of improper disposal and generates economic benefits. Limiting the quantity of photovoltaic panels improperly disposed of has the positive environmental impacts of avoiding lead and cadmium leaching and avoiding potential resource loss due to non-recovery of valuable conventional resources and rare metals in photovoltaic panels.

Quantities of lead leached into the environment are reduced by a factor of 4 when comparing Policy Option A with Baseline Scenario A and by a factor of 6 when comparing Policy Option B with Baseline Scenario B, with external costs of leaching being reduced by the same factor. In 2030, 2040 and 2050, recycling of photovoltaic panels is expected to be profitable, with revenues from high yield material recycling outweighing logistics and recycling costs.

Policy Option B ('All PVs in the scope of the WEEE Directive') has been identified as the recommended policy option. Taking into account the benefits and costs of collection, proper treatment and recycling based on current knowledge and the assumptions described, Policy Option B yields the highest net benefits. In 2050, these net benefits would annually amount to about 16.6 billion Euros compared to Baseline Scenario A, 16.5 billion Euros compared to Baseline Scenario B, and 1.67 billion Euros compared to Policy Option A. The net benefits of Policy Option A ('Residential PVs in the scope of the WEEE Directive') are also clearly positive, and would in 2050 amount annually to about 14.9 billion Euros compared to Baseline Scenario A, and nearly 14.8 billion Euros compared to Baseline Scenario B.

For the recommended policy option B, the benefits identified stem to a very high share from the gain of resources through recycling.

The current analysis seeks to represent the state of photovoltaic recycling possible in 2050; it should be noted that the potential costs and technology shifts required between the current time period and 2050 which may impact the state of photovoltaic panel recycling have not been taken into account. Hypotheses on environmental impacts, recycling costs and potential recycling revenues are based on the current time period, due to a lack of concrete information on trend shifts for these factors in the future. Economies of scale for recycling quantities, changing weight of photovoltaic technologies and actions undertaken to encourage the collection of end-of-life photovoltaic panels in order to increase quantities of waste could impact costs and benefits assessed; however, due to a lack of concrete data on these trends, such factors have been considered as outside the scope of the current study. As a tendency, it is clear that technological advance in recycling efficiencies would increase the benefits of both policy options. At the same time, it would increase the incentives for voluntary recycling, as described in Baseline Scenario B.

8. ANNEX A: BIBLIOGRAPHY

[1]ADEME (2007) Monétarisation des impacts environnementaux du recyclage: méthodologie et applications

[2]BIO Intelligence Service for ADEME (2010) Etude de potentiel de recyclage de certains métaux rares: Partie 1

[3]BIO Intelligence Service for ADEME (2010) Etude de potentiel de recyclage de certains métaux rares: Partie 2

[4]Earth Policy Institute (2009) Solar cell production climbs to another record in 2009 http://www.earth-policy.org/index.php?/indicators/C47/

[5]EC (2008) Proposal for a Directive of the European Parliament and of the Council on waste electrical and electronic equipment (WEEE) (Recast) http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52008PC0810:EN:NOT

[6]EC (2009) Photovoltaic solar energy – Development and current research http://ec.europa.eu/energy/publications/doc/2009_report-solar-energy.pdf

[7]EC (2011) European Parliament legislative resolution of 3 February 2011 on the proposal of the European Parliament and of the Council on waste electrical and electronic equipment (WEEE) (recast) http://www.europarl.europa.eu/sides/getDoc.do?type=TA&language=EN&reference=P7-TA-2011-0037

[8]EC (2011) Evaluation by the Commission services concerning an Environmental Agreement submitted by PV Cycle to the Commission on 03 December 2010 http://ec.europa.eu/environment/waste/weee/pdf/Evaluation%20PV%20Cycle%20Environmental%20Agreement.pdf

[9]ECN & EEA (2011) Renewable energy projections as published in the national renewable energy action plans of the European Member States

[10]EPIA (2007) Global Market Outlook for Photovoltaics until 2012

[11]EPIA & Greenpeace (2011) Solar Generation 6: Solar photovoltaic electricity empowering the world

[12]Eurobserver (2009) Photovoltaic barometer http://www.eurobserv-er.org/pdf/baro190.pdf

[13]European Environmental Agency (2010) The European Environment: State and Outlook 2010, Material Resources and Waste http://www.eea.europa.eu/soer/europe/material-resources-and-waste

[14]Eurostat (2010) Environmental statistics and accounts in Europe http://epp.Eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-32-10-283/EN/KS-32-10-283-EN.PDF

[15]ExterneE-Pol (2005) Externalities of Energy: Extension of accounting framework and Policy Applications.

[16]First Solar (2011) Panel collection and recycling programme http://www.firstsolar.com/en/recycle_program.php

[17]FORWAST (2010) Documentation of the contribution analysis and uncertainty assessment. Results interpretation identifying priority material flows and wastes for waste prevention, recycling and choice

of waste treatment options. Policy recommendations. http://forwast.brgm.fr/Documents/Deliverables/Forwast_D63.pdf

[18] International Agency for Research on Cancer (2010) Agents classified by the IARC Monographs, Volume 1-100 http://monographs.iarc.fr/ENG/Classification/ClassificationsAlphaOrder.pdf

[19]Larsen, Kari (3 August 2009) 'End of life PV: then what? Recycling solar PV panels,' Renewable energy focus http://www.renewableenergyfocus.com/view/3005/endoflife-pv-then-what-recycling-solar-pv-panels/

[20]Metal prices website (Accessed February 2011) http://www.metalprices.com/

[21]MethodEx Project (February 2007) BeTa-MethodEx – Version 2.

[22]NGI (2010) Leaching from mc-Si PV panel material – results from batch, column and availability tests. Comparison with thin film CdTe PV panels

[23]NTSA (2009) An overview of photovoltaic technologies

[24]OECD (2009) OECD Environmental Data: Compendium 2006-2008, Waste http://www.oecd.org/dataoecd/22/58/41878186.pdf

[25]Ökopol et. al. (2007) Study on the development of a take back and recovery system for photovoltaic products

[26]PRé (1999) The Eco-indicator 99: A damage oriented method for Life Cycle Impact Assessment

[27]PV Cycle (2010) Environmental agreement on the separate collection and recycling of photovoltaic panels http://www.pvcycle.org/uploads/media/ENVI_Agreement__final_2010.pdf

[28]PV Cycle (2010) Making the photovoltaic industry 'double green' http://www.pvcycle.eu/fileadmin/pvcycle_docs/documents/membership/PVCYCLE_11_2010.pdf

[29]RPA (2009) Socio-economic impact of a potential update of the restrictions on the marketing and use of cadmium

[30]Solarbuzz (2011) Panel pricing http://www.solarbuzz.com/facts-and-figures/retail-price-environment/panel-prices

[31]WinterGreen Research Inc. (2008) Solar residential panel market shares, forecasts and strategies, 2008-2014 http://www.researchandmarkets.com/reports/650926/solar_residential_panel_market_shares_forecasts

[32]WinterGreen Research Inc. (2008) The enterprise goes green: worldwide commercial solar panel market shares, strategies and forecasts 2008-2014 http://www.marketresearch.com/product/display.asp?productid=1912877

[33]Wuppertal Institute (2010) Appraisal of laboratory analyses conducted on CdTe photovoltaic panels

http://www.ntsa.eu/resources/Wuppertal+Institute+CdTe+lab+tests+appraisal$2C+Aug+2010+final.pdf

9. ANNEX B: GLOSSARY OF TERMS

1st generation: represented by the crystalline silicon (c-Si) family of technologies, includes monocrystalline and multicrystalline photovoltaic panels.

2nd generation: represented by thin film technologies including amorphous silicon, cadmium telluride, copper indium gallium selenide.

3rd generation: represented by the family of emerging PV technologies which have not yet been commercialised on a large scale. Technologies included in this category include concentrator photovoltaics , dye-sensitised solar cells, organic solar cells and hybrid cells.

Amorphous silicon PV panels: a type of 2nd generation thin film PV technology, which uses a non-crystalline form of silicon and less scarce materials than other thin film panels.

Billion tonnes (BT): billion tonnes, represents a unit value of 10^9 tonnes.

Cadmium telluride PV panels: a type of 2nd generation thin film PV technology, which uses a semi-conducter compound formed of cadmium and tellurium, which is cost-effective but not as efficient as crystalline silicon. Cadmium has a high level of toxicity.

CIGS/CIS PV panels: a type of 2nd generation thin film PV technology which is a newer technology and achieves the highest efficiencies of any current thin film technology; however, manufacturing costs are higher due to the use of a more complex process. CIGS and CIS PV panels contain higher quantities of rare metals than other PV panels on the market, such as indium and gallium.

Crystalline silicon PV panels: 1st generation photovoltaic panels characterised by a high percentage composition of silicon, includes monocrystalline and multicrystalline technologies.

Emerging technologies: represent the 3rd generation of photovoltaic panels which have not yet been commercialised on a large scale. Technologies falling into this category include concentrator photovoltaics , dye-sensitised solar cells, organic solar cells and hybrid cells.

High yield recycling: means recycling as defined in the Waste Framework Directive, but taking into account also those operations that require large scale installations and/or substantive investments in order to be performed economically. Because of the profitability of this step, it is assumed to go beyond the requirements of Article 11 of the draft WEEE Directive. Specifically, it is assumed that recycling rates reach 95% for glass, 100% aluminium, and 30% for rare metals and that cadmium and lead would also be recovered, "High yield recycling" is assumed to take place in Policy Option A and B.

Material recycling: recovery of individual material components of photovoltaic panels. Could involve recovery of, for example, aluminium, glass and rare metals.

Million tonnes (MT): million tonnes, represents a unit value of 10^6 tonnes.

Monocrystalline PV panels: a type of 1st generation crystalline silicon panel, very efficient but expensive to produced due to the use of highest purity silicon and sophisticated manufacturing processes.

Multicrystalline PV panels: a type of 1st generation crystalline silicon panel made up of solar cells cut from multifaceted silicon crystals. This is the most common type of crystalline silicon PV panel and is cheaper to produce than monocrystalline PV panels.

Photovoltaic array: represents a linked assembly of PV panels/panels.

Photovoltaic panel: equivalent to a solar panel or panel; refers to a unit composed of individual PV cells.

Photovoltaic module: equivalent to a solar panel or panel; refers to a unit composed of individual PV cells.

Photovoltaic/solar cell: the individual units which make up a photovoltaic panel/panel or a solar panel/panel.

Pre-treatment: refers to the initial stages of the recycling process, involving physical separation of end-of-life photovoltaic panels as well as depending on the type of recycling, could involve shredding or thermal separation. Resulting waste streams such as glass, aluminium, cadmium, lead and rare metals are fed into individual recycling processes following on this initial step.

Proper disposal: used to refer to pre-treatment (physical separation and sometimes thermal separation too) and recycling (material recycling) including the contained disposal of hazardous substances in line WEEE Directive and Waste Framework Directive provisions.

Proper treatment: refers to treatment in line with the requirements of the draft WEEE Directive, especially Article 8 and Annex II. It is assumed to take place for all separately collected PV e-waste in Baseline Scenario B and in Policy Scenarios A and B.

Recycling: in line with the Waste Framework Directive, recycling is defined as the reprocessing in a production process of the waste materials for the original purpose or for other purposes, but excluding energy recovery which means the use of combustible waste as a means of generating energy through direct incineration with or without other waste but with recovery of the heat.

Simple recycling: means recycling as defined in the Waste Framework Directive, but only taking into account those operations that are typically carried out in small scale installations without excessive investments. Specifically, it is assumed that only glass is recovered, not other materials such as aluminium, cadmium, lead and rare metals. "Simple recycling" is assumed to take place in Baseline Scenario B.

Solar panel: equivalent to a photovoltaic panel or panel; refers to a unit composed of individual PV cells.

Solar module: equivalent to a photovoltaic panel or panel or solar panel; refers to a unit composed of individual PV cells.

Thin film PV panels: 2nd generation photovoltaic panels, characterised by one or more thin layers of photovoltaic material on the surface, for example glass, stainless steel or plastic. Technologies included are: amorphous silicon, cadmium telluride, copper indium gallium selenide.

Waste photovoltaic panel: in line with the WEEE Directive and the revised Waste Framework Directive (2006), photovoltaic waste is defined as photovoltaic equipment which the holder discards or intends to discard or is required to discard.

Watt-peak (Wp): the measure of the nominal power of a photovoltaic installation under defined illumination (a light intensity of 1000W/m^2 at a temperature of 25°C). This unit allows a comparison of different panels. Standard crystalline silicon panels have a nominal power ranging from 120 to 300 Wp depending on size and efficiency. Standard thin film panels have lower nominal power (60 to 120 Wp) and their size is generally smaller.

10. ANNEX C: LIST OF EXPERTS CONSULTED

- Giorgia CONCAS and Alexandre ROESCH, EPIA
  Interview 17 February 2011
- Jan CLYNCKE and Virginia GOMEZ,PV Cycle
  Interview 17 February 2011, Interview 8 March 2011, Interview 14 March 2011
- Tone KNUDSEN, Bellona, EEB member
  Interview 15 February 2011
- Lisa KRUEGER, First Solar
  Interview 3 March 2011, 25 March 2011
- Knut SANDER, ÖKOPOL
  Interview 3 March 2011, Interview 14 March 2011
- Dr. Karsten WAMBACH, Sunicon
  Interview 3 March 2011, Interview 16 March 2011

11. ANNEX D: NEW PHOTOVOLTAIC PANELS - ASSUMPTIONS AND COMPLEMENTARY INFORMATION

11.1. CURRENT PHOTOVOLTAIC CAPACITY IN EUROPE

	2008			2009*		
	Réseau On-grid	Hors réseau Off-grid	Total	Réseau On-grid	Hors réseau Off-grid	Total
Germany	5 979,000	40,000	6 019,000	9 785,300	45,000	9 830,300
Spain	3 402,235	18,836	3 421,071	3 500,000	20,082	3 520,082
Italy	445,000	13,300	458,300	1 019,000	13,400	1 032,400
Czech Republic	54,294	0,380	54,674	465,321	0,580	465,901
Belgium	70,870	0,053	70,923	362,970	0,053	363,023
France	82,990	20,912	103,902	268,230	21,119	289,349
Portugal	65,011	2,941	67,952	99,164	3,041	102,205
Netherlands	52,000	5,200	57,200	58,433	5,200	63,633
Greece	12,000	6,500	18,500	48,300	6,700	55,000
Austria	29,030	3,357	32,387	34,130	3,357	37,487
United Kingdom	20,920	1,590	22,510	30,920	1,690	32,610
Luxembourg	24,562	0,000	24,562	26,322	0,000	26,322
Sweden	3,079	4,831	7,910	3,579	5,131	8,710
Slovenia	1,906	0,100	2,006	8,302	0,100	8,402
Finland	0,170	5,479	5,649	0,170	7,479	7,649
Bulgaria	1,375	0,032	1,407	5,300	0,400	5,700
Denmark	2,825	0,440	3,265	4,025	0,540	4,565
Cyprus	1,586	0,571	2,157	2,695	0,633	3,328
Malta	0,238	0,000	0,238	1,527	0,000	1,527
Poland	0,179	0,832	1,011	0,179	0,832	1,011
Hungary	0,270	0,180	0,450	0,290	0,360	0,650
Romania	0,245	0,205	0,450	0,365	0,270	0,635
Ireland	0,100	0,300	0,400	0,100	0,300	0,400
Slovakia	0,046	0,020	0,066	0,176	0,020	0,196
Estonia	0,000	0,012	0,012	0,000	0,060	0,060
Lithuania	0,000	0,055	0,055	0,000	0,055	0,055
Latvia	0,000	0,004	0,004	0,000	0,004	0,004
Total EU 27	**10 249,931**	**126,130**	**10 376,061**	**15 724,798**	**136,406**	**15 861,204**

*Estimation. *Estimate.* Les décimales sont séparées par une virgule. *Decimals are written with a comma.* Source : EurObserv'ER 2010.

Table 16: Estimated cumulated photovoltaic capacity in the European Union countries at the end of 2008 and 2009 (in MWp)[39]

[39] EurobseOrver (2009) Photovoltaic barometer http://www.eurobserv-er.org/pdf/baro190.pdf

11.2. MARKET GROWTH

Different scenarios exist related to the growth of the PV market[40]:

- **Paradigm shift scenario**
  Assumptions: current support levels will be strengthened, deepened and accompanied by a variety of instruments and administrative measures that will push the deployment of PV forward.

- **Accelerated scenario**
  Assumptions: It can be viewed as a continuation of the current support policies and it could easily be achieved in 20 years without any major technology changes in electricity grids

When calculating market growth and resulting quantities of end-of-life photovoltaic panels generated, the growth rate which has been considered is the average of the paradigm shift scenario and the accelerate scenario (e.g. from 2021 to 2025, a growth rate of 12,5% applies each year).

SUMMARY OF EPIA/GREENPEACE PARADIGM SHIFT SCENARIO

	2011-2020	2021-2030	2031-2040	2041-2050
Average market growth rates under the Paradigm Shift	42%	11% for 5 years then 9%	7% for 5 years then 5%	4%

TABLE 15
SUMMARY OF EPIA/GREENPEACE ACCELERATED SCENARIO

	2011-2020	2021-2030	2031-2040	2041-2050
Average market growth rates under the Accelerated scenario	26%	14% for 5 years then 10%	7% for 5 years then 6%	4%

Table 17: Summary of EPIA/Greenpeace paradigm shift scenario

[40] EPIA & Greenpeace (2011) Solar Generation 6: Solar photovoltaic electricity empowering the world

11.3. PROJECTIONS OF TECHNOLOGY MARKET SHARE

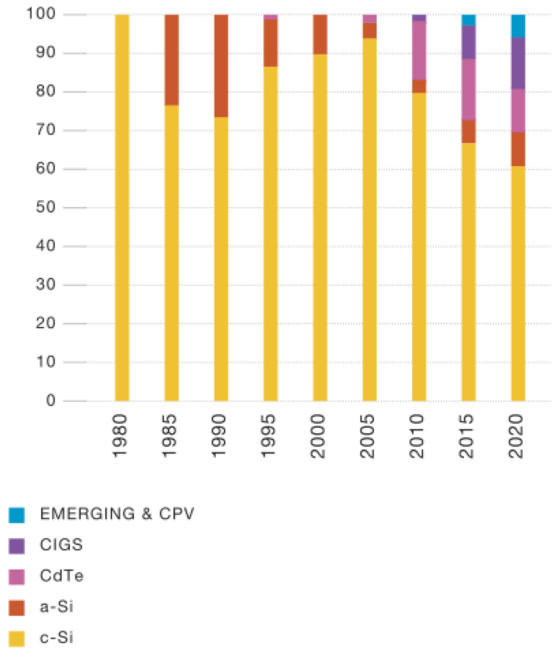


Figure 4: Historical evolution of technology market share and future trends (in %)[41]

[41] EPIA & Greenpeace (2011) Solar Generation 6: Solar photovoltaic electricity empowering the world. Historical data (until 2009) based on Navigant Consulting. Estimations based on EPIA analysis.

12. ANNEX E: WASTE PHOTOVOLTAIC PANELS - ASSUMPTIONS AND COMPLEMENTARY INFORMATION

12.1. CALCULATION METHOD APPLIED IN THIS REPORT

This section details how the projections of the quantities of waste photovoltaic panels for the next decades were calculated by BIO.

The following steps were gone through:

- **Calculation of projected total PV capacity, of newly installed PV panels and end-of-life panels (in MW)**

In order to obtain the projected total PV capacity for the years in question (see first column of Table 18), the following data were used:

- Data for the year 2000 were taken from the 'Global Market Outlook for Photovoltaics until 2012'[42], and data from 2005 to 2020 from 'Renewable Energy Projections'.[43]
- Data from 2025 to 2050 were calculated by BIO using the yearly average growth rates of total PV capacity from 2025 to 2050, see Table 19. They are calculated based on two different scenarios elaborated in the Solar Generation 2010 Report, see Annex D: Section 11. Using those average growth rates for each respective year (e.g. from 2021 to 2025, a growth rate of 12,5% applies each year), the total capacities were obtained, see Table 20.

In order to obtain the quantity of newly installed PV panels per year (second column of Table 18), the total projected capacity of year N-1 was subtracted from the total projected capacity of year N.

The calculation of the quantity of end-of-life PV is based on the assumption that PV panels have a minimum average lifetime of 25 years. Hence, the installed output finds itself in the waste stream, deferred by 25 years (see third column of Table 18)[44].

[42] EPIA (2007) Global Market Outlook for Photovoltaics until 2012

[43] ECN & EEA (2011) Renewable energy projections as published in the national renewable energy action plans of the European Member States

[44] Extending the lifetime of a PV system increases overall electrical output and improves the cost per kWh. Most producers give panel performance warranties for 25 years, and this is now considered the minimum lifetime for a PV panel. The component that affects product lifetime the most is the encapsulating material. Intense research is being carried out in this field. However, the industry is cautious about introducing substitute materials because they need to be tested over the long-term. Today, PV panels are being produced with lifetimes of at least 25 years. The target is to reach lifetimes of 40 years by 2020.

	Projected total PV capacity (MW) *[a]*	New PV panels (MW) *[b] = [a(N) - a (N-1)]*	WEEE (MW)
2000	188	188	0
2005	2221	2033	0
2010	25509	23288	0
2015	54377	28868	0
2020	84376	29999	0
2025	152048	67672	188
2030	239360	87312	2033
2035	335715	96355	23288
2040	438766	103051	28868
2045	533826	95060	29999
2050	649481	115655	67672

Table 18: Projected total PV capacity, new PV panels, WEEE (MW)

	paradigm shift scenario	accelerated scenario	**average (%)**
2025	11%	14%	**12,50%**
2030	9%	10%	**9,50%**
2035	7%	7%	**7,00%**
2040	5%	6%	**5,50%**
2050	4%	4%	**4,00%**

Table 19: Calculation of average growth rates of the PV market

Projected total PV capacity (MW)	
2021	94923
2022	106788,375
2023	120136,9219
2024	135154,0371
2025	**152048,2917**
2026	166492,8795
2027	182309,703
2028	199629,1248
2029	218593,8917
2030	**239360,3114**
2031	256115,5332
2032	274043,6205
2033	293226,6739
2034	313752,5411
2035	**335715,219**
2036	354179,556
2037	373659,4316
2038	394210,7003
2039	415892,2888
2040	**438766,3647**
2041	456317,0193
2042	474569,7001
2043	493552,4881
2044	513294,5876
2045	**533826,3711**
2046	555179,426
2047	577386,603
2048	600482,0671
2049	624501,3498
2050	**649481,4038**

Table 20: Projected total PV capacity (MW)

- **Calculation of end-of-life PV by technology**

In order to obtain the repartition per technology, the following projections were used. Please note that these estimations are based on a graph (see Section 11: Annex D, Projections of technology market share), as the source data are not available. Furthermore, as no repartition is available for 2025, it was assumed that it would be the same as in 2020.

		Repartition by technology				
Installation	WEEE	c-Si	a-Si	CdTe	CIGS	Emerging & CPV
2000	2025	0,9	0,1			
2005	2030	0,95	0,03	0,02		
2010	2035	0,8	0,02	0,17	0,01	
2015	2040	0,68	0,04	0,18	0,08	0,02
2020	2045	0,61	0,08	0,11	0,14	0,06
2025	2050	0,61	0,08	0,11	0,14	0,06

Table 21: Repartition of PV by technology (in %)

In order to obtain the quantities of end-of-life PV, per technology, the calculations were based on the factors in Table 21. The factors for c-Si and a-Si were calculated from compositional figures found in Ökopol's 2007 report, as described in more detail in Annex G: Section 14.1, while the hypotheses concerning CdTe, CIGS and emerging technologies & CPV were made as an expert judgement based on the anticipated decrease in the weight of thin film PV panels and the potential further decrease in weight of emerging technology PV panels due to usage of alternative materials than those available currently.

technology	average weight (kg/W)
c-Si	0,102
a-Si	0,29
CdTe	0,2
CIGS	0,2
Emerging techn. & CPV	0,1

Table 22: Average weight (kg per Watt) per technology

The end-of-life PV in tonnes (see Table 23) were then calculated based on the end-of-life PV in MW (see Table 18).

<u>Explanation</u>:

To obtain the respective quantities (in kg), the WEEE in MW (converted into W), were multiplied by the repartition factor and the average weight. The resulting kg were then converted into tonnes.

<u>Example for 2025 (c-Si)</u>: (188*1000000*0,9*0,102)/1000= 17258,4 tonnes

		waste quantities per technology (t)					
Installation	**WEEE**	**c-Si**	**a-Si**	**CdT**	**CIGS**	**Emerging&CPV**	**TOTAL (t)**
2025	2025	17258	5452				22710
2030	2030	196998	17687	8132			222817
2035	2035	1900301	135070	791792	46576		2873739
2040	2040	2002284	334869	1039248	461888	57736	3896025
2045	2045	1866538	695977	659978	839972	179994	4242459
2050	2050	4210570	1569997	1488790	1894824	406034	9570215

Table 23: Waste quantities per technology (t)

12.2. EXAMPLE OF A DIFFERENT APPROACH TO DERIVE PV WASTE QUANTITIES IN TONNES FROM MW

Another approach to derive the waste quantities in tonnes from the obtained MW is to multiply by a factor also used in the Ökopol study (1MW = 75t)[45], which does not assume a specific weight per technology, but uses a single factor for all technologies. When applying this factor to the previously calculated quantities in MW, the quantities in Table 24 are obtained, with the corresponding graph below (see Table 5). The resulting total quantities (e.g. a total of 9.6t in according to the approach we chose and 4.9t using the Ökopol conversion factor) differ, also within the technologies.

			waste quantities per technology (t)				
Installation	**WEEE**	**c-Si**	**a-Si**	**CdTe**	**CIGS**	**Emerging & CPV**	**TOTAL (t)**
2000	2025	12690	1410				14100
2005	2030	144851	4574	3050			152475
2010	2035	1397280	34932	296922	17 466		1746600
2015	2040	1472268	86604	389718	173 208	43 302	2165100
2020	2045	1372454	179994	247492	314 990	134 996	2249925
2025	2050	3096007	406034	558296	558296	304525	4923159

Table 24: Waste quantities per technology (t) using Ökopol conversion factor

[45] This factor of conversion was elaborated (and validated) with a group of experts (EPIA, producers, researchers etc.) in the course of the Ökopol study.

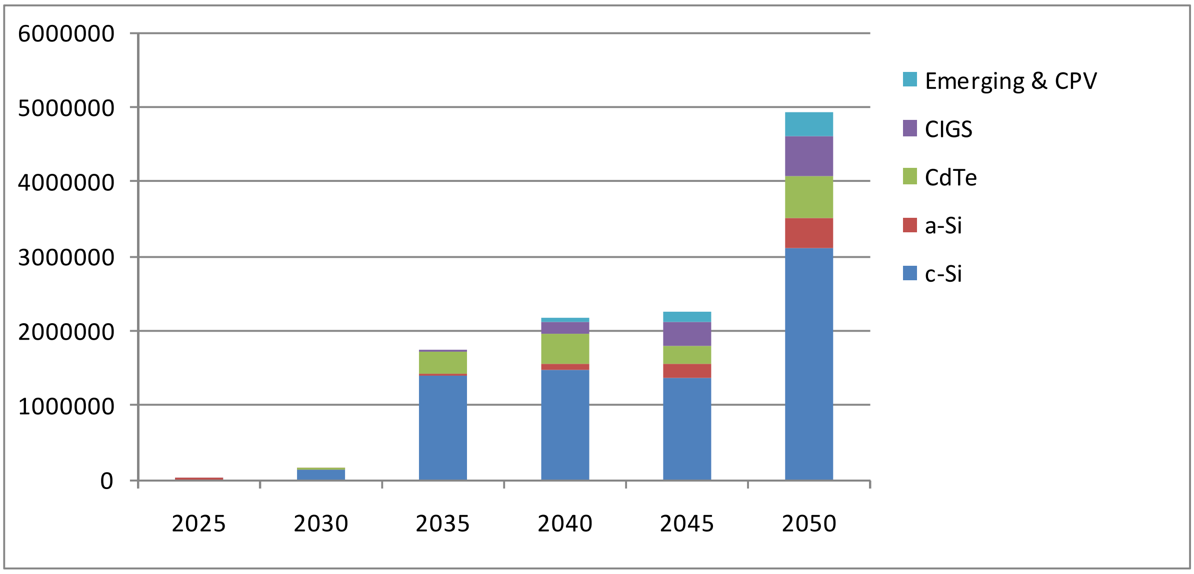


Figure 5: PV e-waste generated by technology (t) using Ökopol conversion factor

13. ANNEX F: ENVIRONMENTAL IMPACTS - ASSUMPTIONS AND COMPLEMENTARY INFORMATION

13.1. CADMIUM AND LEAD LEACHING

Photovoltaic panels contain small volumes of cadmium and lead, substances hazardous to human health and the environment. Quantities of such substances found in photovoltaic panels and their environmental impacts are discussed below. While other substances also have the potential to leach from photovoltaic panels, cadmium and lead represent the largest environmental and health risks as well as the largest quantities, even though representing less than 1% of the mass of photovoltaic panels.

	Leaching with no pH change	At pH level 6-7	At pH level 3-4
Lead (Pb)	Negligible/LOQ	13%	90%

Table 25: Leaching of lead in mc-Si PV panels[46]

Lead is a heavy metal with a high potential for accumulation in humans and the environment; lead is linked with cardiovascular problems and osteoporosis in the elderly, reproduction issues linked with foetus and young, and nervous system issues for foetus and children.[47] Small quantities of lead are found in 1st generation crystalline-silicon photovoltaic panels. Table 25 illustrates the leaching of lead observed in mc-Si photovoltaic panels. According to chemical testing completed by NGI, levels of lead exceed the leaching limits for disposal at landfill for inert waste, but lie within the limits of disposal for an ordinary landfill.[46] High lead leaching occurs at low pH conditions, with leaching increasing substantially in weather impacted or crushed mc-Si panels that are exposed to low pH water. The amount of lead found in an average mc-Si PV panel is 576 mg/kg.

	Leaching with no pH change	At pH level 6-7	At pH level 3-4
Cadmium (Cd)	7%	29%	40%

Table 26: Leaching of cadmium in CdTe PV panels[46]

Cadmium is a heavy metal that accumulates in living organisms and has biological half-life of 30 years. Cadmium is notably linked with cardiovascular problems and osteoporosis in elderly populations.[47] Cadmium telluride photovoltaic panels, a type of 2nd generation thin film panel, include small quantities of cadmium. Cadmium leaching in CdTe PV panels exceeds limits for disposal at landfill for inert waste but lies within limits for disposal at an ordinary landfill. Cadmium leaching is high at all pH levels and increases with a decrease in pH.

CIGS photovoltaic panels, another type of 2nd generation thin film photovoltaic panel contain traces of cadmium which is used as a buffer substance between sheets of glass; these quantities of cadmium have not been considered in the present study due to a lack of data on exact quantities of cadmium found in CIGS panels, although quantities are much lower than in CdTe. It is not yet possible to determine the

[46] NGI (2010) Leaching from mc-Si PV panel material – results from batch, column and availability tests. Comparison with thin film CdTe PV panels

[47] PRé (1999) The Eco-indicator 99: A damage oriented method for Life Cycle Impact Assessment

usage of hazardous substances in future photovoltaic technologies, although there is a trend towards non-lead soldering.

13.2. EXTERNAL COST OF CADMIUM AND LEAD LEACHING

Table 27 below illustrates calculations undertaken to estimate the external cost of cadmium and lead leaching. It should be noted that the external cost factor per kilogram applied to cadmium represents a value related to air emissions, in the absence of another value available, while the external cost factor for per kilogram applied to lead represents soil pollution. Both values capture damage to human health. Leaching for cadmium has only been calculated for CdTe panels, due to a lack of information available on the composition of CIGS and CIS panels. It should be noted that a much smaller quantity of cadmium is contained in CIGS/CIS panels, hence it is assumed that using CdTe panels is relatively representative of quantities of cadmium found in photovoltaic panels. As shown below in Table 27, the external cost per kg of cadmium is 46 Euros (or 46,000 Euros / tonne); improper disposal of one tonne of CdTe PV panels links with 12.04 Euros of external cost. The external cost of lead is 1174 Euros / kg (or 1 174 000 Euros / tonne); improper disposal of one tonne of c-Si PV panels leads to 348 255 Euros of external damage. While overall costs of leaching to soil and air emissions of cadmium and lead may be higher, in the current study only human health damages could be monetised.

	Unit quantity*	Weight per module	Quantity per module	External cost per kg**	External cost per tonne of Cd/Pb	Price of leaching per module	Price of leaching per tonne of PV panels
Cadmium	383 mg/kg	12 kg	4596 mg	46 €	46 000 €	0,14 €	12,04 €
Lead	576 mg/kg	22 kg	12672 mg	1 174 €	1 174 000 €	7 662 €	348 255 €

*Source: NGI (2010) Leaching from mc-Si panel material – results from batch, column and availability tests. Comparison with thin film CdTe PV panels

**Source: ADEME (2007) Monétarisation des impacts environnementaux du recyclage: méthodologie et applications

Table 27: External cost of cadmium and lead leaching for photovoltaic panels[48]

It should be noted that while the International Agency for Research on Cancer (IARC) lists cadmium as Group 1 (Carcinogenic to humans) and lead as Group 2B (Possibly carcinogenic to humans), lead has historically been estimated as having a higher external cost, specifically due to its higher likelihood of entering the human body.[49] Lead is not necessarily less dangerous than cadmium, but is more likely to enter into the human body through a wider set of channels than cadmium, notably through pollution in the atmosphere; also, the effects of lead are difficult to control. As can be seen in Table 28 below, as of 2000 the damage factor of lead was estimated at 41 times higher than that of cadmium. The BeTa-Method*Ex*, developed for the European Commission DG Research assessed cadmium emissions costs at 39,000 Euros / tonne and lead emissions costs at 600,000 Euros / tonne, in line with the external costs of air and soil emissions applied above.[50]

[48] Calculated BIO Intelligence Service

[49] International Agency for Research on Cancer (2010) Agents classified by the IARC Monographs, Volume 1-100 http://monographs.iarc.fr/ENG/Classification/ClassificationsAlphaOrder.pdf

[50] Method*Ex* Project (February 2007) BeTa-MethodEx – Version 2.

Species	Damage factors [$€_{2000}$/ton]
CO_2-equiv.	19
SO_2	2939
NO_x	2908
PM_{10}	11723
$PM_{2.5}$	19539
Arsenic	80000
Cadmium	39000
Chromium	31500
Chromium-VI	240000
Chromium-other	0
Lead	1600000
Nickel	3800
Formaldehyde	120
NMVOC	1124
Nitrates, primary	5862
Sulfates, primary	11723
Radioactive emissions	50000 * [$€_{2000}$/DALY]

Table 28: Damage factors per ton of pollutant emitted in EU15[51]

*Disability-Adjusted Life Years (DALY), assuming equal to the unit value of chronic YOLL

The amount of lead found in c-Si PV panels (1.64 to 11.4 g per panel) is higher than the amount of cadmium found in CdTe PV panels (0.32 g to 11.4 g per panel) and leaching of lead in lower pH conditions can reach much higher values (13% to 90%) than expected leaching for cadmium (29% to 40%). When comparing external costs among Baseline Scenarios and Policy Options assessed, average leaching has been considered.

13.3. PRICES OF RESOURCES LOST

Certain photovoltaic panel technologies contain relatively rare and therefore expensive materials, if only in small quantities. The rare metals found in photovoltaic panels are namely silver, indium, gallium and germanium. Tellurium can also be considered as a rare metal found in photovoltaic panels, primarily CdTe panels. A natural shortage of these materials leads to material price volatility; however, a real lack

[51] ExterneE-Pol (2005) Externalities of Energy: Extension of accounting framework and Policy Applications.

of these raw materials is not anticipated in the foreseeable.[52] Additional information on availability of rare metals found in photovoltaic panels can be found in Ökopol's 2007 report as well as in Parts 1 and 2 of the report entitled 'Etude de potential de recyclage de certains métaux rares' prepared by BIO Intelligence Service for the ADEME. Table 30 below illustrates which of the four rare metals examined in the current analysis are present in various types of photovoltaic panel technologies.

Rare metals	**Types of photovoltaic panels in which present**
Silver (Ag)	Crystalline Silicon
Indium (In)	Amorphous Silicon, CIS, CIGS
Gallium (Ga)	CIGS, CPV and emerging technologies
Germanium (Ge)	Amorphous Silicon, CPV and emerging technologies

Table 29: Rare metals found in PV panels[53]

*Price increase factor is applied at 10 year intervals, from 2011 through 2050.

Table 31 represents the current price (as of February 2011) of the four types of rare metals examined in the current analysis. Current market prices have been applied throughout this study when calculating potential economic loss due to the improper disposal of photovoltaic panels, due to the uncertainty of future market pricing shifts.

An alternative assumption, not used for this study, could have been a scenario of increasing prices, increasing the benefits of recycling. To provide an indication of factors impacting potential market price shifts, an analysis has been made of their current stock, possibility for continued exploitation, future demand, price volatility, and recycling potential, found in Table 32. Taking into account these factors, an expert judgement was made on the potential increase of the market price of each of the four metals, at 10 years intervals from currently until 2020, 2030, 2040, and 2050. Table 32 provides the estimated market price for silver, indium, gallium and germanium from 2011 to 2050, in 10 year intervals. For example, in the case of silver a 20% increase was assumed for each 10 year period assessed. Starting from a price of 650€/kg in February 2011, a 20% increase leads to 780 €/kg market price in 2020 and a 20% increase on the 2020 value leads to a 936 €/kg market price in 2030.

Materials	**Price per kilogram[54]**	**Types of photovoltaic panels in which present**
Aluminium	1.20€	Crystalline Silicon, Amorphous Silicon, CIS, CIGS, emerging technologies

[52] Ökopol et. al. (2007) Study on the development of a take back and recovery system for photovoltaic products

[53] BIO Intelligence Service for ADEME (2010) Etude de potentiel de recyclage de certains métaux rares: Partie 2

[54] Metal prices website (Accessed February 2011) http://www.metalprices.com/

Glass	0.05€	Crystalline Silicon, Amorphous Silicon, CIS, CIGS, emerging technologies
Rare metals		
Silver (Ag)	650€	Crystalline Silicon
Indium (In)	442€	Amorphous Silicon, CIS, CIGS
Gallium (Ga)	515€	CIGS, CPV and emerging technologies
Germanium (Ge)	957€	Amorphous Silicon, CPV and emerging technologies

Table 30: Rare metals in PV panels with market price information (Current – February 2011) [53]

Rare metals	Current natural stocks	Possibility for continuation of production at current rate	Estimated future demand	Price volatility	Current recycling rate	Factor to apply for future price changes*
Silver (Ag)	Very limited	13 years (from 2008)	Strong upward trend	High	30% to 50%	20%
Indium (In)	Quite limited	19.3 yrs (from 2007)	Slight upward trend	Medium	Limited but in development	15%
Gallium (Ga)	Nearly unlimited, but extraction/processing is a limitation	9000 years	Strong upward trend	Medium	20%	10%
Germanium (Ge)	Somewhat limited	Lack of info	Slight upward trend	Low	30%	5%

*Price increase factor is applied at 10 year intervals, from 2011 through 2050.

Table 31: Assessment of factors contributing to rare metal market price[55,56]

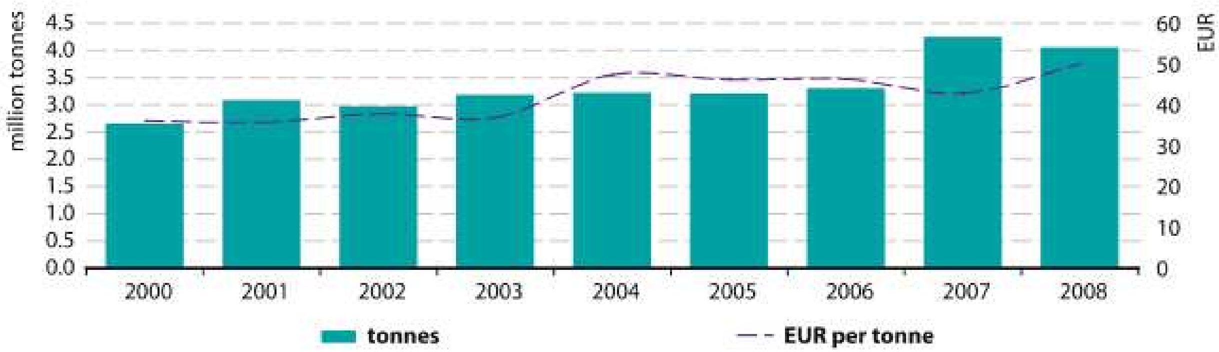
[55] BIO Intelligence Service for ADEME (2010) Etude de potentiel de recyclage de certains métaux rares: Partie 1

[56] Based on USGS data; European Environmental Agency (2010) The European Environment: State and Outlook 2010, Material Resources and Waste http://www.eea.europa.eu/soer/europe/material-resources-and-waste

Rare metals	Current *(February 2011)*	2020	2030	2040	2050
Silver (Ag)	650 €	780 €	936 €	1 123 €	1 348 €
Indium (In)	442 €	508 €	585 €	672 €	773 €
Gallium (Ga)	515 €	567 €	623 €	685 €	754 €
Germanium (Ge)	957 €	1 005 €	1 055 €	1 108 €	1 163 €

Table 32: Estimated future pricing for rare metals found in PV panels [57]

A similar analysis was performed for the conventional resources which are found in photovoltaic panels, aluminium and glass. The assessment considered estimated future demand, price volatility, and current recycling rate to arrive at an expert judgement of the potential increase of the market price of aluminium and glass, at 10 year intervals from currently (February 2011) until 2020, 2030, 2040, and 2050. Figure 6 and Figure 7 below provide market price trend information on glass in the EU.



Source: Environmental Data Centre on Waste.

Figure 6: Volume and price index of glass waste, EU-27 (million tonnes and Euros) [58]

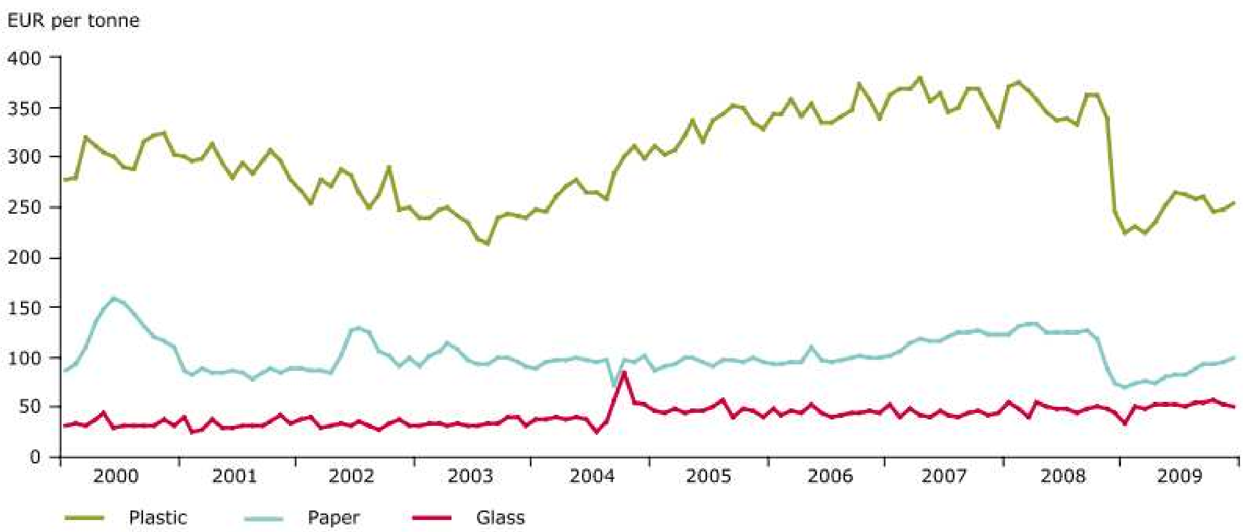


Figure 7: Price developments for selected waste materials in the EU [59]

[57] Calculated by BIO Intelligence Service

[58] Eurostat (2010) Environmental statistics and accounts in Europe http://epp.Eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-32-10-283/EN/KS-32-10-283-EN.PDF

Figure 8 below illustrates the trending of aluminium's market price. Some 40% of EU production is based on recycled aluminium; recycling aluminium only uses 5% of the energy required in its virgin production.

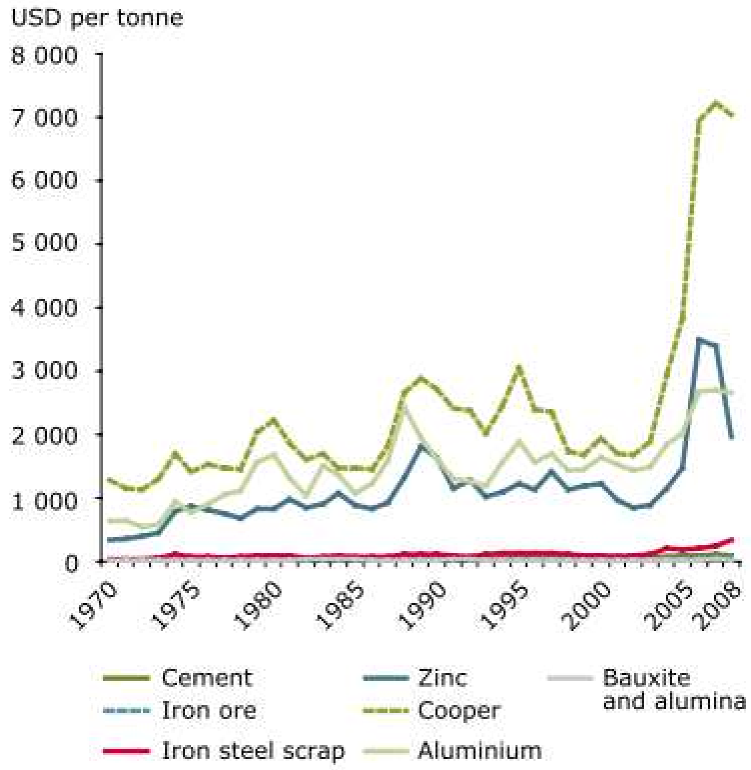


Figure 8: Trends in prices of commodities, 1970-2009 [60]

Conventional resources	Estimated future demand	Price volatility	Current recycling rate	Factor to apply for future price changes*
Aluminium	Strong upward trend	Medium	41% to 95%	15%
Glass	Slight upward trend	Low	64%	10%

*Price increase factor is applied at 10 year intervals, from 2011 through 2050.

Table 33: Assessment of factors contributing to convention resource market price [58,59,61]

[59] European Environmental Agency (2010) The European Environment: State and Outlook 2010, Material Resources and Waste http://www.eea.europa.eu/soer/europe/material-resources-and-waste

[60] Based on USGS data; European Environmental Agency (2010) The European Environment: State and Outlook 2010, Material Resources and Waste http://www.eea.europa.eu/soer/europe/material-resources-and-waste

[61] OECD (2009) OECD Environmental Data: Compendium 2006-2008, Waste http://www.oecd.org/dataoecd/22/58/41878186.pdf

Conventional resources	Current *(February 2011)*	2020	2030	2040	2050
Aluminium	1 200 €	1 380 €	1 587 €	1 825 €	2 099 €
Glass	50 €	55 €	61 €	67 €	73 €

Table 34: Estimated future pricing for conventional resources found in PV panels[62]

13.4. POTENTIAL ECONOMIC LOSS

Potential economic loss due to the improper treatment and recycling of end-of-life photovoltaic panels was estimated using composition information for c-Si and a-Si photovoltaic panels found in Ökopol's 2007 'Study on the development of a take back and recovery system for photovoltaic products'.[63]These two photovoltaic panel technologies were chosen, due to the availability of detailed compositional data on both models, as representative of the crystalline silicon set of photovoltaic panels and the thin film set of photovoltaic panels, respectively. It should be noted that rare metals (e.g. silver, indium, gallium, germanium) were assumed to account for 1% of the composition of each of the panels examined, representing a maximum possible of rare metals which could be found in a photovoltaic panel. Therefore for the sample c-Si module, 1% of the composition is assumed to made up of silver, while for the a-Si module, 1% of the composition is assumed to be made up of indium and germanium (e.g. 0.5% for indium and 0.5% for germanium). The percentage of rare metals found in photovoltaic modules may decrease in the future due to raising rare metal prices and the development of substitute materials.

Potential economic loss is calculated assuming a variable loss of all materials in a photovoltaic panel, with 100% materials entering into recycling and with recycling output assumed to be **100% for aluminium, 95% for glass and 30% for rare metals in the Policy Options A and B, and with only low-quality glass cullet recovered at 95% in Baseline Scenario B.**[64] Economic loss figures are intended to serve as an indicator of potential economic value which could be gained in a situation assuming high quality material recycling.

Table 35 below details the calculations made on the initial kg/Wp figures taken from the Ökopol report to arrive at a 'Price per Wp' figure. Material prices per kg represented below reflect current prices. For rare metals, the price of silver was used for the crystalline silicon panels, while the average price of indium and germanium was used for a-si panels.

The sample weight used for both photovoltaic models reflect the values cited in Table 36 which originate from Ökopol's report. The weight used for the sample c-Si panel considered was 22 kg as cited directly in the Ökopol report, while the weight used for the sample a-Si was an average of the

[62] Calculated by BIO Intelligence Service

[63] Ökopol et. al. (2007) Study on the development of a take back and recovery system for photovoltaic products

[64] Additional detail on recycling hypotheses applied in Baseline Scenario B can be found in Annex H: Section 15.3.

range of weights possible for an a-Si panel, the specific weight of the a-Si panel considered in the Ökopol report not involving weight data, only compositional data. Hence, the weight for the a-Si panel was assumed to 15.85 kg, the average of the range 11.7-20 kg as illustrated in Table 36.

			Crystalline Silicon (1st generation)		a-Si model (2nd generation)	
Material	*Price (per kg)*	*Recovery rate*	*Mass (kg/Wp)*	*Price per Wp*	*Mass (kg/Wp)*	*Price per Wp*
Glass	0,05 €	95%	0,0734	0,0037 €	0,2371	0,0119 €
Aluminium	1,20 €	100%	0,0107	0,0128 €	0,0001	0,0001 €
Rare metals	Variable*	30%	0,0003	0,1989 €	0,0009	0,6086 €
Total				**0,22 €**		**0,62 €**
Per Average Module				**46,31 €**		**37,23 €**
Per Tonne				**2 105 €**		**2 349 €**

* Estimated at €650 for c-Si panels (contain Silver), €700 for a-Si panels (contain Indium and Germanium), based on market pricing as of February 2011

Table 35: Estimated economic value lost at the current time (February 2011) through lack of proper treatment and recycling of PV (per panel) – high yield recycling, variable recovery rate for all materials[65]

[65] Calculated by BIO Intelligence Service

14. ANNEX G: FURTHER COMPLEMENTARY INFORMATION AND DATA

14.1. COMPOSITION OF PHOTOVOLTAIC PANELS

While detailed information was not available for all types of photovoltaic panels currently on the market an effort has made to regroup here basic information available on the composition of various photovoltaic technologies. As emerging technologies are currently under development and not yet commercially available, it is particularly difficult to accurately represent their composition and specifications. Table 36 provides an overview of the weight, capacity and size range of crystalline silicon panels and three types of thin film technologies. More detailed information on material composition of each of these types of photovoltaic technologies can be found in Table 37. Sources for compositional information presented in Table 36 and Table 37 are Ökopol's 2007 study, the study completed by BIO Intelligence Service for ADEME on rare metals, and EPIA and Greenpeace's study entitled 'Solar Generation 2011'. Additional information on panel composition and specifications can be found laid out by technology further below.

	Crystalline Silicon Modules	Thin Film Modules		
		a-Si	*CdTe*	*CIS/CIGS*
Total weight per module	5-28 kg	11.7-20 kg	9-15 kg	10.2-20 kg
Normal capacity	120-300 Wp	60-120 Wp		
Size range	Typically 1.4 to 1.7 m^2, can be up to 2.5 m^2	1.4 to 5.7 m^2	0.6 to 1.0 m^2	

Table 36: Photovoltaic panel specifications by technology[66,67]

[66] Ökopol et. al. (2007) Study on the development of a take back and recovery system for photovoltaic products

[67] EPIA & Greenpeace (2011) Solar Generation 6: Solar photovoltaic electricity empowering the world

Material	Crystalline Silicon Modules	Thin Film Modules		
		a-Si	*CdTe*	*CIS/CIGS*
Glass	74%	86%	95%	84%
Aluminium	10%*	<1%	<1%	12%
Other components (including rare metals)	16%	14%	4%	4%
Other key materials (representing over 1% of composition)	EVA, Tedlar backing film, silicon, adhesive	Polyol, MDI	EVA	EVA
Rare metals included	Silver	Indium, Germanium		Indium, Gallium
Presence of Cadmium (Cd) and Lead (Pb)	Pb		Cd	Cd

Table 37: Examples of average PV composition[66,67, 68]

Table 38 below provides detailed information found originally in Ökopol's report, on the composition of crystalline silicon photovoltaic panels. This information is used in Section 13.4 when calculating the economic loss due to loss of raw materials such as glass and aluminium found in crystalline silicon panels as well as when calculating potential revenues expected from recovery of materials from photovoltaic panels, as represented in Table 44. Table 39 provides information on the composition of a-Si panels, used in economic loss and recycling revenue calculations to represent thin film panels. A-Si panels were used as representative of thin film panels due to a lack of detailed composition information on other types of thin film PV panels. Table 40 provides a summary of the specifications of the two types of panels examined.

[68] BIO Intelligence Service for ADEME (2010) Etude de potentiel de recyclage de certains métaux rares: Partie 2

Component	Quantity (2003) according to [Ökopol 2004]	Quantities 2007	
	%	%	kg/kWp
Glass	62.7	74.16	77.3
Frames (e.g. AlMgSi0,5)	22.0	10.30	10.7
EVA	7.5	6.55	6.8
Solar cells	4.0	3.48	3.6
Backing film (Tedlar)	2.5	3.60	3.8
Junction box	1.2		
Adhesive, potting compound	No data	1.16	1.2
Weight/kWp	103.6 kg/kWp		102.3
Cu	0.37	0.57	
Ag	0.14	0.004 – 0.006	
Sn	0.12	0.12	
Pb	0.12	0.07	
Si	No data	3%	

Table 38: Sample composition for a standard c-Si panel (215 Wp)[69]

Material	Thickness	Weight per module	Weight per surface	Weight per output
		g	g/m²	g/Wp*
Glass	3+2.2 mm	3,483	12,480	249.6
SnO_2		0,96	3,45	0.069
Tin (as oxide)	About 500 nm	0,76	2,72	0.0544857
Boron	-	1.18E-05	4.23E-05	8.46E-07
Silicon	About 400 nm	0,26	0,92	0,0184
Phosphorus	-	1.21E-07	4.33E-07	8.66E-09
Aluminium	< 600 nm	0.452	1,62	0.032
Aluminium strips	0.05 mm	0.988	3,54	0.07
Acryl resin	0.15 mm	19	68,00	1.63
Hot melt glue		0.8	2,87	0.057
Cable	-	40	143.00	2.86
Polyol	-	285	1,021.00	20.3
MDI	-	215	770,00	15.4
Total		4,046	14,497	290

Table 39: Sample composition for a standard a-Si panel (60 Wp)[69]

Specifications	Crystalline Silicon	Thin Film
Total Weight	22 kg	15,85 kg (average of 11,7 and 20)
Normal Capacity	215 Wp (potential range, 120 to 300 Wp)	60 Wp (potential range, 60 to 120 Wp)
Sample Size	165 x 99 cm	120 cm x 60 cm
Size Range	1.4 to 1.7 m²	1.4 to 5.7 m²

Table 40: Sample specifications of crystalline silicon and thin film photovoltaic panels[69]

[69] Ökopol et. al. (2007) Study on the development of a take back and recovery system for photovoltaic products

14.2. CURRENT RECYCLING PRACTICES

Basic disposal options for PV panels are outlined below in Table 41. Due to photovoltaic panels' composition of a diverse set of materials, recycling processes must take into account a wide range of waste characteristics.

Type of treatment	Potential treatment steps involved
Physical/ mechanical	Crushing Attrition Density separation Flotation Adsorption Radiation Metal separator other
Chemical	Acid/base treatment Solvent treatment other
Thermal	Incineration Pyrolysis Melting, slagging other
Biological	-
Radiation	-
Disposal	Recycling into the same product Recycling into another product Recovery of energy from the thermal treatment of organic layers Utilization of the volume of mineral fractions (e.g. concrete aggregates, road construction) Landfill cover other

Table 41: Basic operations for treating and recycling PV panels[70]

A number of different types of recycling and treatment options exist, which vary by producer and type of photovoltaic technology considered. Table 42 below profiles some known recycling activities, which are currently in development and have completed the majority of laboratory tests required.

[70] Ökopol et. al. (2007) Study on the development of a take back and recovery system for photovoltaic products

Operator	Procedure	Size/Stage of Devel-opment	PV Technology
Deutsche Solar AG	Thermal separation, chemi-cal processing	Pilot production, ecological consideration	Crystalline, thin film in laboratory
First Solar (Solar Cells Inc.), BNL	Thermal decomposition in Inert gas	Laboratory	Crystalline
Isofoton	Cell recycling Swelling Shredding Repairable module	Laboratory	Crystalline
AIST, Sharp, Asahi	Wafer recycling with mineral acids Solvent swelling (Cellsepa-Process) Repairable module	Laboratory	Crystalline
Photovoltech	Repairable module	Laboratory	Crystalline
BP Solar, Soltech, Seghers	Wafer recycling with mineral acids Wafer recycling in fluidized bed	Laboratory/Technical college	Crystalline
Pilkington Solar Interna-tional	Thermal separation	Laboratory/Technical college	Crystalline
Siemens Solar, Shell Solar, Showa Shell	Ferrosilicon production High pressure water jet	Laboratory	Crystalline, thin film
Other	Module shredder, Mechanical separation Acid treatment Smelter, MWI Concrete aggregates, road construction	Laboratory	Crystalline, thin film
Disposer	Removal of frames and cable, disposal, incineration	Production	all

Table 42: Some known recycling activities (majority laboratory tests complete)[71]

While a number of treatment and recycling processes are under development globally for photovoltaic panels[72], there are currently only two treatment and recycling methods which have been tested and put into operation: Deutsche Solar's process (previously operational in Germany) which is predominantly used for crystalline silicon panels[73], and First Solar's process (currently operational in the United States, Germany, and Malaysia) which is primarily used for CdTe panels. PV Cycle, founded by the photovoltaic industry as an association to put in place a take back and recycling programme, also offers recycling services in Europe.

Treatment and recycling procedures for photovoltaic panels are similar to recycling for LCDs, screen glass, mirrors, windscreens, other laminated glass and gas discharge lamps, due to their large portion of glass.

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[71] Ökopol et. al. (2007) Study on the development of a take back and recovery system for photovoltaic products

[72] A number of different types of recycling and treatment options exist, which vary by producer and type of photovoltaic technology considered. Table 42 in Section 14: Annex G profiles some known recycling activities, which are currently in development and have completed the majority of laboratory tests required.

[73] Deutsche Solar's treatment process, launched in 2003, has since halted because of its costliness, due to the low quantities of photovoltaic panel waste at the current time; however, the organisation is considering a demo plant at some point in the future.

- **Deutsche Solar AG's treatment process**

Deutsche Solar AG's treatment process for crystalline silicon panels has been operated as a pilot scheme since 2003, but has stopped since because of the high cost of recycling photovoltaic panels due to a limited volume of end-of-life photovoltaic panels at the current time However, the organisation is considering launching a demo plant in the future. Acquired in 2000, Deutsche Solar AG is a subsidiary of SolarWorld AG, headquartered in Bonn, Germany. The treatment and recycling process developed by Deutsche Solar involves the removal of the plastic components of the panel by a thermal process, followed by the manual separation of remaining materials such as solar cells, glass and metals. Glass and metals, including aluminium, steel and copper, are fed into relevant recycling processes and solar cells are re-etched to the wafer. The solar cells are cleaned through a series of chemical stages, until a new silicon wafer emerges. The re-treated wafers fulfil standard quality requirements and can be reprocessed as solar cells and panels. The etching process involves the following sequence of steps: removal of metallization, of removal of AR layer, isotropic removal n+ and p+ doping, a surface finish, rinsing, and drying. In the case of broken solar cells, silicon is recovered in the form of broken wafers for crystallisation.

It is notable that the procedure provides the possibility for recovering intact wafers from panels. The average recycling rate is approximately 80%, without taking into consideration possible thermal treatment of plastic components. If the process is applied correctly, glass can be recovered full intact. Table 43 below depicts the typical recycling and reuse activity for each type of material treated in a c-Si photovoltaic panel. When their recycling process was operating, Deutsche Solar AG reused silicon granules recovered from treatment operations and sold or sent for recycling all other materials. Deutsche Solar AG and its parent group SolarWorld operated a 'bring-in' system for the take-back and treatment of end-of-of life or damaged photovoltaic panels.[74] Figure 9 and Figure 10 below illustrate the inputs and outputs of silicon recycling for c-Si photovoltaic panels.

Silicon wafer	Sale
Silicon granulates	Sale, own use
Silver	Sale, metal recycling
Aluminium	Sale, metal recycling
Steel	Sale, metal recycling
Copper	Sale, metal recycling
Glass	Sale, glass recycling
Packaging	Disposal, recycling, (disposal)
Remnants	Disposal (mixed waste)

Table 43: End products and remnants of recycling and destination[75]

[74] Larsen, Kari (3 August 2009) 'End of life PV: then what? Recycling solar PV panels,' Renewable energy focus http://www.renewableenergyfocus.com/view/3005/endoflife-pv-then-what-recycling-solar-pv-panels/

[75] Ökopol et. al. (2007) Study on the development of a take back and recovery system for photovoltaic products

Figure 9: Broken solar cells for recycling[76]

Figure 10: Recycled silicon granules[76]

- **First Solar's treatment process**

First Solar's treatment process for CdTe panels was developed in the United States in the late nineties and has been established since 2003; it was scaled to full capacity of approximately 10 tonnes per day in 2007. The treatment process currently operates in First Solar's three manufacturing locations in the

[76] Ökopol et. al. (2007) Study on the development of a take back and recovery system for photovoltaic products

United States, Germany and Malaysia. As of 2011, First Solar's recycling plants treat primarily manufacturing scrap, due to the currently limited quantity of end-of-life photovoltaic panels. In order to handle large quantities of end-of-life photovoltaic panels expected to arise around 2025 or 2030, First Solar would need install additional capacity.

Collected panels are shredded and then put through a hammer mill to ensure scraps of glass are broken into 4-5 mm pieces, small enough to ensure the lamination bond is broken. Semi-conductor films are then removed by placing the shards of material in a rotating stainless steel with acid and hydrogen peroxide. Then glass shards are separated from liquid portions of waste and a vibrating screen is used to separate the glass from the pieces of laminate material, which previously sealed the two layers of glass together. Glass is rinsed to remove any remaining semiconductor materials and is then packaged for recycling. The liquid portion of the waste is pumped into a precipitation unit and the metal compounds found in the liquid are precipitated in three stages at increasing pH, using sodium hydroxide. The precipitated materials are concentrated in a thickening tank for dewatering and the resulting unrefined semiconductor materials are packaged for processing by a third party to create semiconductor materials for use in new photovoltaic panels.[77] Primary raw materials recovered from semiconductor waste are Te and Cd.

First Solar's process is expected to recover 90% of the glass used in a photovoltaic unit for usage in new glass products, either photovoltaic panels or a range of other products, as well as 95% of the semiconductor materials for reuse in new photovoltaic panels. Approximately 90%, by mass, of each collected photovoltaic panel is recycled. Since First Solar's process is based around using shredded photovoltaic panel materials, the process allows for the recycling not only of end-of-life fully intact panels, but also broken panels and manufacturing scrap.

First Solar offers a free recycling and collection programme for the recycling and treatment of First Solar photovoltaic panels. First Solar includes contact information for recycling on the back of each photovoltaic panel sold; collection and recycling are free for consumers. First Solar provides packaging material and customers ship used photovoltaic panels to the nearest First Solar manufacturing location. Logistics for the collection and transport of end-of-life or damaged photovoltaic panels to the centralised recycling location are managed by First Solar.[78]

The programme is prefunded by placing money in a custodial trust account at the time of sale of each panel, equal to the estimated cost of collection, transportation and recycling of a panel. As of 2009, First Solar set aside 86 million dollars to fund panel collection and recycling for panels sold since the beginning of commercial production in 2003.

[77] Ökopol et. al. (2007) Study on the development of a take back and recovery system for photovoltaic products

[78] First Solar (2011) Panel collection and recycling programme http://www.firstsolar.com/en/recycle_program.php

Figure 11: Glass fraction of CIS PV panel, after undergoing milling and crushing[79]

Figure 12: Other components of CIS PV panel, after undergoing milling and crushing[79]

- **Current situation of photovoltaic recycling**

Currently photovoltaic panel recycling is not economically viable because waste volumes generated are too small, but over time the introduction of economic incentives and the concept of extended producer responsibility could change this situation.[80] At the current time, without the introduction of a carbon tax or carbon pricing to take into account environmental externalities, despite their higher energy intensity for production, it is cheaper to use virgin raw materials in photovoltaic panel production. While this remains true for silicon-based panels due to the abundant supply of silicon as a raw material, more potential economic incentives exist for CIS, CIGS, and CdTe panels due to the rarity of indium and tellurium, particularly in comparison to expected growth in the photovoltaic industry.

[79] Ökopol et. al. (2007) Study on the development of a take back and recovery system for photovoltaic products

[80] Larsen, Kari (3 August 2009) 'End of life PV: then what? Recycling solar PV panels,' Renewable energy focus http://www.renewableenergyfocus.com/view/3005/endoflife-pv-then-what-recycling-solar-pv-panels/

While Deutsche Solar has operated a pilot programme for the material recycling of silicon photovoltaic panels since 2003, according to Dr. Karsten Wambach of Sunicon, a subsidiary of the SolarWorld Group, it has since been stopped due to the limited volume of photovoltaic panel waste currently being generated. SolarWorld is considering opening a demo plant for silicon photovoltaic panel recycling in the future; however, at the current time in order for recycling to be economically appealing, panels would need to be stored and recycled once a certain quantity had been built up. Dr. Wambach estimates the minimum quantity threshold at which photovoltaic panel recycling would become economically feasible at around 20,000 tonnes per year, although estimates 40,000 to 50,000 tonnes per year as a more realistic point at which photovoltaic panel recycling would be economically attractive.

The large majority of photovoltaic panel waste at the current time is from production or breakage in the first two years of the lifetime of a photovoltaic panel, due typically to incorrect installation. Currently, recycling which does take place is primarily recycling of production waste and is managed through a variety of existing recycling and treatment facilities which operate glass recycling or metal recovery. A number of end-of-life photovoltaic panels are landfilled. While production waste figures are sensitive information not shared by producers, both Dr. Karsten Wambach of Sunicon, a division of SolarWorld and Knut Sander, of Ökopol, estimated photovoltaic waste generation in Germany in 2010 at approximately 15,000.[81] This figure includes production waste, broken panels and end-of-life photovoltaic panels. Of these 15,000 tonnes of overall photovoltaic waste, end-of-life photovoltaic panels account for between 3,000 and 5,000 tonnes. Knut Sander, of Ökopol, estimates the current collection rate of end-of-life photovoltaic panels at around 20% to 30%, with nearly 100% of photovoltaic panels collected being recycled. As recycling possibilities can vary by type of technology, Ökopol cited that in an ideal world, photovoltaic panel technologies would be collected separately for recycling.

In light of the limited quantities of waste currently produced, a challenge in recycling photovoltaic panels is the cost of arranging for their collection and transportation to centralised treatment and recycling locations. Dr. Wambach sees intermediate storage of photovoltaic panel waste as a possible option in the short term until larger quantities of photovoltaic waste enter the market.

In addition to recycling programmes offered through Deutsche Solar AG and its parent group SolarWorld, as well as First Solar, in 2007, PV Cycle, a European organisation for the voluntary take back and recycling of end-of-life photovoltaic panels, was created. In May 2009 PV Cycle took part in its first major dismantling of end-of-life photovoltaic panels in partnership with the domaine of Chevetogne and the electricity company Nizet, in Belgium.[82] As of 2011, PV Cycle reported 91 certified collection points for photovoltaic panel recycling across Europe and counts over 180 member companies. Companies pay an annual fee to join PV Cycle, in part based on the weight of the panels they produce, which covers transport and recycling costs. In 2010 PV Cycle collected 80 tonnes of end-of-life photovoltaic panels and anticipates collection of 1500 tonnes in 2011. PV Cycle collects all photovoltaic technologies for recycling, but does not cover production waste.

[81] Interview 3 March 2011, 16 March 2011 (Dr. Karsten Wambach), Interview 3 March 2011, 14 March 2011 (Knut Sander); Germany is the country in the EU27 with the largest number of photovoltaic panel installations, hence this figure is largely representative of the EU27 at the current time.

[82] PV Cycle (2010) Making the photovoltaic industry 'double green' http://www.pvcycle.eu/fileadmin/pvcycle_docs/documents/membership/PVCYCLE_11_2010.pdf

Future developments in photovoltaic panel recycling

Deutsche Solar AG's process has been used for a variety of types and sizes of silicon-based photovoltaic panels and First Solar shares technical knowledge with other producers and has tested their processes on other CdTe panels and is completing testing on CIS and CIGS technologies. However, the set of products recycled via these process are not necessarily representative of the current set of products installed, making it difficult to forecast the applicability of such processes in the future to end-of-life photovoltaic panels.

The future outcomes of current research, development and testing efforts on photovoltaic panels and new recycling techniques are difficult to assess. Photovoltaic panels with lead-free soldering are being developed. Primary potential future photovoltaic technologies currently under development include:

- Dye-sensitised solar cells
- Organic solar cells
- Hybrid cells

While dye-sensitised solar cells release electrons from, for example, titanium dioxide covered in a sunlight-absorbing pigment, organic solar cells are composed of biodegradable materials, hence introducing a risk of material degradation and instability. Hybrid cells, combining various technologies currently on the market, could be treated by similar recycling techniques to those currently on the market.

15. ANNEX H: ECONOMIC COST ASSUMPTIONS - FURTHER COMPLEMENTARY INFORMATION AND DATA

15.1. ASSUMPTION ABOUT LOGISTICS AND RECYCLING COSTS

Key economic costs considered in analysing the Baselines A and B and Policy Options A and B are costs for transport (collection), proper treatment (in line with Article 8 and Annex II of the WEEE Directive), and recycling (recovery of valuable materials). In Baseline A logistics and recycling costs have been assumed as zero, since end-of-life photovoltaic panels are assumed to be left in nature and undergo no collection, treatment, or recycling. In Baseline B, recycling is assumed, but only in line with minimum quality requirements, that is to say, pre-treatment and recycling in a float glass or similar glass plant, resulting in controlled disposal of lead and cadmium and recovery of glass. In Policy Options A and B, high yield recycling is assumed and therefore higher recycling costs, however, also with higher revenues achieved from material recovery. The assumptions considered in relation to the simple recycling applied in Baseline Scenario B and the high yield recycling applied in Policy Options A and B are outlined below in Figure 13. In both processes physical separation takes place; however in simple recycling this is always preceded by shredding, whereas in high yield recycling this could be preceded by shredding (as in the case of First Solar's process), but this is not necessarily always the case. In high yield recycling, material separation involves the separation of interconnectors such as the cord plate and connection wire; this does not necessarily take place in the simple recycling situation. In simple recycling, only glass is recovered, while in high yield recycling, a range of materials are recovered, including aluminium, glass, cadmium, lead and rare metals. The principal difference between the two pre-treatment and recycling processes is the use of a thermal process in high yield recycling, thereby allowing for the recovery and processing for reuse of lead, cadmium, and rare metals. In simple recycling potentially hazardous materials, such as lead and cadmium, are not recovered and processed for reuse but are disposed of in a controlled way, in line with Article 8 and Annex II of the WEEE Directive, thereby removing the chances of their uncontrolled entry into nature and the possibility of leaching into soil or emissions into air. However, in both low and high yield recycling the possibility for lead and cadmium entering into the environment via leaching is removed.

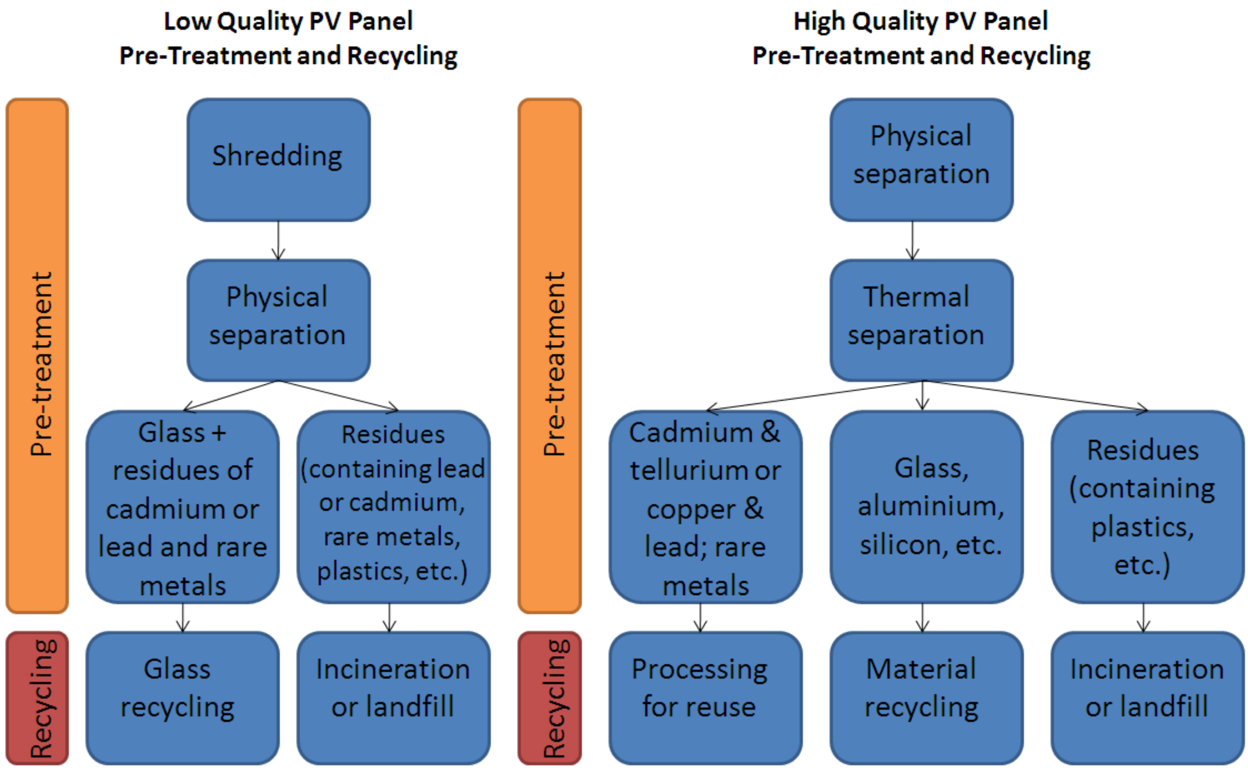

Figure 13: Pre-treatment and recycling processes for PV panels

Logistics costs when collection of photovoltaic panels does occur are assumed to be uniform across technologies and scenarios considered. These costs are estimated at 150€, based on PV Cycle's reported collection and transport experiences in their first year of operation. Table 46 below provides an overview of the logistics and recycling cost hypotheses applied for each scenario. Additional detail on assumptions for each scenario considered can be found below.

It should be noted that due to economies of scale achieved once large quantities of end-of-life photovoltaic panels enter the market, both logistics costs and recycling costs could decrease. Logistics costs depend on the method by which the collection system is set up and the distance between collection points and recycling centres. Recycling costs can also vary depending on the quality of recycling; basic glass recycling represents a limited cost while material separation and recovery could lead to significantly higher recycling costs. Due to the uncertainty of the nature and extent of these cost fluctuations due to economies of scale and the application of new recycling techniques, the current study utilises data currently available to represent what might be imaginable in 2050.

In assessing costs for logistics and recycling of photovoltaic panels, the research and development costs required for the development and testing of new recycling techniques as well as the cost of actions undertaken to encourage collection of end-of-life photovoltaic panels in order to increase quantities of waste and achieve economies of scale have not been considered in the scope of the current study.

15.2. ASSUMPTION ABOUT REVENUES FROM MATERIAL RECOVERY

Revenues from material recovery are assumed to be zero in Baseline Scenario A and low in Baseline Scenario B, while they are assumed to be based on high yield material recycling with variable recovery by material in Policy Options A and B. Market pricing, as of February 2011, is applied to calculate potential revenues of recycling. While market pricing may shift in the future and recycling technologies may also evolve, this model intends to represent the situation of photovoltaic panel recycling in 2050, based off currently available information.

A 100% output recovery rate for aluminium was assumed and a 95% output recycling rate for glass, both based on PV Cycle's de-installation of the Belgian Chevetogne PV generator completed in 2009 and information available on current recycling processes found in Ökopol's 2007 study.

A 30% recovery rate has been applied to rare metals, in alignment with estimations made by experts consulted on potential revenues expected through high yield recycling of end-of-life photovoltaic panels. Knut Sander, of Ökopol, anticipates a 60% recovery rate for rare metals could be achieved currently or in the near future.[83] The 30% recovery rate for rare metals represents a conservative hypothesis.

			Crystalline Silicon (1st generation)		a-Si model (2nd generation)	
Material	*Price (per kg)*	*Recovery rate*	*Mass (kg/Wp)*	*Price per Wp*	*Mass (kg/Wp)*	*Price per Wp*
Glass	0,05 €	95%	0,0734	0,0037 €	0,2371	0,0119 €
Aluminium	1,20 €	100%	0,0107	0,0128 €	0,0001	0,0001 €
Rare metals	Variable*	30%	0,0003	0,1989 €	0,0009	0,6086 €
Total				**0,22 €**		**0,62 €**
Per Average Module				**46,31 €**		**37,23 €**
Per Tonne				**2 105 €**		**2 349 €**

* Estimated at €650 for c-Si panels (contain Silver), €700 for a-Si panels (contain Indium and Germanium), based on market pricing as of February 2011

Table 44: Estimated revenues achievable through high yield recycling of photovoltaic panels, using variable recovery rates by material and current market pricing (February 2011)[28, 84]

High yield recycling with high recovery rates can be considered as a best case recycling scenario for PV panels and has been considered here to demonstrate the high potential benefits attainable through material recovery of the conventional resource and rare metal portions of photovoltaic panels. An alternative to considering high quality material recycling is assuming recycling at a float glass recycling plant, hence implying the recovery of lower quality glass materials, and no recovery of aluminium or rare metals, as in Baseline Scenario B.

The potential of weight reduction in photovoltaic panels has not been considered, although trends indicate a further potential decrease in the size and weight of photovoltaic panels; as the exact extent and nature of such change is difficult to assess, this has not been factored into economic loss assumptions. Also the percentage of rare metals found in photovoltaic modules may decrease in the future due to raising rare metal prices and the development of substitute materials; due to the uncertainty of this trend this has not been factored into the current analysis.

[83] Interview 3 March 2011, 14 March 2011.

[84] 100% recovery of aluminium, 95% of glass and 30% of rare metals; based on information from PVCycle and Ökopol 2007 study.

BASELINE A

	Logistics unit cost	*Treatment and recycling unit cost*	*Total unit cost (euros per tonne collected)*
c-Si	0 €	0 €	0 €
a-Si	0 €	0 €	0 €
CdTe	0 €	0 €	0 €
CIGS/CIS	0 €	0 €	0 €

BASELINE B

	*Logistics unit cost****	*Treatment and recycling unit cost **	*Total unit cost (euros per tonne collected)*
c-Si	150,00 €	25,00 €	175,00 €
a-Si	150,00 €	25,00 €	175,00 €
CdTe	150,00 €	25,00 €	175,00 €
CIGS/CIS	150,00 €	25,00 €	175,00 €

POLICY OPTION A

	*Logistics unit cost****	*Treatment and recycling unit cost***	*Total unit cost (euros per tonne collected)*
c-Si	150,00 €	140,00 €	290,00 €
a-Si	150,00 €	60,00 €	210,00 €
CdTe	150,00 €	119,00 €	269,00 €
CIGS/CIS	150,00 €	120,00 €	270,00 €

POLICY OPTION B

	*Logistics unit cost****	*Treatment and recycling unit cost***	*Total unit cost (euros per tonne collected)*
c-Si	150,00 €	140,00 €	290,00 €
a-Si	150,00 €	60,00 €	210,00 €
CdTe	150,00 €	119,00 €	269,00 €
CIGS/CIS	150,00 €	120,00 €	270,00 €

*Source: Reported by Dr. Karsten Wambach of Sunicon on PV Cycle's 2010 collection experiences

**Source: 2007 Ökopol study

*** Source: Based on PVCycle's reported collection and transport costs from 2010.

Table 45: Logistics and recycling costs considered for each scenario considered[85]

15.3. LOGISTICS/RECYCLING COST AND RECYCLING REVENUES OF BASELINE SCENARIO B

The following table summarises the unit costs for logistics and recycling, revenues from material recycling and the resulting net costs on a per tonne basis. In Baseline Scenario B, basic pre-treatment and

[85] Calculated by BIO Intelligence Service

float glass recycling was hypothesized, leading to a 25 Euro cost for each tonne of end-of-life photovoltaic panels pre-treated and recycled through a float glass plant and revenues of 15 Euros per tonne. In this scenario only low quality glass is recovered and the costs of recycling outweigh the revenues achieved through recycling, as seen in the net costs column in Table 49. While aluminium could be recycled in some situations, it is not consistently assumed to be recycled, therefore the current study has only considered low quality recycling of glass cullet. Recycling in this situation is assumed to take place due to branding and extended producer responsibility concerns on the part of photovoltaic panel producers, notably because solar energy is considered to be a 'green' form of energy. Detail on pre-treatment and recycling assumptions can be found in Section 15.1.

	Economic cost for logistics and recycling (per tonne)	Revenues from material recycling (per tonne)	Net costs (per tonne)
For c-Si PV modules	175 €	15 €	160 €
For a-Si PV modules	175 €	15 €	160 €
For CdTE PV	175 €	15 €	160 €
For CIGS/CIS PV modules	175 €	15 €	160 €

Table 46: Unit costs for logistics, pre-treatment and recycling, revenues from material recycling and net cost difference – Baseline Scenario B[86]

Sensitivity analysis - Recycling revenues

Revenues from low quality glass recycling can be estimated between €0 and €25, according to expert feedback from Deutsche Solar and other experts consulted; a value of €15 has been applied in calculating recycling revenues to represent an average value. With increasing quantities of end-of-life PV panels being recycled, coupled most likely with increasing quality of material recycled due to advances in technology, the amount of revenues gained per tonne of PV panels recycled could increase.

In the event in which €0 or €25 of revenues are applied to Baseline Scenario B, the cost balance of low quality glass recycling changes. As shown below, in a €0 revenues situation, the net cost of PV panel recycling is a cost of €25. In a €25 revenues situation, the net cost of recycling PV panels is €0, with the revenues equalling out the cost of recycling. The application of €15 of revenues per tonne reflects a situation between these two extremes, where low quality glass recycling of PV panels results in revenues, but such revenues do not outweigh costs of recycling.

In this situation, recycling would be primarily motivated by concerns on producer responsibility and company branding. As photovoltaic panel makers produce a source of 'green energy' it is important for them to carry their image of environmental consciousness throughout the entirety of their operations.

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[86] Calculated by BIO Intelligence Service

Revenues from low quality recycling of PV panels	Net cost in 2050
Application of €0 revenues from recycling	€ 25
Application of €25 revenues from recycling	€ 0

Table 47: Sensitivity analysis of recycling revenues hypotheses – Baseline Scenario B

Sensitivity analysis - Recovery of aluminium

Simple recycling, as applied in Baseline Scenario B, does not involve the recovery of aluminium. While aluminium could be recycled in some situations, it is not consistently assumed to be recycled, therefore the current study has only considered low quality recycling of glass cullet. However, in the event in which aluminium was recovered in simple recycling, assuming the same costs of recycling, recycling revenues could increase. As illustrated below in Table 48, while revenues from aluminium recycling would increase overall resource gain to 0.19 billion Euros in total in Scenario B in 2050, this would still not bring recycling revenues above the total amount of costs (0.38 billion Euros). Hence, assumption of recycling of aluminium in a simple recycling scenario, does not change the overall cost-revenue balance.

Revenues from low quality recycling of PV panels	Total recycling revenues in 2050 (in billion euros)
Revenues from glass recycling	€ 0,03
Revenues from aluminium recycling	€ 0,16

Table 48: Sensitivity analysis of recovery of aluminium hypotheses – Baseline Scenario B

15.4. LOGISTICS/RECYCLING COST AND RECYCLING REVENUES OF POLICY OPTIONS A AND B

In Policy Options A and B, assumptions of high yield material recycling were applied, leading to higher costs for recycling but also higher revenues from recycling. High yield recycling assumed was characterised by a 100% recovery of aluminium, 95% recovery of glass and 30% recovery of rare metals.

The following table summarised the net cost for logistics and recycling, when deducing the material recovery revenues from the logistics and recycling costs; the net costs are significantly negative as the revenues largely over-compensate the costs.

	Economic cost for logistics and recycling (per tonne)	Revenues from material recycling (per tonne)	Net costs (per tonne)
For c-Si PV modules	290 €	2 105 €	-1 815 €
For a-Si PV modules	210 €	2 349 €	-2 139 €
For CdTE PV modules	269 €	2 349 €	-2 080 €
For CIGS/CIS PV modules	270 €	2 349 €	-2 079 €

Table 49: Unit costs for logistics, pre-treatment and recycling, revenues from material recycling and net cost difference – Policy Options A and B

16. ANNEX I: ANALYSIS OF POLICY OPTIONS - FURTHER COMPLEMENTARY INFORMATION AND DATA

16.1. BASELINE SCENARIO A

Photovoltaic technology	a Amount of waste generated *(in million tonnes)*			b Collection rate *(percentage)*			c Properly treated and sent for recycling *(in million tonnes)* *c = a x b*			d Not properly treated and not sent for recycling *(in million tonnes)* *d = a - c*		
	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
c-Si	0,20	2,00	4,21	0%	0%	0%	0,00	0,00	0,00	0,20	2,00	4,21
a-Si	0,02	0,33	1,57	0%	0%	0%	0,00	0,00	0,00	0,02	0,33	1,57
CdTe	0,01	0,79	1,49	0%	0%	0%	0,00	0,00	0,00	0,01	0,79	1,49
CIGS/CIS	0,00	0,05	1,89	0%	0%	0%	0,00	0,00	0,00	0,00	0,05	1,89
Total	0,22	3,18	9,16	0%	0%	0%	0,00	0,00	0,00	0,22	3,18	9,16

Table 50: Photovoltaic panel quantities annually in the EU27 - Baseline Scenario A

16.2. BASELINE SCENARIO B

Photovoltaic technology	a Amount of waste generated *(in million tonnes)*			b Collection rate *(percentage)*			c Properly treated and sent for recycling *(in million tonnes)* *c = a x b*			d Not properly treated and not sent for recycling *(in million tonnes)* *d = a - c*		
	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
c-Si	0,20	2,00	4,21	20%	25%	30%	0,04	0,50	1,26	0,16	1,50	2,95
a-Si	0,02	0,33	1,57	20%	25%	30%	0,00	0,08	0,47	0,01	0,25	1,10
CdTe	0,01	0,79	1,49	20%	25%	30%	0,00	0,20	0,45	0,01	0,59	1,04
CIGS/CIS	0,00	0,05	1,89	0%	0%	0%	0,00	0,00	0,00	0,00	0,05	1,89
Total	0,22	3,18	9,16	18%	25%	24%	0,04	0,78	2,18	0,18	2,39	6,98

Table 51: Photovoltaic panel quantities annually in the EU27 - Baseline Scenario B

It is difficult to establish Baseline Scenario B ('voluntary action') due to the low quantity of panels currently reaching end-of-life, the limited economic incentives to recycle with such low waste quantities, the limited amount of specific techniques for applying material recycling to photovoltaic panels, and the varying amounts of installations and recycling facilities between MS. Assumptions made were based on 20-30% recycling rate over the 2030 to 2050 period examined, with no treatment and recycling of CIGS/CIS technologies, due to a lack of current recycling processes for these types of models and the uncertainty of the direction of technical recycling development for these types of photovoltaic panels up to 2050.

16.3. POLICY OPTION A

Photovoltaic technology	a Amount of waste generated from residential photovoltaic module installations (in million tonnes)			b Collection rate (percentage)			c Properly treated and sent for recycling (in million tonnes) c = a x b			d Not properly treated and not sent for recycling (in million tonnes) d = a - c		
	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
c-Si	0,17	1,72	3,62	85%	85%	85%	0,14	1,46	3,08	0,03	0,26	0,54
a-Si	0,02	0,29	1,35	85%	85%	85%	0,01	0,24	1,15	0,002	0,04	0,20
CdTe	0,01	0,68	1,28	85%	85%	85%	0,01	0,58	1,09	0,001	0,10	0,19
CIGS/CIS	0,00	0,04	1,63	85%	85%	85%	0,00	0,03	1,39	0,00	0,01	0,24
Total	0,19	2,73	7,88	85%	85%	85%	0,16	2,32	6,70	0,03	0,41	1,18

Table 52: Residential photovoltaic panel quantities annually in the EU27 – Policy Option A

Photovoltaic technology	a Amount of waste generated from commercial photovoltaic module installations (in million tonnes)			b Collection rate (percentage)			c Properly treated and sent for recycling (in million tonnes) c = a x b			d Not properly treated and not sent for recycling (in million tonnes) d = a - c		
	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
c-Si	0,03	0,28	0,59	20%	25%	30%	0,01	0,07	0,18	0,02	0,21	0,41
a-Si	0,002	0,05	0,22	20%	25%	30%	0,0005	0,01	0,07	0,002	0,04	0,15
CdTe	0,001	0,11	0,21	20%	25%	30%	0,0002	0,03	0,06	0,001	0,08	0,15
CIGS/CIS	0,00	0,01	0,27	0%	0%	0%	0,00	0,00	0,00	0,00	0,01	0,27
Total	0,03	0,44	1,28	20%	25%	24%	0,006	0,11	0,31	0,02	0,34	0,98

Table 53: Commercial photovoltaic panel quantities annually in the EU27 – Policy Option A

Photovoltaic technology	Amount of waste generated from all (residential and commercial) photovoltaic module installations (in million tonnes)			Quantity collected (in million tonnes)			Quantity not properly treated and not sent for recycling (in million tonnes)		
	2030	2040	2050	2030	2040	2050	2030	2040	2050
c-Si	0,20	2,00	4,21	0,15	1,53	3,25	0,05	0,47	0,96
a-Si	0,02	0,33	1,57	0,01	0,26	1,21	0,004	0,08	0,36
CdTe	0,01	0,79	1,49	0,01	0,61	1,15	0,002	0,19	0,34
CIGS/CIS	0,00	0,05	1,89	0,00	0,03	1,39	0,00	0,01	0,51
Total	0,22	3,18	9,16	0,17	2,43	7,00	0,05	0,74	2,16

Table 54: Total (residential and commercial) photovoltaic panel quantities annually in the EU27 – Policy Option A

Sensitivity analysis

In the event in which Baseline A assumptions ('no treatment of photovoltaic panels') is applied to the commercial panels not falling under the WEEE Directive in Policy Option A (instead of applying Baseline B), the difference in impacts is limited. While air and soil pollution and resource loss are higher, the overall impact is thus small compared to the 86% of photovoltaic panel waste produced which falls under the WEEE Directive and 85% of which is collected and recycled. See Table 55 below for an example with lead leaching, which serves as representative of the size of the difference when recycling hypotheses from Baseline Scenario A or from Baseline Scenario B are applied.

Lead leaching from c-Si PV modules	2050
Application of 0% recycling rate to non-residential solar panels	85-587 t
Application of 20-30% recycling rate to non-residential solar panels	72-495 t

Table 55: Sensitivity analysis of recycling hypotheses – Policy Option A

16.4. POLICY OPTION B

Photovoltaic technology	a Amount of waste generated (in million tonnes)			b Collection rate (percentage)			c Properly pre-treated and sent for recycling (in million tonnes) c = a x b			d Not properly pre-treated and not sent for recycling (in million tonnes) d = a - c		
	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
c-Si	0,20	2,00	4,21	85%	85%	85%	0,17	1,70	3,58	0,03	0,30	0,63
a-Si	0,02	0,33	1,57	85%	85%	85%	0,02	0,28	1,33	0,003	0,05	0,24
CdTe	0,01	0,79	1,49	85%	85%	85%	0,01	0,67	1,27	0,001	0,12	0,22
CIGS/CIS	0,00	0,05	1,89	85%	85%	85%	0,00	0,04	1,61	0,00	0,01	0,28
Total	0,22	3,18	9,16	85%	85%	85%	0,19	2,70	7,79	0,03	0,48	1,37

Table 56: Photovoltaic panel quantities annually in the EU27 – Policy Option B

Sensitivity analysis

To test the sensitivity of assumptions, the use of an 85% collection rate with 100% of photovoltaic panel waste collected entering a recycling facility was compared with the use of an 85% collection rate with 85% recycling of the amount of waste collected (therefore 72% recycling rate of all waste generated). **Table 57** below provides an illustration of the difference in results obtained when applying an 85% recycling rate and a 72% recycling rate, using lead leaching as an example. The difference in impact is significant, close to 100% (in the same proportion as for the quantity of waste to be disposed of, which increases from 15% up to 28%), i.e. the impact is almost doubled when considering a recycling rate of 85% of the waste collected (72% of waste arising) instead of 100% of the waste collected (85% of waste arising). However, the impacts are still significantly lower than baseline A and B and thus the conclusions of the study will not be impacted.

Lead leaching from c-Si PV modules	**2050**
Application of 85% recycling rate	47-327 t
Application of 72% recycling rate	88-611 t

Table 57: Sensitivity analysis of recycling hypotheses – Policy Option B

16.5. SUMMARY TABLES – 2030 AND 2040

2030 (annually)	Baseline Scenario A *"Worst Case"*	Baseline Scenario B *"Voluntary Action"*	Policy Option A *"Residential PV in WEEE"*	Policy Option B *"All PV in WEEE"*
Quantities				
Amount of PV waste generated (in million tonnes)	0,22	0,22	0,22	0,22
Amount of PV modules collected, properly treated and sent to recycling (in million tonnes)	0,00	0,04	0,17	0,19
Amount of PV waste improperly disposed of (in million tonnes)	0,22	0,18	0,05	0,03
Environmental benefits of policy action				
Soil and air pollution (in tonnes)				
Lead leaching from c-Si PV modules	15-102	12-82	4-25	2-15
Cadmium leaching from CdTe PV modules	0,22-1	0,18-1	0,053-0,21	0,03-0,19
Soil and air pollution (average external cost, in billion Euros)				
Lead leaching from c-Si PV modules	-0,07	-0,05	-0,02	-0,01
Cadmium leaching from CdTe PV modules	-0,000034	-0,000027	-0,000008	-0,000005
Total external cost ***(in billion Euros)***	-0,07	-0,05	-0,02	-0,01
Gain of resources (recycling input, in million tonnes)				
Glass in c-Si PV modules and Thin film* modules	0,00	0,03	0,13	0,15
Aluminium in c-Si PV modules and Thin film* modules	0,00	0,0041	0,016	0,018
Rare metals in c-Si PV modules and Thin film* modules	0,00	0,0004	0,0017	0,0019
Gain of resources (recycling output, in million tonnes)				
Glass in c-Si PV modules and Thin film* modules	0,00	0,03	0,12	0,14
Aluminium in c-Si PV modules and Thin film* modules	0,00	0,00	0,016	0,018
Rare metals in c-Si PV modules and Thin film* modules	0,00	0,00	0,0005	0,0006
Gain of resources (recycling output, in billion Euros)				
Glass in c-Si PV modules and Thin film* modules	0,00	0,0005	0,006	0,007
Aluminium in c-Si PV modules and Thin film* modules	0,00	0,00	0,019	0,021
Rare metals in c-Si PV modules and Thin film* modules	0,00	0,00	0,34	0,38
Total gain of resources ***(in billion Euros)***	0,00	0,0005	0,36	0,40

Economic cost of policy action				
Costs				
Logistics cost (in billion Euros)	0,00	-0,008	-0,05	-0,05
Proper treatment and recycling cost (in billion Euros)	0,00	-0,001	-0,02	-0,03
Total costs *(in billion Euros)*	0,00	-0,01	-0,07	-0,08
Social impacts				
Impact on employment (number of jobs created)				
Job creation	0	100	3 250	5 000
Net benefits				
Net benefits stand-alone (in billion Euros)	-0,07	-0,06	0,27	0,31
Net benefits vs. Baseline A (in billion Euros)	N/A	0,01	0,342	0,384
Net benefits vs. Baseline B (in billion Euros)	N/A	N/A	0,337	0,378

*Thin film refers to the sum of a-Si, CdTe, CIGS/CIS technologies.

Table 58: Summary table of scenario and policy options evaluation - 2030

2040 (annually)	**Baseline Scenario A** *"Worst Case"*	**Baseline Scenario B** *"Voluntary Action"*	**Policy Option A** *"Residential PV in WEEE"*	**Policy Option B** *"All PV in WEEE"*
Quantities				
Amount of PV waste generated (in million tonnes)	3,18	3,18	3,18	3,18
Amount of PV modules collected, properly treated and sent to recycling (in million tonnes)	0,00	0,78	2,43	2,70
Amount of PV waste improperly disposed of (in million tonnes)	3,18	2,39	0,74	0,48
Environmental benefits of policy action				
Soil and air pollution (in tonnes)				
Lead leaching from c-Si PV modules	150-1037	113-778	35-243	23-156
Cadmium leaching from CdTe PV modules	21-121	16-91	5-28	3-18
Soil and air pollution (average external cost, in billion Euros)				
Lead leaching from c-Si PV modules	-0,70	-0,52	-0,16	-0,10
Cadmium leaching from CdTe PV modules	-0,003	-0,002	-0,001	-0,0005
Total external cost ***(in billion Euros)***	-0,70	-0,53	-0,16	-0,11
Gain of resources (recycling input, in million tonnes)				
Glass in c-Si PV modules and Thin film* modules	0,00	0,64	2,01	2,23
Aluminium in c-Si PV modules and Thin film* modules	0,00	0,05	0,161	0,178
Rare metals in c-Si PV modules and Thin film* modules	0,00	0,01	0,025	0,028
Gain of resources (recycling output, in million tonnes)				
Glass in c-Si PV modules and Thin film* modules	0,00	0,61	1,91	2,12
Aluminium in c-Si PV modules and Thin film* modules	0,00	0,00	0,16	0,18
Rare metals in c-Si PV modules and Thin film* modules	0,00	0,00	0,0075	0,0084
Gain of resources (recycling output, in billion Euros)				
Glass in c-Si PV modules and Thin film* modules	0,00	0,01	0,10	0,11
Aluminium in c-Si PV modules and Thin film* modules	0,00	0,00	0,19	0,21
Rare metals in c-Si PV modules and Thin film* modules	0,00	0,00	5,05	5,60
Total gain of resources ***(in billion Euros)***	0,00	0,01	5,33	5,92

Economic cost of policy action				
Costs				
Logistics cost (in billion Euros)	0,00	-0,14	-0,67	-0,75
Proper treatment and recycling cost (in billion Euros)	0,00	-0,02	-0,31	-0,34
Total costs *(in billion Euros)*	0,00	-0,16	-0,98	-1,09
Social impacts				
Impact on employment (number of jobs created)				
Job creation	0	240	7 800	12 000
Net benefits				
Net benefits stand-alone (in billion Euros)	-0,70	-0,67	4,19	4,73
Net benefits vs. Baseline A (in billion Euros)	N/A	0,03	4,89	5,43
Net benefits vs. Baseline B (in billion Euros)	N/A	N/A	4,87	5,41

*Thin film refers to the sum of a-Si, CdTe, CIGS/CIS technologies.

Table 59: Summary table of scenario and policy options evaluation - 2040

16.6. SOCIAL BENEFITS

Social benefits, considered in the current study as potential for job creation, have been assessed based on information from experts consulted on job creation anticipated in the future, due to the creation of a more robust collection and recycling scheme for PV panels. Due to a lack of other information on potential job creation expected through increased recycling of PV panels, this information has been applied to Policy Option B. Other job creation estimations have been calculated by scaling down the overall percentage of PV panels recycling (as compared to the amount of end-of-life panels put on the market).

In Scenario A no job creation is expected as no collection or recycling of photovoltaic panels takes place. In Baseline Scenario B, job creation is primarily due to increased quantities of end-of-life panels entering the market and being pre-treated and recycled through a glass plant. In Policy Options A and B, high yield recycling of photovoltaic panels is assumed, hence leading to much higher job creation potential.

	Baseline Scenario A *"Worst Case"*	**Baseline Scenario B** *"Voluntary Action"*	**Policy Option A** *"Residential PV in WEEE"*	**Policy Option B** *"All PV in WEEE"*
Overall recycling rate	0%	24%	76%	85%
Number of jobs created				
2030	0	100	3250	5000
2040	0	240	7800	12000
2050	0	400	13000	20000

Table 60: Logistics, pre-treatment and recycling costs compared to material recycling revenues, net cost balance in the EU27- Policy Option B