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Analysis of Material Recovery from Silicon Photovoltaic Panels

Life Cycle Assessment and Implications for Critical Raw Materials and Ecodesign

Cynthia E. L. Latunussa, Lucia Mancini,
Gian Andrea Blengini, Fulvio Ardente,
David Pennington

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Contact information
Name: David Pennington
Address: Joint Research Centre – Via E. Fermi 2749, 21027 Ispra (Italy)
E-mail: david.pennington(at)jrc.ec.europa.eu
Tel.: +(39) 0332 785880

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Executive Summary

The life cycle impacts of photovoltaic (PV) plants have been extensively explored in several studies in the scientific literature. However, the end-of-life phase has been generally excluded or neglected from these analyses, mainly because of the low amount of panels that have so far reached disposal and the lack of data about their end of life. It is expected that the disposal of PV plants will become a relevant environmental issue in the coming decades.

An Italian company is currently developing the project FRELP (Full Recovery End-of-Life Photovoltaic) as part of the European 'LIFE' programme. The FRELP project focuses on the development of an innovative process based on a series of mechanical and chemical treatments to recycle/recover waste crystalline-silicon (c-Si) photovoltaic (PV) panels. The project foresees the development of a pilot-scale plant which could subsequently be developed on an industrial scale.

Thanks to the FRELP process, several materials can be sorted from 1 tonne of PV waste including: glass (98 %), aluminium (99 %), silicon metal (95 %), copper (99 %) and silver (94 %) for a total quantity of 908 kg. Some of these materials (e.g. silicon metal, antimony, chromium and fluorspar) are considered as critical raw materials (CRM) for the European economy, having high economic importance and a high risk to their supply.

The present report describes the application of life cycle assessment (LCA) methodology to analyse the innovative process developed within the FRELP project. The system boundaries of the LCA were set to begin at the collection of the PV waste and end with the production of recyclable materials. For example, results show that the process generates 370 kg CO_2 eq, 2.34E-05 kg CFC-11 eq for ozone depletion impact category and 4.32E-03 kg Sb eq for abiotic resource depletion – mineral per tonne of PV waste treated.

The environmental benefits (i.e. credits) from the potential production of secondary raw materials have been accounted. The benefits of the recycling process were compared to the impacts of the production of raw material and the manufacture of the PV panels. The report shows that, when waste materials are recycled to produce secondary raw materials, relevant environmental benefits can be obtained. As an example, the production of aluminium from aluminium scrap from PV waste would mean saving 2 155 kg CO_2 eq per 1 tonne of PV waste.

The LCA methodology was also applied to assess the environmental performance of the innovative recycling process in comparison with the current treatment of PV waste in generic Waste of Electric and Electronic Equipment (WEEE) recycling plants([1]). The results proved that this innovative recycling implies higher impacts for the processing but much higher benefits in terms of recycled materials. Relevant net benefits have been estimated. For example, compared to current recycling, the FRELP process would allow a reduction of about 10-15 % of different impact categories (as global warming potential, human toxicity-cancer, freshwater ecotoxicity and ionising radiations). Much higher benefits have been observed for human toxicity non-cancer, freshwater eutrophication, acidification potential, particulate matter and ozone depletion. Concerning the abiotic depletion potential, the net benefits of the FRELP recycling process are two orders of magnitude higher compared to those of the current recycling. These benefits are mainly related to the recovery of some fractions currently lost (i.e. silicon and silver) and to the higher quantity and quality of other recycled fractions (aluminium, glass and copper). The innovative recycling process also allows the energy recovery of plastics used in the cables, encapsulation and back-sheet of the PV panel.

([1]) Current treatment of waste PV panel is mainly based to the dismantling of aluminium frame and cables, and the further undifferentiated shredding of the panel.

The LCA identified some hot-spots of the recycling process. Transport has been found to make an important contribution to all life cycle impacts, causing 114 kg CO_2 eq in the climate change impact category for the assumed distance or about 30 % of the total climate change impact.

The presence of some fluorinated or chlorinated plastic in the PV panel can also be responsible for high impacts during energy recovery through incineration. Therefore, the present report focussed on possible improvements in terms of product design (e.g. avoiding the use of halogenated plastics and the adoption of pyrolysis within the recycling treatments) or the development of alternative recycling scenarios (e.g. implementing a local pre-dismantling of PV waste, and the subsequent transport of the remaining recyclable fractions). The use of non-halogenated plastics results in less impact from the treatment for most impact categories, for example 19 % less in the climate change impact category, 30 % less in ozone depletion and 57 % less in the human toxicity (cancer effects) impact category. The adoption of a decentralisation transport scenario would cause a reduction of 19 % of the emissions of greenhouse gases compared to the scenario with a centralised treatment plant.

Finally, the high efficiency and quality of glass separated through the FRELP processes could be used for high quality applications (e.g. glass for the production of new PV panels). The possibility of recovering glass of high quality was assessed in a scenario analysis. This process would allow the recycling of antimony used in the glass and currently dispersed in the secondary glass production. In particular, this scenario would allow an overall benefit of 2 274 kg CO_2 eq avoided per tonne of recycled PV (20 % higher than the FRELP PV waste treatment base-case scenario).

1. Introduction

Photovoltaic (PV) technology has been developing rapidly in Europe over the last two decades. PV technology converts unlimited rays from the sun into electricity. In 2012, electricity generated from PV technology in Europe accounted for 3 % of the total electricity generated (Figure 1).

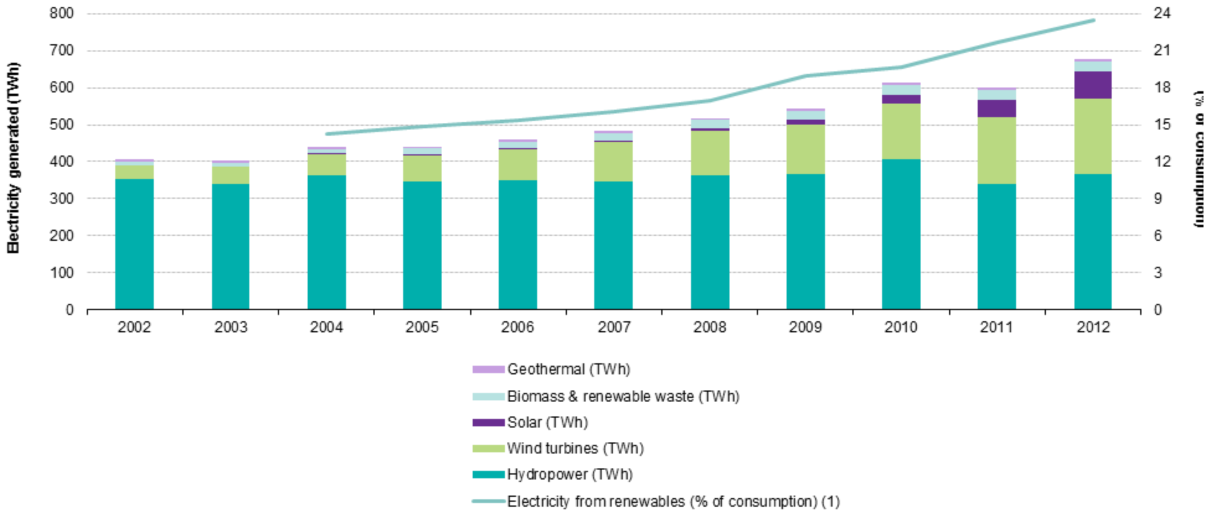


Figure 1: Electricity generated from renewable energy sources in EU-28, 2002-2012 (Eurostat, 2014)

(1): Data on electricity from renewables are not available for 2002 and 2003

PV is a relatively expensive technology. Different incentive schemes have been applied in Europe to fill the price gap of PV technology and to attract consumers. These incentive schemes favoured the development of the PV sector. The major types of programmes commonly practised in Europe are feed-in tariffs (FIT), green certificates with a quota system, investment and tax incentives, and bids on the quota system (Sarasa-Maestro, Dufo-López et al., 2013). Among the different technologies, crystalline-silicon PV technology still dominates the market by accounting for 85-90 % of the technology share (IEA - International Energy Agency, 2014).

PV panels have a potential lifespan of 25-30 years (Granata, Pagnanelli et al., 2014). Given the quantity of the PV panels already installed and its predicted growth, the waste from PV panels will generate environmental problems in the future if the panels are not treated carefully when phased out. Crystalline-silicon panels contain materials that might be lost at the end of life (EoL). Among these materials are glass, aluminium and copper. Apart from these materials which compose the biggest percentage by mass in panels, there are materials which are present in small quantities but are considered precious or critical for the economy, for example silicon metal, antimony (in glass) and silver (in metallisation paste).

Since 2012, PV waste has been formally included as Waste of Electrical and Electronic Equipment within the WEEE recast Directive. This Directive requires producers and importers of PV panels to take responsibility for the end-of-life management of PV waste. The regulation has started to come into force among EU Member States, including Italy.

Recycling PV waste at the moment is challenging as a result of the high operational costs caused by the limited number of PV panels reaching their EoL and by the lack of well-established recycling technologies. However, 20 years from now, a significant amount of PV waste will be generated. For example, in Italy the cumulative number of PV plants installed has reached 590 500 (equivalent to 18 070 MW). Approximately 4.8 million tonnes of PV waste will be generated from this quantity by 2050.

The management of the EoL of PV panels has attracted little interest among researchers in the area of PV technology, partly because of the long lifespan of the panels. However, the treatment of PV panels has important implications both from an environmental point of view (impacts generated by the treatment process and potential benefits arising if the production of primary raw materials is avoided) and from an economic perspective (due to the recovery of valuable materials, having in some cases low security of supply).

In order to analyse the potential environmental impacts and benefits of recycling PV panels in recycling plants, a life cycle approach was adopted. LCA is a method for evaluating the environmental impacts of a product or service by looking at its whole life cycle. In this case study, LCA was used to evaluate the impacts of the material recovery processes from the collection of PV panels up to the separation of the recyclable/recoverable material fractions. The recyclable fractions can be used for the production of secondary raw materials, thereby allowing relevant benefits in terms of substitution of primary raw materials. This present report focuses on the recycling of crystalline-silicon photovoltaic panels which still dominate the present market.

In this study, LCA was also used to identify the CRM directly or indirectly used throughout the life cycle of crystalline-silicon photovoltaic technology and to understand the role of recycling in terms of the use of CRM.

2. Background

2.1 Photovoltaic Market Development in Europe

Renewable energy is one of the priorities of the resource efficient Europe policy initiative (EC - European Commission, 2011a). It is included in one of the seven flagships within the Europe 2020 strategy. The European Union's Renewable Energy Directive requires all Member States to achieve a 20 % reduction in greenhouse gas emissions by 2020, together with a 20 % increase in energy efficiency and to ensure that renewable energy resources account for 20 % of the energy-mix (EC-European Commission, 2016). The implementation of the Renewable Energy Directive and national policies set out in National Renewable Energy Action Plans have resulted in significant growth in renewable energy since 2000 (EC - European Commission, 2013).

In January 2014, an integrated policy framework for the period up to 2030 was proposed by the European Union. This policy framework sets a new target of a 27 % share for renewable energy to be reached by 2030. Renewable energy will enable the EU to cut greenhouse gas emissions and make it less dependent on imported energy (European Commission). In the EU-28, electricity generated from renewable sources contributes up to 23.5 % (Eurostat, 2014). Renewable energy sources include wind, hydro-electric and tidal power, geothermal energy, biomass and solar.

PV is one of the renewable technologies that have been gaining importance globally in the last decade. The International Energy Agency (IEA) estimates around 136.5 GW PV has been installed worldwide at the end of 2013 (IEA, 2014). Annual PV installation increased from 293 MW annually in 2000 to 38 352 MW annually in 2013.

In 2013, PV saw strong growth in comparison with the other renewables (EC - European Commission, 2013). The quantity of electricity generated from photovoltaic has gained importance, increasing from 0.1 % to 10.5 % from 2002 to 2012. Figure 2 shows the share of net electricity production among the EU-28 in 2012. Electricity generated by solar technology accounts for 2.2 % of the total net electricity production in 2012.

The European Union has also supported research and development in PV technology for more than 30 years. The research funding of the EU on PV has diverse focuses, such as (European Union):

- crystalline-silicon cells;
- thin-film cells and modules;
- organic and dye-sensitised solar cells;
- concentration photovoltaics;
- novel concepts for photovoltaics;
- advanced system technologies;
- socio-economic aspects and enabling research.

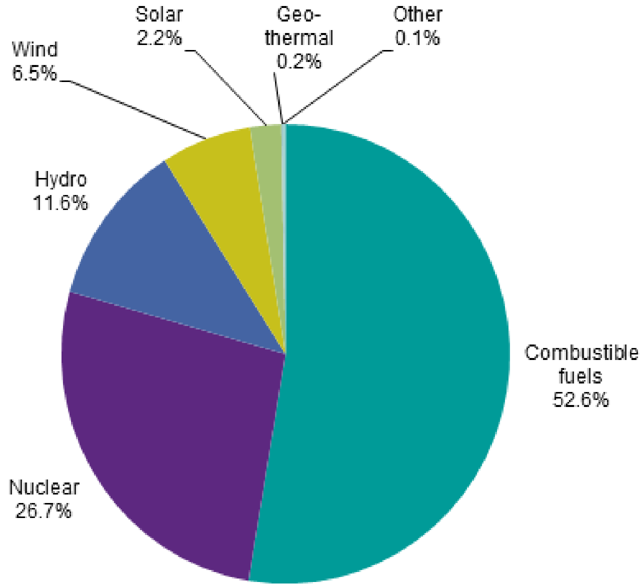


Figure 2: Net electricity production share of EU-28 in 2012; the percentage is based on the GWh share (Eurostat 2016). (Figure do not sum to 100% due to rounding).

Policies play a key role in the development of the PV market by bridging the gap between high PV prices and conventional electricity sources (Berberi, Thodhorjani et al., 2013). There are four types of programme to support PV development in Europe:

- Feed-in tariffs (FIT): Widely used scheme in Europe that has been implemented in Germany, Austria, the Czech Republic, Spain, France, Holland, Italy, Portugal and Switzerland (Sarasa-Maestro, Dufo-López et al., 2013). The FIT mechanism, first created in Germany in the 1990s, works by placing an obligation onto the utility to purchase electricity generated from renewable energy sources at a fixed tariff determined by public authorities and guaranteed for a specific time period.
- Green certificates with a quota system: introduced after FIT, this works by focusing on a guaranteed production quota instead of the price. The production of the electricity from renewables is measured and certified. Trading of quota is possible where a producer has an excess of production or is producing less than the quota (Sarasa-Maestro, Dufo-López et al., 2013).
- Investment and tax incentives (Sarasa-Maestro, Dufo-López et al., 2013).
- Bids on the quota system: in this system, government holds public auctions for certain projects to produce electricity, the producers that wins the bid is paid for it (Sarasa-Maestro, Dufo-López et al., 2013).

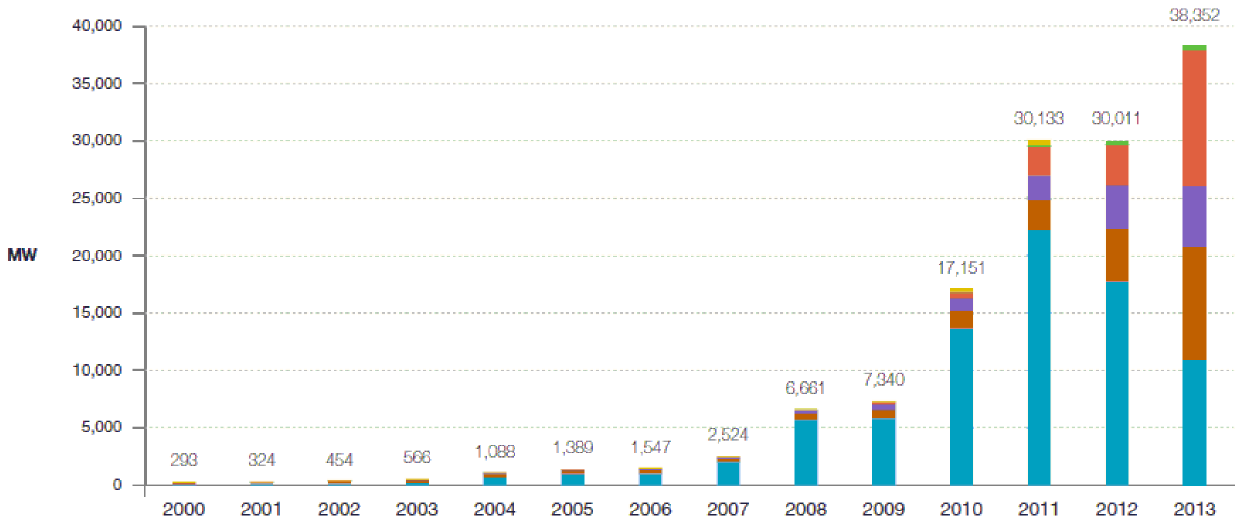
The dependency on the import of energy has been the driving force moving the EU towards renewable energy. The growing demand for clean sources of energy has encouraged the rapid expansion of the production of solar cells and PV systems.

Europe has seen gradual development in PV installation between 2000 and 2013. In 2000, 58 MW of grid-connected PV was installed and within 5 years the annual installation rose to 985 MW with German market domination. By 2007, other countries like Spain and Italy began to increase PV installation. In 2008 the grid-connected capacity reached double its 2005 figure.

After a few years of stable growth, the annual installation of new grid-connected PV capacity in Europe reached 13 651 MW in 2010 and peaked at 22 259 MW in 2011 (Figure 3). Thereafter, it declined to 17 726 MW in 2012 and to 10 975 MW in 2013. This decrease in annual installation of capacity happened in both the former market leaders, Germany and Italy in 2013. The reduction in incentive schemes in Germany, Italy and Spain has dramatically reduced the market growth in Europe. The decrease in Germany was caused by a reduction in the FIT scheme. In Italy, FIT is no longer available, with the focus now more on self-consumption schemes and additional tax rebates. In Spain, the decrease was the result of a new tax imposed on all generation technologies to cover the electricity price deficit caused by overcapacity, reducing the profitability of existing PV plants. In the meantime, several other European countries, like the UK and Greece, showed positive market growth. In the UK it was supported by two schemes: premium FIT for small PV systems and green certificates for larger systems. The market in Greece is driven by FIT, adjusted at the beginning in 2012 (IEA).

The Asia Pacific and American markets showed a positive dynamic for 2011 when compared to Europe (Figure 3). In 2013, China took over as the largest market by accounting for more than one-third of global PV installation. The PV market in China is supported by several schemes: an FIT scheme, a capital subsidy for PV on buildings and funding aimed to develop PV on building and off-grid applications in 2012.

Despite the declining market, Europe still holds the greatest amount of installed PV capacity, with for 70 043 MW or 68.6 % of global capacity. In Europe, PV capacity is able to meet 3 % of the electricity demand and 6 % of peak electricity demand (EPIA-European Photovoltaic Industry Association 2014).



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
RoW	88	56	80	77	29	10	105	42	76	80	284	508	n/a	n/a
MEA	n/a	n/a	n/a	n/a	1	0	0	1	1	22	55	125	365	383
China	19	5	19	10	10	8	10	20	40	160	500	2,500	3,500	11,800*
Americas	2	3	30	48	61	82	110	166	306	500	1,082	2,181	3,774	5,362
APAC	126	128	190	230	282	304	325	271	530	745	1,578	2,562	4,646	9,833
Europe	58	133	134	202	705	985	997	2,023	5,708	5,833	13,651	22,259	17,726	10,975
Total	**293**	**324**	**454**	**566**	**1,088**	**1,389**	**1,547**	**2,524**	**6,661**	**7,340**	**17,151**	**30,133**	**30,011**	**38,352**

Figure 3: Global annual PV installation (2000-2013) from EPIA Report (EPIA-European Photovoltaic Industry Association 2014): RoW (Rest of the World), MEA (Middle East and Africa) and APAC (Asia Pacific)

2.2 Photovoltaic Technology

In photovoltaic technology, solar cells made from semiconducting materials generate electrical power by converting sunlight into DC current. This is the so-called photovoltaic effect. The phenomenon of the photovoltaic effect was discovered time by Becquerel in 1839. The history of photovoltaic technology started with the first silicon module production at Bell Laboratories in 1955 (Green, 2005).

At the beginning, PV panels were mostly used for applications in space, for example on US and Russian satellites in 1958 (Petrova-Koch, Hezel et al., 2008). During the 1960s and 1970s research focussed on terrestrial applications for PV. Adapting from space to terrestrial applications face the challenge of potential mechanical damage due to the harsh environment. Initially, the development of PV panel technology focussed on the use of crystalline silicon.

Between the 1980s and the 2000s, investment in terrestrial uses for PV technology supported the research and development activity. In general, the development in PV technology focussed on increasing its efficiency and reducing its cost. Other than that, the technical limitations of PV technology were identified and some improvements made in terms of material quality, surface treatment and solar-cell assembly. The protection of panels using aluminium, window glass and encapsulation layers was a good example of the innovation in terrestrial PV technology (Petrova-Koch, Hezel et al., 2008). The development of thin-film technology started during the same period.

A PV system is composed of several PV modules which are connected to an electricity network (grid-connected PV) or to a series of loads (off-grid). Using a converter, the first one converts the direct current (DC) produced by the PV array into alternating current (AC) to be supplied to the electricity network. The latter typically uses a storage battery to provide energy during low-light periods (IEA, 2014). A solar module is composed of several solar cells. A solar module is connected, protected by solar glass and packaged within a frame, usually made of aluminium. A solar panel is a group of PV modules electrically connected and supported by a mounting structure and equipped with BOS (Balance of System: other components like wiring, switches, battery bank, solar inverter). Several solar panels form an array which is connected to the same system.

In Europe, the share of off-grid PV is low compared to the grid-connected installation. The off-grid market is mainly for remote areas, leisure and communication devices (IEA, 2014).

2.2.1 Types of photovoltaic cell technologies

Photovoltaic cell technologies are divided into the following four generations:

1. First Generation: wafer-based crystalline silicon (c-Si). The crystalline-silicon panel is still the dominant technology in the PV industry, due to the advantage it derives from microelectronics technology (Tobıas, del Canizo et al., 2003). They are composed of the following types:

    a. monocrystalline silicon (mono c-Si),
    b. multicrystalline silicon (multi c-Si),
    c. ribbon sheet grown silicon.

2. Second Generation: thin films (TF). Cost reduction was a driving force behind TF technology. The focus of the second generation of technology was to optimise material usage and increase its efficiency. In this generation, material reduction cost was achieved by embracing thinner films. TF solar panels are produced by depositing thin layers of substrates (<10 μm) onto a surface (e.g. glass or stainless steel). Examples of TF technology are:

    a. amorphous silicon (a-Si), one of the earliest TF technologies;
    b. Amorphous and micromorph silicon multi-junction (a-Si) — a tandem;
    c. Cadmium-telluride (CdTe). CdTe technology might pose a risk to the environment at its EoL of life because of the toxicity of Cadmium;
    d. Copper-Indium-Gallium-(di) Selenide sulfide, CIGS technology faces a potential future challenge from Indium shortage.

3. Third Generation: focuses on double, triple junction and nanotechnology which have promising efficiency results at lower cost. The emerging and novel PV technologies are:

    a. concentrated photovoltaics (CPV),
    b. organic PV,
    c. advanced thin film.

2.2.2 Efficiency and lifespan of photovoltaic technology

The efficiency of PV cells is defined as the ratio of the electrical output of a solar cell to the incident energy in the form of sunlight. PV cells have different ranges of efficiency depending on the type (Table 1).

The efficiency of solar cells improved from 2-3 % in the 1950s to around 16 % at the beginning of 2000s (Green, 2005). At the same time, the price per watt of PV power decreased. Nowadays, the highest cell efficiency comes from CPV multi-junction with 25 % efficiency at a commercial level and a maximum of 30 % efficiency at laboratory scale. CPV technology is not yet diffuse in the market due to its high price. The monocrystalline technology is one of the most economically accessible PV technologies in the market. The efficiency of this technology ranges from 13-19 % commercially and 25 % at laboratory scale. The TF technologies are relatively cheap compared to their crystalline-based technology counterparts. However, they are less efficient, ranging from 7-12 % at commercial levels and 10-20 % at laboratory scale (Paiano, 2015).

Table 1: Efficiency of different PV technologies (Paiano, 2015)

Technology	Commercial efficiency (%)	Laboratory-scale efficiency (%)
C-Si monocrystalline	13-19	25
C-Si polycrystalline	11-18	20.4
CIGS/CIS	7-12.7	20.3
CdTe	11	16.7
a-Si - μC Si	7-9.8	11.9-13.2
a-Si	4-8	10.4
CPV Multi-junction	25	25-30
Dye-sensitised solar	2-4	8-12

Another important aspect of photovoltaic technology is its lifespan. Nowadays the lifespan of PV modules can reach approximately 25 years (Paiano, 2015). However, the lifespan of PV cells is longer than that of PV modules (Doi, Tsuda et al., 2001). The factors that determine the lifespan of PV modules are mainly the deterioration of the encapsulation resin by UV-ray (Doi, Tsuda et al., 2001; Granata, Pagnanelli et al., 2014) and the breakage of interconnecting wires by thermal stress (Doi, Tsuda et al., 2001).

2.2.3 Crystalline-silicon photovoltaic technology

Among the types of PV technology, crystalline-silicon wafer-based module production still dominates the market according to IEA. In 2013, the production of this type of module accounted for 89.6 % of module production volume among the member countries of IEA PVPS([2]).

Manufacturers do not usually produce the primary materials of PV panels. They are rather supplied by specific companies. The main component of a PV panel is the PV cell. PV cells are semiconductor devices that generate direct current electricity.

([2]) The Photovoltaic Power Systems Program (PVPS), a collaborative research and development agreements within the International Energy Agency (IEA)

In 2013, Polysilicon, the basic input material used to produce the crystalline-silicon wafer was mainly produced by China, Germany, Korea, USA, Japan and Malaysia with China as the largest producer as well as the largest consumer. Between 2009 and 2013, the production of solar cells in China increased dramatically compared to other major producing countries (Figure 5). China is currently the world's largest producer of wafers for solar cells with a capacity of 40 GW/year in 2013. Chinese production in 2013 was approximately 29.5 GW, and 7 GW of these solar wafers were exported. The same situation applied for PV module production. In 2013, China dominated the market by producing 65 % of modules (both TF and wafer-based technologies) in the market.

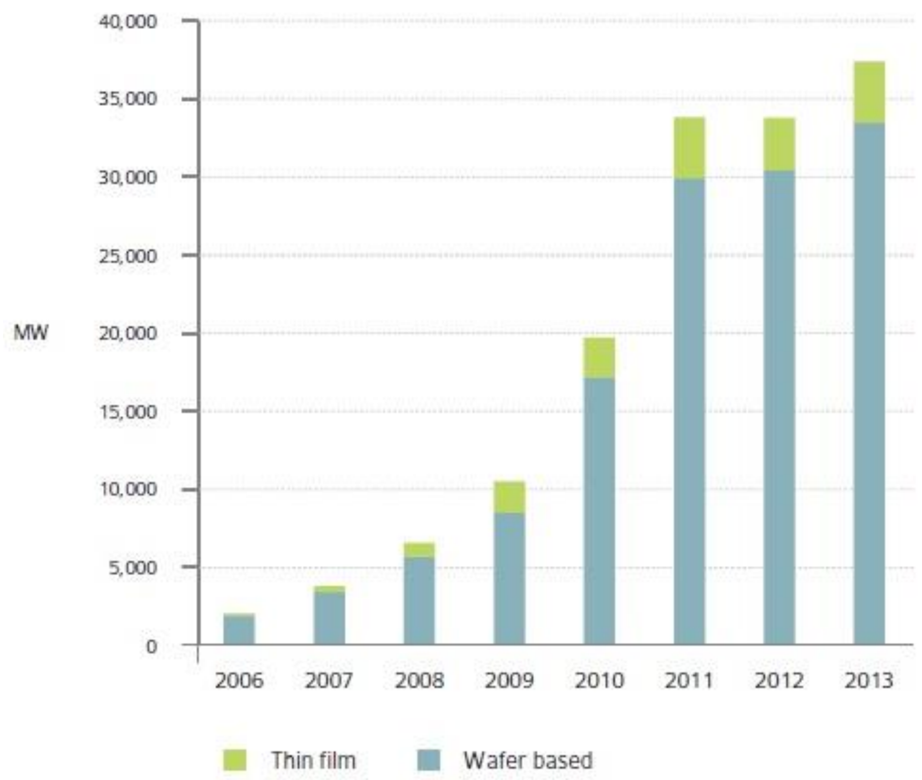


Figure 4: PV module production per technology 2006-2013 (in MW), exclusively in IEA PVPS Countries (IEA, 2014)

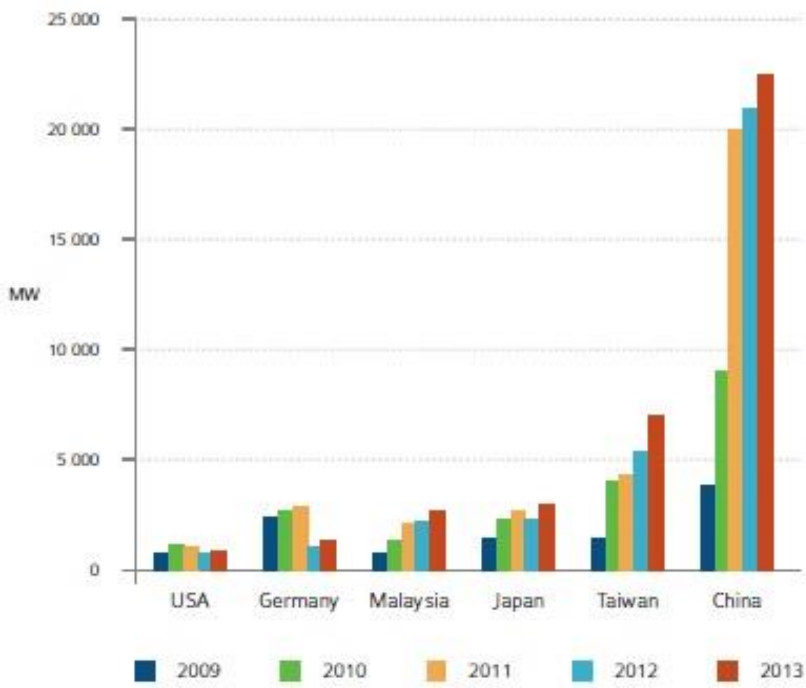


Figure 5: The Evolution of PV cell production in major country producers (IEA, 2014)

C-Si PV cells are made from a process of slicing highly purified silicon metal ingots or casting. The manufacturing process creates a charge-separating junction, deposits passivation layers and an anti-reflective coating, and adds metal contacts. These cells are grouped into modules, with transparent glass for the front, a weatherproof material for the back and are often framed together (IEA, 2014). The complete picture of the manufacturing steps of c-Si PV panels is shown in Figure 6 (Fthenakis and Kim, 2011). Table 2 shows the typical composition and characteristics of a crystalline-based PV module.

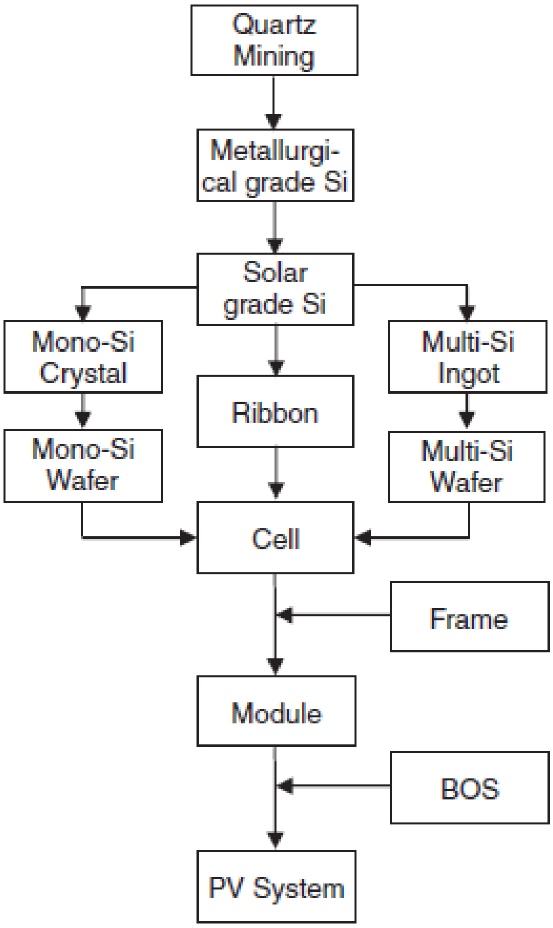


Figure 6: Flow diagram of crystalline-silicon based PV panel production

(Fthenakis and Kim, 2011)

Table 2: Characteristics and composition of multicrystalline-silicon photovoltaic panels by weight (%/%)

Characteristics	(BioIntelligence 2011)	(Notarnicola 2013)
Total weight per module	22 kg	18 kg (60 cells)
Normal capacity	215 Wp	220 Wp
Size range	165 x 99 cm or 1.4-1.7 m^2	1.6 m^2
Glass	74.16 %	80.10 %
Aluminium frames	10.30 %	9.80 %
Encapsulation layer i.e. ethylene vinyl acetate (EVA)	6.55 %	Not specified
Backing film (Tedlar)	3.60 %	4.30 %
Solar cells (Silicon metal based)	3.48 %	4.70 %

2.2.4 Critical raw material used for the production of crystalline-silicon photovoltaic technology

The security of supply of mineral raw materials has become a high-priority political issue for many countries, especially those highly dependent on imports. At the EU level, resource security is identified as a policy objective both in the Raw Materials Initiative (EC - European Commission, 2008) and within the resource efficiency policy (EC - European Commission 2011a; EC - European Commission, 2011b). In particular, the EU has promoted a series of policy actions that focus on non-energy and non-agricultural raw materials, in order to ensure the availability and undistorted access to material resources that are of utmost importance for the competitiveness of the EU economy. One priority action was the identification of raw materials that are critical for the EU economy, based on their economic importance and supply risk. The list of CRM was published in 2010 and updated in 2013 (EC - European Commission, 2010; EC — European Commission, 2014). 'Criticality' has also emerged as a research subject and different methodologies for assessing CRM have been developed (Morley and Eatherley, 2008; Erdmann and Graedel, 2011; Graedel et al., 2012; Goe and Gaustad, 2014). Some studies have also been conducted at sectorial level, e.g. with reference to the energy sector. Especially in the case of low-carbon technologies the requirement for rare or critical metals can produce supply-chain bottlenecks and could, therefore, constrain the decarbonisation of the EU (Moss et al., 2011; Moss et al., 2013).

In the case of crystalline photovoltaic technology, two main CRM (as in the updated list 2013) play a crucial role: silicon metal and antimony. In addition to these, fluorspar is increasingly importance in c-Si photovoltaic technology.

2.2.5 Silicon metal

Crystalline-silicon solar cells are made from silicon metal. Silicon metal has historically been used in the photovoltaic industry because of the ability to control its conductivity through doping. It is estimated that in 2012 Europe's consumption of silicon metal was 540 000 tonnes which made Europe the second biggest consumer after China (Oakdene Hollins and Fraunhofer ISI, 2013). In the EU silicon metal is used in the chemical sector (54 %) and for the production of aluminium. The silicon-based PV industry requires 15-20 tonnes of silicon feedstock to generate 1 MWp, depending on the PV technology (Sarti and Einhaus, 2002).

China is the major producer of silicon metal, accounting for 56 % of global production. The other major producers are Brazil, Norway, France and the US. In the 10 years 2002-2012 the demand for silicon grew on average by 8 % a year, and the price increased substantially, experiencing two peaks in 2008 and 2011. It is estimated that world demand for silicon will increase at 2.7 % a year until 2020, due especially to its use in semiconductors, including solar and chemicals segments (Oakdene Hollins and Fraunhofer ISI, 2013). The EU is a net importer of silicon metal.

Silicon metal for solar-cell application can be produced in two different pathways, both starting from metallurgical-grade (MG) silicon. In the first path, known as chemical route, MG silicon is transformed into electronic-grade silicon with 6-9N purity([3]) and the latter generates upgraded solar grade MG silicon with purity < 5N.

([3]) The purity of silicon metal is expressed in the number of '9', for example 6N or 'six nines' means 99.9999 % pure.

First, quartz sand (SiO_2) is transformed into MG silicon by a coke reduction process in a furnace with temperatures up to 1 800 °C. The output of this process is MG silicon with 98.5 % purity. In order to produce the electronic-grade silicon metal, MG silicon is further treated by a distillation process in a hydrogen chloride solution. The distillation process produces high purity trichlorosilane which will be processed in the Siemens process at 900 °C. The Siemens process is an energy-intensive process, consuming up to 200 kWh/kg of silicon produced (Braga, Moreira et al., 2008). Until 1997 the silicon employed in the production of polycrystalline solar cells originated mostly from waste produced by the microelectronics industry (Braga, Moreira et al., 2008). However, the chemical route has toxicity problems since it involves the production of chlorosilanes and reactions with hydrochloric acid. These components are toxic, corrosive and may cause irritation of the skin and mucous membranes (Safarian, Tranell et al., 2012).

The second path, known as the metallurgical route produces upgraded MG silicon. This is done by a chemical refinement process of MG silicon to remove boron and phosphorous impurities, followed by solidification. The output of this process is MG silicon with a purity of < 5N. This route can be five times more energy efficient than the Siemens process (Braga, Moreira et al., 2008).

After the polysilicon production, the next step is the preparation of the silicon ingot. The ingot is produced differently depending on the type of the final crystalline-silicon material. In order to produce a crystalline-silicon wafer, an ingot of silicon must be grown. The first type is monocrystalline silicon which currently has the highest efficiency in PV technology. The monocrystalline ingot is grown by slowly pulling melted polysilicon. This method is known as the Czochralsky method.

The second type is poly- or multicrystalline silicon. The ingot of polycrystalline silicon can be made by casting molten polysilicon. Both ingots are then cut into wafers using a diamond saw. After that, the wafers will be further treated.

2.2.6 Antimony (stibium)

Antimony is a silvery-white, shiny, very brittle and semiconducting element. Antimony has poor mechanical properties which make its use in a pure form very limited. Antimony is commonly mined as a by-product of gold, silver, lead or zinc (Oakdene Hollins and Fraunhofer ISI, 2013). Antimony (Sb) is used in the glass to improve stability of the solar performance of the glass upon exposure to ultraviolet (UV) radiation and/or sunlight. However, glass constitutes 5 % only of the end uses of antimony; most of it is used in flame retardants and lead-acid batteries.

Antimony has been considered a CRM for the EU since the first study in 2010. This is mainly due to the high import dependency (antimony is not mined in the EU) and the concentration of supply. China is the main producer with 86 % of world production in 2011. According to the OECD´s inventory on export restrictions, China applies export taxes on antimony ores and concentrates and export quotas on antimony and products thereof as well as antimony oxides. During the last century the antimony price has had several significant peaks. The last peak happened in 2008 when supply from China decreased due to the closure of several small and illegal mines. Demand for antimony is projected increase steadily over the next 5 years, due in particular to the increase in demand for flame retardants (Oakdene Hollins and Fraunhofer ISI, 2013).

The main use of antimony is as a dissipative application which essentially means that recycling is not taking place (Oakdene Hollins and Fraunhofer ISI, 2013).

2.2.7 Fluorspar

Fluorspar or fluorite is an industrial mineral composed of calcium and fluorine (CaF_2). It is typically found in vein fillings in rocks that have been subjected to hydrothermal activity, often containing ores which can include sulfides of tin, silver, lead, zinc, copper and other metals.

In order to produce CaF_2, the ore containing CaF_2 is crushed, pre-concentrated and separated using an aqueous suspension in a cone separator. The density differences principle means that the heavier particles rich in fluorspar will stay at the bottom of the cone where they can be recovered (Oakdene Hollins and Fraunhofer ISI, 2013).

Fluorspar has a wide variety of uses, mainly in the metallurgical, ceramic and chemical industries. Fluorspar is sold in three different grades: ceramic, acid and metallurgical. The ceramic grade of fluorspar is used mainly in the manufacture of specialty glass, ceramics and enamelware, while MG fluorspar is mostly used in the production of iron, steel and other metals. The first is a high-purity material used by the chemical industry. It is used mainly in the chemical industry to manufacture hydrofluoric acid (HF).

In c-Si PV technology, HF is used to produce the back-sheet layer, known as polyvinyl fluoride (PVF). PVF is preferable due to its strength, resistance to weather and UV, and its properties as a moisture barrier. The back-sheet layer in PV technology is fundamental to improving the lifespan of PV modules.

Recycling of fluorspar occurs primarily from uranium enrichment and petroleum alkylation and stainless steel pickling. Primary aluminium producers also recycle HF and fluorides from smelting operations.

2.3 End-of-Life Phase of Photovoltaic Waste

The number of PV installations is predicted to continue to increase. Over the next 15 or 20 years currently installed PV panels will become waste. At a rough estimate, given the accumulated installed panels in 2012 70 000 MW 5 250 000 tonnes([4]) of PV waste will be generated in Europe in 2032. A mass of 4 462 500 tonnes of this quantity is monocrystalline and multicrystalline panel waste. This waste might cause large environmental problems at final disposal.

Formally, since August 2012, the recast WEEE (Waste Electrical and Electronic Equipment) Directive 2012/19/EU has provided a legislative framework for extended producer responsibility for PV modules in Europe (PV CYCLE). Since 2014, the collection, transport and treatment of photovoltaic panels have been regulated in every single European Union Member State. PV panels follow category 4 of EEE covered by the WEEE Directive for which, by 2018, the minimum recovery targets have been set as 80 % and 70 % to be prepared for reuse and recycle (EC-European Commission, 2012).

([4]) The lifespan of PV panel is assumed to be 20 years. The estimated waste production factor is: 75 tonnes of waste for every 1 MW of installed power. This number refers to BioIntelligence (2011) "Study on Photovoltaic Panels Supplementing the impact assessment for a recast of the WEEE Directive - Final report."

On 4 February 2013, the European Commission requested that the European Standardisation Organisations develop European standards for the treatment of WEEE. Cenelec, the European Committee for Electro-technical Standardisation, is responsible for standardisation in the electro-technical engineering field and it is currently working on the preparation of the standards. According to the work programme, the following series of standards are under development:

- EN 50625-2-4: Collection, logistics and treatment requirements for WEEE - Part 2-4: Treatment requirements for photovoltaic panels;
- TS 50625-3-5: Collection, logistics and treatment requirements for WEEE - Part 3-5: Specification for de-pollution – photovoltaic panels.

2.3.1 Crystalline-silicon photovoltaic waste in Italy

In Italy, the introduction of the "Conto Energia" national support programme in 2005 stimulated the Italian photovoltaic market. This programme resulted in the installation of off-grid connected photovoltaic plants, particularly in the following sectors (Salvatore Castello (ENEA), 2013):

- Building Integrated Photovoltaics (BIPV), 2 570 MW;
- Building-Applied Photovoltaics (BAPV), 6 556 MW;
- PV (other, on ground), 8 475 MW;
- CPV, 27 MW

Approximately 4.8 million tonnes of c-Si photovoltaic waste will be generated by 2050 in Italy (Paiano 2015) (Table 3). The estimated amounts of material loss potentially caused by improper disposal of PV waste in Italy are: glass (3 million tonnes), aluminium frame (498 000 tonnes), silicon metal (162 000 tonnes), copper (27 000 tonnes), tin and zinc (5 800 tonnes each), lead (2 900 tonnes), and silver (242 tonnes).

In Italy, from 1 July 2012, in order to benefit from the incentives scheme 'IV Conto Energia' and 'V Conto Energia', producers and importers of photovoltaic modules must register themselves with a certified consortium that can guarantee the end-of-life management of PV panels. There are currently 11 authorised PV recyclers in Italy (GSE-Gestore Servizi Energetici 2014).

Table 3: Crystalline-silicon technology potential waste generation in Italy and its composition (Paiano, 2015)

Amount of waste generated per c-Si technology and their composition (t).

Years of waste production	Tons	Waste composition										
		Glass	Frames (Aluminium)	EVA	Backing film (Tedlar)	Adhesive, potting compound	Silicon	Copper	Tin	Lead	Zinc	Silver
2012	*563*	417	58	37	20	7	19	3	1	0	1	0
2017	*307*	228	32	20	11	4	10	2	0	0	0	0
2022	*839*	622	86	55	30	10	28	5	1	1	1	0
2023	*102*	76	11	7	4	1	3	1	0	0	0	0
2024	*82*	61	8	5	3	1	3	0	0	0	0	0
2025	*51*	38	5	3	2	1	2	0	0	0	0	0
2026	*99*	74	10	6	4	1	3	1	0	0	0	0
2027	*198*	147	20	13	7	2	7	1	0	0	0	0
2028	*397*	294	41	26	14	5	13	2	0	0	0	0
2029	*457*	339	47	30	16	5	15	3	1	0	1	0
2030	*661*	490	68	43	24	8	22	4	1	0	1	0
2031	*1215*	901	125	80	44	14	41	7	1	1	1	0
2032	*3558*	2639	366	233	128	41	119	20	4	2	4	0
2033	*32,785*	24,313	3377	2147	1180	380	1098	187	39	20	39	2
2034	*67,048*	49,723	6906	4392	2414	778	2246	382	80	40	80	3
2035	*216,534*	160,582	22,303	14,183	7795	2512	7254	1234	260	130	260	11
2036	*903,059*	669,709	93,015	59,150	32,510	10,475	30,252	5147	1084	542	1084	45
2037	*332,528*	246,603	34,250	21,781	11,971	3857	11,140	1895	399	200	399	17
2038	*110,852*	82,208	11,418	7261	3991	1286	3714	632	133	67	133	6
Total (2012–2038)	*1,671,336*	*1,239,463*	*172,148*	*109,473*	*60,168*	*19,387*	*55,990*	*9527*	*2006*	1003	*2006*	*84*
2045	1,389,286	1,030,295	143,096	90,998	50,014	16,116	46,541	7919	1667	834	1667	69
2050	1,783,268	1,322,472	183,677	116,804	64,198	20,686	59,739	10,165	2140	1070	2140	89
Total (2012–2050)	*4843891*	*3,592,229*	*498,921*	*317,275*	*174,380*	*56,189*	*162,270*	*27,610*	*5813*	*2906*	*5813*	*242*

2.3.2 Potential impacts caused by the disposal of crystalline-silicon photovoltaic waste

The improper handling of c-Si PV waste may cause environmental issues (BioIntelligence, 2011). Some environmental impact may emerge from lead leaching. Lead is a heavy metal with high potential for accumulation in humans and the environment. Lead is used in c-Si PV panels. The levels of lead found in c-Si PV panels exceed the leaching limits for disposal in landfill for inert waste, but still lie within the limits of disposal for an ordinary landfill (BioIntelligence, 2011). The amount of lead in an average mc-Si PV panel is estimated as 576 mg/kg.

The disposal of c-Si PV waste into landfill may result in the loss of valuable materials and therefore economic loss from the following materials:

- Conventional resources, primarily glass and aluminium, which are the main materials of PV panels in terms of weight, having a total share of approximately 88 %. The improper treatment of PV waste may result in the loss of these potentially reusable materials.
- Rare and/or critical metals (e.g. silver and silicon metal): the c-Si photovoltaic panels utilise materials that are defined as critical for the EU economy such as silicon metal. Silicon metal makes up 3.8 % of the weight of PV panels and it is the core of photovoltaic technology. Among precious metals that are normally found in the c-Si PV panels is silver. Silver is found in relatively small quantities as in metallisation paste but it plays an important role as a conductor.

2.3.3 The development of recycling technologies

A literature review was done to trace back the development of recycling of c-Si PV modules. The following summary presents a review of the recycling/material recovery techniques applied for c-Si PV waste.

In 1990, there were a significant number of PV installations which held out the prospect of potential waste in the future (Solar waste EU, 2014). In the same period, the possibility of recycling PV module waste from a technical point of view was assessed. The challenging part in recycling photovoltaic waste is the removal of the encapsulation layer (Notarnicola, 2013).

Studies into the possibility of modules from technical and cost points of view had already been presented in photovoltaic technology conferences in the 1990s (Doi, Tsuda et al., 2001). A study identified the challenges and the possible approach in the USA and concluded that PV recycling was feasible (Fthenakis, 2000).

Several studies concerning the development of technologies for the recycling of PV panels have been identified as follow:

1. *Thermal and/or chemical-based process to remove the ethylene vinyl acetate (EVA) polymer layer* (Bohland and Anisimov, 1997; Doi, Tsuda et al., 2001; Zeng, Born et al., 2004; Yamashita, Miyazawa et al., 2006). In the early 1990s, experiments on PV module recycling were based on chemical and thermal processes. The EVA layer, being a material intended to protect the PV cells, is difficult to resolve. One study evaluated the pyrolysis process of EVA at different heating rates under different oxidising atmospheres and demonstrated its feasibility in the application of PV module recycling (Zeng, Born et al., 2004).

Another study also evaluated EVA removal by dissolution of EVA in trichloroethylene, an organic solvent (Doi, Tsuda et al., 2001). Among the possible techniques were nitric acid dissolution, thermal decomposition in inert gas, fluidised bed combustion, and the use of organic solvent in place of chemical solvent (Doi, Tsuda et al., 2001).

Deutsche Solar conducted field experiments into PV module recycling and the results were presented in 2006 during the European Photovoltaic Solar Energy Conference in 2006. The field experiment was done on crystalline-based PV modules produced in 1983. The recycling method was based on thermal and chemical processes (Bombach, Röver et al., 2006).

In another experiment, a thermal process was conducted at the beginning to remove the EVA layer. This thermal process was followed by a chemical treatment to separate silicon and other metals. The chemical treatment phase in the recycling of crystalline-silicon solar cells was found to be the most important stage in achieving a high purity level of silicon (Klugmann-Radziemska and Ostrowski, 2010).

Soltech, a Belgian company in PV solar energy systems, under the Brite Euram Project supported by the European Commission, conducted several experiments into recycling processes. Among the methods tested was pyrolysis with microwave heating which failed due to the cell breakage resulting from non-uniform temperature distribution. Another method was dissolving the modules in a chemical reactor with triethylene glycol at 220-290 °C which failed because the EVA layer did not release from the module. Another proposed chemical method was immersion in hot nitric acid which showed positive results. However, this method was not viable because it required a large amount of acid for the process.

Soltech suggested pyrolysis in a conveyor belt furnace and pyrolysis in a fluidised bed reactor as processes for recycling PV modules. The tests resulted in 80 % mechanical yield of the wafers. Almost 100 % was achieved for glass sheets. Silicon was recovered with a chemical etching method by using an acid solution. They claimed to have recovered silicon wafers without any noticeable difference in mechanical yield. A life cycle analysis was performed to compare the production of a module with 125 x 125 mm multicrystalline-silicon cells, comparing a standard module and a module using recycled wafers. The result showed 40 % reduced energy consumption per generated kWh (Frisson, Lieten et al. 2000).

In Taiwan, two-step heating and chemical processes were tested to recover materials from silicon-base solar-cell modules (Teng-Yu Wang, 2011). By using this method, glass plate was recovered without it breaking. The chemical treatment using acid solution was able to recover copper and silicon up to 8N purity (Kang, Yoo et al., 2012).

Similar to those mentioned previously, chemical, thermal and laser processes were tested in recycling photovoltaic silicon solar cells and modules (Radziemska, Ostrowski et al., 2010). The treatment was conducted in two steps: the first step was the separation of cells, comparing chemical processes and thermal treatment and the second step was the refining of separated cells, comparing laser and chemical treatments. Thermal treatment was shown to be sufficient in the first step while chemical was shown to be more advantageous in the second step.

2. *Recycling of crystalline-based solar cells into building material* (Fernández, Ferrer et al., 2011). The experiment was done by incorporating used solar cells ground up to calcium aluminate cement matrix at a maximum of 5 %.

3. *Recycling of panels by physical and thermal operations* (Granata, Pagnanelli et al., 2014). Two different methods were tested for three kinds of PV device, polycrystalline silicon modules, amorphous silicon modules and CdTe PV modules. The first method was crushing the modules using two-blade rotor crushers, followed by thermal treatment to separate EVA. The second method was crushing the modules by two-blade rotor crushers, followed by further crushing using a hammer and a possible thermal treatment. Both methods were then followed by sieving to separate glass from the metals (metals were supposed to be treated further).

2.3.4 C-Si PV waste treatment: current practice

Currently, the recycling of PV panels faces challenges by comparison with recycling of other consumer products. Insufficient inputs (used PV panels), high operating costs and low profitability due to small concentrations of valuable materials are among these challenges. A study of PV module recycling options showed PV recycling to be technologically and economically feasible (Fthenakis, 2000). Two strategies were identified: near term with a centralised approach (a unique PV module recycling site) and a decentralised approach (recycling by different stakeholders based on the material of interest) and future term with a centralised strategy (Fthenakis, 2000).

Germany has been the pioneer in PV recycling technology in Europe. In 2010, the BINE Information service provider, which is promoted by the German Federal Ministry of Economics and Technology (BMWi) reported the results of the Freiberg pilot system([5]). The system attempted to reprocess PV solar cells in as environmentally-friendly a way as possible. The focus of the pilot project was to minimise the use of toxic etching solutions. The treatment in the pilot project was based on chemical and thermal processes. The recovered silicon cells are expected to substitute MG silicon (MG-Si). This pilot system has been running since 2002. The report underlined the lack of sufficient quantities of PV waste as the main obstacle to establishing a PV recycling infrastructure (BINE Informatisn Service).

There are some companies already established that adapt recycling schemes for PV panels in Europe, namely Deutsche Solar and PV CYCLE. Both of them adapted decentralised strategies by doing material recovery and sent the recovered materials to the specific material recyclers. These are discussed more fully in the following sections.

Deutsche Solar

Deutsche Solar GmbH is a subsidiary of SolarWorld AG. Deutsche Solar is known as a pioneer of the silicon recycling industry. Deutsche Solar's research into silicon-based PV

([5]) The Freiberg pilot project was funded by BMWi, some researchers from Deutsche Solar, and TU Bergakademie Freiberg panel began in 2003 in Germany. In 2006, Deutsche Solar conducted field experiments of silicon-based PV module recycling based on thermal and chemical recycling processes (Bombach, Röver et al., 2006). The treatment process involved the removal of the plastic components of the panel by a thermal process, followed by manual separation of the remaining materials such as solar cells, glass and metals. Glass and metals were further treated in relevant recycling processes and solar cells were re-etched to the wafer. The silicon wafer was treated with a chemical process (known as the etching process) to remove impurities, such as the metallisation layer, n+ and p+ doping. Most of the materials were then sold and sent for metal recycling (Table 4). In 2011, Deutsche Solar's operations was terminated because of the high cost and the low quantities of PV waste input at that time (BioIntelligence, 2011).

Table 4: End products and remnants of recycling and the destination of Deutsche Solar treatment process (BioIntelligence, 2011)

Material	End-product destination
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, metal recycling
Packaging	Disposal, recycling
Residuals	Disposal (mixed waste)

PV CYCLE

PV CYCLE was founded by the solar industry in Europe as a joint initiative to prepare a high quality comprehensive PV recycling system at an EU level (BINE Informatisn Service). PV CYCLE has been dealing with the end-of-life treatment of PV waste since 2010. PV CYCLE works with take-back and recycling schemes and offers waste treatment and WEEE compliance in Europe. PV CYCLE collaborates with industry associations, research institutes, national partners, manufacturers and importers. PV CYCLE also conducts research and development activities, for example in the FRELP project funded by the EU's LIFE project, focusing on recycling 100 % of PV materials and reducing the overall energy consumption of a PV module.

PV CYCLE in their Operational Status Report claimed to have treated 9 548 tonnes of PV waste in Europe through their take-back and collection service. PV CYCLE's recycling site is based in Germany and it has 351 collection points throughout Europe and the EoL service includes both crystalline silicon and TF technology.

PV CYCLE treats mainly silicon-based PV panels (79.4 %). Silicon-based PV panel recycling is operated by separating the frame and the junction box, shredding the panel and processing the flat glass. The non-silicon PV panels are treated by on chemical process to separate the different PV module components and 95 % of materials were claimed to be able to be recovered for use in new materials (PV CYCLE, 2013).

In 2012, PV CYCLE and Maltha Glass Recycling in Lommel, Belgium conducted a screening LCA study on their recycling process for silicon-based PV modules. The process in the plant was mainly based on the processes of a flat-glass recycling line. The process is composed of the following steps: manual removal of aluminium frames and junction boxes, shredding the rest of the PV waste and the recycling of glass. The glass recycling line includes manual pre-sorting of the shredded PV waste, crushing of the laminates, separation and extraction of materials. The output of this process is further separated according to their material fractions i.e. ferrous metals, plastics, PV cell/polymer foil laminate and glass cullet. The recovered valuable materials are sent to respective recyclers.

The LCA study of this treatment showed that the main impacts of the recycling process at Maltha recycling were related to the transport of PV module waste to the recycling site and the electricity demand for running the processes. However, the report mentioned the need to address further research on the process to separate the broken PV cells from the lamination foil (Michael Held, 2013).

Other than the specialised recycling technique developed by Deutsche Solar, the recycling of PV panels focuses on glass recovery (BioIntelligence, 2011). In some cases, PV panels are treated in WEEE recycling plants that are not specialised in the treatment of PV waste. This implies that the frame is disassembled, while the remaining parts are treated by undifferentiated shredding together with other WEEE.

3. Case Study: Life Cycle Assessment of Photovoltaic Waste Treatment

This chapter presents the LCA study of the photovoltaic waste treatment being developed by the collaborating company.

The waste treatment process studied in this report has been designed by an Italian company, SASIL S.p.A. The company is based in the Piedmont region and it has been operating since 1975 in mining and in the production of industrial minerals. In recent years it has specialised in the recovery of industrial waste from different backgrounds of glass base. In the following sections the project and the phases of the LCA study (goal and scope, life cycle inventory, impact assessment, result interpretation and discussion) are described in detail.

3.1 Methodology: Life Cycle Assessment

In this study an LCA of the recycling scheme was performed in compliance with the international series of standard ISO 14040 (ISO 14044, 2006) and ILCD recommendations (EC - European Commission, 2011b). LCA is traditionally defined as a methodology to assess the environmental impact of a product or service during all stages of its life (production phase, use phase, EoL phase). LCA can be defined as a methodology for the appraisal of burdens along the supply chains of goods and services related to resource use and emissions (Mancini et al., 2014).

Figure 7 shows the phases of an LCA study. An LCA study is initiated by defining the goals and scope of the study, the functional unit and the system boundary of the study. This step is followed by identifying inputs and outputs associated with each product life stage, also known as a life cycle inventory (LCI). The evaluation of potential impacts is conducted based on the inventory. This phase is called life cycle impact assessment (LCIA). The last step is known as the interpretation phase. In this phase, the results of the impact assessment are analysed. The interpretation step also includes analysis of the data completeness, sensitivity and consistency.

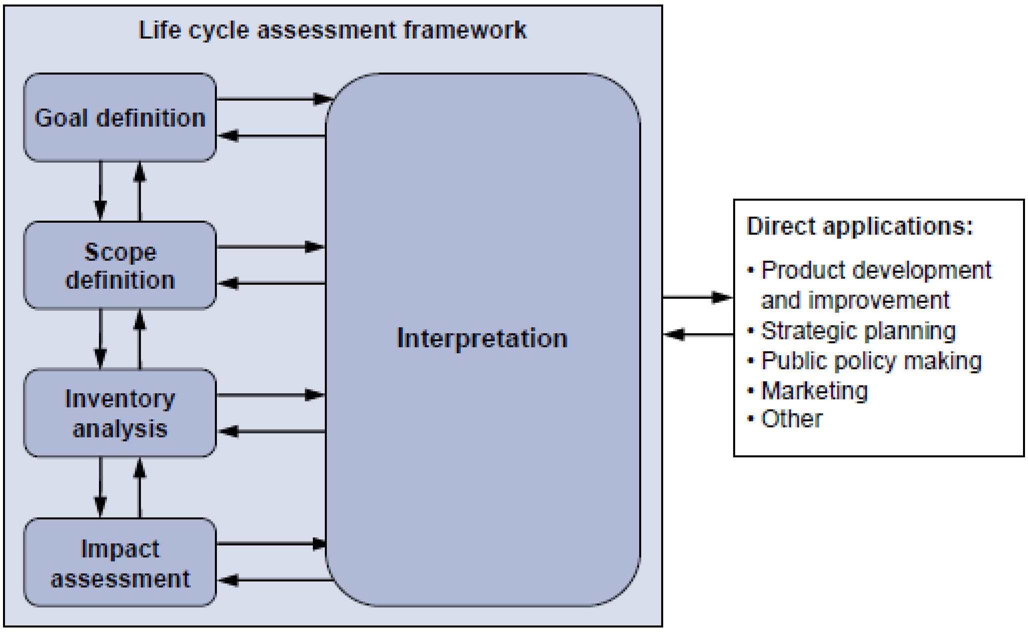


Figure 7: Framework for life cycle assessment (EC-European Commission, 2010)

3.2 LCA Studies on the End-of-Life Phase of Photovoltaic Panels

LCA methodology has been used to evaluate the impacts of each phase in the life cycle of photovoltaic technology. The life cycle approach evaluates the environmental impacts of a PV technology during its life cycle, from raw material production, manufacturing process, use phase and up to the EoL phase. In many LCA studies of photovoltaic technology the end-of-life phase was often omitted due to the long lifespan of photovoltaic panels. Lack of information regarding this EoL phase and recycling technology at the moment of the study was also mentioned as the reasons for this exclusion (Alsema 2000; Reich, Alsema et al., 2011). Many LCA studies focussed more on the production process and energy generation (Alsema and de Wild-Scholten, 2006; Pacca, Sivaraman et al., 2007; Stoppato 2008; Laleman, Albrecht et al., 2011; Perez-Gallardo, Azzaro-Pantel et al., 2014).

However, several LCA studies treated the end-of-life part of PV technology by assuming recycling scenarios (Jungbluth, 2005; García-Valverde, Miguel et al., 2009; Berger, Simon et al., 2010; Zhong, Song et al., 2011; Lamnatou and Chemisana 2014; SASIL, 2014; Stylos and Koroneos, 2014; FEVE, 2015; First Solar, 2015).

In one study, metal components of the module were assumed to be recycled while the silicon metal part was assumed to be landfilled or incinerated (Jungbluth 2005; García-Valverde, Miguel et al., 2009). Another study adopted a scenario in which only 50 % of aluminium was recycled and it showed a low environmental benefit. The study suggested that wider usage of recycling materials in PV components would increase this benefit (Stylos and Koroneos, 2014).

An LCA study was also performed based on the field experiments of Deutsche Solar AG. The LCA study assessed the energy consumption aspect of new crystalline-silicon module production compared to module production using recycled PV wafer. The result showed that recycling process saved two-thirds of the necessary energy for new wafer production. The production of a module with 160 Wp of capacity required 459 kWh/module without recycling and 196 kWh/module with recycling. The environmental impacts of the recycling process are compensated mainly due to the reuse of the recovered wafers. The recycling process was also showed to have a much lower environmental impact compared to incineration with subsequent landfill scenarios (Muller, 2006).

3.3 Project Description: Full Recovery End-of-Life Photovoltaic (FRELP)

SASIL S.p.A. was established in 1975 with the initial objective of supplying raw material for glass production. Since 2005, SASIL has been participating in the EU-funded project 'LIFE ENVIRONMENT' with a focus on glass recovery and treatment from industrial waste. The ongoing SASIL project, in partnership with PV CYCLE Italia's FRELP started on 1 July 2013 with the objective of maximising the recovery of the materials used in photovoltaic panels at their end-of-life phase. The processes that are going to be implemented are based on a sequence of mechanical, thermal and chemical treatments. The project aims to develop an operational pilot-scale plant and, subsequently, to design an industrial scale plant to treat 7 000 tonnes of PV panel waste annually.

SASIL proposed the following two main environmental objectives (SASIL, 2014):

- the recovery of high quality extra clear glass, to be used in the hollow and flat glass industry, thus implying very significant energy and CO_2 emission savings in the glass melting process;
- the recovery of (metallic) silicon, to be used as ferrosilicon in iron silicon alloys or, if pure enough, transformed into amorphous silicon for the production of TFs, thus greatly reducing the energy consumption and CO_2 emissions associated with the production of primary silicon.

The PV module waste generated from different places in Italy is transported and loaded into the treatment plant. First, a mechanical disassembly process is implemented to remove the aluminium frame and the cables/junction box. The module, without frame and cable, is the brought into a high temperature process to separate solar glass from PV sandwich layer. The glass will go through an optical separation process to obtain clean glass for recycling. The remaining sandwich is cut into pieces of 2 x 3 cm before being sent to an authorised incineration plant, assumed to be located 200 km away from SASIL. Afterwards, the pieces of PV sandwich will be sent to an authorised incinerator where the polymer part is burned and energy is recovered from this process.

The remaining ash is sent back to SASIL to be transferred into a sieving process in order to recover the aluminium mixture part from the ash. The residual ash containing silicon metal and various other metals is further treated through an acid leaching process. In the acid leaching process, a solution of water and acid will dissolve the metals, producing metallic oxides, while the silicon metal will remain as a residue. The liquid solution containing dissolved metallic oxides and silicon metal is transferred to a vacuum filtration process where the silicon metal is recovered at metallurgical grade and a part of the acid solution is recirculated.

Afterwards, the residuals from acid leaching are treated with electrolysis to recover silver and copper. The last part of the process consists of the neutralisation of the acid solution containing metal residuals by the addition of calcium hydroxide. The output of this process is subsequently filtered by a filter press, separating liquid waste from the sludge containing unrecovered metals and residual calcium hydroxide. These final wastes are transported to different landfill sites for final disposal.

The recovered materials are expected to be substitutes for primary materials, therefore avoiding the impacts of the production of these materials.

3.4 Goals and Scope of the Study

3.4.1 General

Setting the goals and defining the scope for the initial phase of an LCA study. The scope definition sets the frame for the analysis, while the goal definition synthesises the objective of the study.

The LCA has been applied to the processes and treatments initially designed within the FRELP project.

3.4.2 Scope

The scope of the study is the analysis of the impacts of a PV waste recycling system based on the innovative technologies developed in the FRELP project.

3.4.3 Goal

3.4.3.1 The intended application(s)

The objectives of the present study are the following:

- assessment of the potential environmental impacts of the innovative processes and treatments for the PV waste recycling developed by the FRELP project and identification of the environmental 'hot spot' (potentially significant area);
- analysis of CRM used in Si PV: the LCA is used to verify the capability of LCA to appraise resource security in supply chains;
- comparison of the environmental benefits due to the recycling with the environmental impacts of the production of crystalline-silicon PV panels;
- identification of the potential improvements for the design of PV panels (ecodesign analysis).

3.4.3.2 The reason for carrying out the study and decision context

The reasons for carrying out this study can be divided into two groups depending on the target audience. With respect to the scientific target audience, the LCA aims to assess the environmental benefits of the innovative recycling process and the identification of the factors that most influence the environmental performance of the process. Results can be also useful in disclosing areas of improvement and optimisation of the process.

With respect to the policymakers' target audience, the study is intended to support product policies, highlighting the potential ecodesign improvements that might facilitate the waste management and enhance the environmental performance and resource efficiency of the entire process. Moreover, the study provides an insight into the capability of this process to recover CRMs and therefore to its potential contribution to the EU resource security policy.

3.4.3.3 The intended audience

The target audience of this case study is the following:

- the company SASIL, which will benefit from the results in identifying potential areas of improvement to the plant under design within the FRELP project;
- policymakers, for the development of product policies and policies related to raw materials/resource efficiency fields;
- manufacturers, who will benefit from the results by being able to develop more resource-efficient PV technologies;
- recyclers, who will benefit from the results with the ability to develop innovative recycling plants for PV waste;
- the scientific community, which will benefit from the results by being able to improve the quality and detail of the modelling of the EoL of PV panels in LCA.

3.4.3.4 Functional unit

The functional unit of the analysis is the treatment of 1 000 kg of crystalline-silicon PV waste in a recycling plant, based on the processes and technologies developed in the FRELP project.

3.4.3.5 System boundary

The system boundary of an LCA defines the unit processes to be included in the system. The system boundary should take into consideration elements such as raw materials acquisition, inputs and outputs in the main processing sequence, distribution, use of fuels, electricity, and heat and so on. The boundary of the evaluated system includes all the processes for the treatment of PV waste, from the waste collection up to the separation of recyclable/recoverable fractions. The system boundary of the LCA includes:

- the transport of PV waste to the recycling plants;
- impacts([6]) due to the innovative recycling processes developed by the FRELP project;
- impacts due to additional recycling processes (incineration of PV sandwich([7]), treatment of electric cables);

([6]) These include the consumption of energy and auxiliary materials, and emissions to the environment.
([7]) The analysis also includes the benefits of the energy recovered during the incineration of plastic materials.

- impacts due to the transport and disposal of residual materials.

The diagram of the study's system boundaries is shown in Figure 8 (confined within the big square).

Furthermore, the evaluation of the environmental benefit of recycling PV waste is performed by expanding the system boundary. The extended system boundary includes the impacts of the secondary raw material production process and the avoided impact of primary raw materials production. The secondary material production process has been based on studies and data available in the scientific literature.

The analysis of the impact and benefits of the recycling of PV waste is presented in the interpretation phase.

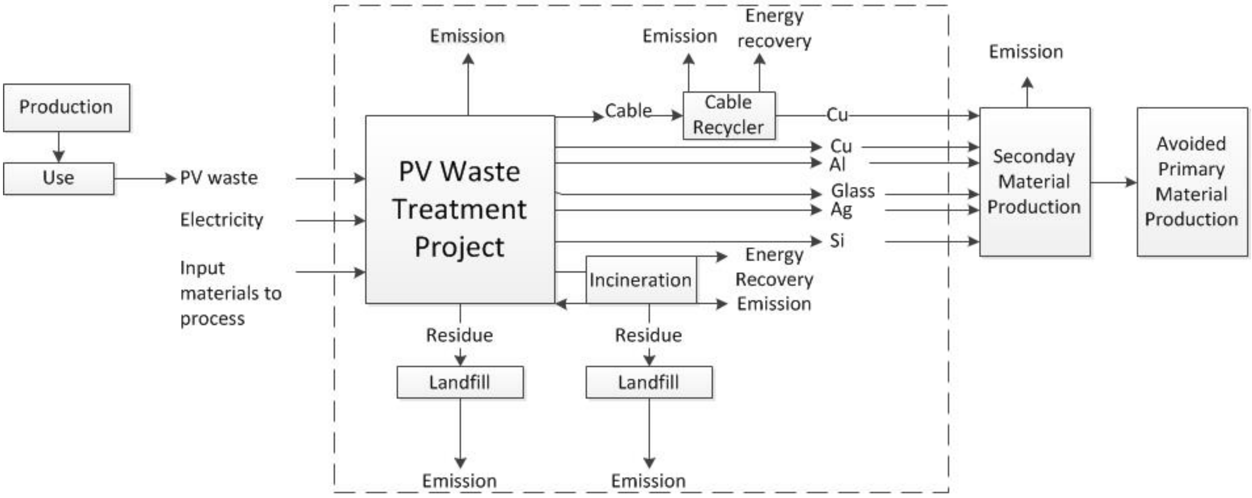


Figure 8: System boundaries of the case study

3.4.3.6 The product system under study

The innovative recycling process for PV waste developed by the PV waste treatment project consists of a sequence of 12 unit processes (Figure 9) that are almost all expected to occur within an innovative recycling facility (to be built on SASIL premises). Only two processes are carried out in external facilities: the incineration of the PV sandwich and the treatment of electrical cables.

The analysis of each unit process has been performed jointly with the experts of the FRELP project to obtain primary data input for the LCA. This section provides a detailed description of each unit of process.

1. Transport of waste PV modules to the recycling facility

This phase includes transferring waste PV panel to the recycling facility. The PV waste is assumed to be transported by a truck with maximum capacity 7.5 tonnes to a local collection area located at a distance of 100 km. The PV waste from this local collection point is then transported to the recycling facility. The PV waste from the collection point is assumed to be transported by a truck with maximum capacity 32 tonnes. The distance from the collection point to SASIL site is assumed to be 400 km.

2. **Unloading of the waste panels**

The PV waste is unloaded using a forklift and then transferred onto a conveyor belt that transports the modules to the dismantling part. The process is expected to unload 1 tonne of PV waste per hour.

3. **Disassembly**

At the end of the conveyor belt, a robotic system will be used to dismantle the PV waste. The aluminium frame and cables/junction box are separated from the layer of photovoltaic cells, glass and polymers. The aluminium and cables are separated into different containers to be sent to further recyclers, assuming both are located 100 km away from the recycling plant.

4. **Cable treatment**

Cables are separated from the PV waste during the disassembly process. These cables are sent to a separate plant for cable recycling([8]), assumed to be located at a distance of 100 km from the recycling facility. The cable treatment is assumed to involve automated cable chopping. The metal recovery from this process is around 94-99 % (Lenka Muchova, 2011).

5. **Incineration of cable polymers**

The polymers of cables from the cable treatment are assumed to be incinerated with energy recovery.

6. **Glass separation**

The objective of this process is to separate glass from the PV sandwich. This is done by putting the panels into a furnace with a controlled atmosphere to separate the glass from the sandwich of EVA containing silicon metal and other materials.

In the pre-prototype plant, the heat treatment prior to the detachment was made with a mixed system for medium- and short-wave infrared. The separation occurs by means of a device with a high frequency knife button and modulated in amplitude and speed (SASIL, 2014). The process requires electricity during its operation.

The output of this process is the separated glass from the PV sandwich. The sandwich layer undergoes a cutting process while the glass is treated further in the next phase, by an optical process.

7. **Glass refinement**

The optical glass separation process aims to separate the pieces of clean glass from those contaminated by polymers. In this process, the glass output from the thermal process is separated by sieving into two size categories: 1-2.5 mm in diameter and 2.5-5 mm. Optical separation is applied to remove the contaminated part. The process consumes electricity during operation. The efficiency of this process is approximately 98 %.

The recovered glass is sent to the glass recycler while residuals are assumed to be sent to landfill with at a distance of 100 km from the recycling plant.

([8]) According to the literature, the predominant method for recycling electrical cables is via an automated process, which implies, cable chopping, granulation, screening, and density separation.

8. Cutting of modules

In this process, the PV sandwich from the thermal process containing silicon metal, polymer and various materials is cut into 2 x 3 cm pieces. The objective of this process is to facilitate treatment in the following step. The cutting of the sandwich requires electricity during its operation.

9. Incineration of encapsulation and back-sheet layer with energy recovery

An encapsulation layer is a polymer used for binding all the components of PV together and to protect the components of PV modules from foreign impurities, moisture and mechanical damage. It also plays a role as an electrical insulator between cells/interconnects. In order to perform these functions, an encapsulation layer is expected to have a high light transmittance, good thermal conduction and operating range (Hasan and Arif, 2014). In the 1960s and the 1970s, polydimethylsiloxane (PDMS)/silicone was used as an encapsulation for PV modules, but from the 1980s to the present day, EVA is the most commonly used material mostly due to its low cost (Hasan and Arif, 2014).

According to laboratory tests conducted on samples of PV waste, panels may contain chlorine in the form of PVC (Polyvinyl Chlorine) or fluorine in the form of Polyvinyl Fluorine (PVF) within the back-sheet layer (SASIL, 2014). This halogenated-back-sheet PV waste has to be thermally treated in an authorised facility. This study focuses on the treatment of fluorine-back-sheet PV waste. In this study, it is assumed that the sandwich is treated in an external authorised incineration plant located at a distance of 200 km from the recycling plant. After the incineration, the residual ash containing silicon and other recyclable metals is collected. The ash is sent back to the recycling plant to be further treated. The energy released during the incineration is assumed to be recovered in the form of heat and electricity([9]).

A part of the fly-ashes, consisting approximately 0.2 % of the PV module weight is sent to the hazardous landfill, assuming a distance of 50 km from the incineration plant.

10. Sieving

Once ashes are returned to the recycling plant, they are treated via sieving. The objective of this process is to separate residues of aluminium connectors (originally used in the sandwich) from the ashes. The efficiency of this process in separating aluminium is approximately 50 %. The residues are therefore transferred to the acid leaching phase. This process uses electricity during its operation.

11. Acid leaching

The objective of this phase is to recover silicon metal from the ash. The silicon metal is separated using a solution of water and 65 % nitric acid (HNO_3). During the leaching process, the ash containing metals is mixed with the solution of water and nitric acid (HNO_3), which dissolves the metals (producing various metallic oxides) and leaves the silicon metal in the residues.

The acid leaching treatment phase is designed to treat 308 tonnes of ash per year which is 61 kg per hour. This process is expected to recover silicon metal as MG silicon with

([9]) Emissions and energy outputs of the incineration refer to average data on a plastic incineration plant in the literature.

95 % efficiency. The remaining silicon and other dissolved metals in the acid solution are subsequently treated in a filtration phase.

In addition to the acid solution, this process uses electricity during its operation. However it has not been possible to be estimate the electricity consumption.

12.Filtration

The mixture containing the dissolved metallic oxides and the silicon metal residues from the acid leaching process is transferred to a vacuum filtration process. In this phase, the silicon metal is recovered and a part of the acid solution is recirculated (around 80 %).

13. Electrolysis

The last part of the metal separation is expected to be flexible depending on the target materials to be recovered. In fact, the composition of the silicon PV panel can change over the time (especially when the lifespan of the product is very long). Therefore, the recycling processes should be adapted accordingly.

According to the literature and laboratory tests conducted within the PV waste treatment project, the main recoverable metals that are present in the residuals after the leaching are silver, copper, lead and tin. In this analysis, silver and copper are expected to be recovered (with an efficiency of 95 %). The electrolysis process also emits NOx gases at the anode of the electrolysis (estimated at 2 kg per tonne of PV waste treated). The remaining metal residues remain in the solution to be further neutralised. Electricity is used as input energy for the electrolysis.

14. Neutralisation

In this process, the acid solution in output from the electrolysis is neutralised completely by the addition of calcium hydroxide — $Ca(OH)_2$). The final output of the neutralisation process is a sludge containing calcium nitrate — $Ca(NO_3)_2$ — liquid, residual calcium hydroxide and unrecovered metals.

The specific electricity consumption for sieving, acid leaching and electrolysis is approximately 1.29 kWh/kg of ash input.

15. Filter press

In this phase, the output of the neutralisation is filtered, which mainly involves separation of the liquid waste part (constituted by water and calcium nitrate) from the sludge containing the unrecovered metals with some residual calcium hydroxide (classified as hazardous waste). These wastes are finally transported to different landfills (assumed to be 100 km away) for the final disposal.

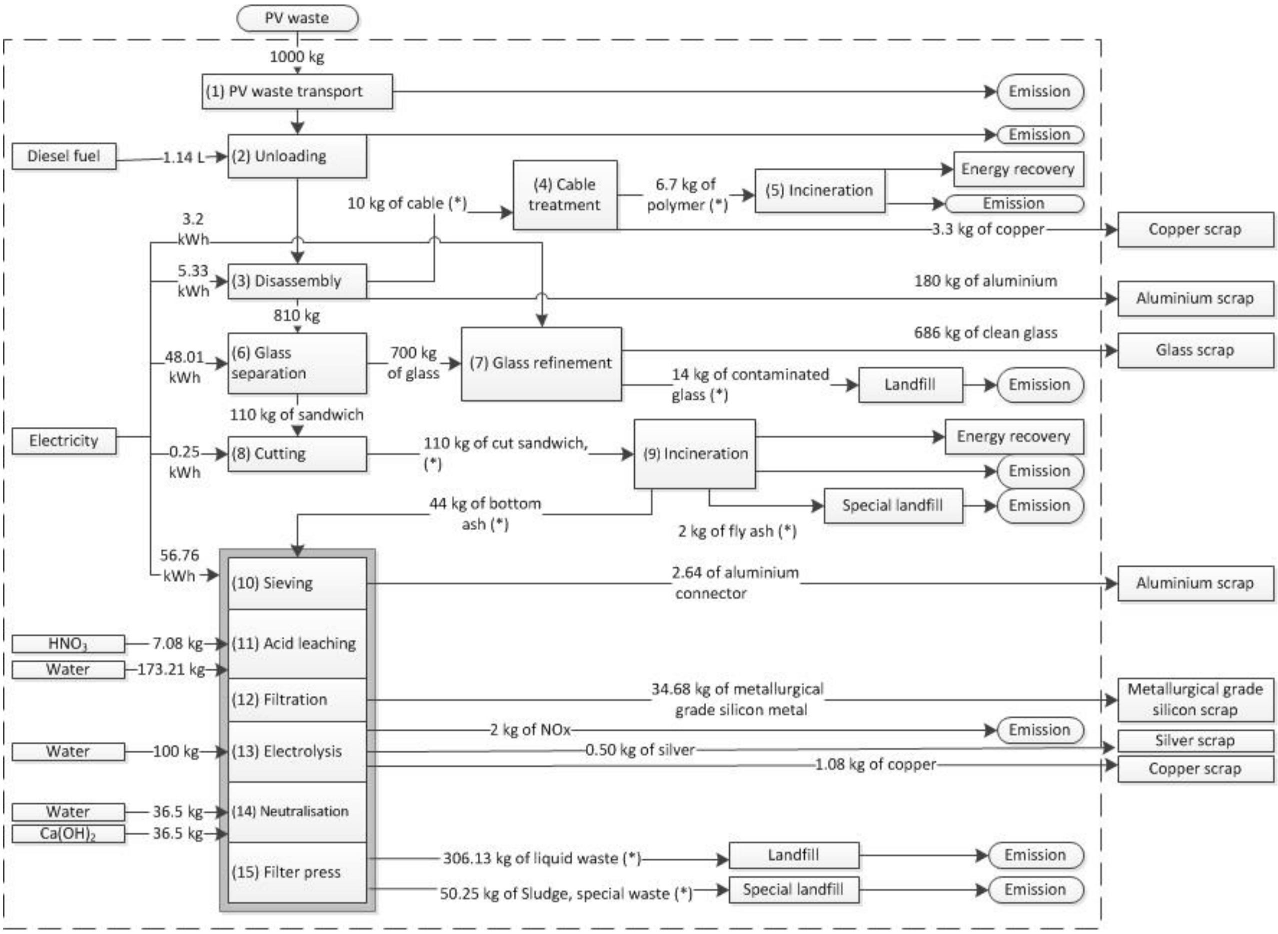


Figure 9: Detail of the recycling process studied (transport between the processes is indicated with an asterisk (*))

3.4.3.7 Material and energy recovery credit

The PV waste treatment process that was studied is expected to recover several materials, mainly aluminium, from the frame and internal connectors, copper, cables, glass, silicon metal and silver. Energy is also expected to be recovered from the incineration of the encapsulation and back-sheet layer.

The recoverable materials are assumed to substitute primary materials, therefore avoiding the impacts of the production of these primary materials. The assumptions regarding the calculation of the environmental saving (benefits) for each recovered material are further detailed in the following paragraphs.

- **Aluminium**

The recycling of aluminium has been an important activity in Europe for some decades. The production of aluminium from scrap can cut energy consumption by up to 95 % compared to primary aluminium. Before the processing of aluminium scrap, the scrap has to be controlled to meet certain levels of quality. Scrap types in Europe have been standardised since 2003 by the European Standard EN. Refiners and smelters, the two important players in aluminium recycling, have specialised over the years to treat different kinds of aluminium scrap. Clean scrap can be directly shredded or baled to be sent for subsequent handling. Large scrap pieces are fragmented to separate iron from the aluminium. Aluminium cans are often cleaned to remove coatings and residues. These scraps are then melted and formed into ingots or transported directly as molten metal (Alueu and OEA, 2007). Aluminium EoL recycling rates in Europe range from 55-63 % for packaging/beverage cans, 95 % for building and construction, and 95 % in transport sector (Labberton, 2011).

In the recycling process studied, at least 180 kg of aluminium scrap is expected to be obtained from the disassembled PV panel frames and 2.64 kg from the solar-cell internal connector after the sieving process. The recovered aluminium is assumed to be aluminium scrap suitable for producing secondary aluminium. The scrap is assumed to be transported from the recycling facility site to further treatments for the production of secondary aluminium. This aluminium is supposed to substitute primary aluminium, therefore avoiding the impacts of the production of primary aluminium.

- **Treatment of Cables**

In this study, the copper part of the cable in the cable treatment plant is assumed to be sent to a copper recycler at a distance of 100 km from the cable recycler. The polymer part of the cable that might contain PVC is assumed to be treated in an authorised incineration plant located at a distance of 200 km from the cable recycler. Energy is expected to be recovered from the incineration of the polymer.

In general, the metal recovery rate from cable scrap is around 94-99 % (Lenka Muchova, 2011). In this study, the copper recovery rate from the cable treatment process is assumed to be an average of 96.5 %. The estimated amount of recovered energy per kg of incinerated polymer is 2.86 MJ/kg of electricity and 5.8 MJ of heat([10]).

- **Glass**

Glass can be recycled without affecting its properties too much. The recovery process of 1 tonne of PV panel is expected to generate 686 kg of low iron scrap glass. The glass scrap is assumed to be collected as glass cullet. The glass cullet is assumed to substitute the raw materials for primary packaging glass production. The production of glass from glass cullet consumes 25 % less energy compared to the production of primary glass (FEVE 2015). The transport distance from the recycling facility to the glass recycler is assumed to be 100 km.

- **Copper**

Recycling of copper is common in Europe. In 2010, recycled copper scrap accounted for 40 % of the total copper refined production (European Copper Institute, 2013). Copper is used in many applications, both in its pure forms or as an alloy with other materials. This fact makes the recycling rate of copper dependant on the nature and quality of waste and the efficiency of the recycling treatments. However, a great part of copper scrap and residues is transformed into secondary refined copper shapes through smelters and refineries (Ruhrberg, 2006).

([10]) Emissions and energy outputs of the incineration refer to average data on a plastic incineration plant in the literature (Ecoinvent)

The expected quantity of copper recovered directly from the PV waste treatment plant is 1.14 kg for every 1 000 kg of panel. Copper is assumed to be collected as copper scrap and transported to a copper recycler. The copper scrap is expected to be used to produce secondary copper. In this study, the recycling rate of copper is assumed to be 96.5 %. The environmental benefit of the copper recycling is related to the avoided impacts of the production of primary copper. The transport distance to the copper recycler is assumed to be 100 km.

- **Encapsulation and back-sheet layer**

Normally, the encapsulation layer can be made of EVA, polyvinyl butyral (PVB), polydimethylsiloxane (PDMS), or thermoplastic polyurethane (TPU). In this case study, the encapsulation layer is assumed to be made of EVA, which is the most common type in the market at the moment. The adhesive layer is incinerated and energy is expected to be recovered from this process.

According to the laboratory analysis done as part of the FRELP project, there are mainly two categories of back-sheet layer: The first type, which is the focus of this LCA study, is the halogenated-contained back-sheet. This type of back-sheet layer is incinerated together with the adhesive layer and energy is recovered from this process. The second type is non-halogenated back-sheet layer which would undergo a different treatment path.

The EVA encapsulation layer and the fluorine-containing back-sheet layer are incinerated in an authorised plant. The incineration process is expected to recover energy. The amount of recovered energy per kg of this layer is 3.48 MJ/kg of electricity and 7.03 MJ of thermal energy, referring to mixed plastic([11]).

- **Silicon Metal**

The silicon metal recovery rate in the process is assumed to be 95 %. The recovered silicon metal scrap from the treatment is assumed to substitute MG silicon metal thereby avoiding the environmental impacts related to its production.

- **Silver**

In crystalline-silicon based PV technology, silver is utilised for the metallisation of the modules. Silver belongs to the group of precious metals, together with gold, ruthenium, rhodium, palladium, osmium, iridium and platinum. The silver used in PV is estimated to be 10 grams of silver/m^2 of PV panel. Silver is one of the main cost drivers in the cell manufacturing process even though it is present in very low quantities (Grandell and Thorenz, 2014). Global silver markets handle in the range of 35 000 metric tonnes a year, mainly from the mining sector (65 %) (Grandell and Thorenz, 2014).

The recycling of silver scrap plays an important role in the silver market by accounting for one-third of the total market (Grandell and Thorenz, 2014). In the past, the main source of recycled silver came mainly from the photographic sector. Nowadays, the main sources of recycled silver are some industrial sectors, consisting of electronic scrap, jewellery as well as the photographic sector. Silver in PV panels can be recovered through electrolysis or through precipitation in a leaching solution (Grandell and Thorenz, 2014).

([11]) Emissions and energy outputs of the incineration refer to average data on a plastic incineration plant in the literature (Ecoinvent)

Silver is used in relatively small quantities in metallisation paste of PV panel. In the recycling process studied, the quantity of silver recovered is expected to be 0.5 kg per tonne of PV panel waste. The silver separated from the recycling processes is assumed to be used for the production of secondary silver. This is supposed to replace an average primary silver, thus avoiding the impacts of primary silver production. The silver recycler is assumed to be located 100 km from the plant.

3.4.4 Limitations of the study and sources of uncertainty

The uncertainty related to the study results mainly from three different aspects: availability and accuracy of the data used for the compilation of the inventory; the robustness of the LCIA methods and the assumptions and simplifications made in the study.

3.4.4.1 Limitations related to the data

The main limitations related to the data in this LCA study are the following:

- The PV waste treatment is currently at a design phase. The data regarding the impacts of the recycling plant are, therefore, estimates based on the pilot-scale project plant and do not necessarily reflect the real future plant operation data.
- The data used in the LCI modelling are taken from the Ecoinvent 2.2 database. However, these data are in some cases not recent and nor do they refer fully referring to the Italian context. In some cases, average data have been used (e.g. for the estimation of impacts of incineration and landfill and for the estimation of impacts of secondary material production).
- During the life cycle interpretation phase, the LCIA results were compared with some estimated impacts due to the production of new c-Si PV panel. However, the impacts of this manufacturing process are rough estimates, mostly based on average data available in the Ecoinvent database.

3.4.4.2 Robustness of the impact methods

The impact assessment of the process and the benefit of the recycling of materials are modelled in SimaPro software version 8.0. The ILCD midpoint method was selected to model the potential environmental impacts. It includes the following 16 impact categories (EC-European Commission, 2010):

1. climate change,
2. ozone depletion,
3. human toxicity, cancer effects,
4. human toxicity, non-cancer effects,
5. particulate matter,
6. ionising radiation HH,
7. ionising radiation E (interim),
8. photochemical ozone formation,
9. acidification,
10. terrestrial eutrophication,
11. freshwater eutrophication,
12. marine eutrophication,

13. freshwater ecotoxicity,
14. land use,
15. water resource depletion,
16. mineral, fossil and renewable resource depletion.

Environmental impact methods are recommended by the 'ILCD Handbook: Recommendations for LCIA in the European context — based on existing environmental impact assessment models and factors'([12]) ([13]) (Table 5). Based on this classification, one should also be aware that the degree of confidence of the LCA results differs across the impact categories considered. For more information, reference will be made to the ILCD Handbook — Recommendations for LCIA in the European context, Chapter 2([14]).

([12]) Available online at http://lct.jrc.ec.europa.eu/assessment/publications.

([13]) The characterisation models and associated characterisation factors are classified according to their quality into three **levels: level 'I'** (recommended and satisfactory), **level 'II'** (recommended but in need of some improvements) or **level 'III'** (recommended, but to be applied with caution). The classification, **'interim'** indicates that a method was considered the best among the analysed methods for the impact category, but is still not ready to be recommended. For this reason, the impact category **'ionising radiation, ecosystem'** has been excluded from the impact assessment.

([14]) Available online at http://lct.jrc.ec.europa.eu /publications.

Table 5: ILCD recommended methods for impact assessment

Impact category	Recommended default LCIA method	Indicator	Classification
Climate change	Baseline model of 100 years of the IPCC	Radiative forcing as global warming potential (GWP100) (kg CO_2-eq)	I
Ozone depletion	Steady-state ODPs 1999 as in WMO assessment	Ozone depletion potential (ODP) (kg CFC-11 equivalent)	I
Human toxicity, cancer effects	USEtox model (Rosenbaum et al., 2008)	Comparative toxic unit for humans (CTUh)	II/III
Human toxicity, non-cancer effects	USEtox model (Rosenbaum et al., 2008)	Comparative toxic unit for humans (CTUh)	II/III
Particulate matter/Respiratory inorganics	RiskPoll model (Rabl and Spadaro, 2004) and Greco et al. 2007	Intake fraction for fine particles (kg PM2.5-eq/kg)	I
Ionising radiation, human health	Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al., 2000)	Human exposure efficiency relative to U235 (kg U235-eq)	II
Ionising radiation, ecosystems	Interim (excluded from the impact assessment)		
Photochemical ozone formation	LOTOS-EUROS (Van Zelm et al., 2008) as applied in ReCiPe	Tropospheric ozone concentration increase (kg NMVOC eq)	II
Acidification	Accumulated exceedance (Seppälä et al. 2006, Posch et al., 2008)	Accumulated exceedance (molc H^+-eq)	II
Eutrophication, terrestrial	Accumulated exceedance (Seppälä et al. 2006, Posch et al., 2008)	Accumulated exceedance (AE) (molc N-eq)	II
Eutrophication, freshwater	EUTREND model (Struijs et al., 2009) as implemented in ReCiPe	Fraction of nutrients reaching freshwater end compartment (P) (molc P-eq)	II
Eutrophication, marine	EUTREND model (Struijs et al., 2009) as implemented in ReCiPe	Fraction of nutrients reaching or marine end compartment (N) (molc N-eq)	II

Impact category	Recommended default LCIA method	Indicator	Classification
Ecotoxicity, freshwater	USEtox model, (Rosenbaum et al., 2008)	Comparative toxic unit for ecosystems (CTUe)	II/III
Land use	Model based on soil organic matter (SOM) (Milà i Canals et al., 2007)	Soil organic matter (kg C deficit)	III
Resource depletion, water	Model for water consumption as in Swiss Ecoscarcity (Frischknecht et al., 2008)	Water use related to local scarcity of water (kg)	III
Resource depletion, mineral, fossil and renewable	CML 2002 (Guinée et al., 2002)	Scarcity (kg Sb eq)	II

In this study, the 'Mineral, fossil and renewable resource depletion' impact category has been subdivided into 'Abiotic depletion, fossil' and 'Abiotic depletion, mineral' (L. Van Oers, 2002). The land use impact category was not taken into consideration in this analysis due to its high uncertainty.

3.4.4.3 Key modelling assumptions

A number of assumptions and simplifications have been made in conducting this case study. These assumptions may influence the overall results of the analysis (see section 3.4.4 for a detailed discussion of assumptions). Assumptions have also been made to estimate the credits assigned to the end-destination of the recoverable materials of PV waste. The recovered/recycled materials and energy are assumed to produce some environmental benefits in terms of avoided energy sources and production of primary materials.

3.4.5 Data quality requirements

As described in the ILCD Handbook (General guide for LCA – detailed guidance, Chapter 12.2)([15]), the six criteria adopted for evaluating the data's quality are:

- technological representativeness: defines the degree to which the datasets reflect the true population of interest regarding technology, including background datasets;
- geographical representativeness: defines the degree to which the datasets reflect the true population of interest regarding geography, including for included background datasets;

([15]) Available online at http://eplca.jrc.ec.europa.eu/?page_id=86.

- time-related representativeness: defines the degree to which datasets reflect the true population of interest regarding time/age of the data, including for included background datasets;
- completeness: defines the share of (elementary) flows that are quantitatively included in the inventory;
- precision/uncertainty: defines the measure of the variability of the data values for each data expressed;
- methodological appropriateness and consistency: defines if the applied LCI methods and methodological choices (e.g. allocation, substitution, etc.) are in line with the goal and scope of the data set, especially its intended applications and decision support context.

Each data quality criterion is evaluated according to the following rating:

- very good: meets the criterion to a very high degree, no relevant need for improvement;
- good: meets the criterion to a high degree, little need for improvement;
- fair: meets the criterion to a sufficient degree, still some need for improvement;
- poor: does not meet the criterion to a sufficient degree, needing relevant improvement;
- very poor: does not meet the criterion at all, needing very substantial improvement.

Data quality is only evaluated here for data used to cover foreground processes. It should be noticed that data covering foreground processes can be both foreground or background data, depending on where they are sourced.

Overall, the quality of the data used for foreground processes is judged as follows:

- technological representativeness: Good,
- geographical representativeness: Fair,
- time-related representativeness: Fair,
- completeness: Good,
- precision/uncertainty: Fair,
- methodological appropriateness and consistency: Good.

3.5 Life Cycle Inventory Analysis

3.5.1 General

Inventory analysis is the activity of data collection and calculation used to quantify the relevant inputs and outputs of a product system. The process of conducting an inventory analysis is iterative. New data requirements may be identified during the activity.

In this study, attributional LCI modelling has been applied to assign the potential environmental impacts and benefits from the PV waste treatment process and the benefit from recovery of several materials.

3.5.2 Data collection

According to ISO 14044, the data for each unit process within the system boundary are classified under the following headings:

- inputs: energy, raw material, ancillary and other physical inputs;
- products, co-products and waste;
- emissions to air, discharges to water and soil;
- other environmental aspects.

The main data requirement in this study is the data of the PV waste treatment based on the PV waste treatment project. The foreground data in PV waste material recovery processes were gathered by interviewing the company's experts.

The data from the incineration process and the cable treatment — which are necessary for the PV recycling process — refer to the average data available in the Ecoinvent database.

Other required information includes the further treatment of separated material for the production of secondary raw materials. These data refer to the average data available in the Ecoinvent database.

3.5.3 Data calculation

The quantity of inputs and outputs in this study has been calculated according to the functional unit, the treatment of 1 000 kg of crystalline-based photovoltaic waste.

3.5.4 Assumptions

The following assumptions have been considered in this case study:

- *C-si PV waste input*. The input of the recycling process is 1 000 kg of crystalline-silicon PV panel waste generated in Italy. The composition of the PV module is based on laboratory tests provided by the FRELP project (Table 6). The mass of each panel is approximately 22 kg for an area of 1.6 m^2.

Table 6: Crystalline-silicon based PV panel composition.

Material	Quantity	Unit	(wt/wt)
Glass, containing antimony (0.01-1 %/kg of glass)	700	kg	70 %
Aluminium frame	180	kg	18 %
Copper connector	10	kg	1 %
Polymer-based adhesive (EVA) encapsulation layer	51	kg	5.1 %
Back-sheet layer (based on polyvinyl fluoride)	15	kg	1.5 %
Silicon metal solar cell	36.5	kg	3.56 %
Silver	0.53	kg	0.053 %
Aluminium, internal conductor	5.3	kg	0.53 %
Copper, internal conductor	1.14	kg	1.14 %
Various metal (tin, lead)	0.53	kg	0.053 %
Total	**1 000**	**kg**	**100 %**

- *PV panel production.*
  The final result of the LCIA is also compared to the impacts of the production of a new PV panel. The PV panel is assumed to be produced in Europe with average

European technology. The transportation of each material to the manufacturer company has not been taken into account. The life cycle inventory of the PV panel production refers to average data from Ecoinvent database.

- *Material recyclers*. The recyclers of aluminium, copper, glass and silver are assumed to be located 100 km away from the company's treatment plant in Italy. In the case of silicon metal, the silicon metal is recovered as ready-to-sell metal.
- *Substituted materials.* In the case of aluminium, copper and silver, the expected recovered/recycled materials are assumed to substitute primary materials. The recovered solar glass is assumed to be down-cycled into glass for packaging; electronic-grade silicon metal used in photovoltaic panels is assumed to be recovered as MG silicon metal with lower purity. The complete list of the assumptions of material substitution from materials recycled from the PV waste treatment is shown in Table 7.
- *Energy recovery* (Table 8). The incineration of encapsulation and back-sheet layer and polymer from cable is expected to produce energy. The amount of energy recovered from this process has been estimated on the basis of average data from the incineration process of plastic mix in Switzerland (Ecoinvent data). The energy content of the cable encapsulation refers to incineration of plastic wire waste in municipal waste incineration in Switzerland (Ecoinvent data).

Table 7: Materials whose production is avoided due to material being recycled from the PV waste treatment

Avoided Production of primary materials	Quantity	Unit
Primary aluminium	182.65	kg
Raw materials for the production of primary white glass for packaging	686	kg
Primary copper	4.38	Kg
Primary Metallurgical-grade silicon metal (MG-Si)	34.68	kg
Primary silver	0.50	kg

Table 8: Energy recovery from the PV waste treatment per kg of material

Material	Energy recovered	Energy content per kg	Unit
Polymers from cable	Electricity production	2.86	MJ
	Thermal energy	5.80	MJ
PV encapsulation and back-sheet layer	Electricity production	3.48	MJ
	Thermal energy	7.03	MJ

3.5.5 Life cycle inventory analysis, modelling the system, life cycle inventory calculation

The inventory analysis involves data gathering and certain calculations necessary to quantify the inputs and outputs of the PV waste treatment. Data are related to the foreground and background systems, as described below.

3.5.5.1 Data for the foreground system

The foreground data (or primary data) in this study were provided by the company SASIL during the development of the FRELP project. Data collection was conducted through interviews with the company's experts. The company provided the description of the plant operation, the inputs and outputs of each process, and the further treatments and potential final destination of the different material flows separated. The primary data were obtained by the company through:

- estimations of each unit process in the pilot plant;
- laboratory tests to analyse the composition of the PV waste.

The data have been continuously updated/reviewed with SASIL's experts to be in line with the development of the FRELP project. When possible, data and assumptions have also been checked against available information in the literature to grant the robustness of the modelled system.

3.5.5.2 List of background datasets used in the life cycle inventory modelling

Inventory data from the background system (the production of primary and secondary materials, production of energy sources and transport) refer to the information available in LCA databases. The list of the selected datasets is shown in Table 9.

Table 9: List of selected Ecoinvent datasets and related processes in PV waste recycling

Item	Used for the process phase	Datasets used
Electricity	Disassembly, cable treatment, glass separation, glass refinement, cutting of PV sandwich, sieving, acid leaching, filtration, electrolysis, neutralisation and filter press	Electricity medium voltage at grid/IT
Diesel fuel	Unloading	Diesel burned in building machine/GLO
Transport	Transport of PV waste to the recycling plant	Transport lorry 16-32 t EURO5/RER
	Transport of: PV waste to local collection point; cables to cable treatment plant and cable polymer to the incineration plant; glass residue to landfill; PV sandwich to incinerator; ash to the treatment plant; fly ash to special landfill	Transport, lorry 3.5-7.5 t, EURO5/RER
	Transport of sludge from the recycling plant to landfills	Transport lorry 7.5-16 t EURO5/RER
Treatment for the recycling of cables	Cable treatment	Disposal, treatment of cables/GLO
Landfilling of the contaminated glass	Glass refinement	Disposal glass 0 % water to inert material landfill/CH

Item	Used for the process phase	Datasets used
Incineration of EVA	PV sandwich incineration	Disposal, plastics, mixture, 15.3 % water, to municipal incineration/CH
Incineration of PVF	PV sandwich incineration	Disposal, polyvinylfluoride, 0.2 % water, to municipal incineration/CH
Incineration of plastics from cables	Cable treatment	Disposal, wire plastic, 3.55 % water, to municipal incineration/CH
Disposal of fly ash in a landfill	Incineration	Disposal average incineration residue 0 % water to residual material landfill/CH
Production of electricity (impacts avoided from energy recovery during the incineration)	Incineration of cable polymer and PV sandwich, energy recovery	Electricity medium voltage at grid/IT
Production of heat (impacts avoided from energy recovery during the incineration)	Incineration of cable polymer and PV sandwich, energy recovery	Heat natural gas at industrial furnace >100 kW/RER
Water	Acid leaching, electrolysis, neutralisation	Water, completely softened, at plant/RER
Nitric acid	Acid leaching	Nitric acid 50 % in H_2O at plant/RER
$Ca(OH)_2$	Neutralisation	Lime hydrated loose at plant/CH
Landfilling of inert sludge	Filter press	Disposal, limestone residue, 5 % water, to inert material landfill/CH S
Landfilling of sludge with metal residuals	Filter press	Disposal, sludge, pig iron production, 8.6 % water, to residual material landfill/CH S

3.5.6 LCI results

The inputs and outputs of the system under study are presented in Table 10, while the material and energy flows diagram of the PV waste treatment is shown in Figure 10.
Several materials are expected to be recovered from photovoltaic waste after going through the material separation processes as developed in the PV waste treatment. Energy is expected to be recovered from the incineration of EVA and back-sheet layer. The calorific value of these polymers refers to the calorific value of mixed plastics.

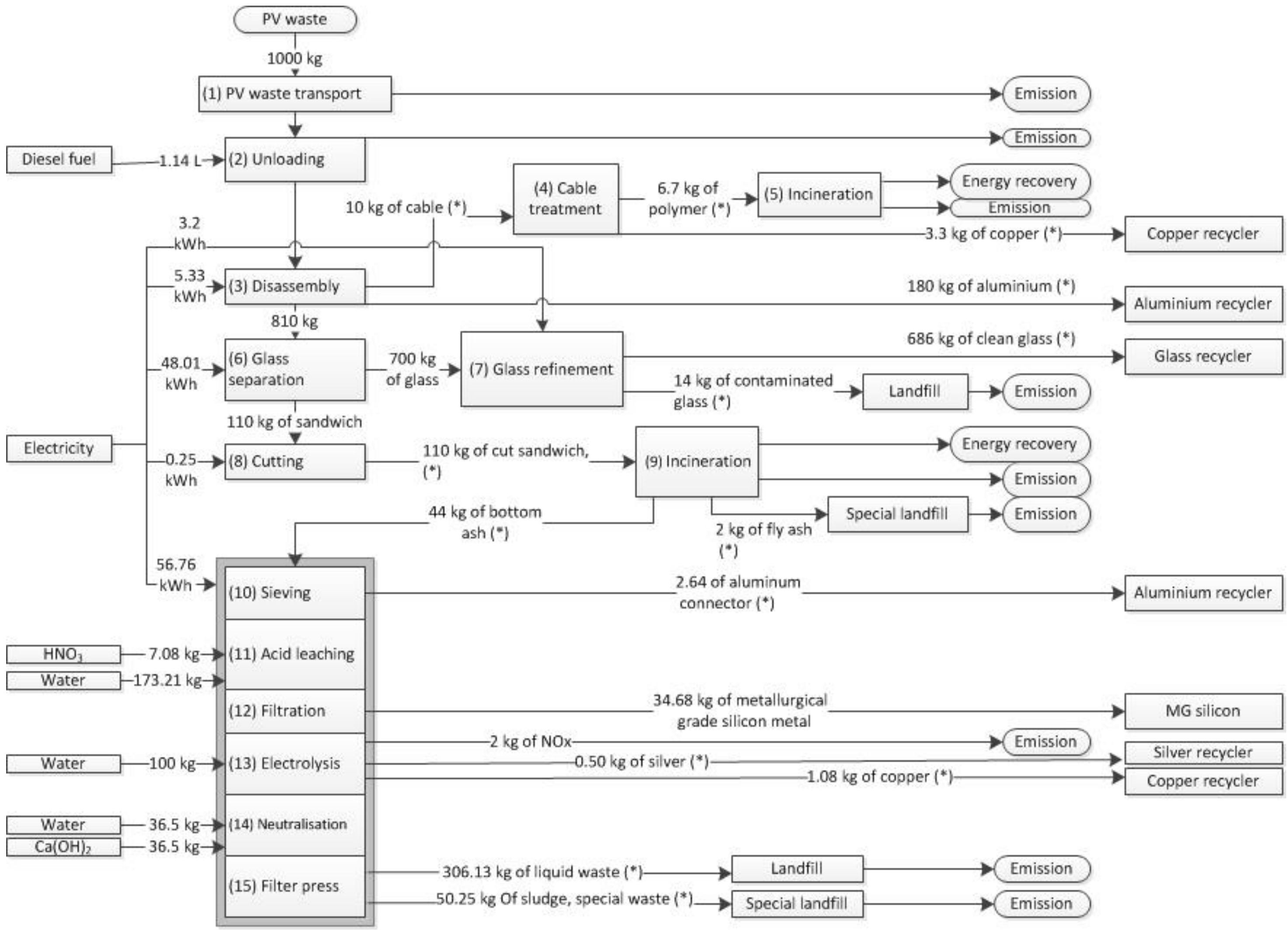


Figure 10: Material and energy flow diagram of the PV waste treatment process

Table 10: Life cycle inventory data of PV waste treatment project

Input/output	Quantity	Unit	Note
Input			
PV waste	1 000	kg	
Electricity	113.55	kWh	Required in various treatment processes such as: disassembly, glass separation, cutting, sieving, acid leaching, electrolysis
Diesel fuel	1.14	L	Unloading
Water	309.71	kg	Water consumption for acid leaching, electrolysis and neutralisation process
HNO_3	7.08	kg	Acid leaching process
$Ca(OH)_2$	36.5	kg	Neutralisation of acid solution
Output, recovered materials			
Aluminium scrap	182.65	kg	
Glass scrap	686	kg	
Copper scrap	4.38	kg	
MG silicon (metallurgical-grade silicon metal)	34.68	kg	
Silver	0.5	kg	
Output, energy recovery			
Electricity	248.84	MJ	Produced by the incineration of PV Encapsulation, back-sheet layer and polymers from cables
Thermal Energy	502.84	MJ	Produced by the incineration of PV Encapsulation, back-sheet layer and polymers from cables
Output, waste to landfill			
Contaminated glass	14	kg	Disposal in landfill
Fly ash (hazardous waste)	2	kg	Disposal in special landfill
Liquid waste	306.13	kg	Disposal in landfill
Sludge (hazardous waste)	50.25	kg	Contains metallic residue, disposal in special landfill
Output, emission to air			
NOx	2	kg	Emission from electrolysis

3.6 Life Cycle Impact Assessment

3.6.1 General

Life cycle impact assessment (LCIA) is the phase of evaluation of the potential environmental impacts based on the results of LCI. The following are the steps in LCIA:

1. Classification: in this step all elementary flows in the inventory phase are assigned to one or more impact category that they contribute.
2. Characterisation: in this step the classified elementary flows are multiplied by a characterisation factor for each impact category to which they contribute. The factor expresses how much each flow contributes to a certain impact category indicator, which can be at midpoint level or at endpoint level. They are usually

compared to a reference flow, for example kg CO_2 equivalents per kg of elementary flow for global warming potential.

3. Normalisation: an optional step in which, for each impact category either on midpoint or endpoint level, the relative share of the impact of the system is expressed as an average per citizen, per country etc. The normalisation step is excluded from this study.
4. Weighting: an optional step. It involves assigning quantitative weights to all impact categories expressing their relative importance. The weighting step is excluded from this study

3.6.2 LCIA results

This section presents the results of the impact assessment related to the functional unit, i.e. treatment of 1 000 kg of PV waste in a recycling plant, according to the processes and technologies developed within the PV waste treatment project, as described in section 3.4.3.6.

The potential environmental impacts of PV Waste Treatment

Table 11 shows the environmental impact of PV waste treatment per midpoint category related to the functional unit '1 000 kg of treated PV waste'. The contribution of each phase in the PV waste treatment is shown in Figure 11. Based on the results, the most impactful processes are the transport of PV waste to the company, incineration and the further metal recovery process which comprises sieving, acid leaching, electrolysis and neutralisation.

Table 11: Potential environmental impacts of the treatment of 1 000 kg of PV waste

Impact category	Unit	Total
Climate change	kg CO_2 eq	3.70E+02
Ozone depletion	kg CFC-11 eq	2.34E-05
Human toxicity, cancer effects	CTUh	2.83E-05
Human toxicity, non-cancer effects	CTUh	1.84E-05
Particulate matter	kg PM2.5 eq	8.17E-02
Ionising radiation HH	kg U235 eq	2.29E+01
Ionising radiation E (interim)	CTUe	6.96E-05
Photochemical ozone formation	kg NMVOC eq	2.86E+00
Acidification	molc H^+ eq	2.41E+00
Terrestrial eutrophication	molc N eq	1.17E+01
Freshwater eutrophication	kg P eq	4.56E-02
Marine eutrophication	kg N eq	1.05E+00
Freshwater ecotoxicity	CTUe	1.31E+03
Water resource depletion	m^3 water eq	7.93E+01
Abiotic resource depletion - mineral([16])	kg Sb eq	4.32E-03
Abiotic Depletion (Fossil fuel)	MJ	2.54E+03

([16]) Excludes energy carriers.

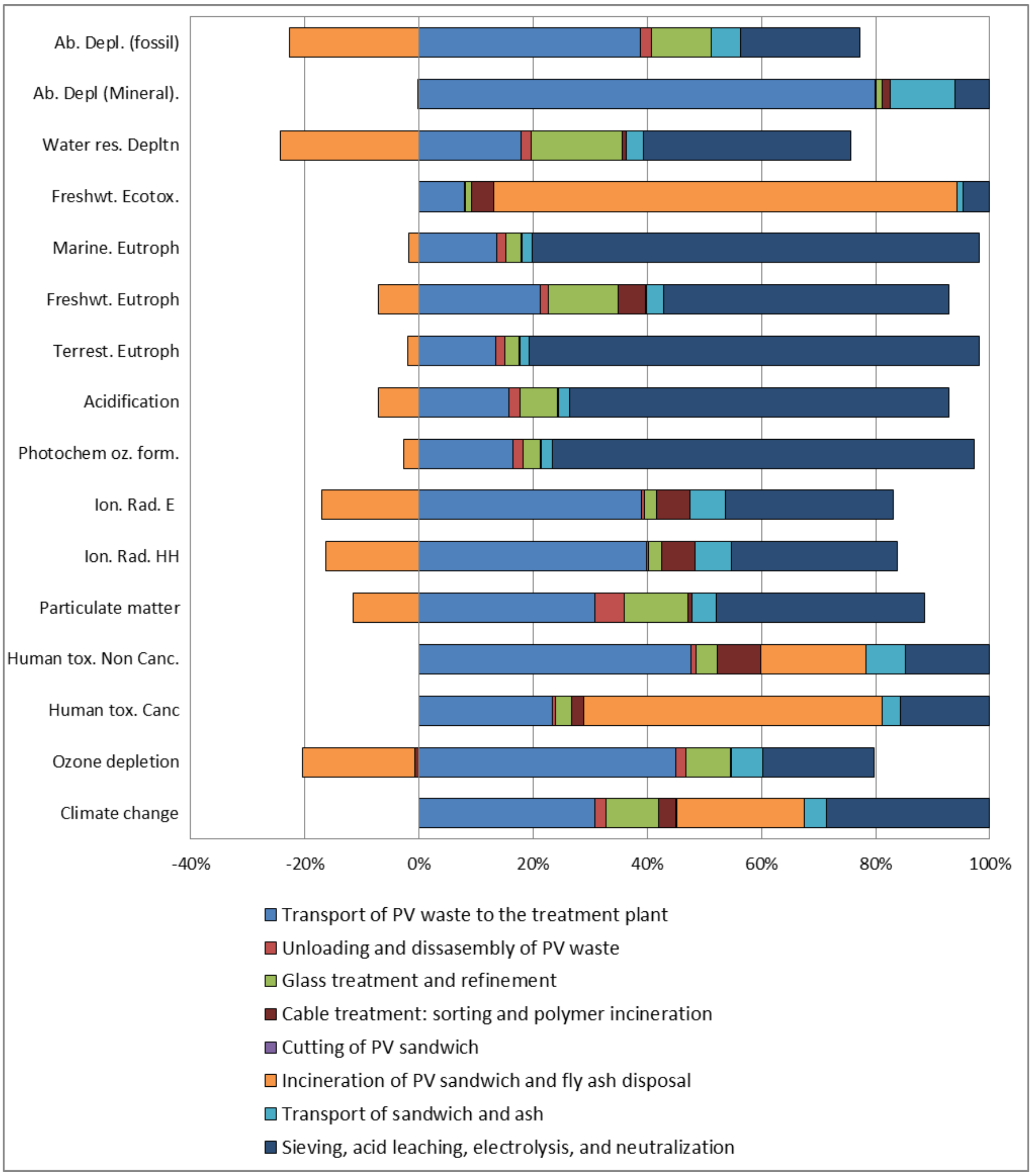


Figure 11: The potential impact contribution of each phase of PV waste treatment

3.7 Life Cycle Interpretation

The objective of this section is to analyse the quality and robustness of the previous phases and how the results from these phases can be used to derive conclusions relevant to the aims of the study. In particular, attention will be focussed on identifying the processes with high impacts and quantifying the potential environmental benefits that could be achieved thanks to materials recovery/recycling. In order to compare these impacts with the impacts of the production process for PV panels, the section estimated the potential environmental impacts of the production of 1 000 kg of new c-Si PV panels. Furthermore, this section also estimates the potential environmental benefits related to the production of secondary materials derived from PV recycling.

An analysis of the impacts and benefits of PV waste treatment in comparison with the current situation in PV waste treatment is also presented in this section.

3.7.1 Identification of key drivers and significant issues in the photovoltaic waste treatment

Table 11 in section 3.6 showed the potential environmental impacts of the treatment of 1 000 kg of PV waste. The LCIA result shows that in all impact categories, the highest impact contribution is given by the incineration process, transport of PV waste to the site and further metal recovery that includes sieving, acid leaching, electrolysis and neutralisation.

The transport, incineration and metal recovery treatments also have a significant influence on the climate change impact (each one about 25-30 % of the overall global warming potential).

The potential environmental impacts of the transport of PV waste to the site are seen particularly in abiotic depletion (fossil), abiotic resource depletion (mineral), human toxicity non-cancer effect, ionising radiation and ozone depletion.

The recovery of further metals from PV waste ash has a high impact in the cases of particulate matter, acidification, terrestrial eutrophication, marine eutrophication, freshwater eutrophication, water resource depletion and photochemical ozone formation. The consumption of electricity and acid solutions are the major causes of the impacts.

The incineration process is expected to recover some energy derived from the burning of polymers. The energy recovery is observed in the negative values in 11 impact categories. The negative values refer to the impacts that are avoided by the generation of heat and electricity from incinerating polymers. The burden to the environment related to the incineration is seen particularly in the freshwater ecotoxicity impact category and human toxicity-cancer effect. In these two impact categories, the most impactful process is the environmental burdens from the disposal of residual material (fly ash) to landfill.

3.7.2 Impacts due to the production of c-Si photovoltaic panels and potential benefits due to materials recycled from photovoltaic waste treatment

The potential environmental impacts of c-Si PV panel production

The production of c-Si PV panels in this study is estimated from the literature and the characteristics of PV panels presented in Table 6. The production technology refers to the average production plant of multicrystalline PV panels in 2005 in western Europe. The process includes raw material extraction, the manufacturing process i.e. production of the cell matrix, cutting of foils and washing of glass, production of laminate, isolation and the aluminium frame of the panel. Data for direct air and water emissions were not available.

The environmental impacts of the production of c-Si PV waste are presented in Table 12. The impact contribution of the main unit processes in the production is shown in Figure 12. The highest impact contributor in all impact categories is the production of PV cells (involving the purification of silicon metal), the production of aluminium and solar glass.

Table 12: The potential environmental impacts of the production of 1 000 kg of new c-Si PV panels

Impact category	Unit	Total
Climate change	kg CO_2 eq	9.35E+03
Ozone depletion	kg CFC-11 eq	1.82E-03
Human toxicity, cancer effects	CTUh	1.16E-03
Human toxicity, non-cancer effects	CTUh	1.71E-03
Particulate matter	kg PM2.5 eq	4.35E+00
Ionising radiation HH	kg U235 eq	2.31E+03
Ionising radiation E (interim)	CTUe	6.98E-03
Photochemical ozone formation	kg NMVOC eq	3.11E+01
Acidification	molc H^+ eq	4.86E+01
Terrestrial eutrophication	molc N eq	9.02E+01
Freshwater eutrophication	kg P eq	5.81E+00
Marine eutrophication	kg N eq	9.47E+00
Freshwater ecotoxicity	CTUe	2.15E+04
Water resource depletion	m^3 water eq	3.41E+04
Abiotic resource depletion – mineral	kg Sb eq	1.07E+01
Abiotic depletion (fossil fuels)	MJ	1.44E+05

LCIA results of the production of c-Si PV Panels

The LCIA result of the production of 1 000 kg of PV panels is shown in Figure 12. In all impact categories, aluminium alloy production, solar glass production and PV cell production are seen to be the major impacts.

The high impact contribution of PV cell production is observed in 14 impact categories. In the production of PV panels, PV cell production dominates most of the potential environmental impacts. The purification of MG silicon into electronic grade in the production process of PV cells is known to be energy intensive, requiring 1 190 MJ/panel (Stoppato, 2008).

In the 'resource depletion, mineral' impact category, the production of low iron solar glass dominates the impact because of the production of antimony. The abiotic depletion (fossil fuel) impact category is dominated by the production of PV cells and of the aluminium frame, both energy-intensive processes.

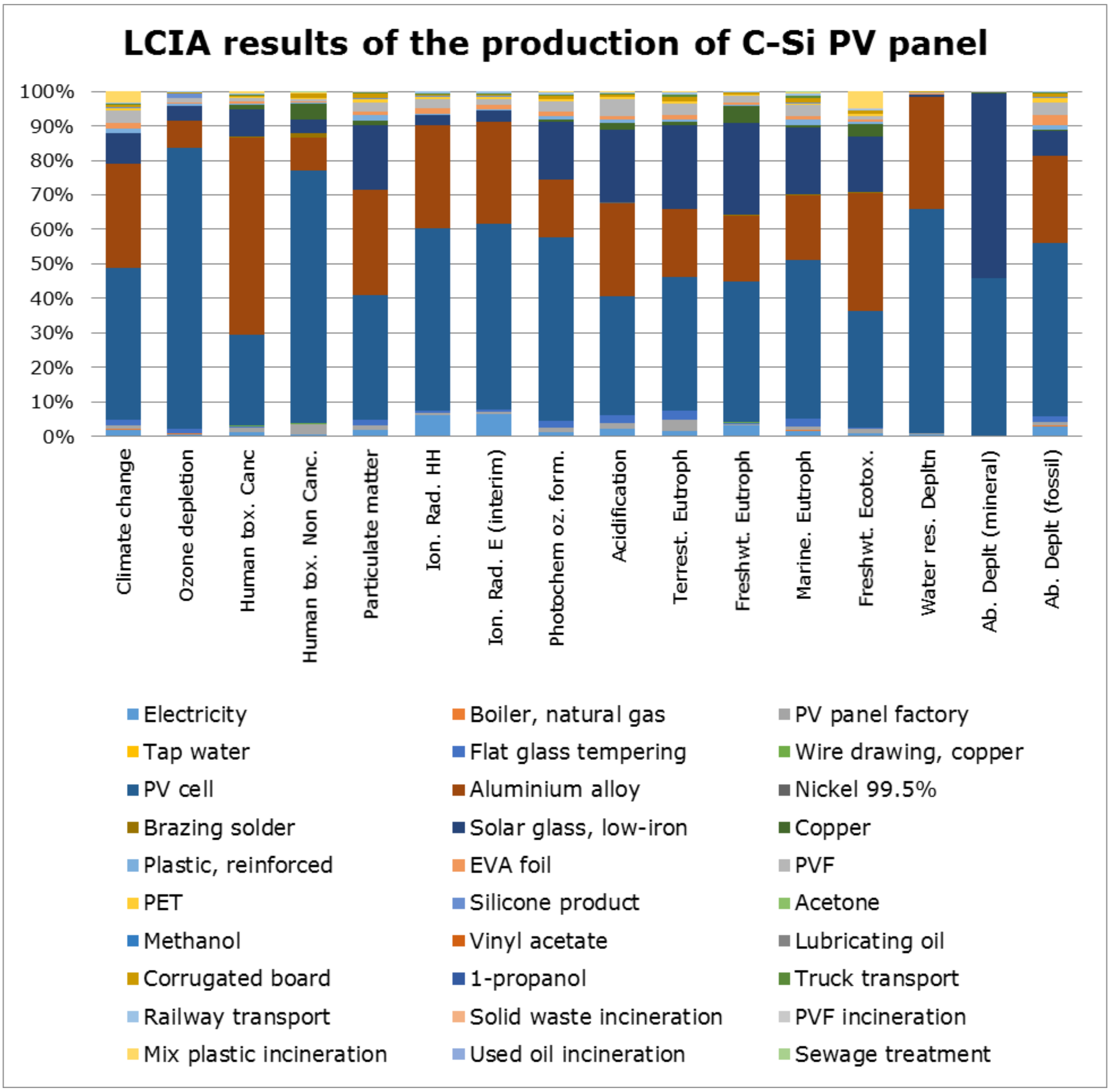


Figure 12: The LCIA results of the production of 1 000 kg of c-Si PV panels

Potential environmental benefits due to secondary material production

The materials derived from the PV waste treatment can be attributed to the production of secondary materials. The analysis of the impacts and benefits of the production of secondary materials resulting from PV waste treatment is presented in this section.

LCIA results of the environmental benefits due to secondary material production

The expected potential benefits of PV waste treatment are due to the avoidance of the production of primary materials for the manufacture of PV panels. The benefits are evaluated as an aggregation of the total recovered/recycled materials.

Figure 13 presents the impacts due to the production of 1 000 kg of PV panels, the impacts due to the treatment of PV waste, and the cumulative potential benefit due to the production of secondary materials (expressed as negative value in green). The benefit of energy recovery from the incineration of cables and polymers is accounted for in the impacts of the PV waste treatment.

The figure shows that the impacts related to the treatment of PV waste and the production of secondary materials are relatively low when compared to the impact of PV production. The figure also shows that the recycling of materials from PV waste generated an environmental benefit in all impact categories.

The detailed potential benefit of the recovery/recycling of the materials derived from the treatment of PV waste is shown in Figure 14. The figure also shows the relative contribution of material recycling/recovery to the total benefit of PV waste treatment. The results show that in most of the impact categories, the recycling of aluminium gives a major environmental saving. In some impact categories, the recycling of silver makes a significant contribution, particularly in the mineral depletion impact category.

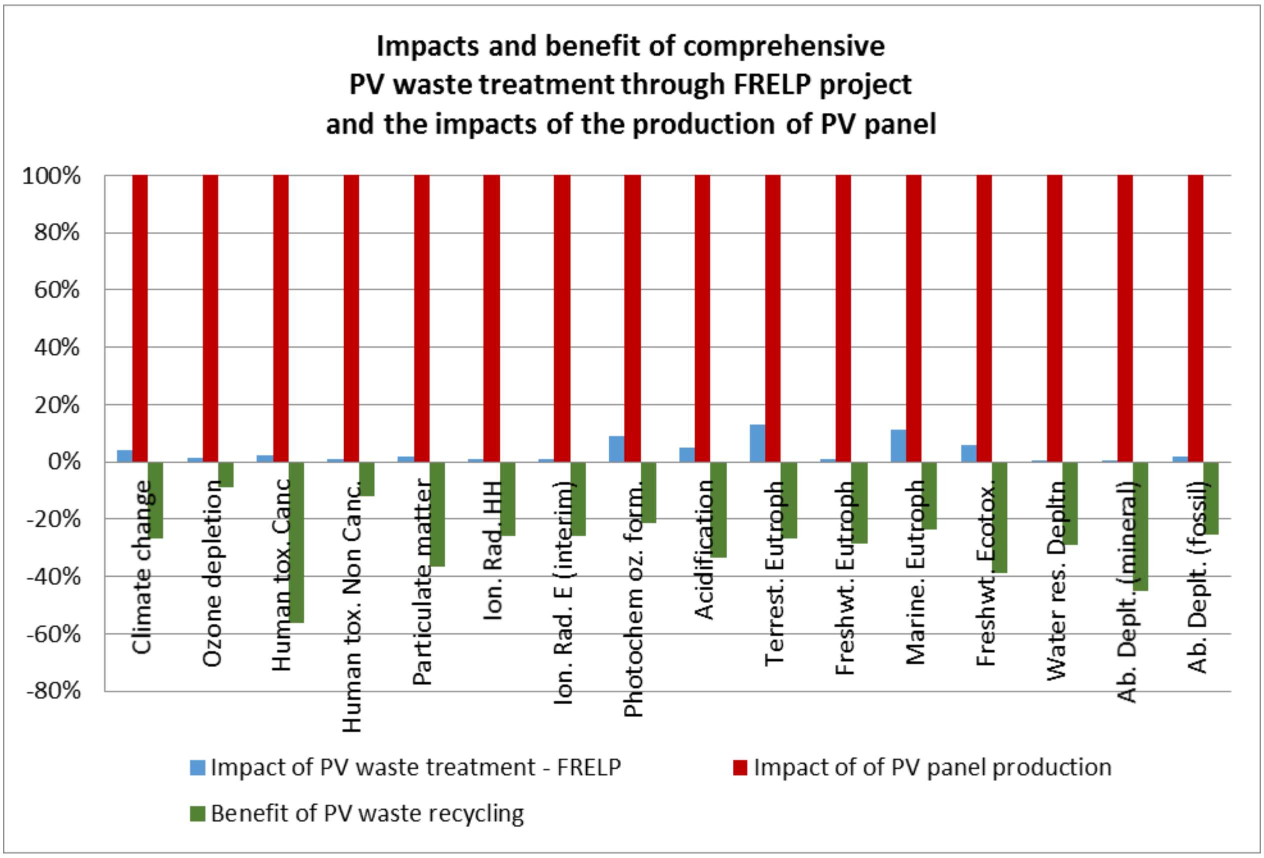


Figure 13: Comparison of the impacts due to the production and EoL treatment of PV panels and the potential benefits due to secondary material production

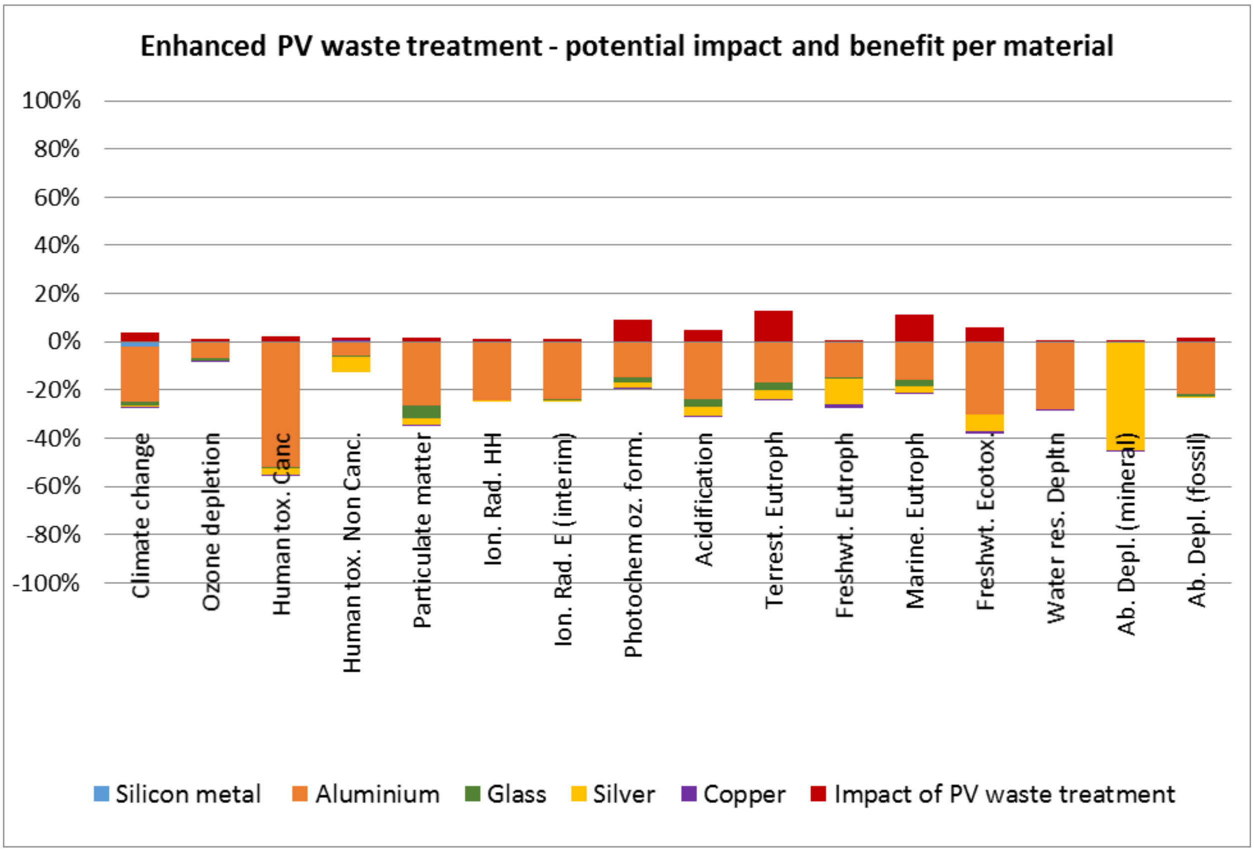


Figure 14: Impacts of PV waste treatment compared to potential benefits due to the recycling of materials

3.7.3 Analysis of current scenario for photovoltaic waste treatment

The objective of the current PV waste recycling processes is to recycle more than 80 % of PV modules by weight (Olson, Geerligs et al., 2013). The treatment of PV waste based on the FRELP project represents a potential enhancement compared to current PV recycling systems. In order to estimate potential additional benefits, a base-case scenario of current treatments of PV waste has been set, based on information provided by an Italian WEEE recycling plant([17]).

The process begins with a manual disassembly to separate the aluminium frame and the junction box. The remaining parts of the panel (composed of glass, encapsulation and back-sheet layer, crystalline-silicon cells, and various metals) are crushed under hammer mills and shredders into smaller fragments. Glass is partially separated from the residuals. However, the complexity of the PV sandwich (multi-materials with plastics, glass and metal inserts) does not allow normal mechanical systems to separate further other materials. The residual fraction is therefore of poor quality and not suitable for the further recycling of materials. PV sandwich is assumed to be landfilled after the shredding. A diagram of the current PV waste treatment is shown in Figure 15.

([17]) The plant is equipped to treat generic WEEE, but it has no specific technologies for the treatment of PV waste.

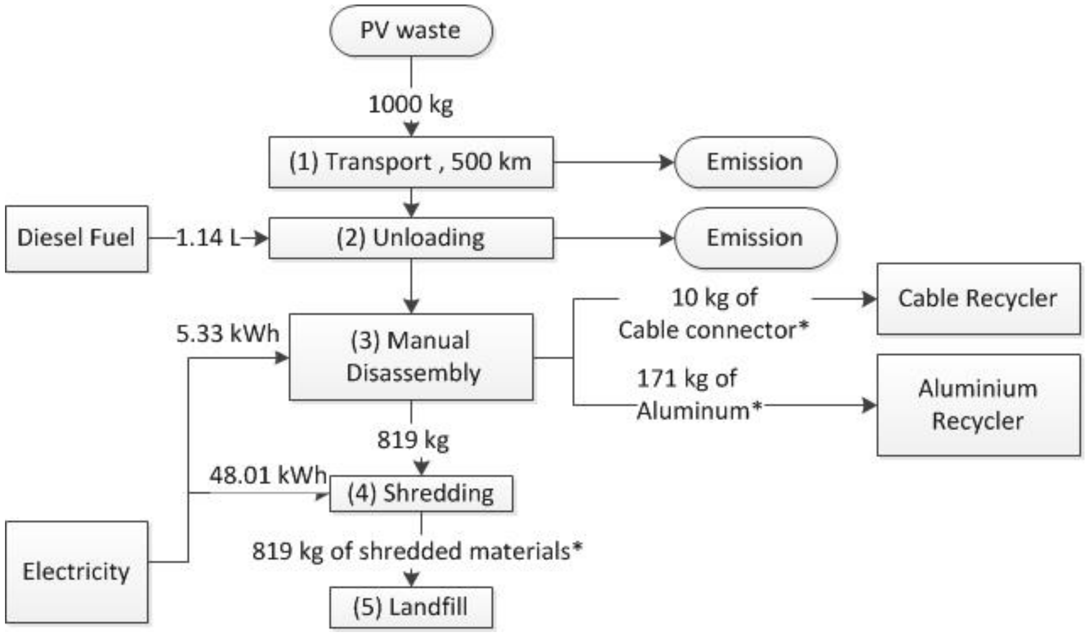


Figure 15: The process diagram of current practice in PV waste treatment

(*) Includes transport

PV waste is assumed to be transported for 500 km as in the analysis of the treatments developed by the FRELP project. The disassembly process is assumed to be performed manually. Manual disassembly is highly efficient for the separation of the PV panel's aluminium frame (95 %). However, this efficiency level is lower than for the automatic disassembly line developed in the FRELP project. The remaining layers of glass, solar cells with crystalline silicon and various metals are successively shredded. Therefore, the recovered materials from this base case are aluminium and cables. The fragments of the shredded sandwich of solar cells, the encapsulation and back-sheet layers, and various metals are sent to landfill, assuming a distance of 100 km from the treatment plant. The recycling of aluminium, copper in cables and glass allows some environmental benefits in terms of the avoidance of impacts from the production of the primary raw materials. Energy is recovered from the incineration of the polymer part of the cables([18]).

The summary of the materials and energy recovery resulting from current PV waste treatment is shown in Table 13.

([18]) For the calculation the use of an average calorific value referring to mixed plastics is assumed (Ecoinvent).

Table 13: Expected material and energy recovery from current PV waste treatment

Material	Estimated Quantity	Unit	Avoided Product	Quantity	Unit
Aluminium	180	kg	Primary aluminium	171	kg
Low iron solar glass	700	kg	Raw materials for the production of primary white glass for packaging	686	kg
Copper from cable and connector	3.30	kg	Primary copper	3.30	kg
Polymers from waste cable	6.70	kg	Electricity Production	19.16	MJ
			Thermal Energy	38.86	MJ

Comparison between the impacts/benefits of PV waste treatment and current practices from the study

Figure 16 shows the environmental impacts and benefit of treating 1 000 kg of c-Si PV waste according to the PV waste process that was studied and the current treatment in a WEEE plant. The figure also illustrates the impacts of the production of new PV panels.

The potential environmental benefit of current PV waste treatment derives mainly from the recovery of aluminium. The benefits produce a reduction of 10-50 % in the production of new aluminium. However, for all the impact categories considered, these benefits are lower compared to the benefits of the PV waste treatment developed by FRELP project. This is even more evident in the abiotic depletion (mineral) impact category due to the loss of valuable materials such as silicon metal, copper and especially silver.

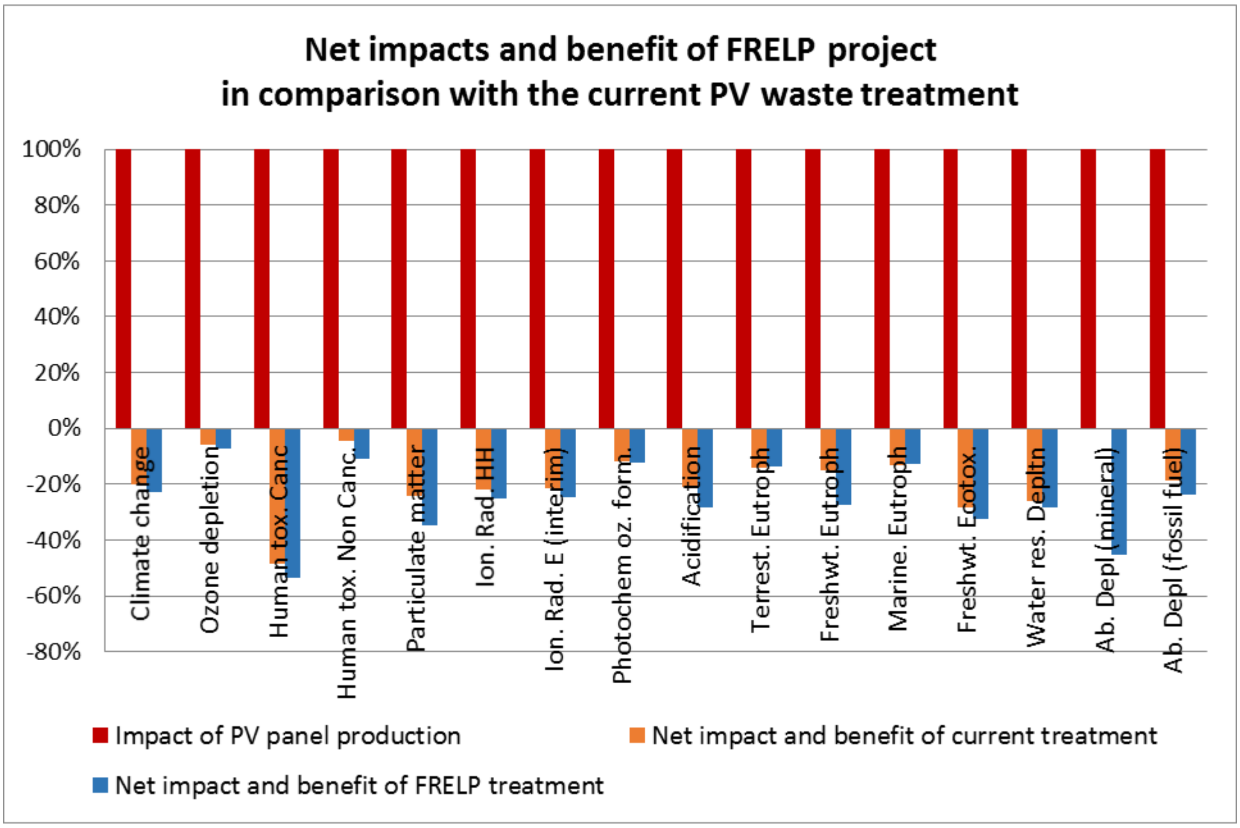


Figure 16: Comparison between the net benefits of current PV waste treatment and FRELP PV waste treatment

3.7.4 Completeness check

A completeness check is performed on the inventory to determine the level of its completeness and to check whether the cut-off criterion, if applied, has been met.

Background datasets from Ecoinvent v 2.2 were used to complement foreground datasets provided by the company. Some of these background datasets have been selected to complete the inventory of foreground processes in case of insufficiency. Below is a detailed explanation of the selected background processes from Ecoinvent v 2.2:

- The emissions from forklift work during the unloading phase was an estimation based on the emission of building machinery, since no LCI was found specific to this specific process.
- The emissions from the incineration of the polymer part of the cable encapsulation were estimated based on the emissions from the incineration of mix plastic.
- The quantity of heat and electricity produced by the incineration of the cable encapsulation was estimated based on the energy content of incinerating plastic mixture.
- The emissions from the incineration of the encapsulation and fluorine-containing back-sheet layer were estimated based on the emissions from the incineration of mixed plastic. The quantity of the fluorine in the LCI data does not accurately represent the quantity of the fluorine within the back-sheet layer.

- The quantity of heat and electricity produced from the incineration of the encapsulation and back-sheet layers was estimated based on the energy content of incinerating mix plastic.
- The emissions from the production of various secondary materials from PV waste were estimated using available Ecoinvent datasets.

3.7.5 Sensitivity analysis

Sensitivity analysis is a procedure for estimating the influence on the outcome of a study of the selected assumptions and data. The sensitivity analysis in this study has been performed through different scenarios which reflect different possible options for treating PV waste. The scenarios are the following:

- Sensitivity scenario 1 – treatment of PV panels that do not contain fluorine in their back-sheet layer. The PV waste will undergo the same treatment from automatic disassembly, high temperature glass separation, optical glass separation and module cutting. The non-fluorine sandwich layer will be treated inside the plant with pyrolysis process.
- Sensitivity scenario 2 – decentralised treatments in different plants, with a local pre-treatment of PV waste before further treatments in the recycling plant. The main focus in this scenario is the analysis of impacts due to transport and potential strategies to reduce them.
- Sensitivity scenario 3 – recycling of highly transparent glass containing antimony.

3.7.5.1 Sensitivity scenario 1 — pyrolysis

The back-sheet layer of PV may be composed of materials other than halogenated materials such as PET. In that case, the PV sandwich can be treated directly in the recycling facility through a pyrolysis process, instead of being treated in an external incineration plant. The objective of the pyrolysis process is to separate the encapsulation layer from the sandwich. Pyrolysis means treatment at high temperatures in the absence of oxygen. The emissions from pyrolysis treatment are mainly caused by EVA decomposition (Granata, Pagnanelli et al. 2014). EVA decomposition occurs in a two-stage process, the first is deacetylation which generates acetic acid and the second is random/chain scissions with the release of mainly propane, propene, ethane, butane, hexane-1 and butane-1 (Granata, Pagnanelli et al., 2014).

Potential impacts due to pyrolysis have been estimated based on information provided by experts from the FRELP project. The pyrolysis of the EVA encapsulation layer process is expected to be operated at 450-500 °C. The capacity of the reactor is assumed to be 400 kg/hour of sandwich. The pyrolysis process would work for 2 400 hours/year. In this process, Nitrogen (N_2) is supplied at 5 m^3 of N_2/500 kg of sandwich. Natural gas is supplied to heat up the encapsulation layer. Figure 17 shows the flow diagram of the PV waste treatment along the pyrolysis route.

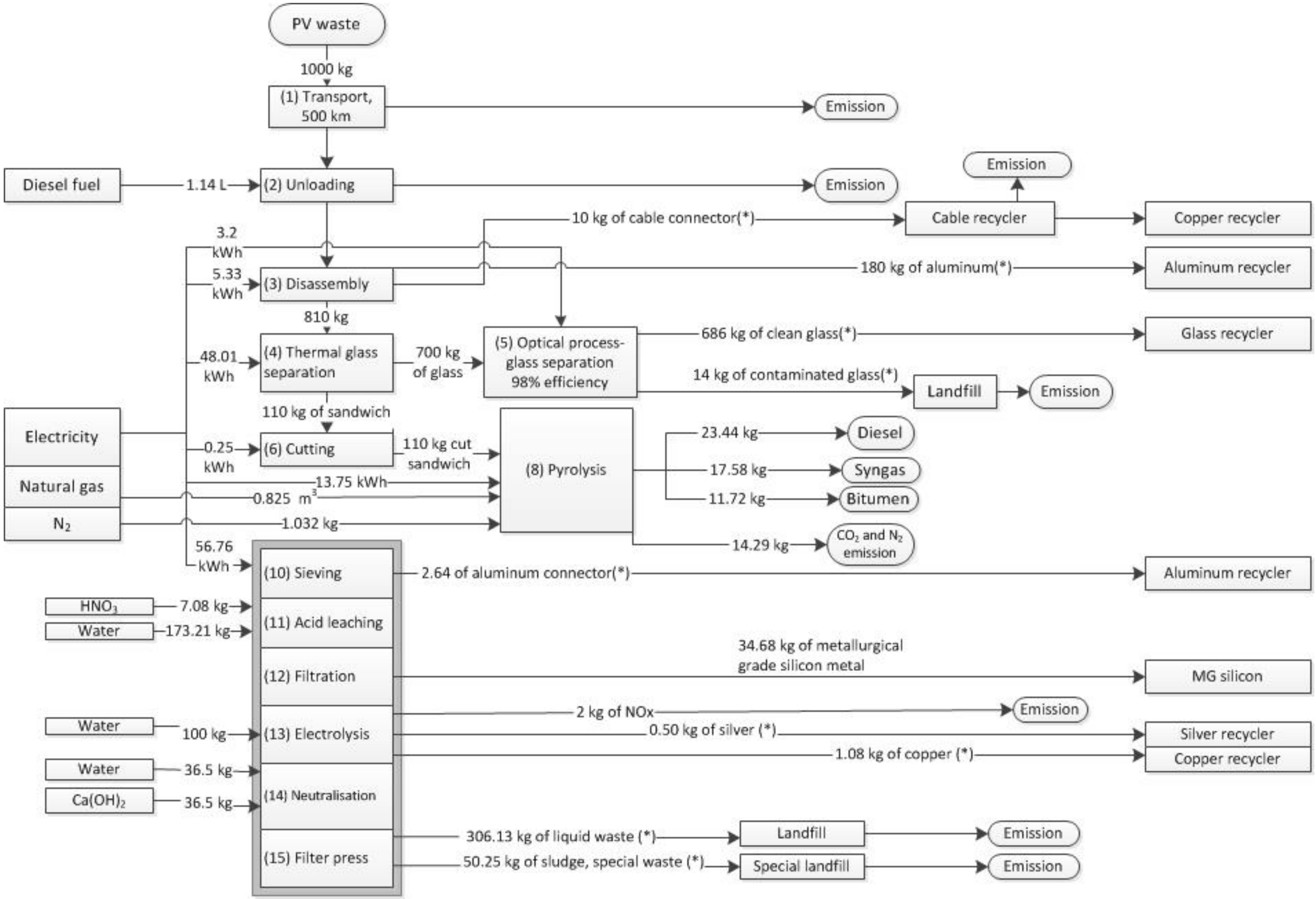


Figure 17: The flow diagram of PV waste treatment along the pyrolysis route

The main difference between the PV waste treatment with incineration and with pyrolysis is essentially in the treatment of the encapsulation and back-sheet layer. The amounts of recovered aluminium, glass, silicon metal, copper and silver between the two different treatments are assumed to be the same. However, the pyrolysis process may allow the recovery of the polymers in the encapsulation and back-sheet layer and produce diesel fuel and heat.

Material and energy recovery derived from pyrolysis of PV sandwich

In this process, the encapsulation and back-sheet layer are expected to be recovered as gas and diesel. The diesel is used as fuel while the gas will be burned to generate electricity for the pyrolysis process. This process also potentially generates bitumen waste.

Environmental benefit from material and energy recovery

The summary of the materials expected to be recovered and the energy from 1 000 kg of c-Si PV waste is presented in Table 14.

Energy is expected to be recovered from the pyrolysis of PV encapsulation and back-sheet layer. The calorific value of these polymers refers to mixed plastics.

Table 14: Materials recycled and energy recovered by the treatment (including pyrolysis) of 1 000 kg of PV waste

Material	Estimated Quantity	Unit	Avoided Product	Quantity	Unit
Aluminium	182.65	kg	Primary aluminium	182.65	kg
Low iron solar glass	700	kg	Raw materials for the production of primary white glass for packaging	686	kg
Copper from cable and connector	3.30	kg	Primary copper	3.13	kg
Copper from connector	1.14	kg	Primary copper	1.08	kg
Silicon metal-solar cell	36.5	kg	Primary MG silicon Metal (MG-Si)	34.68	kg
Silver	0.53	kg	Primary Silver	0.50	kg
PV encapsulation and non-fluorine back-sheet layer	66	kg	Production of primary diesel fuel	23.44	kg

Material	Estimated Quantity	Unit	Avoided Product	Quantity	Unit
Polymer from copper cable encapsulation	6.70	kg	Electricity Production	19.16	MJ
			Thermal energy	38.86	MJ
PV encapsulation and non-fluorine back-sheet layer	66	kg	Thermal energy	276.28	MJ

The comparison between the impacts of the two PV treatments, with incineration and pyrolysis, is shown in Table 15.

The LCIA results show that for the majority of the impact categories the scenario with pyrolysis performs better than with incineration. This outcome is related to the lower impacts caused by the incineration process, the avoidance of transport and landfill of hazardous waste, and higher energy recovery.

The comparison between the net impact and benefit of the two PV treatments, with incineration and pyrolysis, is shown in Figure 18. The figure suggests that for most of the impact categories, the pyrolysis route results in a slightly higher environmental saving.

Table 15: Comparison of LCIA results of the treatment of PV waste with fluorine-containing back-sheet layer (via incineration) and non-fluorine-containing back-sheet layer (via pyrolysis)

Impact category	FRELP PV waste treatment	Pyrolysis	Unit	% of change
Climate change	3.70E+02	2.96E+02	kg CO_2 eq	-19.93
Ozone depletion	2.34E-05	1.63E-05	kg CFC-11 eq	-30.19
Human toxicity, cancer effects	2.83E-05	1.21E-05	CTUh	-57.41
Human toxicity, non-cancer effects	1.84E-05	1.29E-05	CTUh	-29.90
Particulate matter	8.17E-02	7.69E-02	kg PM2.5 eq	-5.89
Ionising radiation HH	2.29E+01	2.45E+01	kg U235 eq	6.97
Ionising radiation E (interim)	6.96E-05	7.55E-05	CTUe	8.54
Photochemical ozone formation	2.86E+00	2.81E+00	kg NMVOC eq	-1.86
Acidification	2.41E+00	2.39E+00	molc H^+ eq	-0.89
Terrestrial eutrophication	1.17E+01	1.16E+01	molc N eq	-0.89
Freshwater eutrophication	4.56E-02	4.69E-02	kg P eq	2.76
Marine eutrophication	1.05E+00	1.04E+00	kg N eq	-0.92
Freshwater ecotoxicity	1.31E+03	2.23E+02	CTUe	-83.01
Water resource depletion	7.93E+01	1.16E+02	m^3 water eq	46.33
Abiotic depletion (mineral)	4.32E-03	3.80E-03	kg Sb eq	-12.01
Abiotic depletion (fossil fuel)	2.54E+03	2.04E+03	MJ	-19.66

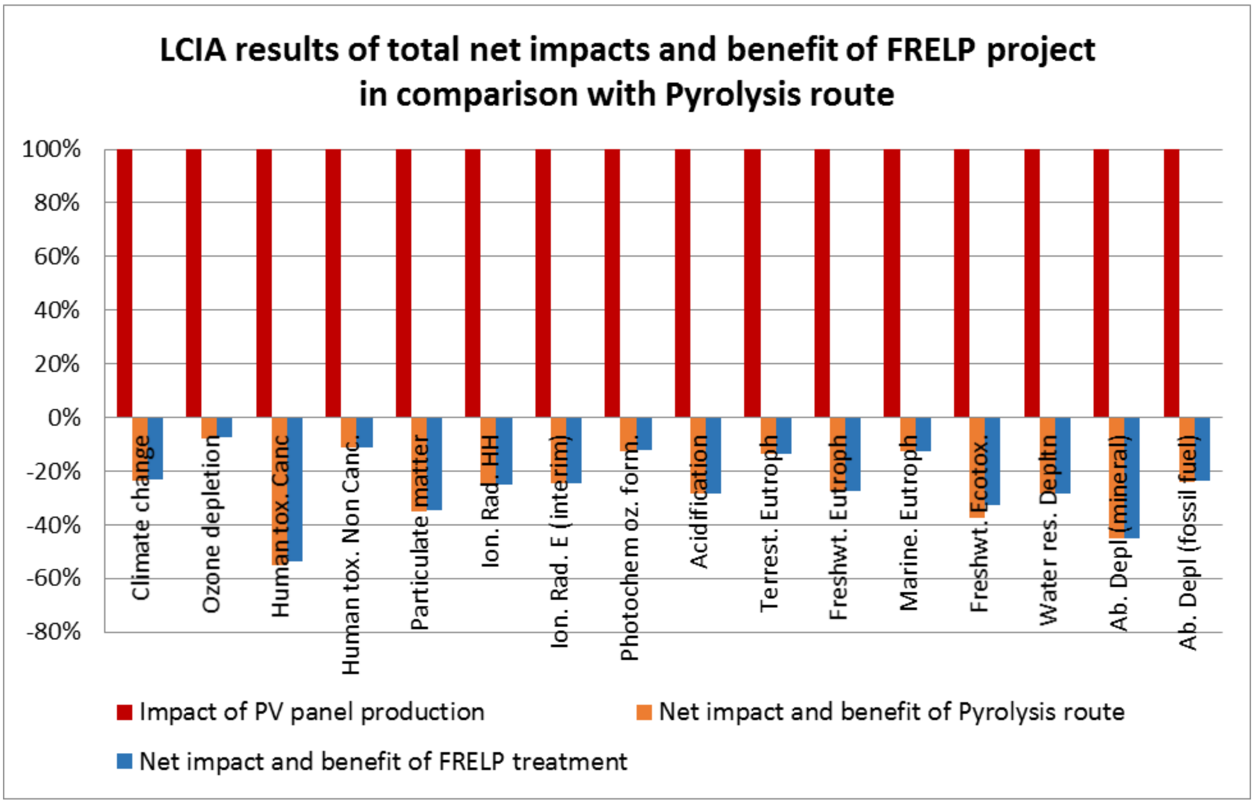


Figure 18: Net impact and benefit of PV waste treatment and the pyrolysis route, in comparison with the impact of the production of c-Si PV panel

3.7.5.2 Sensitivity scenario 2 — use of decentralised treatment plants

The LCIA result of the treatment of one tonne of PV waste shows that in most of the environmental impact categories, the highest contribution to the impacts is from the transport of PV waste to the recycling plant.

A decentralised plant scenario is evaluated in this study. The scenario assumes a pre-processing of PV waste in decentralised plants. This pre-processing implies the separation of the aluminium frame, copper cable and solar glass (units of process for 3 to 6, as in Figure 19). This pre-processing could also occur within normal WEEE recycling plants, implying a lower distance for transport. It is assumed that the distance to a local plant for the pre-processing would be 100 km.

The remaining PV waste sandwich is then transported to the recycling plant for the further treatments. The subsequent processes are the same as those previously analysed.

The two scenarios — with the centralised and decentralised plants — are shown in Figure 19. The comparison of LCIA results between the scenarios with centralised and decentralised plants is shown in Table 16.

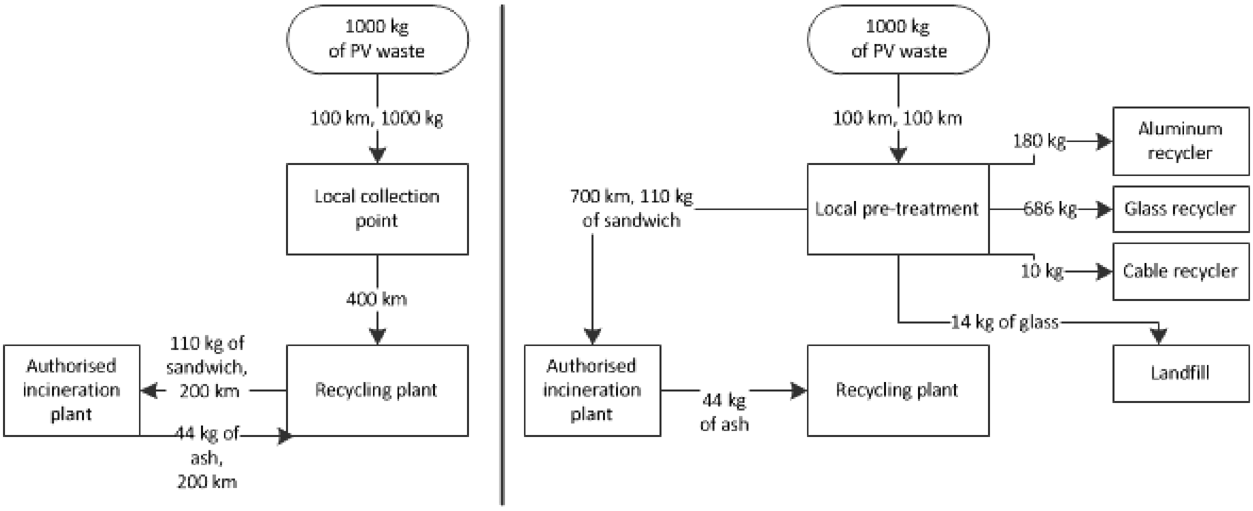


Figure 19: Scenarios of treatment with a centralised treatment plant (left) and decentralised treatment plant (right)

Table 16: Comparison of the potential environmental impacts of centralised and decentralised PV waste treatment plants

Impact category	Recycling plant (centralised)	Recycling plant (decentralised)	Unit	% of change
Climate change	3.70E+02	2.98E+02	kg CO_2 eq	-19.39
Ozone depletion	2.34E-05	1.22E-05	kg CFC-11 eq	-47.66
Human toxicity, cancer effects	2.83E-05	2.42E-05	CTUh	-14.51
Human toxicity, non-cancer effects	1.84E-05	1.31E-05	CTUh	-28.74
Particulate matter	8.17E-02	6.15E-02	kg PM2.5 eq	-24.74
Ionising radiation HH	2.29E+01	1.49E+01	kg U235 eq	-34.95
Ionising radiation E (interim)	6.96E-05	4.53E-05	CTUe	-34.87
Photochemical ozone formation	2.86E+00	2.55E+00	kg NMVOC eq	-10.98
Acidification	2.41E+00	2.13E+00	molc H^+ eq	-11.57
Terrestrial eutrophication	1.17E+01	1.07E+01	molc N eq	-8.95
Freshwater eutrophication	4.56E-02	3.87E-02	kg P eq	-15.07
Marine eutrophication	1.05E+00	9.56E-01	kg N eq	-8.93
Freshwater ecotoxicity	1.31E+03	1.23E+03	CTUe	-4.94
Water resource depletion	7.93E+01	6.35E+01	m^3 water eq	-20.70
Abiotic depletion (mineral)	4.32E-03	2.38E-03	kg Sb eq	-48.88
Abiotic depletion (fossil fuel)	2.54E+03	1.53E+03	MJ	-44.43

The result shows that for all impact categories, the decentralised plant has a better environmental performance. This implies that better rationalisation of the transport with the use of decentralised plants may potentially reduce significantly the environmental impact of PV waste treatment, without affecting the efficiency in the recycling of materials.

3.7.5.3 Sensitivity Scenario 3 — photovoltaic waste treatment involving the recycling of high quality solar glass

PV waste treatment is expected to separate glass fractions for recycling. In the LCA this glass was assumed to be recycled as secondary glass for packaging. This assumption was based on the analysis of the current market for recycled glass from WEEE. In fact, the high risk of contamination of the glass in the WEEE treatment facilities does not allow it to be recycled for high quality applications. However, the PV waste treatment developed by the FRELP project is expected to recover glass with a high purity and containing antimony as an additive. An additional scenario of the recovery of high quality solar glass has been assumed. Glass cullets separated from the PV waste are assumed to be collected and recycled to produce solar glass. The environmental saving is, therefore, due to the avoided environmental impacts of solar glass production, including the benefits of recycling antimony. The LCIA results of the net benefit of this scenario compared to the initial enhanced PV waste treatment are shown in Figure 20. The figure shows that for most impact categories, this new scenario related to the recovery of solar glass generates a higher environmental saving, especially for the impact category of the abiotic depletion — mineral.

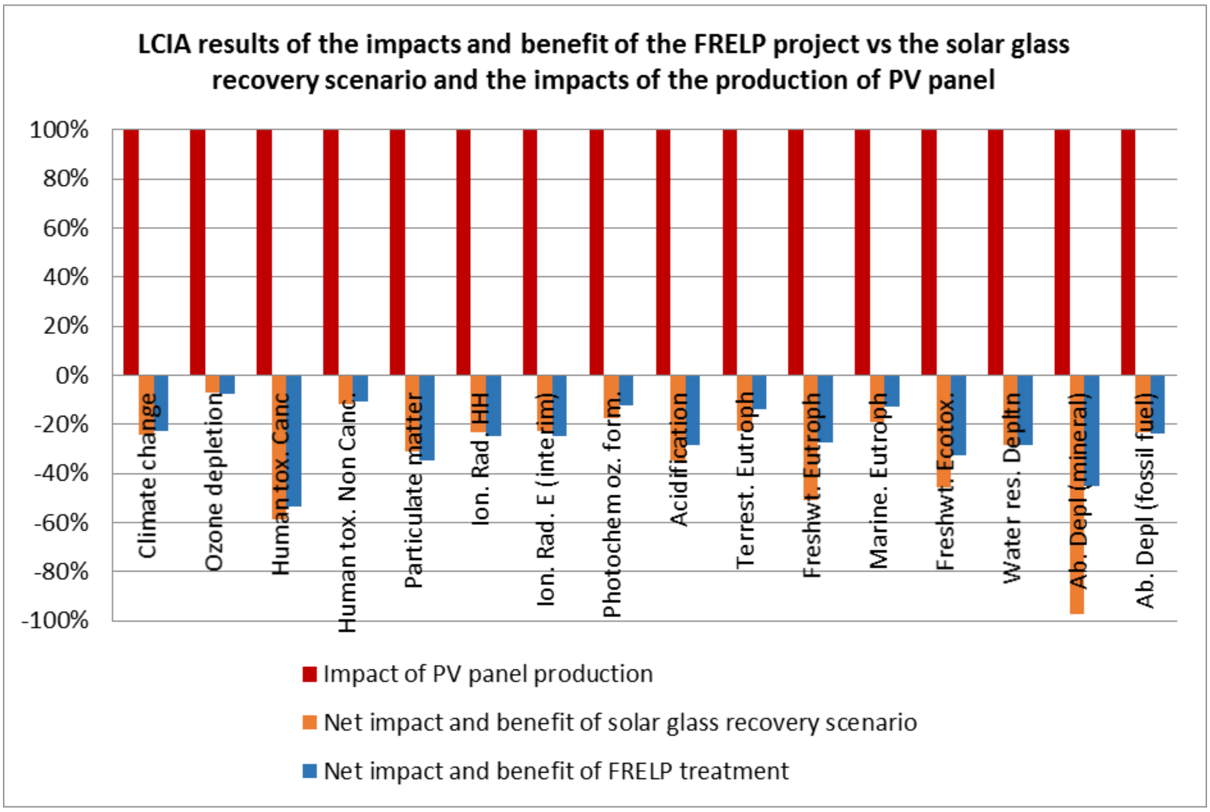


Figure 20: The LCIA results from the midpoint impact category for PV waste treatment with solar glass recovery in comparison with current FRELP treatment.

3.7.6 Consistency check

The objective of the consistency check is to investigate whether the assumptions, methods and data have been applied consistently throughout the LCI/LCIA study.

3.7.7 Consistency of data quality

The information on inputs and outputs at each unit process of the FRELP project is based on a pilot-scale test in the company. Therefore, the estimated impacts do not necessarily reflect those of a future large-scale treatment plant. Assumptions have also been made to model the final disposal of residual materials generated from the process. The potential environmental benefits of recycled materials were estimated based on inventory data of secondary material production as available in the Ecoinvent database.

A number of data sets from the Ecoinvent database have been included in the LCA modelling. The datasets in Ecoinvent have been selected to obtain the best geographical, technological and time-related representativeness.

3.8 Discussion of the Results

The LCA has been conducted in accordance with ISO 14044 and ILCD guidelines. The main objective of this study is to assess the potential impacts and benefits of an innovative method for PV waste treatment based on technologies and processes currently under development by the FRELP project. The functional unit of the study is the treatment of 1 000 kg of c-Si PV panel waste. The result of the LCIA phase shows that the recycling of PV waste is beneficial for all impact categories, i.e. the impacts due to recycling are lower than the potential benefits achievable by the production of secondary raw materials. This innovative method of PV waste treatment clearly shows higher environmental benefits when compared to other methods currently adopted in WEEE recycling plants. These plants are, in fact, affected by higher loss of materials, including precious metals and materials critical for the EU. The results of the LCIA also indicate the impact contribution made by each unit of process in the innovative recycling process, thereby identifying potential opportunities for improvement. The analysis of the material fractions separated from the PV waste also enabled the potential benefits due to recycling the different materials to be estimated.

3.8.1 Critical raw materials

Silicon metal and antimony are the main CRM contained in PV panels, having a potential for recovery from the PV waste treatment. However, other CRM are involved in the life cycle of PV panels, albeit though in very small amounts, including fluorspar used for the production of some plastics. Changes in the production and recycling processes could imply the reduction of the use of such CRM or the recycling of additional materials. For example, the process could allow the separation of high purity glass containing antimony, to be recycled for the production of solar glass. In the case of fluorspar, the substitution of fluorinated plastic in the PV back-sheet with non-fluorinated ones would allow the production of fluorspar to be avoided.

Table 17 illustrates the amount of materials used along the life cycle (i.e. including the production of PV panels and the waste treatment). The results are presented as 'material requirement along the life cycle' and compared with the 'benefit of recycling', i.e. the amount of materials that can be 'saved' by the PV waste treatment. The data are retrieved from the LC inventory, and refer to elementary flows used as inputs along the life cycle of PV panels. As silicon metal is an intermediate product it doesn't appear in the inventory, while gravel, from which silicon is produced, is the first raw material contributing both to the total material requirement and to the overall benefit of recycling. The benefit of recycling silicon metal is evident in the energy saving potential.

Table 17: Data from the life cycle inventory, showing the material requirement related to one tonne of PV panel during its life cycle (production and waste treatment) and amount of materials avoided.

Material	Material requirement for the production and recycling of PV panels (base-case) (kg)	Benefit of recycling due to avoided primary production of materials (base-case) (kg)
Gravel, in ground	1.87E+03	-5.38E+02
Aluminium	2.21E+02	-2.13E+02
Iron	1.01E+02	-1.23E+01
Clay	1.08E+02	-1.13E+01
Fluorspar	1.86E+01	-5.26E-01
Copper, total	6.99E+00	-4.31E+00
Nickel, total	6.04E+00	-5.53E-01
Antimony	5.24E+00	-3.99E-09
Barite	4.22E+00	-1.39E+00
Chromium	3.17E+00	-2.13E-01
Manganese	3.18E+00	-2.67E-02
Sand, unspecified, in ground	2.79E+00	-2.78E-03
Zinc	2.42E+00	-4.06E-02
Clay, bentonite, in ground	1.64E+00	-2.69E-01
Magnesite, 60 % in crude ore, in ground	1.35E+00	-1.41E-01
Gypsum, in ground	1.02E+00	-5.97E-05
Silver, total	5.52E-01	-5.46E-01
Phosphorus, total	2.59E-01	-1.33E-02
Molybdenum, total	1.47E-01	-9.57E-02
Tin	5.63E-02	-2.35E-04
Tellurium	2.72E-02	-2.69E-02
Talc	1.96E-02	-1.75E-03
Diatomite, in ground	6.95E-05	-5.36E-08
Gold, total	3.83E-05	-4.01E-06
Tantalum	3.83E-05	-3.93E-06
Feldspar, in ground	1.52E-05	-1.30E-06
Indium	1.53E-05	-1.30E-06
Cobalt	5.65E-06	-2.89E-06
Lithium	3.70E-06	-2.76E-08
Palladium, total	3.61E-06	-1.15E-06
Platinum, total	5.68E-07	-4.51E-08
Rhenium, total	2.01E-08	-9.12E-09
Gallium	1.28E-08	-7.37E-10

3.8.2 Ecodesign

The objective of ecodesign is the implementation of environmental considerations at the product design phase. These considerations lead to the adoption of improvement measures for the product, implemented by a company on a voluntary basis or as a consequence of legislation.

The analysis of the EoL of silicon PV panels has identified some criticalities in the recycling treatments.

First of all, the uncertainty of the composition of the panels affects the efficiency of the treatments. The content of valuable substances (as critical, scarce and precious metals) is a driver for the selection of recycling treatments. The aim of the recycling is indeed to maximise the recovery of the most relevant fractions. On the other hand, the presence of hazardous substances influences the type of treatment and the quality and quantity of recycled materials. In the present study there was a general lack of information on the composition of the silicon PV panels. This was due to the age of panels currently reaching their EoL and the different technologies used in their manufacture. Some experimental tests on the composition of the panels have been performed within the FRELP project (and used as input for the current analysis). However the provision by the manufacturers of detailed information on the composition of the panels would help further optimise the recycling efficiency.

Another key aspect in the recycling was the content of some specific halogenated plastics (especially for chlorinated and fluorinated plastics used in the back-sheet). According to the analysis in the FRELP project, PV without halogenated plastics can be treated in a pyrolysis plant, while PV with halogenated plastics have to be treated in specialised incineration plants. This latter would cause higher impacts compared to the pyrolysis scenario due to additional transport as well as the production of hazardous air pollutants and waste in the incineration plant.

According to this analysis, two potential ecodesign measures for PV could focus on:

- avoiding the use of halogenated plastics in PV. When halogenated plastics are used, this should be clearly labelled in the product;
- provision, by manufacturers, of detailed information on the composition of the PV panel with special care on the content in the back-sheet of: plastics; hazardous substances (such as heavy metals or some flame retardants); CRM (especially silicon, antimony and other CRM present in traces in the cells); and precious metals (especially silver). It is important that this information be available at the EoL of the panels, which can occur several decades after their manufacture. This information should, therefore, be displayed, as far as possible, in the product (e.g. via durable labels) or an ad hoc website maintained for a sufficient length of time.

4. Conclusions

The FRELP project, funded by the European Union with the participation of SASIL in partnership with PV CYCLE Italia, aims to develop an innovative PV waste treatment process with the objective of maximising the recycling/recovery of the materials used in panels.

The present report analysed the potential environmental impacts of the waste treatment of PV and the potential environmental benefits related to the recovery and recycling of PV waste through an LCA approach. The analysis also compared the impacts and benefits of the innovative PV waste treatment process with the current PV waste treatments in non-specialist WEEE recycling plants. An analysis of the LC inventories enabled an estimate to be made of the benefit of the process in terms of saving material resources that are critical for the EU economy. Several scenarios were evaluated in the report, such as decentralisation of PV waste treatment, pyrolysis to treat non-fluorine PV waste, and solar glass recovery. The net benefit of each case in different impact categories is presented in Table 18.

Table 18: Net benefit of the FRELP project in comparison with other scenarios

Impact category	FRELP	Current treatment	Decentral. scenario	Pyrolysis scenario	Solar glass recovery scenario	Unit
Climate change	-2.15E+03	-1.90E+03	-2.64E+03	-2.22E+03	-2.27E+03	kg CO_2 eq
Ozone depletion	-1.35E-04	-1.04E-04	-1.49E-04	-1.42E-04	-1.26E-04	kg CFC-11 eq
Human toxicity, cancer effects	-6.22E-04	-5.62E-04	-7.11E-04	-6.38E-04	-6.83E-04	CTUh
Human toxicity, non-cancer effects	-1.88E-04	-7.74E-05	-2.21E-04	-1.93E-04	-2.03E-04	CTUh
Particulate matter	-1.52E+00	-1.06E+00	-1.43E+00	-1.52E+00	-1.35E+00	kg PM2.5 eq
Ionising radiation HH	-5.78E+02	-5.06E+02	-5.62E+02	-5.76E+02	-5.40E+02	kg U235 eq
Ionising radiation E (interim)	-1.72E-03	-1.51E-03	-1.67E-03	-1.72E-03	-1.60E-03	CTUe
Photochemical ozone formation	-3.81E+00	-3.69E+00	-8.24E+00	-3.86E+00	-5.38E+00	kg NMVOC eq
Acidification	-1.38E+01	-1.03E+01	-1.94E+01	-1.38E+01	-1.70E+01	molc H^+ eq
Terrestrial eutrophication	-1.23E+01	-1.25E+01	-3.22E+01	-1.24E+01	-2.05E+01	molc N eq
Freshwater eutrophication	-1.60E+00	-8.60E-01	-2.99E+00	-1.60E+00	-2.95E+00	kg P eq
Marine eutrophication	-1.20E+00	-1.25E+00	-2.87E+00	-1.21E+00	-1.82E+00	kg N eq
Freshwater ecotoxicity	-7.01E+03	-6.07E+03	-1.11E+04	-8.10E+03	-9.84E+03	CTUe

Impact category	FRELP	Current treatment	Decentral. scenario	Pyrolysis scenario	Solar glass recovery scenario	Unit
Water resource depletion	-9.72E+03	-8.88E+03	-9.81E+03	-9.69E+03	-9.73E+03	m^3 water eq
Abiotic depletion (mineral)	-4.82E+00	-1.84E-02	-1.04E+01	-4.82E+00	-1.04E+01	kg Sb eq
Abiotic depletion (fossil fuel)	-3.42E+04	-2.70E+04	-3.56E+04	-3.47E+04	-3.31E+04	MJ

The following section provides the main conclusions of the case study.

- The LCA study of PV waste treatment represents one of the early LCA assessments of PV recycling technology, which is gaining in importance after the introduction of WEEE Directive for PV waste. The study also adds to the general picture of the potential environmental impacts of the PV panel along its life cycle, from the production to its EoL. The production of secondary materials recovered from the innovative PV waste treatment process would allow significant environmental benefits for all the impact categories considered.
- The innovative PV waste treatment process demonstrated a higher environmental benefit compared to current processes. These higher benefits are due to the higher recovery rates that are achieved, especially concerning some precious and CRMs.
- The main environmental benefits in PV waste treatment are related to the recycling of aluminium. However, the recovery of silver also makes a significant contribution, especially in the mineral fossil and renewable resource depletion impact category.
- The transport of PV waste to the recycling plant makes a significant contribution to the overall LCIA results. A scenario has been developed in which waste panels are partially dismantled in decentralised WEEE plants to remove the frame, cables and glass, while the remaining PV sandwich is transported to a specialised plant for further treatments. The results proved that the adoption of local pre-treatments could significantly reduce the impacts of transport. Therefore, the management of PV waste recycling in the future should take into consideration strategies for an efficient logistics.
- Pyrolysis is a potential treatment for non-fluorine back-sheet in PV waste. This option shows a better environmental performance in several impact categories compared to processing with incineration. Moreover, avoiding fluorine-based materials would mean avoiding the use of fluorspar, a raw material considered critical for the economy of Europe.
- The potential environmental benefit of PV waste recycling could be improved through further recovery of solar glass which is manufactured using antimony-based substance.

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List of Abbreviations

AC	Alternating Current
A-Si	Amorphous silicon
BAPV	Building-Applied Photovoltaics
BIPV	Building Integrated Photovoltaics
BOS	Balance of System
CdTe	Cadmium-telluride
CIGS	Copper Indium Gallium di Selenide sulphide
CPV	Concentrated Photovoltaics
CRM	Critical Raw Materials
C-Si	Crystalline-silicon
DC	Direct Current
EC	European Commission
ENEA	Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile (Italian National Agency for New Technologies, Energy and Sustainable Economic Development)
EoL	End of Life
EPIA	European Photovoltaic Industry Association
EU	European Union
EVA	Ethylene-vinyl acetate
FEVE	European Federation of glass packaging and glass tableware makers
FIT	Feed in Tariffs
FRELP	Full Recovery End of Life Photovoltaic
GSE	Gestore Servizi Energetici
HF	Hydrofluoric Acid
IEA	International Energy Agency
ILCD	The International Reference Life Cycle Data System
ISI	Institut für System — und Innovationsforschung Fraunhofer
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MG	Metallurgical Grade
MJ	Mega Joule
MW	Megawatt
OECD	Organisation for Economic Co-operation and Development
PDMS	Polydimethylsiloxane
PV	Photovoltaic
PVC	Polyvinyl Chlorine
PVF	Polyvinyl Fluoride
PVPS	The Photovoltaic Power Systems Program, from IEA
TF	Thin Films
TPU	Thermoplastic polyurethane
UV	Ultra Violet
WEEE	Waste of Electric and Electronic Equipment

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