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2013

Dubey, S., Jadhav, N. Y., & Zakirova, B. (2013). Socio-economic and environmental impacts of silicon based photovoltaic (PV) technologies. Energy procedia, 33, 322-334.

<https://hdl.handle.net/10356/106550>

<https://doi.org/10.1016/j.egypro.2013.05.073>

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PV Asia Pacific Conference 2012

Socio-Economic and Environmental Impacts of Silicon Based Photovoltaic (PV) Technologies

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Abstract

Solar photovoltaic (PV) system provides significant social and environmental benefits in comparison to the conventional energy sources, thus contributing to sustainable development. The worldwide PV market installations reached a very high growth in 2011 (27.4 GW). These are encouraging news since electricity generation from PV produces no greenhouse gas emissions and as such provides a clean alternative to fossil fuels, contributes to job creation and economic prosperity even in less developed areas. However, manufacturing PV modules can have consequences for workers and on the environment throughout their life cycle (from raw material extraction and procurement, to manufacturing, disposal, and/or recycling). Large scale PV deployment also needs land that may not be available, or in competition with other land uses. These potential problems seem to be strong barriers for a further dissemination of PV technologies. Conventional PV (silicon based) manufacturing processes have roots in the electronics industry, many of the chemicals found in e-waste are also found in solar PV, including lead, brominated flame retardants, cadmium, and chromium. The manufacturing of solar cells involves several toxic, flammable and explosive chemicals. Many of those components suppose a health hazard to workers involved in manufacturing of solar cells. Solar panels are often in competition with agriculture and can cause soil erosion. The disposal of electronic products is becoming an escalating environmental and health problem in many countries. Recycling of PV panel is currently not economically viable because waste volumes generated are too small; significant volumes of end-of-life photovoltaic panels will begin to appear in 2025 or 2030. An overview of social and environmental impacts of PV technologies is presented in this paper along with potential benefits and pitfalls.

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Selection and peer-review under responsibility of Solar Energy Research Institute of Singapore (SERIS) – National University of Singapore (NUS). The PV Asia Pacific Conference 2012 was jointly organised by SERIS and the Asian Photovoltaic Industry Association (APVIA)

Keywords: Solar energy; photovoltaic (silicon based); environmental and socio-economic impacts

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1. Introduction

In order to understand which processes during c-Si PV module manufacturing and recycling cause environmental and social impacts, it is firstly essential to know the main components a PV module: Fig. 1, top-down.

- Composed glass to protect the cells from damage;
- Laminating mostly consists of Ethylene vinyl acetate (EVA). The solar cells are embedded in the two layers of laminating;
- Mono- or poly-crystalline solar cells which are connected with copper ribbons;
- Weatherproof plastic backing made from Polyvinyl fluoride (PVF) and Polyethylene (PET);
- Junction box for connecting the PV modules to each other

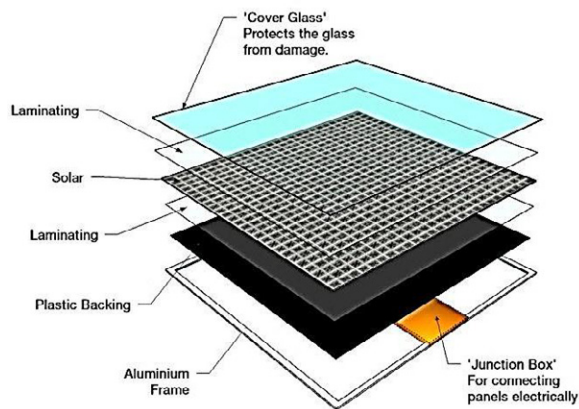


Fig. 1. Components of a PV module.

All these components are manufactured in different ways by various producers and are then assembled by the providers of PV modules. Secondly, information about the mass portions of the c-Si components is crucial for understanding manufacturing and recycling processes of PV modules (see Table 1). Glass takes 74% of mass which is highest. The aluminium frame amounts to 10% whereas all polymers add to approximately 6.5%. In contrast, the mass of solar cells is 3% only. All other materials (like Zn, Pb) contribute less than 1%.

Table 1. Mass portions of a c-Si (crystalline silicon) PV module component.

Main materials		Other materials	
Material	% (wt)	Material	% (wt)
Composed glass	74	Zinc	0.12
Polymers (laminating and plastic backing)	≈ 6.5	Lead	< 0.1
Solar cells	≈ 3	Copper (ribbons)	0.6
Aluminium frame	10	Silver	< 0.006

1.1. Conventional PV manufacturing

Most of the PV manufacturers do not produce all components by themselves: materials like glass, aluminium and copper are produced in conventional processes by traditional manufacturers. These processes are very well developed - efficiency improvements in manufacturing are hard to achieve. By contrast, silicon production is a rather new branch. Hence prospects for reduction of energy need for manufacturing solar cells are clear [1]. The current processes, techniques and energy expenditures for production of solar cells are indicated in the following section.

1.1.1. Metallurgical grade silicon

Metallurgical grade silicon (MGS) is produced in an electric air furnace (EAF). During this process silicon is reduced by carbon in a fused salt electrolysis. Thereby a purity of silicon of 98 to 99.5 % can be achieved.

Chemical equation:



Energy expenditure: 150 kWh_{el}/kg-Si

As solar cells require a purity of at least 1 part per billion, further processing is necessary. In order to achieve the required purity the MGS must be converted to either electronic grade silicon (EGS) or upgraded metallurgical grade silicon (UMGS) (Table 2). UMGS is directly processed from MGS

Table 2. List of energy expenditure in electronic grade (EGS) or upgraded metallurgical grade silicon (UMGS) processes [2].

Electronic Grade Silicon			Upgraded Metallurgical Grade Silicon (Energy expenditure 15-20 kWh _{el} /kg-Si)		
Processes	Description	Energy expenditure (kWh _{el} /kg-Si)	Processes	Description	Energy expenditure (kWh _{el} /kg-Si)
Silane Production	The MGS is grounded and lapped with hydrogen chloride gas in a fluidised-bed reactor. This takes place at a temperature of 300 to 400 °C. Gaseous chlorosilanes arise. Chemical equation: $\text{Si} + 3\text{HCl} + 50 \text{ kWh/kg-Si} \rightarrow \text{SiHCl}_3 + \text{H}_2$	50	Monocrystalline Silicon	Monocrystalline silicon can be produced by further processing the EGS or UMGS in the Czochralski or float-zone pulling process.	15-20
Fractional Distillation	The chlorosilanes are separated and high purity trichlorosilane SiHCl ₃ gases are the product.	100	Polycrystalline Silicon	The processes for producing polycrystalline silicon are ingot casting, edge defined film-fed growth method or the string-ribbon process.	50
Separation	The last step is adding hydrogen. This can either be done during the Chemical-Vapour-Deposition process at 1100 °C or in a fluidised bed reactor at 700 °C. $\text{SiHCl}_3 + \text{H}_2 + 50 \text{ kWh/kg-Si} \rightarrow \text{Si} + 3\text{HCl}$	200	Cutting ingots and Wafers	The silicon cells are cut or milled into ingots. Normal measures for ingots are 100×100 mm, 125×125 mm and 156×156 mm. Then wafers are milled from the ingots, which is coupled with material losses of 30 to 50 %, this is due to the use of silicon carbide for milling.	50

bypassing the process of silane production. As results process has lower efficiencies due to lower purity. In order to produce UMGS the liquid phase epitaxy, segregation or solving silicon in aluminium is used. Due to the reason that high material losses arise from milling the wafers, other methods were developed. Some of them are pulling methods (EFG and String-Ribbon), tearing with a thin layer of silver and using laser.

1.1.2. Total energy expenditure for solar cell manufacturing

The total energy expenditure for solar cell manufacturing is the sum of the aforementioned processes. Mono-crystalline cells require up to 1000 kWh/kg-Si. Manufacturing of poly-crystalline cells has energy expenditures of up to 700 kWh/kg-Si.

2. Environmental effects from PV manufacturing

As outlined in the above the main manufacturing processes are driven by electricity. That is why the environmental effects strongly depend on the energy mix the modules are produced in. Assuming that the energy used for manufacturing was 100% renewable, there would be no environmental impact apart from few hazardous materials which are used during the production. In order to rate the environmental effects it is important to consider the exhaustion of raw material, energy needed, global warming, acidification, and waste [3].

2.1. Hazardous materials

Purification of silicon hazardous material such as silane might be required. Additionally, other toxic chemicals, e.g. diborane and phosphine, are necessary for doping the silicon. Only small quantities which are diluted in inert gas are used for this process. As these materials are commonly used in the microelectronic industry, a well-established control and monitoring exists. Nevertheless, silane and phosphine are inflammable gases, the latter is even highly toxic. During regular operation of the manufacturing processes these gases are not dangerous, but in case of any accident or leakage dangerous emissions of the aforementioned gases can happen. Using zinc should be avoided as this contributes to the exhaustion of raw materials as well as to the solid waste. Regular materials like aluminium and copper are associated with the standard industrial hazards [3]. Although PV modules might be transported across long distances, only 0.1% to 1% of the emissions arise from transportation [4]. To sum up, during production the following hazardous materials are emitted, Silica dust, Silanes, Diborane, Phosphine, and Solvents [3].

Table 3. Emissions form photovoltaic module and system.

		SO ₂	NO _x	Particles	CO ₂	CH ₄	N ₂ O	Source
Emissions (kg/kW _p)	PV Module 1995/1998	5 - 5.5	4.5 - 5.3	No Info	2.7 - 3.8	No Info	No Info	[5, 6]
	Entire PV System 1998	1.9	1.8	0.11	971,000	1.6	0.0031	[3]

Table 3 shows the emissions from PV Module manufacturing and an entire PV System. The data is about 15 years old; therefore there must have been improvements in the manufacturing processes. In contrast to the information in Table 3, recent studies indicate the environmental effect in the emissions of

grams of CO₂-equivalent per kWh produced electricity during the life cycle of a PV module. The major studies provide the CO₂-equivalent instead of distinguishing different types of emissions. A roof-top PV system with poly-Si produced with hydropower and wafers, cells and modules manufactured with UCTE electricity has a *carbon footprint of 34 g CO₂-eq/kWh* [7]. This was calculated assuming a PV system installed in Southern Europe with a solar irradiation of 1700 kWh/m² per year. Experts predict further improvement of the manufacturing processes which will cut footprint by 40-50% [1]. The local electricity mix, i.e. the electricity sources used for manufacturing the modules, influence the primary energy needed as well as the CO₂-equivalent emitted per kWh produced. Differences occur especially in the production of silicon [7].

The following chart (Fig. 2) indicates that mono-crystalline cells have the greatest environmental impact. The environmental effect of multi-crystalline cells is lower as less energy is required for the manufacturing process. Basically, only the abiotic depletion, the GWP and the acidification effect the environment. Due to the burning of fossil fuels for energy (electricity) generation during manufacturing, the fossil fuel deposits are depleted. This causes the abiotic depletion. The GWP as well the acidification potential is caused by emissions from fuel combustion (Fig. 2).

In terms of carbon footprints of PV modules it is crucial to give information on the location and especially the electricity mix which was used for PV manufacturing. Assuming that 100% renewable energy was used for production of the PV modules, they would have no carbon footprint. In this context, production of silicon significantly affects the carbon footprint. Some silicon grade manufacturers for example use hydropower for silicon production. The following table shows differences in the carbon footprints of PV module production with different energy mixes. Particularly notable is the fact that it is possible to reduce the carbon footprint by 50% when producing wafers, cells and modules with hydropower and UCTE instead of using the average electricity mix from countries (Fig. 3).

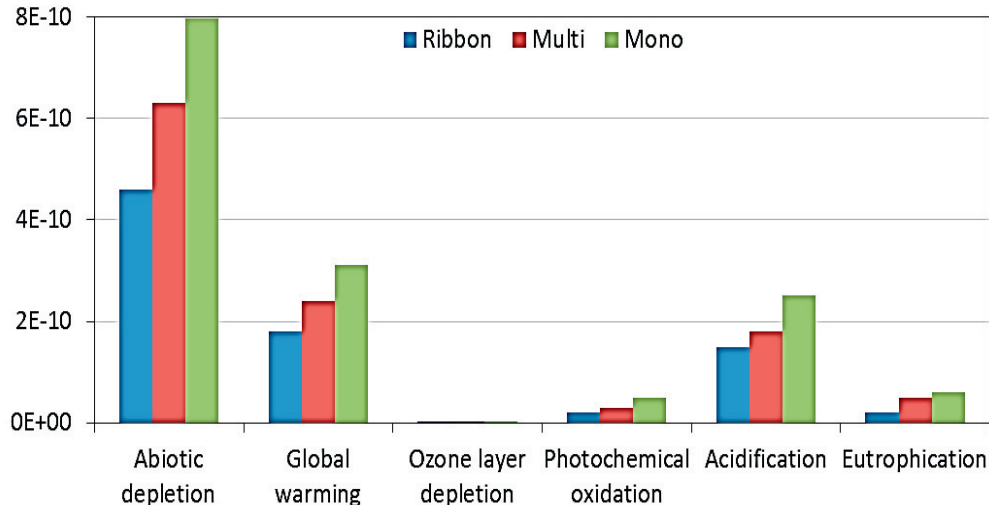


Fig. 2. Normalised LCA results for the three module types, functional unit 1 kW_p [1].

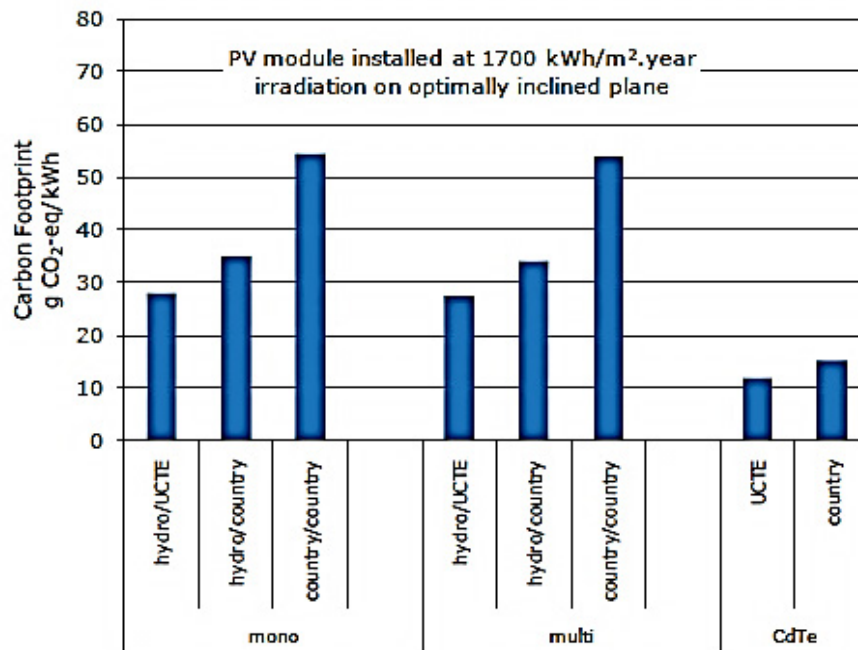


Fig. 3. Comparison of carbon footprints of PV modules. Assumptions: irradiation 1700 kWh/m² year, optimally inclined modules. Poly-silicon produced with hydropower or electricity mix. Wafer, cells and modules produced with UCTE or country electricity mix [7].

2.2. Energy demand and energy payback time (EPT) for conventional PV modules

The energy demand for one PV module with 160 W_p is approximately 460 kWh_{el} [8], i.e. that about 2.9 kWh_{el} per W_p are required for PV manufacturing. The energy payback time depends on various factors, e.g. location, solar irradiation, shadowing, electricity mix used for manufacturing, efficiency etc. Case studies have shown that crystalline PV panels have an EPT of 1.7 to 1.9 years when installed in southern Europe (1700 kWh/m² year). This applies to PV systems with poly-Si from hydropower and wafer/cell/module from UCTE electricity [7]. Figure 4 shows the influences on the EPT. There is a vast difference between systems installed in N and S Europe. Furthermore, the table displays that the EPT for mono crystalline modules is the longest. This is due to the fact that they require the most energy to be manufactured.

3. PV recycling

Recycling of PV modules is a very complex process because the modules consist of many different materials. If the materials from PV modules are separated with certain purity, most of the materials get recycled in standardised way. Examples are glass, copper, aluminium as well as other metals. In contrast, processes for reclaiming solar silicon and solar cells are mainly still in R&D phase. First, all sorts of materials used in the PV module have to be detected; otherwise no efficient recycling is possible. The recycling process depends on the type of PV module, i.e., not one process fits to all, but different

recycling processes for crystalline, thin film, amorphous and organic PV modules. Figure 5 displays the ecological efficiency of different recycling processes.

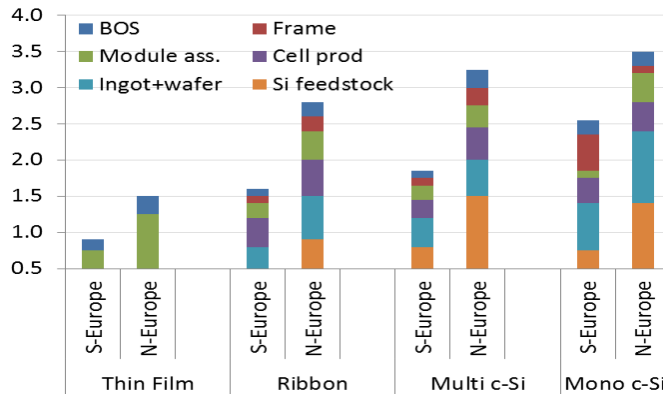


Fig. 4. Energy payback time for different PV systems in different locations (rooftop system, irradiation. 1700 resp. 1000 kWh/m² year) [9] (Source: Alsema, DeWild, Fthenakis, 21st European Photovoltaic European Energy Conference)

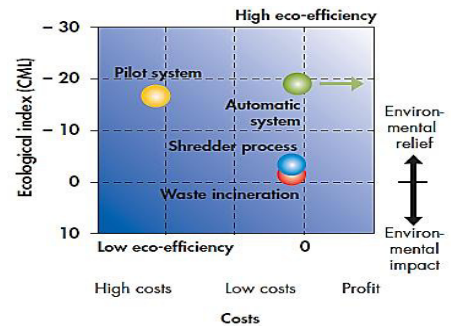


Fig. 5. Comparison of recycling processes [10].

3.1. Recycling of modules with intact cells

Separation of the module by thermal treatment [11]: The modules are stacked and put into a furnace. All synthetic materials are burnt at a temperature of 600°C. A negative side effect of the thermal treatment is the emission of gas due to EVA copolymer thermal degradation [12]. All organic materials are fully gasified in this stage. The remaining materials, e.g. solar cells, glass and metals are then transported to an automatic separator and sorter. Conventional materials like glass and metals are transferred to standardised recycling facilities. The glass is sufficiently pure to be used as raw material for float glass recycling. The solar cells have to be processed further. Figure 6 shows the stages of recycling PV modules.

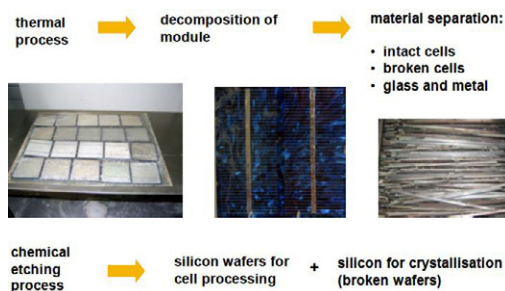


Fig. 6. Stages of separation and recycling [11].

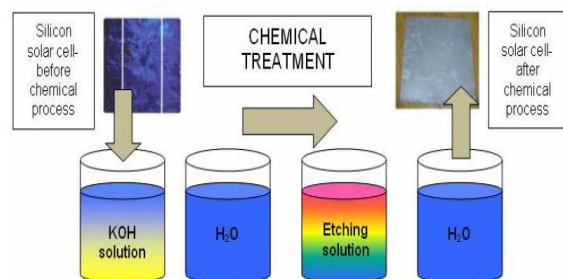


Fig. 7. Chemical etching of crystalline solar cells [12].

Chemical etching: When the surface of the solar cells is damaged only slightly, it is possible to clean the solar cells in a series of chemical processes. In this case, wafers can be recovered to the condition as good as new. These wafers meet the quality requirements and can be processed to solar cells and modules again. Figure 7 shows the chemical etching of crystalline solar cells.

3.2. Recycling of modules with broken cells

Solar Cycle which is part of SolarWorld provides a detailed description of the recycling process for crystalline PV modules [13]. The process is described by separation of the module by thermal treatment, separation of glass and broken cells, optical separation, silicon purification, exhaust air treatment, and chemical etching.

4. Environmental impacts of recycling and energy payback time

Following scenarios were analysed to compare the environmental impact of recycling of PV modules (Figs. 8 and 9) [11]:

- High value recycling: recovery of silicon and all valuable substances
- Simplified process: crushing, incineration of plastic materials in MWI, disposal of inorganic components
- Incineration of modules without prior material separation

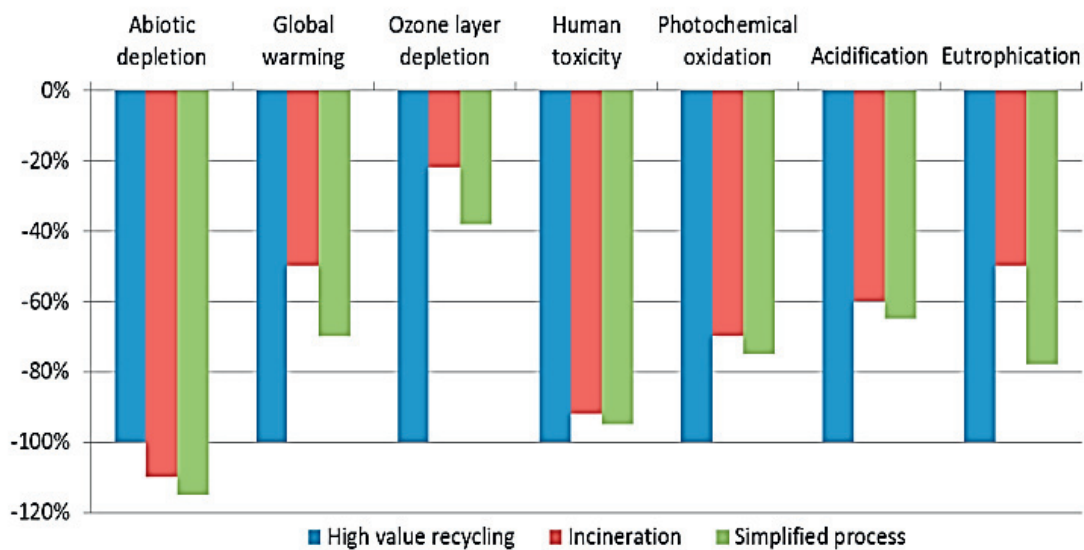


Fig. 8. Comparison of disposal methods [11].

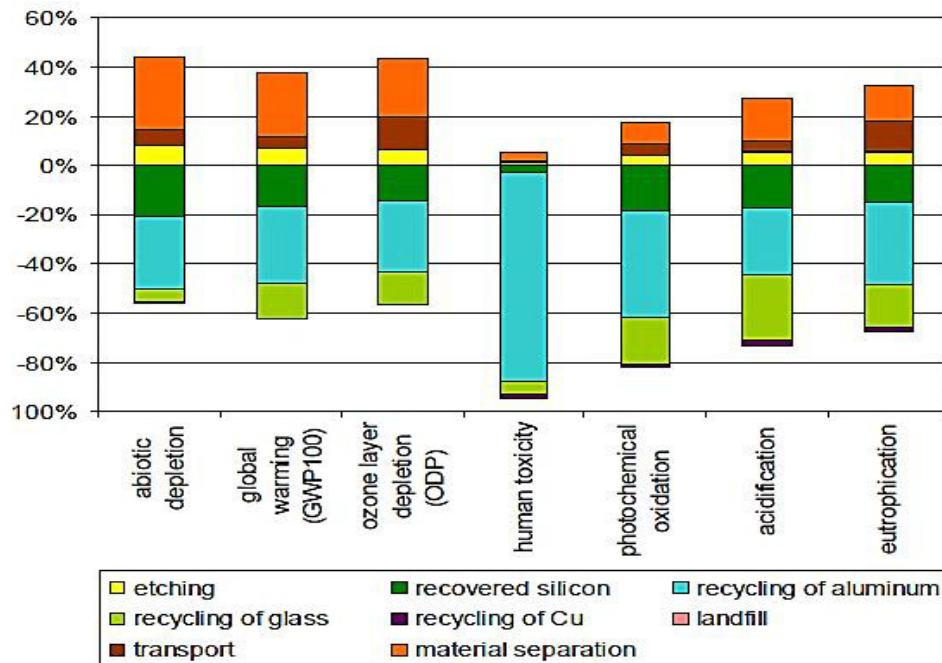


Fig. 9. Environmental balance of high value recycling scenario [11].

The energy demand for recycling and reprocessing PV modules is approximately 200 kWh per module. This energy demand applies to a module with 160 W_p [8], i.e. the energy the demand is approximately 1.25 kWh per W_p. The recycling process itself requires about 90 kWh per module or 0.6 kWh per W_p. This shows that the energy demand for recycling modules is much smaller than the energy necessary for manufacturing a new module. More than 50% of energy can be saved when PV modules are recycled. Table 4 shows the comparison of energy payback time of standard and recycled module.

Table 4. Comparison of energy payback time of standard and recycled module [14].

	Standard	Recycled
Energy Input	9.32 kWh/wafer or 4.26 kWh/W _p	2.17 kWh/wafer or 0.99 kWh/W _p
Energy payback time		
Sunny regions	2.58 years	0.6 years
Continental regions	4.92 years	1.14 years

5. Social and economic impact

There is a lack of knowledge about the social and political impacts of solar panels. Most of the research has been dealing with the technical and economic aspects of the evaluation [15]. It is still little known about the impacts in general because the solar technology is young and its life cycle is long. Beside the fact that the impacts of the first generation of solar panels will be evident after 25 years starting recording from the early 1990s trends [16], new technologies and components are yet to be

developed. Hence research is based on limited assumptions which are made after comparing the solar with the impacts from electrical devices. Furthermore estimations are based on laboratories tests - they can differ from the consequences in the real world. Usually scientists tend to underestimate impacts such as a past example on ozone hole. Still if we can estimate risks and hazards we can develop alternative materials and components aiming to achieve 100% recycle-ability.

Main social and correlated economic impacts which are split in positive and negative aspects are shown in the Table 5. Although the benefits are clear, the market - and not policies - mostly decides about adopting solar PV successfully [17]. From an experience on subsidies in the EU rooftop market we can learn that this kind of market cannot sustain in the long term. Not only that solar has reached competitiveness with the coal, oil, gas and other carbon generating resources but also it needs no water for energy generation. Finally by implementing solar energy many international conflicts for oil and water can disappear and save the enormous military costs. Hence by redirecting investments from military use to solar energy can also significantly mitigate climate change.

Table 5. Social and economic impacts of solar PV.

Social/Economic		
Impacts	Positive	Negative
Land use and landscape	<ul style="list-style-type: none"> • Decreased land use compared to conventional energy resources • Reuse of degraded sites • Use of unused sites (such as in deserts) • Multi-purpose and integrated use on existing developments or buildings (like rooftops, façades) 	<ul style="list-style-type: none"> • Unavailable land/ high competition with other land uses (such as agriculture) • Degradation of vegetation and soil erosion • Higher up-front costs • Visual/landscape experience • Microclimatic change • Glare risk by reflection
Infrastructure	<ul style="list-style-type: none"> • Reduced transmission lines/grids • Energy supply for decentralized, low-density off-grid areas, also in developing countries 	<ul style="list-style-type: none"> • Requirement for energy storage for continuous supply
Political	<ul style="list-style-type: none"> • National energy independency from import • Lower military expenses (less conflicts in the oil rich countries) 	<ul style="list-style-type: none"> • Economically detrimental subsidies such as uncontrolled and miscalculated fee-in-tariff mechanisms
Energy market	<ul style="list-style-type: none"> • Diversification • Deregulation 	<ul style="list-style-type: none"> • Intermittent supply issues
Industry, R&D, education	<ul style="list-style-type: none"> • Jobs creation • Higher development and education level 	<ul style="list-style-type: none"> • Health hazards and risks during manufacturing phase
Public & marketing	<ul style="list-style-type: none"> • Increased environmental consciousness • Improved image 	<ul style="list-style-type: none"> • None.

Entire global peak load capacity is 5,000 GW which is generated by (1) coal (32%), (2) natural gas (24%) and (3) hydroelectric power (19%). Solar can be great replacement for peak energy produced by fossil fuels in developed countries, and for oil generated energy in India and Middle East. In China solar has been introduced as new source of clean energy. An explanation is dropping prices of solar energy: in

2012 retail electricity price in EU and some US markets were met by decreased price of solar energy generated on rooftops. At the same time price of solar against distributed power based on off-site diesel has turned to be competitive in Asia Pacific Region as well. In the Middle East price of solar power is already lower than the price of fired power generator. These trends are expected to continue since we expect breakthrough technologies and many advantages of solar compared to classical wholesale peak prices and retail rates [18].

The main key drivers for future markets of solar energy are (1) market sustained without subsidies, (2) technological innovations for increased efficiency, reduced manufacturing costs and improved balance of plant, (3) diversified capital flow from financial and corporate sponsors and (4) penetration of conglomerate participation which go along with acting locally and having global impact. The driver #2 will be able to make solar power competitive to peaking retail and wholesale price, and #4 shall be seen as an opportunity for consolidating several global players with the strong market brands in the next five years. Out of #1 market researchers expect US, China, India, SE Asia and Middle East to reach sustainable markets, whereas European market will continue to have small share related to rapid expansion of exclusive rooftops through subsidies in the past. Therefore the long-term winners on the solar market incorporate core values or goal to satisfy following points of interest: utility, consumer, financing provider, lower cost producers and large conglomerates.

One remaining point is to discuss health impacts from the entire life cycle of the PV cells: (a) production/ manufacturing, (b) operation and (c) recycling of waste. One particular advantage of PV materials is that they are 99% recyclable (see Table 1), require low maintenance and small material mass as compared with classical energy resources. The main variables affecting human health are:

- Toxicological properties of materials (toxic, carcinogenic or flammable)
- Degree of concentration
- Frequency and length of exposures
- Ability of receptor to absorb the compound, and
- Individual sensibility of human bodies

(a) Primary health concern of Si-based panels[†] might affect manufacturer and residents nearby via accidental use of toxic gases and solvents (such as arsine and phosphine) or simple inhalation of fumes (from diverse acids such as HF and HNO₃, alkalis, dopant gases and vapors like POCl₃). The disposable chemicals used during the manufacturing can have negative effects on public health. Yet they aim to have lower affects by reducing disposal and replacing harmful chemicals with friendly alternatives. (b) When the solar panels are installed, the risks of chemicals coming out on the surface are very low because the modules are very well sealed and the chemicals appear in a very small amount[‡] [19, 20]. Aspect on (c) has still potential for development. For example Deutsche Solar recycles silicon wafer by treating fluorine and acetic acid in afterburner and washer and recycled wafers show improved performance compared to the original wafers [21].

[†] The health matter of thin-film PV cells - which are minor spread compared to Si-based - are cadmium telluride (CdTe), amorphous silicon (α -Si) and copper indium selenide (CIS)/ copper indium gallium diselenide (CIGS). The latter can be layered with CdS layer which is carcinogenic if leaked in water.

[‡] Exceptions are fire and other disasters.

6. Conclusions

It must be realised that no manmade project can completely avoid some impact to the environment, so neither can photovoltaics. Potential environmental burdens depend on the size and nature of the project and are often location specific. Most of these burdens are associated with loss of amenity (e.g., visual impact or noise in the case of central systems). However, adverse effects are generally small and can be minimised by appropriate mitigation measures, including the use of the best available abatement technologies.

- In the module production process hazardous gases are used. The handling of hazardous gases in the module production should be a point of attention, especially where large scale production is concerned.
- Research should be carried out as to how recycling of 80% to 95% of the modules can be achieved.
- Because availability, completeness and quality of the data on materials and processes is far from ideal, future research for LCA-studies should include the development of a database with data from both national and international (material) processes.

It is up to the involved factors (investors, developers, and permitting authorities) to make the appropriate decisions by taking environmental issues into serious consideration. To that end, an Environmental Impact Assessment for central systems, which should estimate the magnitude of potential environmental impacts and propose appropriate mitigation measures, can play a significant role to proper project design and to a subsequent project public acceptance.

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