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Environmental footprinting of photovoltaic module production

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ABSTRACT

Several PV module producers have performed a carbon footprint analysis and published a sustainability report as part of their corporate social responsibility policy. Comparison of carbon footprint results is difficult because several international standards and life cycle assessment (LCA) databases are used. No product footprint category rules (PFCR) or product category rules (PCRs) for photovoltaics exist, so LCAs are performed with varying underlying assumptions. Furthermore, a fair comparison can only be made when all environmental footprints of a product are taken into account.

Sustainability reporting

One important step in corporate social responsibility (CSR) policy is publishing a sustainability report. The most used reporting framework is that of the Global Reporting Initiative (GRI) [1]. The content of the report is selected on the basis of the principles of materiality (significance), stakeholder inclusiveness, sustainability context and completeness. To ensure the quality of the report it must be well balanced, comparable, accurate, timely, clear and reliable.

> "One way to determine the significance of an environmental performance indicator is to carry out an LCA of the PV module."

Environmental performance indicators

How does one go about selecting the key GRI environmental performance indicators to be included in the report? First of all, the environmental issue must be significant. One way to determine the significance of an environmental performance indicator is to carry out an LCA of the PV module and analyze the possible environmental impacts from cradle to grave. The environmental impact assessment method ReCiPe [2] can be used for this purpose.

Fig. 1 shows the ReCiPe steps from calculating the inventory of life cycle emissions, through determining midpoint environmental impacts, to evaluating endpoint damages to human health and ecosystems and depletion of resources. After normalization of midpoint environmental impacts to the impact of one citizen, the researcher has an idea of which indicators are significant. For a multicrystalline silicon PV module produced in China these are (see Fig. 2):

1. Fossil depletion
2. Climate change (human and ecosystem)
3. Particulate matter formation
5. Human toxicity

In this case the solar cell is the largest contributor to all impacts.

Stakeholders – such as governments/policy makers, suppliers, employees, customers, competitors, neighbouring communities, banks, investors, advocacy NGOs, media and scientists – can be asked which environmental issues they would like to see reported. One environmental advocacy organization is the Silicon Valley Toxics Coalition (SVTC). They envision a safe and sustainable solar PV industry that

- takes responsibility for the environmental and health impacts of its products throughout their lifecycles, including adherence to a mandatory policy for responsible recycling;
- implements and monitors equitable environmental and labour standards throughout product supply chains;
- pursues innovative approaches to reducing toxic chemicals in PV module manufacturing.

Each year, SVTC publishes a solar scorecard based on questionnaires sent to PV module manufacturers. The 2010 results of the top 10 PV module manufacturers are given in Fig. 3 [3]. This 2011 solar scorecard represents 46.6% of the industry market share, based on solar PV module

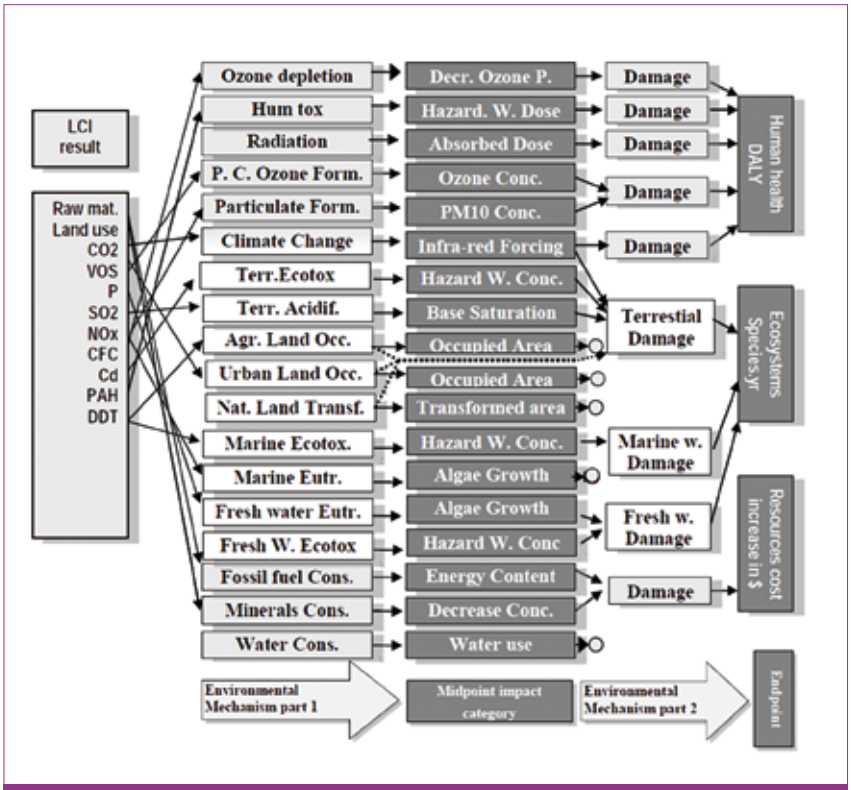

Figure 1. ReCiPe environmental impact assessment method [2].

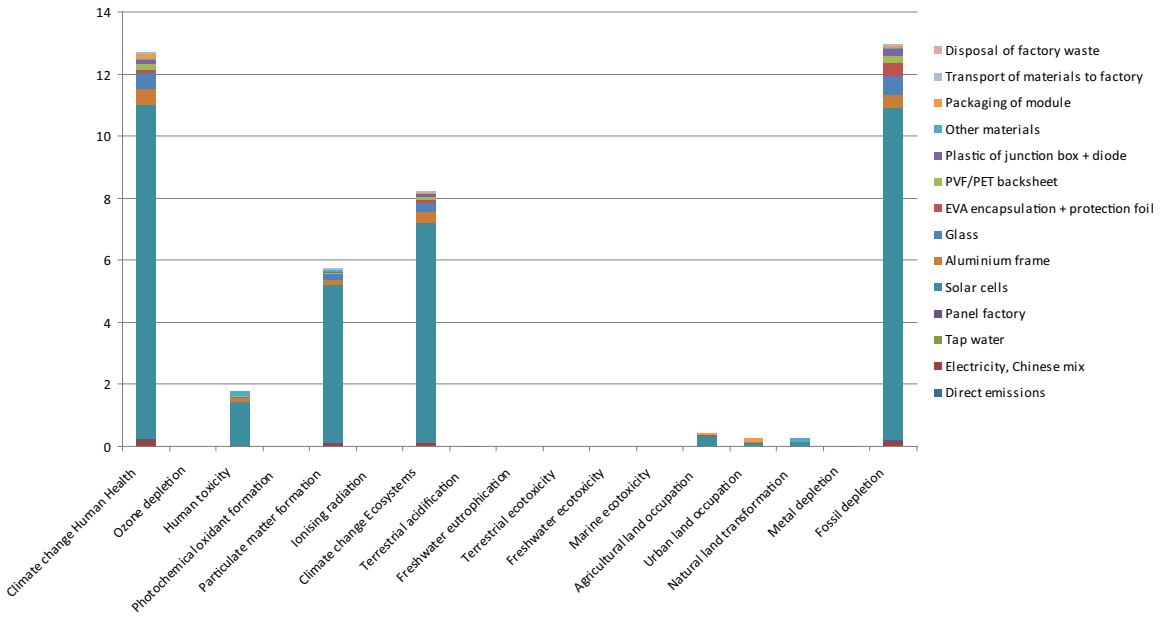

Figure 2. Environmental impact assessment of a multicrystalline silicon PV module produced in China using the ReCiPe H endpoint method and Europe ReCiPe H/A [2] normalization with weighting in Simapro software. The y-axis units are ReCiPe points.

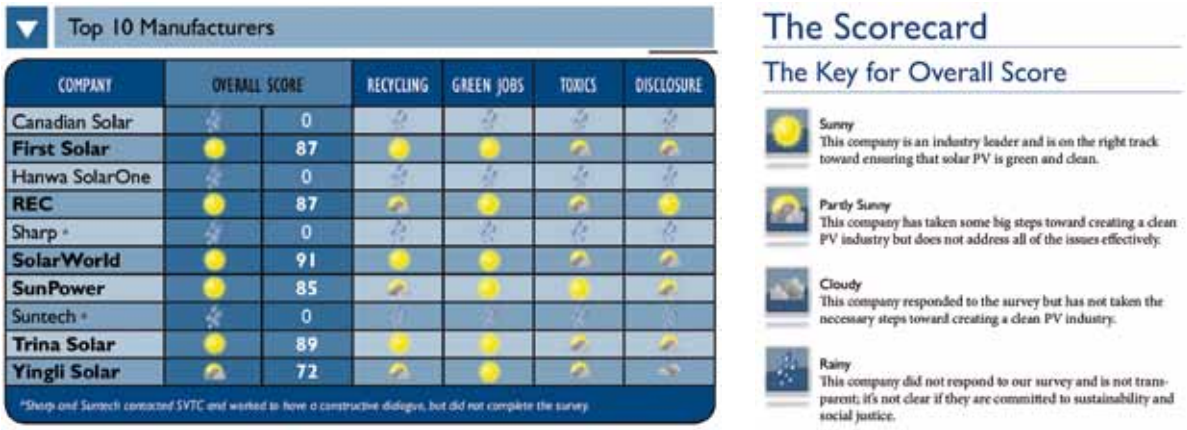

Figure 3. Overall score in the 2011 solar scorecard of the top 10 PV module manufacturers [3].

shipment statistics for 2009. The indicators put forward by SVTC can be considered to be important for environmental advocacy stakeholders. Table 1 gives an overview of the 2012 PV module manufacturer survey by SVTC, and a mapping with the paragraphs and performance indicators of the GRI sustainability reporting structure.

> "Knowing your environmental profile is the first step in the implementation of improvements, which reduce costs as well."

Ecodesigners need to know the most significant contributors to the environmental impacts as revealed by a full LCA. Knowing your environmental profile is the first step in the implementation of improvements, which reduce costs as well.

Carbon footprinting

One of the most significant environmental impacts from the production of PV modules is climate change, and this is the reason why life cycle greenhouse gas emissions need to be considered. There are several *international* standardization initiatives for creating a standard for product carbon footprint, including:

- ISO 14067, expected in 2012 [4]
- Greenhouse Gas Protocol (GHG Protocol), published in September 2011 [5]

In 2010 more than 85% of the 2487 respondents to the Carbon Disclosure Project survey used the GHG Protocol Corporate Standard to measure and report their emissions. The Carbon Disclosure Project is globally the largest collection of self-reported climate change data [6]. There is also a British specification called PAS2050 that is applied by several solar cell and PV module producers (Motech, AOU, Upsolar, Yingli Solar, NexPower), but PAS2050 is *not* a standard [7].

Special attention is required when gases such as NF_3, SF_6, C_2F_6, CF_4 and N_2O are used in solar cell and module manufacturing, since they have high global warming effects that are, respectively, 17200, 22800, 12200, 7390 and 298 times that of CO_2 [8]. Control of emissions by the installation of abatement systems is necessary.

Water footprinting

The consumption of water in the manufacturing of PV modules and their components may also be important for

Aspect	Paragraph / Indicator			Question	
Standard disclosure: profile					
Strategy and analysis	in 1.2, Targets and goals section 2			III-2	Does your company post on its website annual hazardous chemical reduction targets?
				V-6	Has your company set any 'zero waste' and/or annual waste diversion targets for PV modelling facilities?
				V-7	Does your company set goals for improving recyclability or reducing the amount of packaging materials used for shipping PV modules?
Organizational profile	2.5	Number of countries in which the organization operates, and names of countries either with major operations or that are specifically relevant to the sustainability issues covered in the report			Countries where PV module manufacturing occurs
	in 2.8	Quantity of products or services provided			Total volume of PV modules manufactured in 2011 in MWp
					PV module manufacturing capacity in MWp as of January 1st 2012
Environmental performance indicators					
Materials	EN1	Materials used by weight or volume	CORE	III-4	Do your PV modules contain cadmium, lead or selenium?
				III-5	Do your processes or products use, generate or contain engineered nanoparticles?
				IV-7	Can you verify that your supply chain does not contain conflict materials? 'Blood diamonds', coltan, tungsten, cassiterite (tin ore) and gold from the Great Lakes Region of Africa are widely considered the most common conflict materials.
	EN2	Percentage of materials used that are recycled input materials	CORE	V-2	What percentage of your PV module (by weight) is made from recycled materials?
Energy	EN3	Direct energy consumption by primary energy source	CORE	V-4	Do you report your company's overall direct and indirect energy consumption by primary energy source (via your own website or a third party such as Carbon Disclosure Project or Global Reporting Initiative)?
	EN4	Indirect energy consumption by primary energy source	CORE		
				V-3	Have you conducted a life cycle analysis on your PV modules (energy payback time)?
	EN5	Energy saved due to conservation and efficiency improvements	ADD		
	EN6	Initiatives to provide products and services that are energy-efficient or based on renewable energy, and reductions in energy requirements as a result of these initiatives	ADD	V-8	What percentage of your manufacturing operations is conducted in LEED-certified, zero-energy or green buildings?
	EN7	Initiatives to reduce indirect energy consumption and the reductions achieved	ADD		
Water	EN8	Total water withdrawal by source	CORE	III-6	Do you post on your website the volume of water that is used in production each year?
	EN9	Water sources significantly affected by withdrawal of water	ADD		
	EN10	Percentage and total volume of water recycled and reused	ADD		
Biodiversity	EN11	Location and size of land owned, leased, managed in (or adjacent to) protected areas and areas of high biodiversity value outside protected areas	CORE		

Table 1. Mapping of performance indicators in a GRI sustainability report and questions from a 2012 survey by the Silicon Valley Toxics Coalition (SVTC) for the solar scorecard.

	EN12	Description of significant impacts of activities, products and services on biodiversity in protected areas and areas of high biodiversity value outside protected areas	CORE	V-9	Describe significant impacts of activities from your company or its subsidiaries on biodiversity in protected areas and areas of high biodiversity value outside protected areas.
	EN13	Habitats protected or restored	ADD		
	EN14	Strategies, current actions and future plans for managing impacts on biodiversity	ADD		
	EN15	Number of IUCN Red List species and national conservation list species with habitats in areas affected by operations, by level of extinction risk	ADD		
Emissions, effluents and waste	EN16	Total direct and indirect greenhouse gas emissions by weight	CORE	III-1	Do you post on your website the following environmental releases: greenhouse gases/ CO_2e; perfluorocarbons, SF_6, NF_3, CHF_3, CF_4, C_2F_6?
	EN17	Other relevant indirect greenhouse gas emissions by weight	CORE	V-3	Have you conducted a life cycle analysis on your PV modules (greenhouse gas/carbon footprint)?
	EN18	Initiatives to reduce greenhouse gas emissions and reductions achieved	ADD		
	EN19	Emissions of ozone-depleting substances by weight	CORE		
	EN20	NO, SO and other significant air emissions by type and weight	CORE	III-1	Do you post on your website the following environmental releases: air emissions - SOx, NOx, VOCs, PM10, hazardous; total heavy metal emissions?
				V-3	Have you conducted a life cycle analysis on your PV modules: criteria - air pollutants (according to US EPA: ozone, particulate matter, carbon monoxide, nitrogen oxides, sulphur dioxide, lead)?
	EN21	Total water discharge by quality and destination	CORE		Do you post on your website your annual volume of waste water discharged?
					Do you post on your website the following waste water discharge quality indicators: chemical oxygen demand, biological oxygen demand, heavy metals, total suspended solids?
				III-1	Do you post on your website the following environmental releases: total heavy metal emissions?
	EN22	Total weight of waste by type and disposal method	CORE	I-4	What is the final destination for end-of-life and defective PV modules (by weight)?
				I-5	Are waste or scrap PV modules recycled at a facility with a documented environmental management system and worker safeguards and protection that is consistent with ISO 14001?
				I-6	Have you performed a hazardous waste determination for your PV modules?
				III-1	Do you post on your website the following environmental releases: landfill disposal by weight; weight of hazardous waste released and transferred?
	EN23	Total number and volume of significant spills	CORE		
	EN24	Weight of transported, imported, exported or treated waste deemed hazardous under the terms of the Basel Convention Annex I, II, III and VIII, and percentage of transported waste shipped internationally	ADD		

Table 1. Mapping of performance indicators in a GRI sustainability report and questions from a 2012 survey by the Silicon Valley Toxics Coalition (SVTC) for the solar scorecard.

	EN25	Identity, size, protected status and biodiversity value of water bodies and related habitats significantly affected by the reporting organization's discharges of water and runoff	ADD		
Products and services	EN26	Initiatives to mitigate environmental impacts of products and services, and extent of impact mitigation	CORE		
	EN27	Percentage of products sold and their packaging materials that are reclaimed by category	CORE		
Compliance	EN28	Monetary value of significant fines, and total number of non-monetary sanctions for non-compliance with environmental laws and regulations	CORE		How many sanctions for non-compliance with health, safety or environmental violations occurred in the past three years at facilities where you operate or that manufacture your brand-name products?
Transport	EN29	Significant environmental impacts of transporting products and other goods and materials used for the organization's operations, and transporting members of the workforce	ADD		
Overall	EN30	Total environmental protection expenditures and investments by type	ADD	I-2	Does your company currently set aside money to finance the collection and management of end-of-life PV modules?
				V-3	Have you conducted a life cycle analysis on your PV modules (toxicity)?
				V-5	Has your company offered 'design for recycling', 'cradle-to-cradle' or similar training to product designers in the past three years?
Product responsibility performance indicators					
Product and service labelling	PR3	Type of product and service information required by procedures, and percentage of significant products and services subject to such information requirements	CORE	I-3	Does your website let customers know how to recycle/take back their PV modules?

Table 1. Mapping of performance indicators in a GRI sustainability report and questions from a 2012 survey by the Silicon Valley Toxics Coalition (SVTC) for the solar scorecard.

certain factory locations. Tap water and/or (for example) river or lake water are withdrawn from nature. The cooling water is heated up during use, and this heat is removed in the cooling tower by evaporating water. The remaining liquid water is discharged to the municipal water system, and then back to nature after on-site wastewater treatment.

At the moment, the calculation of life cycle water consumption is hindered by the fact that in the ecoinvent database [9] the water discharged is not included, so it is only possible to model water withdrawal and not the net water consumption. Fair comparisons cannot be made on the basis of water withdrawal alone.

Fair comparison of environmental footprints

A fair comparison of environmental impacts of PV modules is only possible when:

- the same standard is used
- the same impact assessment method is used
- underlying LCAs used are transparent
- underlying assumptions are the same

Category rules for PV modules

Unfortunately no environmental product footprint category rules (PFCRs) or product category rules (PCRs) exist for PV modules. PFCRs provide detailed technical guidance and complement general methodological guidance for environmental footprinting by providing further specification at the product level.

As defined in ISO 14025(2006), PCRs include sets of specific rules, guidelines and requirements that are aimed at developing Type III environmental declarations (quantitative, LCA-based claims of the environmental aspects of a certain product or service). Since PV modules are sold to many different countries, what installation location should be assumed when analyzing the use phase of the PV module? Transport distances, irradiation on the module and the electricity mix replaced all depend on the location. The IEA PVPS task 12, which deals with environmental health and safety aspects of photovoltaics, has published guidelines [10], but these are not official PFCRs or PCRs.

LCA databases

Only the ecoinvent database is transparent and discloses all underlying data such as the energy and material consumption and waste and emissions of all data sets. The ELCD and Gabi databases [11,12] are not transparent because they are only available as data sets in which all life cycle resources from nature and emissions to the environment are aggregated. The ELCD database currently contains only very little data. A transparent database is the most suitable if it is desired to tweak a data set with one's own collected data. Using a transparent database is also the fastest way of generating LCA results that show all contributions from upstream process steps.

Different LCA databases will generate different results because all underlying data are different. Understanding these differences is impossible when the data sets are not transparent.

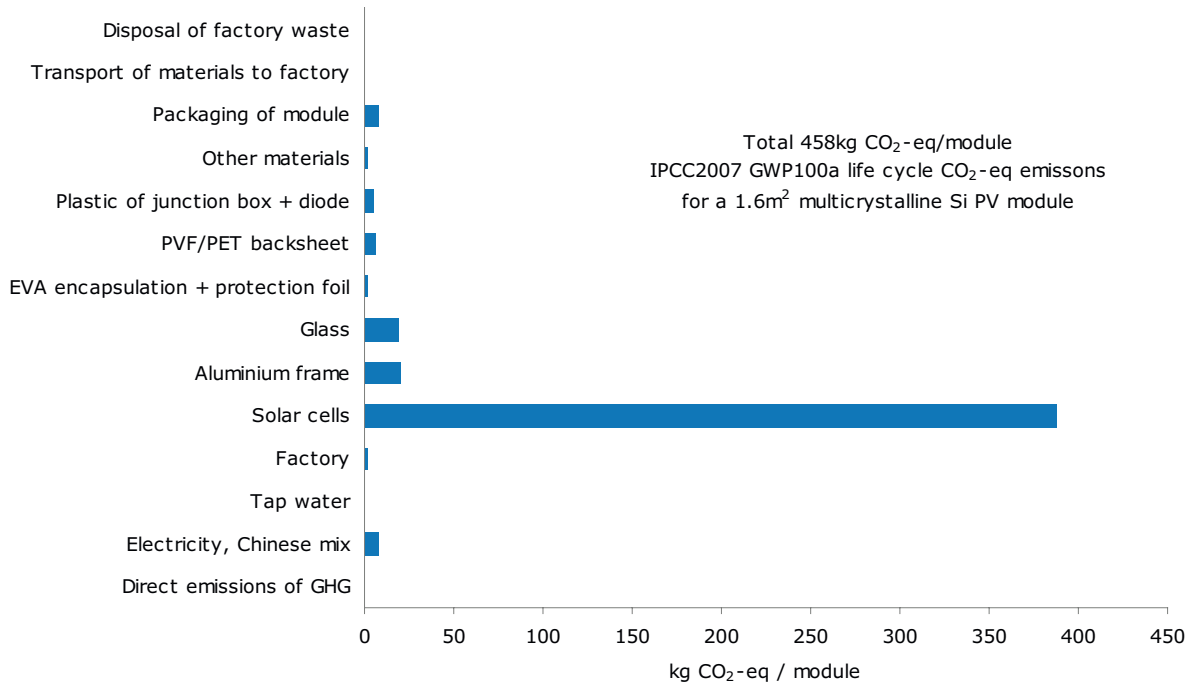

Figure 4. Carbon footprint in kg CO_2-eq/module of a 1.6m^2 commercial multicrystalline Si PV module made from polysilicon, ingot, wafer, cell and module produced in China (ecoinvent 2.2 data for other materials).

LCA data for commercial PV modules

Data collection for LCA is a time-consuming process. PV module manufacturers must set up a systematic data-monitoring system on different levels. First, data need to be collected on the entire factory level. However, for product environmental footprinting, operational data need to be broken down from total factory level to module type. The data required for LCA are basically the input and outputs from the factory: amounts of materials and energy consumed, waste streams, emissions to the environment (to air and water) and products produced. In addition, data need to be collected about the means of transport and distances covered for all materials transported to the factory. It is even more challenging to obtain these types of data from suppliers.

LCA data for PV module production are available in the ecoinvent 2.2 database and also in a compilation from the IEA PVPS task 12 [13]; unfortunately, these data sets are outdated. This year, SmartGreenScans [14] will publish a new data set for commercial production of PV modules and their components, namely polysilicon, crystals/ingots, wafers and solar cells for the following technologies: crystalline silicon, silicon thin-film, CdTe and CIGS. Public data on module recycling are lacking at the moment.

LCA results for commercial PV modules

The current globalization trend is that production of PV modules and their components is shifting to Asia. In order to calculate actual environmental impacts, the actual electricity mixes need to be used. Energy payback time and carbon footprint results were calculated on the basis of actual electricity mixes used in the production of polysilicon, ingots/crystals, wafers, solar cells and modules [15]. Fig. 4 shows the carbon footprint of a 1.6m^2 PV module for which the polysilicon, ingot, wafer and solar cells are all produced in China. The other materials are all taken unmodified from the ecoinvent 2.2 database.

> "The number of PV module manufacturers publishing sustainability reports and performing carbon and water footprinting is increasing and shows their corporate social responsibility."

Conclusions

The number of PV module manufacturers publishing sustainability reports and performing carbon and water footprinting is increasing and shows their corporate social responsibility. A comparison of carbon footprint results is difficult because several international standards and LCA databases are used. No product rules for photovoltaics exist, so LCAs are performed with varying underlying assumptions. A fair comparison can only be made when all environmental footprints of a product are taken into account.

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