Primer on environmental sustainability research on photovoltaic (PV) modules (Phase 2)

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1 Introduction and summary

To assess the sustainability of PV modules and installations, all three pillars of sustainability—economic, social and environmental— should be considered while taking the entire lifecycle into account, from sourcing of raw materials to production, operation, and end-of-life reclamation.

This report focuses on environmental sustainability and includes research, some regulatory developments and a number of other resources on environmental sustainability as relevant for the PV solar sector. It also touches on some health & safety and ethics references.

This report starts with an overview of key environmental issues, priorities and recommended practices in the solar PV sector, as raised by key stakeholders and opinion formers. These include the responsible and safe use of hazardous substances, carbon footprint and energy use, emissions reporting, design for recycling and management of end-of-life PV solar panels.

Most research 'out there' on the environmental profile of PV solar energy has been based on Life Cycle Assessment (LCA), as this approach gives a scientifically justified picture of key environmental impacts throughout the entire life cycle of solar panels. This report will therefore provide an overview of key developments in, and conclusions from LCA research. Some environmental concerns and priorities raised by key stakeholders are not sufficiently or explicitly brought to the forefront in results from LCA research, hence the report also includes references to other resources.

Supplying solar power, the PV industry is often assumed to be harmless for the environment and human health, especially when compared with fossil fuels. From an environmental point of view, solar PV is one of the most benign energy technologies that exist today. To illustrate this, all PV technologies generate far less life-cycle air emissions per GWh than conventional fossil-fuel-based electricity generation technologies. At least 89% of air emissions associated with electricity generation could be prevented if electricity from photovoltaics displaces electricity from the grid, as an article on Emissions from Photovoltaic Life Cycles highlights[1]. The PV industry however uses potentially toxic substances and manufacturing processes that *can* present environmental, health and safety problems if not well managed. This is especially a concern considering the sector's forecasted rapid growth.

In summary, based on pertinent research and available resources, key areas of potential concern related to solar PV panels are:

- The energy required to produce solar cells and panels and the corresponding greenhouse gas emissions (aka carbon footprint)
- Managing panels at the end of their lifetime
- The use of toxic and other potentially harmful materials in the production of PV panels/cells, and in different supply chain stages.

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[1] Fthenakis, V., H. C. Kim, and E. Alsema. 2008. "Emissions from Photovoltaic Life Cycles, "Environ. Sci. Technol., 42 (6), 2168-2174. Retrieved from: http://web.mit.edu/2.813/www/readings/esandtPV2008.pdf.

Other impacts recently gaining more attention include water quality and use, and landscape and ecology.

One of the challenges in addressing environmental impacts related to solar PV modules is that impacts vary depending on the solar PV technology that is used. For example, the production process for crystalline-Si production uses different substances and raw materials, and involves different production steps from say, CdTe modules, and therefore has different kinds of impacts, making it difficult to compare.

2 Overview of environmental issues

This section looks at environmental and broader corporate responsibility issues and suggested practices raised by key stakeholders and opinion leaders.

2.1 Solar PV company commitment and corporate responsibility

One of the issues is the general concern about companies producing PV modules and raw materials, and the extent to which they protect their workers and the environment. The pressure on the industry to manage its environmental impacts from production throughout the supply chain is increasing.

To a large extent, this pressure is the result of PV manufacturing moving from countries with strict environmental legislation and enforcement to countries that perform less well on protecting the environment and their workers.

The article 'Solar energy isn't always as Green as You Think'[2] by Dustin Mulvaney summarizes these concerns in more detail, giving a good overview of the types of environmental issues the solar PV sector is facing and needs to address.

Greenpeace East Asia, in a 2012 report "Unravelling the puzzle that is called solar PV pollution – clean production of solar PV manufacture in China"[3], argues that while clean energy should be clean, "clean production in solar PV industry has yet to come to fruition". Greenpeace reviewed multiple stages of production throughout the solar PV industry chain, and found that not meeting clean production is not related to the technology itself but rather to commitment. According to Greenpeace, "the Solar PV industry can and should upgrade itself according to the current environmental discharge standards, as well as implement environmental protection standards to realize clean production."

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[2] Mulvaney, D. (August 2014). "Solar Energy Isn't Always as Green as You Think
Do cheaper photovoltaics come with a higher environmental price tag?" Retrieved from:
http://spectrum.ieee.org/green-tech/solar/solar-energy-isnt-always-as-green-as-you-think

[3] Greenpeace East Asia (March 2012). " Unraveling the puzzle that is solar PV pollution
Clean production of solar PV manufacture in China". Retrieved from:
http://www.greenpeace.org/eastasia/publications/reports/climate-energy/2012/solar-pv-pollution-report/

A relatively recent report “Clean & Green: Best Practices in Photovoltaics”[4] gives a good overview of environmental, health and safety considerations with Solar PV and what companies already doing, thereby highlighting best practices of photovoltaic (PV) manufacturers to protect workers and the environment during the production of solar panels. The report -launched by As You Sow, a non-profit organization that promotes environmental and social corporate responsibility- presents the process of manufacturing PV panels, the risks involved, and how companies mitigate those risks. It focuses on practices and policies some leading companies use to mitigate risks from hazardous compounds, reduce environmental impact, and responsibly manage their supply chains.

The report states that “Solar PV manufacturers as a whole have continued to be ahead of international standards for air emissions at manufacturing sites, are taking steps to reduce water use in order to more efficiently produce panels, and are participating in voluntary international programs that monitor and assess worker safety“. It also suggests that “additional EHS activities that some PV manufacturers are taking include a move toward safer materials in both the manufacture and components of the panels themselves, siting factories in cleaner utility power grids and/or powering a portion of their operations with on-site renewable energy, and reducing waste by designing panels with fully recyclable components that aim to 'close the loop' of solar panel material resource use.“

As You Sow’s list of best practices for solar PV manufacturers includes:

- Implementing worker safety and public health protocols.
- Manufacturing facilities to monitor treated water and ensure their outflows are safe.
- Reducing water use.
- Implementing producer responsibility programs.
- Considering environmental and social criteria when selecting suppliers. Companies require their suppliers to implement environmental management systems and meet their standards for treatment of workers.
- Ensuring a system for audits that contain transparent criteria, corrective actions, and regular auditing cycles.
- Publishing corporate social responsibility (CSR) reports.
- Design for environment. E.g. using recycled and recyclable materials.
- Linking executive compensation to environmental or safety metrics.

Another useful overview of sustainability, health and safety principles and practices in the PV industry is provided by the The Silicon Valley Toxics Coalition (SVTC). The SCTC began conducting surveys of PV module manufacturers in 2009, focusing on the following elements:

- Extended Producer Responsibility
- Green Jobs
- Toxic Reduction and;
- Transparency

[4] Galland, A. (2012) As You Sow. “Clean & Green: Best Practices in Photovoltaics”. Retrieved from: http://www.asyousow.org/ays_report/clean-green-best-practices-in-photovoltaics/

Dustin Mulvaney summarizes these principles and practices in: "Greening Photovoltaics: An Overview of the Silicon Valley Toxic Coalition's Solar Scorecard and Industry Trends"[5] – a report he prepared for the Green Electronics Council.

2.2 Management of substances in PV panels and production

Solar PV electricity generation, regardless of which technology is used, is a zero-emissions process and does not produce any noise, toxic-gas emissions, or greenhouse gases while in operation. However, there are environmental, health and safety (EHS) hazards associated with the manufacture of solar cells. The PV industry uses toxic and flammable substances, although in smaller amounts than many other industries, and the use of hazardous chemicals can involve occupational and environmental hazards.

The second edition of 'Solar Cells – Materials, Manufacture and Operation"[6] has a chapter devoted to the potential hazards related to the production of solar cells.

The manufacture of photovoltaic modules uses some hazardous materials which can present health and safety hazards, if adequate precautions are not taken. Routine conditions in manufacturing facilities should not pose any threats to health and the environment. Hazardous materials could adversely affect occupational health and, in some instances, public health during accidents. Such hazards arise primarily from the toxicity and explosiveness of specific gases. Accidental releases of hazardous gases and vapors can be prevented through choosing safer technologies, processes, and materials, better use of materials, and by employee training and safety procedures.

Handling of hazardous substances and materials is also tackled by a specific task force (EH&S in Manufacturing Facilities) of the IEA's PVPS, by advocating best EH&S practices throughout the solar value chain. This task force has the following objectives:

- Develop risk factors and compare with other energy technologies
- Identify accident prevention and control options for specific technologies
- Identify pollution control technologies for major types of PV manufacturing facilities
- Identify prevention and control strategies for green-house gases (GHG) in PV manufacturing facilities

2.3 End-of-life management of PV modules

Another often-raised concern, relates to the take-back and recycling of end-of-life (EOL) PV modules.

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[5] Mulvaney, D. (2015). „Greening Photovoltaics: An Overview of the Silicon Valley Toxic Coalition's Solar Scorecard and Industry Trends". Retrieved from: http://greenelectronicscouncil.org/wp-content/uploads/2015/10/Overview_SVTC_Scorecard_and_Industry_Trends_Oct2015.pdf

[6] Fthenakis, V.M. (2012), "Overview of Potential Hazards" (Chapter IV-1, Pages 1083–1097) in:
McEvoy, A., Markvart, T. and Castañer, L. "Solar Cells Materials Manufacture and Operation" (second edition). Retrieved from:
https://books.google.be/books?id=vDYa247WHysC&pg=PA1095&dq=Overview+of+Potential+Hazards+Fthenakis&hl=en&sa=X&ved=0ahUKEwizuqPYgMXJAhXFNhoKHdXfAmQQ6AEIUjAI#v=onepage&q=Overview%20of%20Potential%20Hazards%20Fthenakis&f=false

As a way to improve the green footprint of all PV companies, take back and recycling allows for material recovery and for reduction of cumulative energy demand and associated carbon footprint of PV modules. Volumes of EOL panels are still relatively low (PV panels have a long life time, 20-30 years) but are expected to considerably grow when larger amounts of solar panels are retired and returned. The first significant PV installations happened in the early 1990s, hence an increasing number of modules will reach the end of their life in the coming years.

A 2011 report titled 'Study on the Photovoltaic panels supplementing the impact assessment for a recast of the WEEE Directive'[7], which was drafted to support the decision to include solar PV panels in the scope of the WEEE Directive, provides a good overview of the main environmental problems related to PV panels if they are not properly disposed of: leaching of lead, leaching of cadmium, loss of conventional resources (primarily aluminum and glass) and loss of rare metals (silver, indium, gallium and germanium).

Improving and regulating waste management is mainly a regional issue and determined by regional/national waste legislative schemes (where they exist), e.g. the European Union (EU) Directive on Waste from Electrical and Electronic Equipment (or "the WEEE Directive") (see section 4.2).

While a number of treatment and recycling processes are under development globally for photovoltaic panels, there are only few treatment and recycling methods tailored to PV panels which have been tested and put into operation. And high-volume recycling is still another 10-15 years away.

There are other sources that argue in favor of policies for producer responsibility and recycling of end-of-life PV modules. One such source is an article on "Producer responsibility and recycling solar photovoltaic modules"[8], the authors of which find that the economic motivation to recycle most PV modules is unfavorable without appropriate policies.

A 2013 report 'Eco-efficiency Analysis of Photovoltaic Modules'[9] commissioned by the Bavarian State Ministry of the Environment and Consumer Protection refers to the relative importance of high-quality recycling from an environmental protection point of view. Overall, the environmental impact can be reduced by approx. 10% through the establishment of high-quality PV recycling.

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[7] Monier, V. and Hestin, M. (2011) "Study on the Photovoltaic panels supplementing the impact assessment for a recast of the WEEE Directive". Final report delivered to the European Commission – DG Environment. Retrieved from: http://ec.europa.eu/environment/waste/weee/pdf/Study%20on%20PVs%20Bio%20final.pdf

[8] McDonald, N.C., Pearce, J.M. (2010). "Producer responsibility and recycling solar photovoltaic modules". In Energy Policy, Volume 38, Issue 11, Pages 7041–7047. Retrieved from: http://www.sciencedirect.com/science/article/pii/S0301421510005537

[9] Matthias Seitz, M., Kroban, M., Pitschke, T., Kreibe, S. (2013). "Eco-efficiency Analysis of Photovoltaic Modules". Bifa environmental institute. bifa-Text No. 62 - ISSN 2198-8056

2.4 Energy use and greenhouse gas emissions

This is one of the key, if not the most important and highlighted environmental issues (and benefit) for the solar PV sector. Increasing the use of solar PV energy can contribute to addressing climate change and the transition to a low-carbon energy mix. For this contribution to be maximized, it is key to ensure short energy-pay-back times and minimized carbon footprint of solar PV technologies used.

The solar PV sector is already using energy use and carbon footprint indicators (Life Cycle GHG-emissions) in two key ways: 1) to identify improvement potential of PV technologies and to compare different PV technologies 2) to compare PV electricity generation with other renewable and non-renewable electricity generating technologies/feed-stocks.

2.4.1 Carbon footprint

Carbon footprint is the most commonly used indicator and established measurement of the life cycle GHG-emissions of a product and is expressed as 'the amount of carbon dioxide equivalent (CO2e)'. Actual carbon footprint calculations show large variations, depending on geography and climate, technology and application used, and scope.

Fthenakis and Alsema [10] report that GHG emissions of multi- and mono-Si modules corresponding to 2004-2005 production are within a 37 and 45 g CO2- eq./kWh for a rooftop application under Southern European insolation of 1700 kWh/m2/yr and a performance ratio (PR) of 0.75. De Wild-Scholten[11] recently updated these estimates based on thinner modules and more efficient processes, reporting GHG emissions of ~30 g CO2-eq./kWh for both multi- and mono-Si PVs (see).

There are fewer life-cycle studies of thin film PV technologies. Fthenakis and Kim [12] estimated Greenhouse Gas Emissions (GHG) of ground-mounted CdTe PV modules under the average US insolation condition, 1800 kWh/m2/yr, of 24 g CO2-eq./kWh. These estimates were later updated based on data from First Solar's plant in Frankfurt- Oder, Germany, reporting an EPBT of ~0.87 yrs and GHG emissions of ~18 g CO2-eq/kWh.

According to EPIA,[13] the carbon footprint of PV has decreased by approximately 50% in the last 10 years as a result of performance improvements, raw material savings and manufacturing process improvements. illustrates the most recent comparison of three commonly used PV module technologies.

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[10] Fthenakis, V. and Alsema, E., Photovoltaics Energy Payback Times, Greenhouse Gas Emissions and External Costs: 2004-early 2005 Status. Progress in Photovoltaics: Research and Applications, 2006. 14(3): p. 275-280.

[11] de Wild-Scholten, M.J., Renewable and Sustainable. Presentation at the CrystalClear final event, 2009: Munich.

[12] Fthenakis, V.M., H.C. Kim, and E. Alsema, Emissions from photovoltaic life cycles. Environmental Science & Technology, 2008. 42(6): p. 2168-2174.

[13] EPIA SUSTAINABILITY WORKING GROUP FACT SHEET. SUSTAINABILITY OF PHOTOVOLTAIC SYSTEMS: The Carbon Footprint

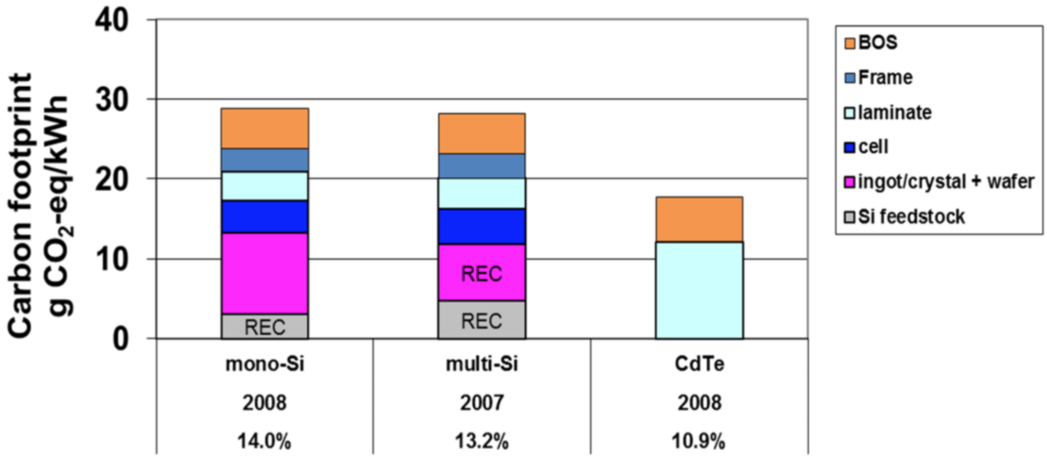

Figure 1: Life Cycle GHG emissions from rooftop mounted PV systems for European production and installation under Southern European irradiation of 1700 kWh/m2/yr, performance ratio of 0.75, and lifetime of 30 yrs. The module production for Si-technologies is further differentiated in Si-feedstock, ingot & wafer supply, cell manufacturing.

As illustrated, the carbon footprint profile of Si-modules and thin film PV modules differ considerably. For Si-modules, ingot and wafer production are the most relevant life cycle stages.

With a view to developing a leadership standard, this is an area where a performance indicator and value could be identified (carbon footprint/kWh). Questions that will come up in the development include whether there would be one indicator for all technologies, or different ones for different technologies. There could be different benchmarks for different technologies, as is considered for the EU PEF (see section 4.3). Another option could be to have performance classes (e.g., A-E). Another question is whether to have absolute targets or relative ones, whereby a relative target would be one against which manufacturers have to show improvements.

It is also crucial to explore what the remaining room for technical improvements is for each of the 'considerably contributing' life cycle stages is (e.g. through improvements of conversion efficiency, manufacturing process efficiency and raw material savings). Note that these are all key focus areas for the sector as they do not only create environmental benefits but also constitute real drivers for cost reduction and overall business results.

2.4.2 Energy use indicators

In the PV sector two energy use indicators are frequently used:

- Cumulative Primary Energy Demand and
- Energy Pay-back Times

Cumulative Primary Energy is defined as the energy embodied in natural resources (e.g., coal, crude oil, natural gas, uranium) that has not undergone any anthropogenic conversion and needs to be converted and transported to become usable energy.

Energy Pay-back Times (EPBT) is defined as the period required for a renewable energy system to generate the same amount of energy (in terms of primary energy equivalent) that was used to produce the system itself. This indicator is often used by single companies and also has been calculated by the IEA PVPS-task group in its recent report. This is an important indicator – and already an important disclosure indicator within the sector. Calculation methodologies are already available, and therefore a next step could be about defining a minimum performance level.

Alsema and de Wild-Scholten [14] demonstrated life-cycle primary energy of complete rooftop Si-PV systems of 3700 and 4200 MJ/m2, respectively, for multi- and mono- Si modules. De Wild-Scholten[15] recently updated these estimates based on thinner modules and more efficient processes, reporting an EPBT of ~1.8 yrs for both multi- and mono-Si PVs (see).

Regarding thin film PV technologies, Fthenakis and Kim [16] estimated a life cycle energy consumption of 1200 MJ/m2, based on the actual 2005 production from First Solar's 25 MWp prototype plant in Ohio, United States. The primary energy consumption and EPBT of ground-mounted CdTe PV modules under the average US insolation condition, are reported with 1800 kWh/m2/yr, and 1.1 years, respectively.

These estimates have later been updated based on data from First Solar's plant in Frankfurt- Oder, Germany, reporting an EPBT of ~0.87 yrs.

2.5 Water use in production and operation of PV modules

Water is another issue mentioned in resources on environmental impacts of PV modules. Photovoltaic manufacturers use water for various purposes, including cooling, chemical processing, and air-pollution control. Water is also used during installation and use.

2.6 Solar PV and land use

While a sustainability leadership standard addressing PV solar modules may not include criteria for land use impacts as these are often difficult to control or influence by solar PV producers, it is important to highlight that there is a growing attention on how solar parks affect both climate

[14] Alsema, E. and M. de Wild-Scholten. Environmental Impact of Crystalline Silicon Photovoltaic Module Production. in Material Research Society Fall Meeting, Symposium G: Life Cycle Analysis Tools for ''Green'' Materials and Process Selection. 2005. Boston, MA.

[15] de Wild-Scholten, M.J., Renewable and Sustainable. Presentation at the CrystalClear final event, 2009: Munich.

[16] Fthenakis, V.M., H.C. Kim, and E. Alsema, Emissions from photovoltaic life cycles. Environmental Science & Technology, 2008. 42(6): p. 2168-2174.

change and biodiversity. Although land use for solar parks is minimal compared to other uses, the solar sector must also evaluate and manage any negative impacts of its activities on the environment.

Overall, research has consistently found that when developed responsibly, ground-mounted solar PV power plants provide considerable environmental benefits.

A 2011 study[17] of PV solar generation environmental impacts found that, "Solar technology is concluded to be much preferable to traditional means of power generation, even considering wildlife and land use impacts". From the 32 environmental impact categories the researchers identified for solar power plants, they found that 22 were beneficial relative to traditional power generation, 4 were neutral, none were detrimental, and 6 needed further research.

In 2005, German NGO NABU and Solar Association BSW issued the first guidelines for solar PV. A 2010 report[18] by the German Renewable Energies Agency (AEE) summarizes the results of an assessment of eight solar parks, looking at several years' worth of monitoring data and best practices. The report concludes that using land for PV development, climate protection and environmental protection can happen simultaneously provided that solar plants are responsibly planned, constructed and operated, and sensitive areas are properly protected or avoided.

The report describes good practices and gives recommendations on planning and management of solar parks, including dedicating buffer areas in solar parks that can grow into important biotopes for endangered species, and conducting environmental impact assessments with a view to considering specific local conditions and involving (local) experts for ecologically sound project planning.

In 2010, CLER, a French umbrella NGO promoting renewable energies, developed a position paper "Solar Parks, Yes, But Not at All Costs"[19] and in 2011 launched a guide for responsible solar parks that is in line with the NABU/BSW guidance and with the AEE report's best practices list. In 2013, WWF issued the "Solar PV Atlas: Solar Power in Harmony with Nature"[20], which includes a summary

[17] Turney, D. and Fthenakis, V. (2011). „Environmental impacts from the installation and operation of large-scale solar power plants". In: Renewable and Sustainable Energy Reviews. Retrieved from: http://www.researchgate.net/publication/227421587_Environmental_impacts_from_the_installation_and_operation_of_large-scale_solar_power_plants

[18] Renewable Energies Agency (AEE – Germany) (2010). "Solar parks: Opportunities for biodiversity – a report about biodiversity in and around ground-mounted photovoltaic solar plants". Backgound paper published in: Renews Spezial 45/2010. Retrieved from: http://www.unendlich-viel-energie.de/media-library/background-papers/solar-parks-%E2%80%93-opportunities-for-biodiversity

[19] CLER, FNE, WWF, Greenpeace, LPO, HESPUL, SOLAGRO, RAC-F (2010). "Parcs photovoltaïques au sol : oui, mais pas à tout prix et pas n'importe comment (Solar parks, yes, but not at all costs). Position paper. Retrieved from: http://www.fne.asso.fr/actualites/parcs-photovolta%C3%AFques-au-sol-oui-mais-pas-%C3%A0-tout-prix-et-pas-n%E2%80%99importe-comment

[20] WWF (2012). "Solar PV Atlas: Solar Power in Harmony with Nature". Retrieved from: http://awsassets.panda.org/downloads/solar_pv_atlas_final_screen_version_feb_2013.pdf

overview of impacts that can arise and should be addressed when developing ground-mounted solar projects. This summary is based on current and best practices and of guidelines described by a number a number of organizations such as the AEE and CLER.

3 LCA-based research on the environmental sustainability of PV modules

3.1 Research activities

Life Cycle Assessment (LCA) is a tool that describes energy, material and emission flows as well as environmental impacts in all stages of the life cycle of PV (from cradle to grave). LCA research identifies improvement potential in the PV supply chain and compares the environmental profile of PV solar panels with the profile of electricity produced with other energy technologies.

Today, most international research on methodology development is performed under the umbrella of the International Energy Agency's Photovoltaic Power Systems Program.[21] Environmental Sustainability is addressed in Task 12 "PV ENVIRONMENTAL HEALTH & SAFETY ACTIVITIES". Task 12 was initiated by Brookhaven National Laboratory under the auspices of the U.S. Department of Energy and is now operated jointly by the National Renewable Energy Laboratory (NREL) in the US and the Energy Center of the Netherlands (ECN).

Research on Life Cycle Assessment of PV modules has been conducted for more than 20 years. Published studies show a high variation in results and conclusions. This is the result of not only the rapid development in the PV sector –leading to improvements in all parts of the production chain- but also of different methodological assumptions.

3.2 Scope of Life Cycle Assessment

Figure 2 illustrates the general scope and life cycle stages of PV modules as proposed by the task force of PVPS.

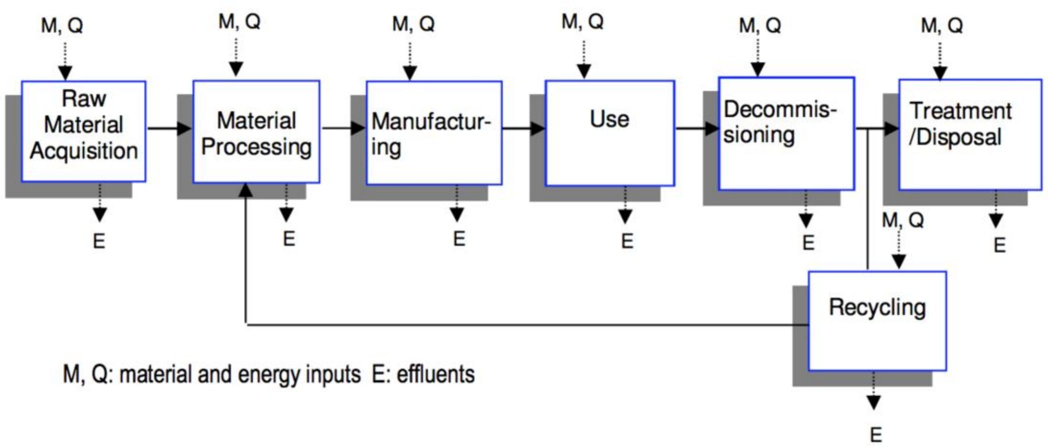

Figure 2: General Scope and Life Cycle Stages of PV Life Cycle Assessment

[21] http://www.iea-pvps.org.

For PV LCA, the following system components are proposed to be considered and distinguished in LCA modeling and in the results:

- Module
- Frame (if needed)
- Balance of System (BOS)

Environmental Life Cycle Indicators

From LCA results, we learn that among all key environmental impact areas reported, cumulative primary energy demand and Life Cycle GHG emissions are the most prominent and also the most robust ones with respect to results.

In addition to these indicators, there are number of other life cycle indicators and Life Cycle Impact Categories frequently used in Life Cycle Assessment.

The work of the PVPS-task force includes the assessment of various cumulative single pollutant/emissions of selected pollutants. The task force hereby makes a basic distinction between criteria pollutant emissions and heavy metal emissions. Criteria pollutants include NOx and SO2 emissions. Heavy metal emissions assessed are: cadmium, arsenic, chromium, lead, mercury and nickel.

The European Commission has -within the framework of the Environmental Footprint Initiative-developed a comprehensive list of environmental impact categories and impact category methods The applicability, robustness and relevance of theses impact categories for the PV sector are currently tested in the PEF pilots. See **Figure 3** for an overview of relevant impact categories. Initial calculations indicate that the results of the listed toxicity indicators need further investigation.

Impact category	Indicator	Source
Indicators required according to the PEF guide		
Climate change	Radiative forcing as Global Warming Potential (GWP100)	IPCC 2007
Ozone depletion	Ozone Depletion Potential (ODP)	WMO 1999
Human toxicity, cancer effects	Comparative Toxic Unit for humans (CTUh)	Rosenbaum et al. 2008
Human toxicity, non-cancer effects	Comparative Toxic Unit for humans (CTUh)	Rosenbaum et al. 2008
Particulate matter / respiratory effects	Intake fraction for fine particles (kg PM2.5-eq/kg)	Greco et al. 2007; Rabl & Spadaro 2004
Ionizing radiation, human health	Human exposure efficiency relative to U235	Frischknecht et al. 2000
Photochemical ozone formation	Tropospheric ozone concentration increase	Van Zelm et al. 2008 as applied in ReCiPe
Acidification	Accumulated Exceedance (AE)	Posch et al. 2008; Seppälä et al. 2006
Eutrophication, terrestrial	Accumulated Exceedance (AE)	Posch et al. 2008; Seppälä et al. 2006
Eutrophication, aquatic	Fraction of nutrients reaching freshwater end compartment (P) or marine end compartment (N)	Struijs et al. 2009 as implemented in ReCiPe
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	Rosenbaum et al. 2008
Land use	Soil Organic Matter	Milà i Canals et al. 2007
Resource depletion, water	Water use related to local scarcity of water	Frischknecht et al. 2008
Resource depletion, mineral, fossil, renewable	Scarcity	Guinée et al. 2001
Additional indicators		
Cumulative energy demand,	Gross energy content of renewable	Frischknecht et al. 2015b

Figure 3: Default List of life cycle impact assessment indicators according to the PEF recommendation document.

3.3 Current limitations of Life Cycle Assessment methodology

In a recent article "The photovoltaic industry on the path to a sustainable future — Environmental and occupational health issues"[22], the authors describe some of the information gaps needing to be addressed in PV systems life cycle assessments. They argue that chemical and physical hazards threatening PV workers are still poorly documented, and that prevention of potential risks requires concerted action from all stakeholders.

For example, this paper reveals information deficits concerning some sensitive life cycle indicators and environmental impacts, together with incomplete information on toxicological data and studies of workers' exposure to different chemical and physical hazards. The authors argue that "Although solar panel installation is generally considered relatively safe, the occupational health concerns related to the growing number of hazardous materials handled in the PV industry warrants an all-inclusive occupational health and safety approach in order to achieve an optimal equilibrium with

[22] Bakhiyia, B., Labrèchea, F., and Zayed, J. (2014). "The photovoltaic industry on the path to a sustainable future — Environmental and occupational health issues". In: Environment International, Volume 73, Pages 224–234. Retrieved from: http://www.sciencedirect.com/science/article/pii/S0160412014002487

sustainability." They also advise that in order to prevent eco-health problems from offsetting the benefits currently offered by the PV industry, manufacturers should "cooperate actively with workers, researchers and government agencies toward improved and more transparent research, the adoption of specific and stricter regulations, the implementation of preventive risk management of occupational health and safety and, lastly, greater responsibility toward PV systems from their design until their end of life."

3.4 Environmental sustainability data

Performing Life Cycle Assessment today can only be done by using Life Cycle Inventory databases (LCI databases) which include the necessary background data for the environmental performance (emission factors) of used materials and consumed energy. Various LCI databases are available, including ecoinvent, ELCD and GaBi-data. For the PV sector, ecoinvent is the most frequently used database.

As part of its specific mandates for the Environmental Footprint Initiative (PEF), the European Commission has asked for making Life Cycle Inventory data for basic processes and materials freely accessible. These freely available LCI data may become the standard data to be used in various industries, including the PV sector.

IEA Task 12 LCA experts have put great efforts and achieved continuous progress on gathering and compiling the LCI data representing the PV module Life Cycle for different PV technologies[23]. These include detailed inputs and outputs during manufacturing of cell, wafer, module, and balance-of-system (i.e., structural- and electrical- components) that were estimated based on actual production and operation facilities. In addition to the LCI data supporting LCA results, data are also presented to enable analyses of various types of PV installations and to compare with operational data of rooftop and ground-mount PV systems and country-specific PV mixes.

4 Relevant environmental regulatory developments and industry commitments

This section highlights some of the most recent environmental sustainability regulatory developments that can be relevant in the context of developing a leadership standard for PV solar.

4.1 Legislation to regulate use of chemical use

REACH (EC 1907/2006) is EU legislation aiming to improve the protection of human health and the environment through the better and earlier identification of the intrinsic properties of chemical substances. This is done by the four processes of REACH, namely the registration, evaluation, authorisation and restriction of chemicals.

[23] R. Frischknecht, R. Itten, P. Sinha, M. de Wild-Scholten, J. Zhang, V. Fthenakis, H. C. Kim, M. Raugei, M. Stucki, 2015, Life Cycle Inventories and Life Cycle Assessment of Photovoltaic Systems, International Energy Agency (IEA) PVPS Task 12, Report T12-04:2015.

The extent of the obligations placed on industry sectors will vary depending on the quantity of each chemical substance manufactured in, or exported to, or incorporated into finished products exported to Europe by each affected company, and on the hazard properties of the particular chemical substance.

In the U.S., the federal Toxic Substances Control Act ("TSCA") gives the Environmental protection Agency a broad authority to regulate, and even ban, the manufacture, use and distribution of both new and existing chemicals. In addition, chemical producers are required to track chemical health effects information and to immediately supply EPA with information about the substantial risks of particular chemical substances.

In developing a leadership standard for solar PV, it will be impossible to refer to all different approaches used by different countries to manage. It will be key however to include safe and responsible handling of potentially harmful substances. One way of going about this is to include producer performance criteria on transparency and reporting on a number of environmental and health & safety impact areas. See also 2.2.4.

4.2 EU WEEE Directive

Since 13 August 2012, in the European Union, the recast WEEE (Waste Electrical and Electronic Equipment) Directive 2012/19/EU provides a legislative framework for extended producer responsibility of PV modules at European scale. As from 14 February 2014, the collection, transport and treatment (recycling) of photovoltaic panels is regulated in every single European Union (EU) country. The EU WEEE Directive mandates recycling for all PV module technologies, with collection and recovery targets, as well as minimum treatment requirements. There are other developments around the world regarding producer responsibility legislation for waste from electronic products, which to date do not always include PV solar panels in its scope.

4.3 Environmental Footprint Initiative of the European Commission

The European Commission is currently testing the possibility to develop and establish ‘product environmental footprint category rules’ (PEFCR) during a three-year pilot phase. PV modules have been selected as one of the 25 product categories (ranging from metal sheets to food, t-shirts to batteries).

The information calculated on the basis of these PEFCRs –once approved¬– can be used for communication purposes, including, where appropriate, comparisons and comparative assertions of products fulfilling the same primary function.

The pilot phase for the PEFCR development of PV modules started in November 2014 and will run for 3 years. In 2018, after finalizing the pilot, the Commission plans a review and policy evaluation. It is not clear as yet whether and to what extent the Commission plans to use the outcomes of the pilot phase to ask for mandatory reporting, benchmarking and labeling based on definition of environmental performance classes.

The PEFCR development is performed by a working group ('Technical Secretariat') which in turn is led by the International Energy Agency's Photovoltaic Power Systems Task 12 (IEA PVPS Task 12). The group focuses on a number of solar PV technologies, including: mono-Si & multi-Si, CdTe, CI(G)S) and micro-Si.

4.4 Carbon Footprint reporting integration in tender processes for photovoltaic systems in France

In 2011, the French Government introduced a tender process for support measures to encourage the development of the PV sector in France.

The tender process is managed by the 'Commission de régulation de l'énergie' (CRE - French Energy Regulation Commission), France's electricity and gas market regulator. In 2013, CRE launched a new tender process for the above 100 kW power category, which is different from the process launched in 2011. In addition to the proposed electricity purchase price, the amended specifications also include criteria on the carbon footprint of the PV module manufacturing process and on technical innovation and the carbon footprint of the PV modules concerned.

The Carbon Footprint assessment as included in the 2013 tender process shall be done based on a specific methodology (Evaluation Methodology for simplified carbon assessment) as provided by the Energy Regulatory Commission (CRE). The requirements for the calculation of GHG-emissions are specified in appendix 4 of the tender document.

4.5 The SEIA Solar Industry Commitment

In 2013, the US-based Solar Energy Industries Association (SEIA) issued the Solar Industry Commitment to Environmental and Social Responsibility, also referred to as the Solar Commitment.

The Solar Commitment is a voluntary commitment and details a set of solar industry guidelines which promote environmental and social responsibility. These guidelines include solar-specific practices that are of particular interest to the solar industry and/or its stakeholders, including human rights, electrical safety, energy and environment, fall protection, and reporting misconduct, and also general best practice provisions regarding the environment, labor, ethics, health and safety, and management practices of the company.

The Solar Commitment may be adopted by companies throughout the solar supply chain. Companies that sign on to the Solar Commitment must provide an annual report on several key performance indicators under the Solar Commitment.

In order to reduce duplication, promote harmonization, and advance shared approaches, SEIA has adopted the Electronics Industry Code of Conduct ("EICC") V.3.0 (developed by the Electronic Industry Citizenship Coalition) as its core compliance standards for Labor, Health & Safety, the Environment, Management Systems, and Ethics.

One specific issue that EICC includes in its Code of Conduct and that is also relevant and increasingly raised in relation to the solar sector is 'conflict minerals'. This is about operating a supply chain free of "conflict minerals", which include cassiterite, columbite-tantalite (colton), gold and wolframite and their derivatives, tin, tantalum, and tungsten (or any other mineral or its derivative determined by the Secretary of State) which are sourced from the eastern Democratic Republic of the Congo ("DRC") or an adjoining country (together, the "Conflict Region") whose extraction and trade are financing conflict in the Conflict Region.

Committing to the EICC CoC means condemning human rights abuses associated with the extraction, transport, or trade of minerals and any direct or indirect support to non-state armed groups or security forces that illegally control or tax mine sites, transport routes, trade points, or any upstream actors in the supply chain. It also involves expecting from suppliers to cooperate in providing information to confirm that their supply chain is free of conflict minerals or sourced responsibly in accordance with internationally recognized due diligence guidance.

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