Solar Cells: Energy Payback Times and Environmental Issues

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Glossary a-Si Amorphous silicon - AC Alternate current - BOS Balance of system (includes all system parts except modules, i.e., inverters, transformers, wiring, mounting structure tracking if applicable, foundations) - c-Si Crystalline silicon - CdS Cadmium sulfide - CdTe Cadmium telluride - CIGS Copper indium gallium diselenide - CIS Copper indium diselenide - DC Direct current - DNI Direct normal irradiance - EPBT Energy payback time - ESP Electrostatic precipitators - FBR Fluidized bed reactor - GaAs Gallium arsenide - GHG Greenhouse gas - GWP Global warming potential - HCPV High-concentration PV - LCA Life cycle analysis (or assessment) - LCI Life cycle inventory - mc-Si Multicrystalline silicon - mono-Si Monocrystalline silicon - PR Performance ratio - PV Photovoltaics - SiH_4 Silane - $SiHCl_3$ Trichlorosilane - SOx Sulfur oxide - TeO_2 Tellurium dioxide - UCTE Union for the Coordination of Transmission of Electricity - VTD Vapor transport deposition

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Authors Bio-sketches:

Vasilis Fthenakis is the Founder and Director of the Center for Life Cycle Analysis at Columbia University and Senior Scientist Emeritus Brookhaven National Laboratory where he held a distinguished scientist tenured appointment till 2016. He is the author of 400 publications, Editor-in-Chief of Energies, Energy-Environment section, Associate Editor of Progress in Energy, and member of the Editorial Boards of Energy Technology, Progress in Photovoltaics and the Journal of Loss Prevention. He is also a Fellow of the American Institute of Chemical Engineers (AIChE), a Fellow of the International Energy Foundation (IEF), Senior Member of the Institute of Electrical and Electronic Engineers (IEEE), and member of several energy- and sustainability expert panels. In 2015 he co-founded the Global Clean Water Alliance (GCDA) that was launched in COP21, in Paris. In 2018 he was honored with the IEEE William R. Cherry Award "for his pioneering research at the interface of energy and the environment that catalyzed photovoltaic technology advancement and deployment world-wide."

Enrica Leccisi completed her Ph.D. in Environment, Resources and Sustainable Development on LCA methodology and energy and environmental analyses of future scenarios of large-scale penetration of PV in electric grids. She is currently working as Postdoctoral Research Scientist at Columbia University in New York (CLCA - Center for Life Cycle Analysis). She has worked – in academia and also in the private sector – on projects related to Sustainable Engineering. She is registered as a Civil and Environmental Engineer at the Professional Association of Engineers, and as a member of the Institute of Electrical and Electronic Engineers (IEEE). She has authored and co-authored several scientific papers published in international Journals, Books of Proceedings, and presented at international conferences.

Marco Raugei holds a PhD in Chemical Sciences and is an expert in LCA, net energy analysis and sustainability assessment. Currently, he is Senior Research Fellow and Associate Lecturer in the School of Engineering, Computing and Mathematics, Oxford Brookes University (UK), as well as a Visiting Scientist at the Center for Life Cycle Analysis, Columbia University, New York (USA). He is also a member of the International Energy Agency Photovoltaic Power Systems (PVPS) programme, Task 12. He has published over 50 scientific papers in peer-reviewed international journals, as well as almost 100 other scientific documents among conference proceedings, reports, and chapters for scientific books and encyclopedias.

Definition of the Subject

Assessments of the environmental impacts of energy-generation technologies are essential in evaluating their sustainability. Common metrics for evaluations of renewable energy systems include energy payback times, greenhouse gas emissions, and toxic emissions in their cradle-to-grave life cycles. This chapter discusses the energy payback times (EPBTs) and environmental profiles of major commercial types of photovoltaics, i.e., single-crystalline silicon (sc-Si), multi-crystalline silicon (mc-Si), cadmium telluride (CdTe), and CIGS (copper indium gallium selenide) all mounted on fixed-tilt ground-mount systems, and GaInP/GaInAs/Ge high-concentration solar tracking systems.

Introduction

Life cycle assessment (LCA) is a tool for measuring the indicators of environmental sustainability of products and technologies, including the generation of electricity through solar PV devices. Recent LCA studies show that PV technologies have very low environmental impacts compared to those of conventional electricity generation (Fthenakis et al., 2008; Leccisi et al., 2016).

However, a broad review of the literature reveals several PV LCA studies with widely differing estimates. For example, the reported life cycle greenhouse gas (GHG) emissions of thin-film amorphous silicon (a-Si) PV systems range from 11- to 226-g CO_2-eq. per kWh of electricity produced (Hsu et al., 2012). Such divergence reflects different assumptions about key parameters, like product design, solar irradiation, performance ratio (PR), and lifetime. The estimates also deviate because of the different types of installation used, such as ground-mounts, rooftops, and façades. Most importantly, the assessments often are made from outdated information in the literature collected from antiquated PV systems, and are used for guiding policy analyses.

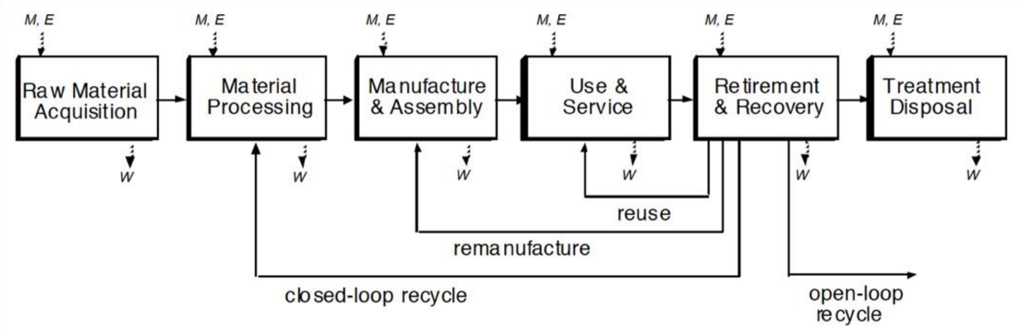
This chapter summarizes the results of PV life cycle analyses using as the main indicators energy payback times (EPBTs), greenhouse gas (GHG) emissions, and toxic emissions, based on actual data from the present-day commercial production of sc-Si, mc-Si, CdTe and CIGS photovoltaic systems. We also included the results of a-Si and III/V concentrator PV as these technologies had not evolved over the last seven years.

Material and Energy Inventories in the Life Cycle of Photovoltaics

The life cycle stages of photovoltaics involve (1) the production of raw materials, (2) their processing and purification, (3) the manufacture of solar cells, modules, and the balance of system (BOS) components, (4) the installation and operation of the systems, and, (5) their decommissioning, disposal, or recycling (Fig. 1). Typically, separate life cycle assessments

(LCAs) are undertaken for the modules and the BOS components (inverters, transformers, mounting, supports, wiring), as the module's technologies evolve more rapidly and entail more options than do the BOS structures. The latter were considered herein for both ground-mount and rooftop installations; façade systems are not described as they are very much site specific. Processes in the life cycle stages of PV systems include the following:

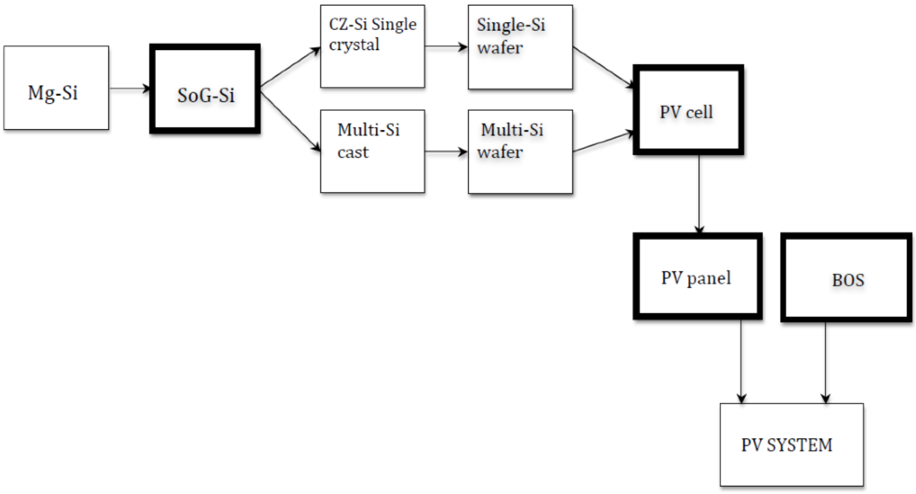
1. Upstream Processes
    - Raw-material acquisition: e.g., mining the ores, extracting the fossil fuel, and growing trees
    - Materials production: e.g., metal smelting, purification, alloying, polymerization, wafer production)
    - Solar-cell production or thin-film deposition: e.g., wafer cutting, sputtering, chemical vapor deposition, vapor transport deposition
    - Module production: e.g., contact formation, encapsulation, wiring, and assembly
    - Module and BOS installation: e.g., installing module, inverter, and support structures
2. Operation and Maintenance: e.g., tracker operation, if applicable, rinsing if applicable, other scheduled maintenance, and office use for utility-scale plant
3. Downstream Processes
    - Decommissioning and disposal: demolition and transportation
    - Recycling: collection, disassembly, shredding, and material separation



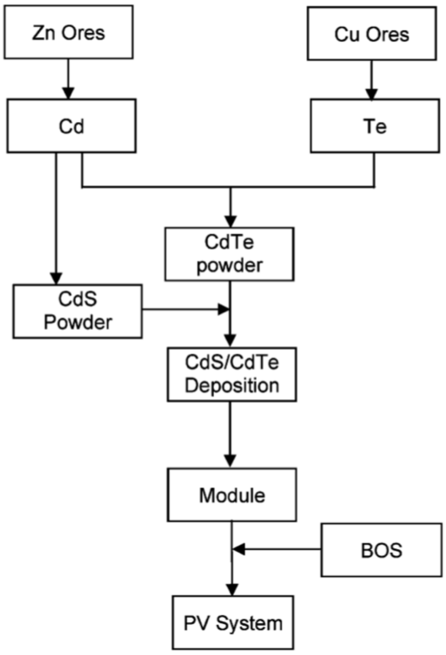
Solar Cells: Energy Payback Times and Environmental Issues. Figure 1 Flow of the life cycle stages, energy, materials, and wastes for PV systems (M stands for material inputs, E stands for energy inputs, and W stands for air emissions, liquid effluents and solid waste generation).

Crystalline Si-PV Modules

A life cycle analysis starts with mining the raw materials (i.e., quartz sand for silicon PV; Zn- and Cu-ores for CdTe PV and the metals used in the balance of systems - BOS), and continues with their processing and purification. The silica in the quartz sand is reduced in an arc furnace to metallurgical-grade silicon, which is purified into solar-grade polysilicon by either a silane (SiH_4)- or a trichlorosilane ($SiHCl_3$)-based process. The energy requirement for purification is the largest expense for making crystalline Si-PV modules, accounting for 45% of the primary energy used in fabricating multi-Si modules. Two technologies are employed for producing polysilicon from silicon gases: the Siemens reactor method, and the fluidized bed reactor (FBR) method. In the former, which accounts for the majority (~90% in 2004) of solar-grade silicon production in the United States, silane or trichlorosilane is introduced into a thermal-decomposition reactor with high-temperature (~1,100-1,200°C) polysilicon rods (Aulich and Schulze, 2002; Woditsch and Koch, 2002). The silicon rods grow as silicon atoms from the gas phase deposited on them (Aulich and Schulze, 2002). In 1987, MEMC Electronic Materials commercialized the FBR method on a small scale; recent developments show promise for scaling up production to meet the needs of the emerging solar industry. In this approach, granular polysilicon is produced by decomposing silane around seed particles in a mixture of silane/hydrogen fed into the reactor. This continuous production process offers inherent advantages over the Siemens batch-process, requiring lower energy consumption while enabling higher throughput. However, such advantages have not been quantified in all life cycle analysis studies (Williams, 2000). The life cycle inventory (LCI) data used in the studies reviewed here correspond to polysilicon production via the Siemens method, and were gathered in the European "Crystal Clear" project (Aulich and Schulze, 2002; Woditsch and Koch, 2002). Table 1 presents the aggregated life cycle inventories (LCIs), compiled from data from 11 European and a US plant (Alsema and De Wild-Scholten, 2006; Fthenakis and Alsema, 2006). Data on ribbon-silicon technologies are not presented herein, because these were found to be insufficiently documented. Detailed LCIs are included in the IEA PVPS Task 12 report (V Fthenakis et al., 2011). The results for crystalline silicon and CIGS presented here are based on the latest LCI published in the IEA PVPS Task 12 report (Frischknecht et al., 2015).



Solar Cells: Energy Payback Times and Environmental Issues. Figure 2a – Flow diagram for sc-Si and mc-Si PV systems.



Solar Cells: Energy Payback Times and Environmental Issues. Figure 2b – Flow diagram for CdTe PV systems (frameless).

Solar Cells: Energy Payback Times and Environmental Issues. Table 1 Materials and energy inputs in the production of Si and CdTe PV modules -per square meters of module (excluding frames, commonly used for Si modules) (Frischknecht et al., 2015; Fthenakis and Alsema, 2006; Leccisi et al., 2016)

Category	**Inputs**	**Multi-Si**	**Mono-Si**	**CdTe**
Components (kg)	Cell materials	1.6	1.5	0.065
	Glass	9.1	9.1	24
	Ethylene vinyl acetate	0.9	0.9	0.5
	Others	1.8	1.8	2.0
Consumables (kg)	Gases	2.2	7.8	0.001
	Liquid	6.8	6.6	0.67
	Others	4.3	4.3	0.4
Energy	Electricity (kWh)	233	175	36
	Natural gas (MJ/)	72	4	25

CdTe PV Modules

Fthenakis and Kim reported the LCI data for CdTe thin-film technology gleaned from the 2005 production data from First Solar's plants, Perrysburg, United States in 2005, and from Frankfurt-Oder, Germany data in 2008 (V. M. Fthenakis et al., 2009; Fthenakis and Kim, 2007). Held (Held, 2009; Held and Ilg, 2011) and Raugei (Raugei et al., 2007) used the same data in their independent investigations. Currently, the most up-to-date production data were provided directly by First Solar, who also provide information on the balance of system (BOS) for typical ground-mounted installations, and the associated LCAs have been published by Leccisi et al., 2016. (Leccisi et al., 2016).

The life cycle inventories of the minor metals used in thin-film CdTe PVs (e.g., Cd and Te) are related closely to the production cycle of the respective base metals, Zn and Cu (V. Fthenakis et al., 2009). Cadmium is obtained from the waste streams in zinc smelting, mainly in the slimes from the Zn-electrolyte purification stages, and the particulates collected in baghouses, electrostatic precipitators, and cyclones in the thermal-oxidation units; thereafter, it is processed further and purified to the 99.999% purity required for synthesizing CdTe. Te is recovered after treating with dilute sulfuric acid the slimes produced during electrolytic copper refining; these slimes also contain Cu and other metals. After its cementation with copper, CuTe is leached out with caustic soda to produce a sodium-telluride solution that is used as the feed for Te and TeO_2. Additional leaching and vacuum-distillation produces Te- and TeO_2-powders of 99.999% purity required for synthesizing pure CdTe. This same route is followed in generating solar-grade CdS, used as a window layer in CdTe PV. Both the CdTe- and CdS-layers are placed by vapor-transport deposition, based on subliming the powders and condensing the vapors on glass substrates. A stream of inert carrier gas guides the cloud of sublimed dense vapor to deposit the films on glass substrates at 500-600°C at a line speed of up to 8 ft/min (Powell, R.C., Jayamaha, U., Dorer, G.L. and McMaster, 1999), followed by depositing layers of metals. Thereafter, a series of scribing and heat treatments form interconnections and back contacts. Currently (4Q2010), First Solar produces CdTe PV modules with an efficiency of 17.5%.

Glass is the heaviest part of PV module, particularly in frameless CdTe modules where two panes of glass ensure their structural toughness. The double-glass design eliminates the need for an aluminum frame that accounts for a significant fraction of emissions from making silicon modules. The use of thin-film layers per unit area of thin-film CdTe, CIGS, and a-SiGe is minimal compared with silicon modules since the thickness of cell materials in the former is 1-3 μm compared with ~200 μm for the latter. Thin-film modules also require lesser amounts of consumables than do silicon modules, as fewer process steps are involved (Table 1).

CIGS PV Modules

Currently, CIGS PV are available in several major layer configurations depending on the substrate and encapsulation materials, including glass/glass, glass/polymer, and polymer/polymer. Reported module efficiencies range from 9.4% to 13.9%. In double-glass configuration, manufacturers offer frameless modules as the two glass sheets provide sufficient structural integrity.

The European Commission's project ECLIPSE (Environmental and Ecological Life Cycle Inventories for present and future Power Systems in Europe) was the first major research on the life cycle inventory of commercial CIGS PV. This project compiled life cycle inventories of emerging options for power generation, including PV, wind, and biomass. The PV technologies investigated were single- and multicrystalline silicon modules, and thin-film modules, such as amorphous silicon (a-Si), copper indium gallium diselenide (CIGS), and cadmium telluride (CdTe). This study reported the usage of mass of metals, glass, encapsulating polymer, and a frame, along with electricity requirement during manufacturing based on data from the literature (Raugei, 2010).

Raugei et al. (Raugei et al., 2007) collected the first life cycle inventory from an actual production line of CIGS PV, from a pilot-scale manufacturing process of Würth Solar, Germany (Raugei, 2010). The SENSE report (SENSE (Sustainability Evaluation of Solar Energy Systems), 2006) gave information on the production of CIGS solar modules by Würth Solar; Lazonovski and Held (Lozanovski and Held, 2010). Currently, the most up-to-date inventory data source for CIGS is the latest IEA-photovoltaic power systems (PVPS) Task 12 Report (Frischknecht et al., 2015), which show data of the CIGS laminate and cell production in Europe (Germany, DE), and the most up-to-date LCA for CIGS PV is published by Leccisi et al., 2016 (Leccisi et al., 2016).

The sputtering of molybdenum aims at coating the "back contact." The substrates are structured by laser techniques. Targets of copper, indium, gallium, and selenium are co-evaporated, and substrates carry the vapors under an inert-gas-flow process. A buffering layer of CdS (cadmium sulfide) is put on to the substrates by dip coating. The front electrode is deposited by the sputtering of zinc oxide, doped with Al_2O_3. Laser scribing follows the deposition of each layer. A functional test identifies the defective products. The addition of interconnects and front glass completes the module production. Section "Energy Payback Times and Greenhouse Gas Emissions: Results" shows the results of the most-up-to date inventory data source for CIGS (Frischknecht et al., 2015) published in (Leccisi et al., 2016).

Amorphous Si and Microcrystalline Silicon PV Modules

Uni-Solar in Michigan, US used to, manufactures triple junction a-SiGe photovoltaics on rolls of stainless steel that are cut to different sizes, varying from solar shingles to large laminates that follow the curvature of any roof. Kim and Fthenakis (Kim and Fthenakis, 2010) conducted a life cycle analysis of replacing the intrinsic a-Si layer with a nano-crystalline Si layer. The investigators modeled a triple junction a-Si module, a-Si:H/a-SiGe:H/a-SiGe:H, while for nanotechnology, they assessed three prospective combinations of hybrid amorphous- and crystalline silicon cells. The first configuration is a tandem junction that consists of a-Si top layer and nc-Si bottom layer, i.e., a-Si:H/nc-Si:H; the second configuration is a triple junction with nc-Si as the bottom layer, i.e., a-Si:H/a-SiGe:H/nc-Si:H; and, lastly, a triple junction with two layers of nc-Si, i.e., a-Si:H/nc-Si:H/nc-Si:H. Oerlikon Solar developed a design called "Micromorph" that employs a glass substrate on which it laid out a TCO layer (transparent conductive oxide), followed by a-Si- and nc-Si-films. The life cycle energy demand of this design was compared with the above triple junction designs (Kim and Fthenakis, 2010).

Other companies that tried to commercialize thin-film silicon (TF-Si) included Oerlikon and Applied Materials, both of which used NF_3, a potent greenhouse gas for cleaning the reactor in glass-based TF-Si;. Fthenakis et al. (Fthenakis et al., 2010) completed a comprehensive study on NF_3 emissions, from its production by Air Products and its use by Applied Materials.

High-Concentration Photovoltaics

High-concentration PV systems are equipped with GaInP/GaInAs/Ge triple junction cells produced by Spectrolab Inc. The cells have a nominal aperture-area efficiency of 37% under 500 kW/m^2, 25°C, and AM1.5 conditions. The semiconductor layers are grown on a germanium substrate via metal-organic vapor-phase epitaxy (MOVPE). In 2009 Spectrolab Inc. provided the data on materials and energy input for the cell processing that are and summarized in Table 2; unfortunately, newer data do not exist. A 10% loss of inputs was assumed during the solar-cell production/dicing and assembly. The inventories are scaled for processing 1,000 wafers into 50,000 cells, corresponding to 915 kWp of capacity (Kim et al., 2008).

Solar Cells: Energy Payback Times and Environmental Issues. Table 2 Materials and energy inputs for processing 1,000 wafers, corresponding to 915 kWp[a] of GaInP/GaInAs/Ge terrestrial concentrator solar cell (Kim et al., 2012).

Inputs	**Amount**
Materials for components (kg)	
Wafer/precursors	21.7
Contact metals	3.4
Anti-reflection coating	0.02
Materials use for process (kg)	
Hydrogen	57.2
Nitrogen	0.2
Photoresist	2.3
Solvents	1073.4
Acids	255.8
Bases	161.3

Electricity (kWh)	
MOVPE	2,365
Others[b] (gas scrubbing and cell processing)	470

[a]At 37% rated efficiency
[b]Estimated from literature (Aulich and Schulze, 2002)

Amonix is one of the companies that used these cells in concentrating PV. Although they deployed several units world-wide, they were hit hard by the competition with cheap flat panels from Asia and ceased operation on or about 2012. The intellectual property of this technology is currently with Azton Solar. Fthenakis and Kim (Fthenakis and Kim, 2013) reported an LCA of the Amonix 7700 high-concentration PV system employing these cells. This consists of seven concentrating module units, the MegaModules, mounted on a two-axis tracker. Sunlight is concentrated on to 7,560 focal spots at a rate of 500:1. This system uses multijunction GaInP/GaInAs/Ge cells, grown on a germanium substrate rated at 37% efficiency, under the test condition of 50 W/cm^2, 25°C, and AM1.5D conditions. With an aperture area of 267 m^2, the capacity of this unit corresponds to 53 kW$_p$ AC power.

Table 3 shows the materials composition and mass balance of the Amonix 7700 system. While the measurements of the mass of manufactured parts were taken directly from the assembly line, the quantity of concrete used was calculated from the foundation's dimensions, i.e., 5.5 m deep, and 1.1 m diameter. The detailed material compositions of electrical parts, i.e., motor, transformer, and inverter, were estimated from Mason et al. (Mason et al., 2006). The LCI includes the materials used in scheduled maintenance over an expected life time of 30 years; they include changing the hydraulic- and bearing-oils, cleaning the lens, and changing the air- and oil-filters. The MegaModules (36%) and tracker (58%) account for most of the components, while steel (75%), concrete (11%), and aluminum (11%) dominate the material usages.

Solar Cells: Energy Payback Times and Environmental Issues. Table 3 Material breakdown of the Amonix 7700

Sub module	**Components**	**Materials**	**Mass (kg)**	**Fraction (%)**
MegaModules	Cell	Semiconductor	0.2	0.001
	Frame	Steel	6,566	23.0
	Fresnel lenses	Acrylic	1,143	4.0
	Heat sink	Aluminum	3,086	10.8

Tracker	Foundation	Concrete	3,126	10.9
	Hydraulic drive	Steel	2,724	9.5
	Pedestal and torque tube	Steel	11,260	39.4
	Motor	Various	16	0.1
Electrical	Inverter	Various	500	1.7
	Transformer	Various	100	0.3
	Cables	Copper/PVC	35	0.1
Other	Controller	Various	18	0.1
	Sensor	Various	1.4	0.005
	Anemometer	Various	0.1	0.0003

Balance of System (BOS)

Photovoltaic modules are either rooftop- or ground-mounted. Silicon modules need an aluminum frame for structural robustness, while a second glass back-sheet performs the same function for thin-film CdTe PV. For a rooftop PV application, the BOS typically includes inverters, mounting structures, cables, and connectors. Large-scale ground-mounted PV installations require additional equipment and facilities, such as transformers for grid connections, office facilities, and, in some cases, concrete for installations.

De Wild-Scholten et al. (De Wild-Scholten and Alsema, 2006) report the material inventories for two types of rooftop-mounting systems : on-roof mounting wherein the system is built on existing roofing material, and in-roof mounting where the modules replace the roof tiles. Table 4 shows the material life cycle inventory (LCI) of common rooftop-mounting systems, cabling, inverters, and transformers, including two sizes (500 W and 2,500 W) of small inverters adequate for rooftop PV designs.

Solar Cells: Energy Payback Times and Environmental Issues. Table 4 LCI of balance of system (BOS) for rooftop-mounted PV systems (Keoleian and Lewis, 2003; Lozanovski and Held, 2010)

(a) Mounting system (kg/m^2 module)

	On-roof		*In-roof*	
	Phönix, TectoSun	Schletter Eco05 + EcoG	Schletter, Plandach 5	Schweizer, Solrif
Low alloy steel	0	0	0	0
Stainless steel	0.49	0.72	0.28	0.08
Aluminum	0.54	0.97	1.21	1.71
Concrete	0	0	0	0
Frame	3.04	0	0	0
(b) Cabling (g/m^2)				
	Helukabel, Solarflex 101, 4 mm 2 , DC		*Helukabel, NYM-J, 6 mm 2 , AC*	
Copper	83.0		19.9	
Thermoplastic elastomer (TPE)	64.0		0.0	
PVC	0.0		16.9	
(c) Inverters (g)				
	Philips PSI 500 (500 W)		*Mastervolt SunMaster 2,500 (2,500 W)*	
Steel	78		9,800	
Aluminum	682		1,400	
Copper	2			
Polycarbonate	68			
ABS	148			

Other plastics	5.4	
Printed circuit board	100	1,800[a]
Connector	50	
Transformers, wire-wound	310	5,500
Coils	74	
Transistor diode	10	
Capacitor, film	72	
Capacitor, electrolytic	54	
Other electric components	20	

[a]Including electric components (e.g., connectors, transistors)

Data on materials- and energy use for a ground-mounted BOS reported in Table 5 were provided by First Solar, and it includes mounting, cabling, supporter structures, transformer, construction, O&M, inverter, and transport. The results presented here for c-Si, CdTe and CIGS are based on this inventory.

Solar Cells: Energy Payback Times and Environmental Issues. Table 5 LCI of 1 m2 of ground-mounted balance of system (BOS).

	Balance of system	**Unit**	**Quantity**
mounting	Steel, low-alloyed, at plant	**kg/m2**	10.2
	Section bar rolling, steel	**kg/m2**	10.2
	Aluminium, production mix, at plant	**kg/m2**	0.13
	Section bar extrusion, aluminium	**kg/m2**	0.13
	Synthetic rubber, at plant	**kg/m2**	0.06

cabling	Copper, at regional storage	**kg/m2**	0.88
	Wire drawing, copper	**kg/m2**	0.88
	Polyethylene, HDPE, granulate, at plant	**kg/m2**	0.29
	Aluminium, production mix, at plant	**kg/m2**	0.03
other support structures	Concrete block, at plant	**kg/m2**	3.74
	Polyvinylchloride, at regional storage	**kg/m2**	0.04
	Sawn timber, softwood, raw, air dried, u=20%, at plant	**m3**	0.001
transformer	Steel, low-allowed, at plant	**kg/m2**	0.75
	Copper, at regional storage	**kg/m2**	0.18
	Polyethylene, HDPE, granulate, at plant	**kg/m2**	0.03
	Transformer, high voltage use, at plant	**kg/m2**	0.03
	Soybean oil, at oil mill	**kg/m2**	0.67
construction	Diesel, at regional storage	**kg/m2**	1.72
	Electricity, medium voltage, at grid	kWh/m2	0.13
O&M	Electricity, medium voltage, at grid	kWh/m2	1.16
	Natural gas, at long-distance pipeline	m3/m2	0.01
	Petrol, unleaded, at regional storage	kg/m2	0.05
inverter	Inverter, 500 kW, at plant	p/mk	0.000237
water	tap water, at user	kg/m2	89.13
transport	Transport, transoceanic freight ship/OCE U	tkm/m2	274.13

	Transport, lorry >16t, fleet average/RER U	tkm/m2	274.13

Energy Payback Times and Greenhouse Gas Emissions: Methodology

The methodology employed in PV LCA studies conforms to the ISO standards 14040 and 14044. Furthermore, the basic assumptions employed for photovoltaics-specific parameters are those agreed within the International Energy Agency (IEA) PVPS Task 12 (Frischknecht et al., 2016; V. Fthenakis et al., 2011); they are summarized below:

- Life expectancy
    - Modules: 30 years
    - Inverters: 15 years for small plants (residential PV); 30 years with 10% of replacement of parts every 10 year for large plants
    - Structure: 30 years for rooftop- and façade-installations and 60 years for ground-mounted ones
    - Cabling: 30 years
- Performance ratio
    - The performance ratio (PR) accounts for the losses from dc to ac conversion, thermal losses, and wire losses, and depends on the kind of installation. In general, the ratio increases with a decline in temperature build-up and monitoring the PV systems for early detection of defects; this means that well-ventilated and large-scale systems have a high-performance ratio. There have been steady improvements in PR ratio over the years, with the latest reported figures indicating current values between 80% and 90% (Fraunhofer Institute for Solar Energy Systems, 2019). A conservative PR of 80% was assumed here for ground-mount utility-scale installations.
- Degradation
    - The degradation of the modules lowers efficiency over the life time. For mature module technologies, a linear degradation of 80% of the initial efficiency was assumed at the end of the 30 years life, which corresponds to an average degradation rate of 0.7% per year. This is a conservative assumption that is consistent with the system-level values reported by an extensive study by NREL (0.36% - 0.59% for c-Si, 0.95 for a-Si, and 0.30% for CdTe) (Jordan and Kurtz, 2013).

Energy Payback Time

The energy payback time (EPBT), measured in years [yr], is defined as the time required for a renewable energy system to generate the same amount of energy as that used by the system from cradle to grave. For a PV system, it is quantified as follows:

$$\text{Energy Payback Time} = (E_{mat} + E_{manuf} + E_{trans} + E_{inst} + E_{EOL}) / ((E_{agen} / \eta_G) - E_{O\&M})$$

where,

- E_{mat}: Primary-energy demand to produce materials comprising PV system [MJ]
- E_{manuf}: Primary-energy demand to manufacture PV system [MJ]

- E_{trans}: Primary-energy demand to transport materials used during the life cycle [MJ]
- E_{inst}: Primary-energy demand to install the system [MJ]
- E_{EOL}: Primary-energy demand for end-of-life management [MJ]
- E_{agen}: Annual electricity generation [MJ/yr]
- η_G: Grid efficiency, the average primary energy to electricity conversion efficiency at the demand side [MJ/MJ]
- $E_{O\&M}$: Annual primary energy demand for operation and maintenance [MJ/yr]

Calculating the primary-energy equivalent requires knowing the country-specific, energy mixture used to generate electricity and produce materials. The annual electricity generation (E_{agen}) is converted to the primary-energy equivalent by dividing it by the average life-cycle conversion efficiency of grid mix into which the PV system is embedded (e.g., $\eta_G = 0.3$ for a grid mix heavily reliant on thermal technologies).

Greenhouse Gas Emissions

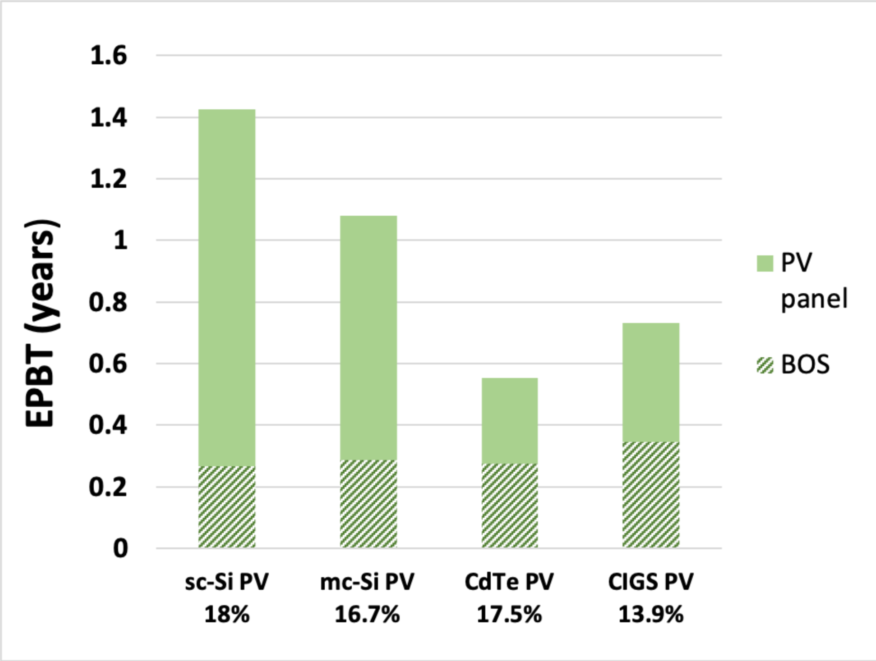
Greenhouse gas (GHG) emissions during the life cycle stages of a PV system are estimated as equivalents of CO_2 using an integrated time-horizon of 100 years; the major emissions included in GHG emissions are CO_2 (GWP = 1), CH_4 (GWP = 25), N_2O (GWP = 296) and chlorofluorocarbons (GWP = 4,600-10,600) (International Panel on Climate Change IPCC, 2001). (Global Warming Potential is an indicator of the relative radiative effect of a substance compared to CO_2, integrated over a chosen time-horizon; the GWP_{100} corresponding to a 100 year horizon is used here.) Electricity- and fuel use during the production of the PV materials and modules are the main sources of the GHG emissions for PV cycles. Methods of generating the upstream electricity also play an important role in determining the total GHG emissions, as the higher the mixture of fossil fuels is in the grid, the higher are the GHG- and toxic-emissions. Thus, the GHG emission factor of the average US electricity grid is higher than that of the average Western European (ENTSO-E) grid; that of China is higher than both of them. During 1999-2002, the US average CO_2 emissions inventory from electricity production and transmission was 676 g CO_2/kWh, while in China, it was 839 g CO_2/kWh (US Department of Energy, Energy Information Administration, 2007). These differences correspond to an estimated increase of 20% in the GHG emissions for producing modules and BOS components in China versus in the United States. Furthermore, transporting the modules and BOS components from China to either the United States or Europe could add an additional 15% to the GHG emissions.

Energy Payback Times and Greenhouse Gas Emissions: Results

EPBT

The latest (2016) estimates of the cumulative energy demand used in the life cycle of complete ground-mounted Si-PV systems are 24,735 MJ/kW_p and 18,724 MJ_{PE}/kW_p , respectively, for mono- and multi-crystalline Si PV manufactured in China (Leccisi et al., 2016). The EPBT of these systems is 1.4 years for mono-crystalline Si PV systems, and 1.1 years for multi-crystalline Si PV systems, considering the current average commercial module efficiencies of 18% and 16.7% respectively (Fraunhofer Institute for Solar Energy Systems, 2019), a Southern European insolation of 1,700 kWh/m^2/year, and a performance ratio (ratio between the dc-rated and actual ac electricity output) (PR) of 0.8 (Fig. 3). In these estimates, the BOS for ground-mounted application accounts for approximately 0.3 years of EPBT.

For CdTe PV, the energy consumption is 9603 MJ/kW$_p$ based on actual production from First Solar's plant in Malaysia (Leccisi et al., 2016). For insolation levels of 1,700 kWh/m^2/year, and current module efficiency of 17.5%, the EPBT of CdTe PV systems is 0.3 year.



Solar Cells: Energy Payback Times and Environmental Issues. Figure 3 EPBT of PV systems: Ground-mounted systems with insolation =1,700 kWh/m^2/year and performance ratio = 0.8; Chinese (c-Si), Malaysian (CdTe), and European (CIGS) production; assuming a generalized average grid mix efficiency = 0.30

The EPBT decreases as the solar irradiation levels increases; for example, in Phoenix, Arizona, US Southwest, (latitude optimal irradiation of 2,370 kWh/m^2/year), the EPBTs of mono- and multi-crystalline Si PV systems are 1 and 0.7 years, while the EPBT of cadmium telluride-PV systems is 0.4 year, and CIGS PV systems range at 0.5 year, all in fixed-tilt ground-mount utility installations. At the same location, the two-axis Amonix HCPV would have an EPBT of 0.9 years (Table 6).

Solar Cells: Energy Payback Times and Environmental Issues. Table 6 Comparison of life cycle parameters and performances across PV technologies (normalized for Phoenix insolation)

PV system	**Amonix HCPV, 7700 current**	**Multi c-Si ground-mount**[a]	**Mono c-Si ground-mount**[a]	**CdTe ground-mount**[a]

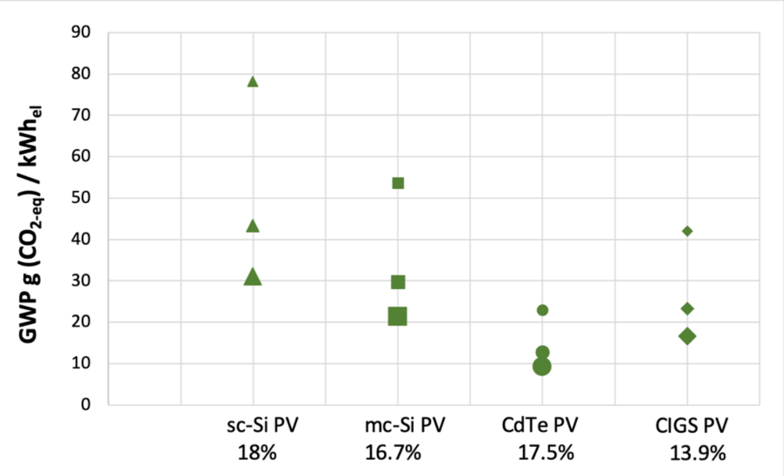
Module DC efficiency (%)	37 (cell)	18	16.7	17.5
Insolation (kWh/m^2/year)	2480^c	2370	2370	2370
EPBT (years)	0.9	0.7	1	0.4

^{a} Adapted from (Leccisi et al., 2016)

^{c}Direct normal insolation with 2-axis tracker

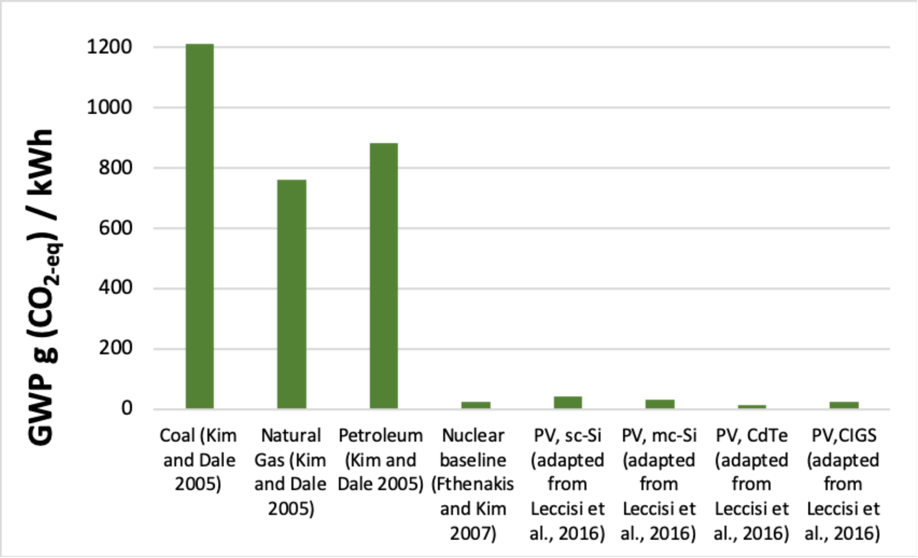
Greenhouse Gas Emissions

The most recent LCAs for crystalline silicon modules are those based on the latest published inventory data from the IEA PVPS (Frischknecht et al., 2015) and published by (Leccisi et al., 2016). The GHG emissions of mono- and multi-crystalline Si PV systems (produced in China) are respectively 43 and 30 g CO_2-eq./kWh, for a ground-mounted application under Southern European insolation of 1,700 kWh/m^2/year, and a performance ratio (ratio between the dc-rated and actual ac electricity output) (PR) of 0. 8 (Fig. 4). With the same conditions, the GHG emissions of CdTe PV systems (Malaysian production) are 12 g CO_2-eq./kWh, while CIGS PV systems (European production) range at 23 g CO_2-eq./kWh.



Solar Cells: Energy Payback Times and Environmental Issues. Figure 4 GHG emissions of PV systems: ground-mounted installed PV systems with performance ratio = 0.8; Chinese production for c-Si, Malaysian production for CdTe, and European production for CIGS, under three irradiation levels. Smalls symbols: 1,000 kWh/(m^{2*}yr); medium symbols: 1,700 kWh/(m^{2*}yr); large symbols: 2,370 kWh/(m^{2*}yr). Adapted from (Leccisi et al., 2016)

Figure 5 compares GHG emissions from the life cycle of PV with those of conventional fuel-burning power plants, revealing the environmental advantage of using PV technologies. The majority of GHG emissions come from the operational stage for the coal-, natural gas-, and oil fuel cycles, while the material and device production accounts for nearly all the emissions for the PV cycles. With over 50% contributions, the GHG emissions from the electricity demand in the life cycle of PV are the most impactful input. Therefore, the LCA results strongly depend on the available electricity mix. The GHG emissions from the nuclear fuel cycle mainly are related to the fuel production, i.e., mining, milling, fabrication, conversion, and the enrichment of uranium fuel.

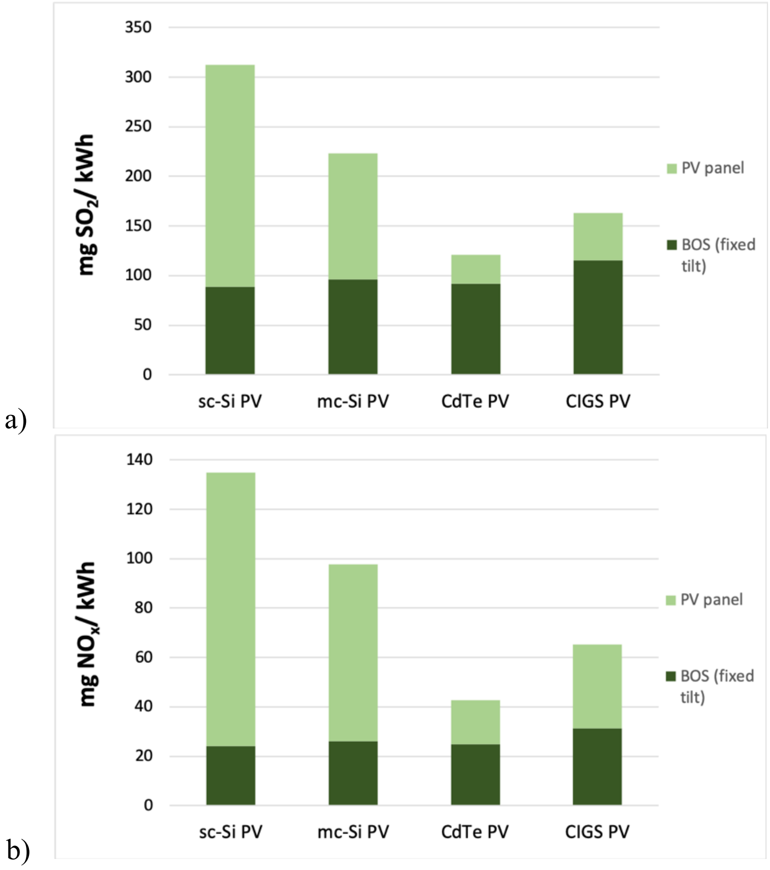


Solar Cells: Energy Payback Times and Environmental Issues. Figure 5 Comparison of emissions from ground-mounted PVs with those from conventional power plants (Insolation of 1,700 kWh/m^2/year, performance ratio of 0.8)

Other comparisons between the life cycles of photovoltaics and conventional power generation cover land use (Fthenakis and Kim, 2009) and water use (Fthenakis and Kim, 2010). Accounting for the land occupation in coal mining, it is shown that the life cycles of PV in the US-SW occupy about the same or less land, and orders of magnitude less water, on an electricity produced (GWh) basis, than the average coal-based power generation.

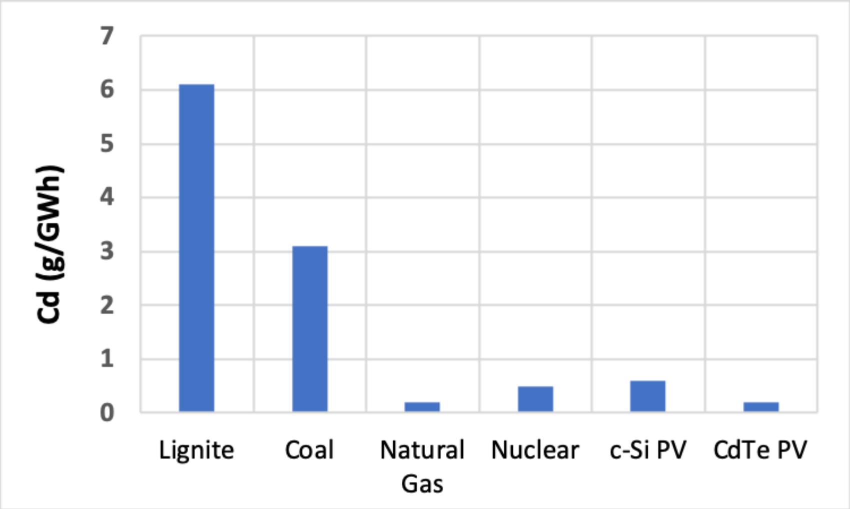
Acidic and Heavy Metal Emissions

The emissions of acidic gases (e.g., SO_2, NO_x) and heavy metals (e.g., As, Cd, Hg, Cr, Ni, Pb) during the life cycle of a PV system are largely proportional to the amount of fossil fuel consumed during its various phases, in particular, processing and manufacturing PV materials. Figure 6 shows estimates of SO_2 and NO_x emissions. Heavy metals may be emitted directly from material processing and PV manufacturing, and indirectly from generating the energy used at both stages. For the most part, they originate as trace metals in the coal used.

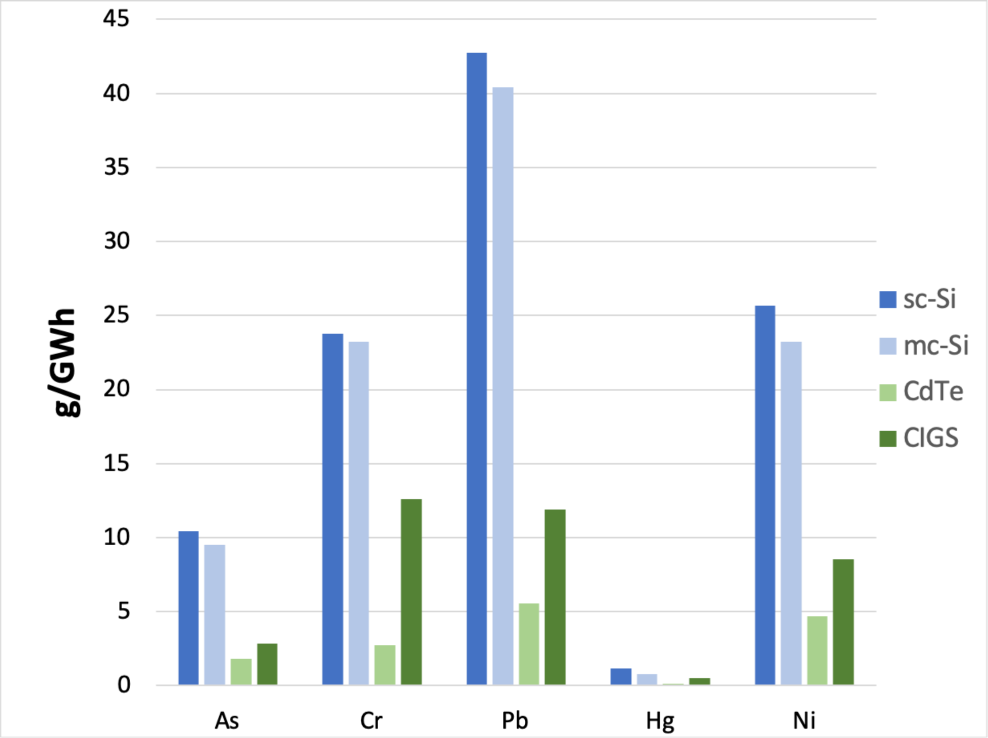


Solar Cells: Energy Payback Times and Environmental Issues. Figure 6 Life cycle emissions of (**a**) SO_2, and (**b**) NO_x emissions from silicon and CdTe PV modules. BOS includes inverter, transformers, module supports, cabling, and power conditioning. The estimates are based on rooftop-mount installation, insolation of 1,700 kWh/m^2/year, performance ratio of 0.8, lifetime of 30 years, and Chinese production for c-Si and Malaysian production for CdTe.

Direct emissions of cadmium in the life cycle of CdTe PV were assessed in detail (Fthenakis, 2004). They total 0.016 g per GWh of PV-produced energy under an irradiation of 1,700 kWh/m^2/year (Table 7); this includes emissions during fires on rooftop residential systems, quantified in experiments at Brookhaven National Laboratory that simulated actual fires (Fthenakis et al., 2005). These experiments were designed to replicate average conditions, and the estimated emissions were calculated by accounting for US fire-statistics pointing to 1/10,000 houses catching fire over the course of a year in the United States where most houses have wood-frames, by assuming that all fires involve the roof. The indirect Cd emissions from electricity usage during the life cycle of CdTe PV modules (i.e., 0.24 g/GWh) are an order-of-magnitude greater than the direct ones (routine and accidental) (i.e., 0.016 g/GWh) (Fthenakis et al., 2008; Fthenakis and Kim, 2007). (Indirect emissions of heavy metals result mainly from the trace elements in coal and oil. According to the US Electric Power Research Institute's (EPRI's) data, under the best/optimized operational- and maintenance conditions, burning coal for electricity releases into the air between 2- and 7-g of Cd/GWh (Electric Power Research Institute (EPRI), n.d.). In addition, 140 g/GWh of Cd inevitably collects as fine dust in boilers, baghouses, and electrostatic precipitators (ESPs). Furthermore, a typical US coal-powered plant emits per GWh about 1,000 t of CO_2, 8 t of SO_2, 3 t of NO_x, and 0.4 t of particulates. The emissions of Cd from heavy oil burning power plants are 12-14 times higher than those from coal plants , even though heavy oil contains much less Cd than coal (~0.1 ppm); this is because these plants do not have particulate-control equipment (Fthenakis, 2004). The complete life cycle atmospheric Cd emissions, estimated by adding those from the usage of electricity and fuel in manufacturing and producing materials for various PV modules and Balance of System (BOS), were compared with the emissions from other electricity-generating technologies (Fig. 7) (Fthenakis et al., 2008). Undoubtedly, displacing others with Cd PV markedly lowers the amount of Cd released into the air. In addition, the direct emissions of Cd during the life cycle of CdTe PV are ten times lower than the indirect ones due to use of electricity and fuel in the same life cycle, and about 30 times less than those indirect emissions from crystalline photovoltaics. Furthermore, examining the indirect heavy metal emissions in the life cycle of the three silicon technologies discussed earlier revealed that, among the PV technologies, CdTe PV had the lowest energy burden and, consequently, the fewest heavy metal emissions (Fig. 8) (Fthenakis et al., 2008). Regardless of the particular PV technology, these emissions are extremely small compared to the emissions from the fossil fuel-based plants that PV will replace.



Solar Cells: Energy Payback Times and Environmental Issues. Figure 7 Life cycle atmospheric Cd emissions for PV systems from electricity and fuel consumption, normalized for a Southern Europe average insolation of 1,700 kWh/m^2/year, performance ratio of 0.8, and lifetime of 30 year. Data are from (Fthenakis et al., 2008).



Solar Cells: Energy Payback Times and Environmental Issues. Figure 8 Emissions of heavy metals per unit of electricity delivered. Sc-si and mc-Si PV are manufactured in China, CdTe PV in Malaysia, and CIGS in Europe. Emissions are normalized for Southern European average insolation of 1,700 kWh/m^2/year, performance ratio of 0.8, and lifetime of 30 year

Solar Cells: Energy Payback Times and Environmental Issues. Table 7 Direct, atmospheric Cd emissions during the life cycle of the CdTe PV module (Allocation of emissions to coproduction of Zn, Cd, Ge, and In)

	Air emissions (g Cd/tonne Cd[a])	**Allocation (%)[b]**	**Air emissions (g Cd/ton Cd[a])**	**mg Cd/GWh[c]**
Mining of Zn ores	2.7	0.58	0.016	0.01
Zn smelting/refining	40	0.58	0.23	0.15
Cd purification	6	100	5.97	3.9
CdTe production	6	100	5.97	3.9
PV manufacturing	3	100	0.40	0.26
Operation	0.3	100	0.05	0.03

Disposal/recycling	0	100	0.10	0.07
Total			12.74	8.3

[a] Ton of Cd produced

[b] Emissions are allocated between coproducts (Zn, Cd and other) based on mass and cost proportioning, according to ISO 14040 guidelines

[c] Energy produced assuming average Southern European insolation (i.e., 1,700 kWh/m^2/year), 17.5% electrical conversion efficiency, and a 30-year life for the modules

Conclusion

This chapter gives an overview of the life cycle environmental performance of photovoltaic (PV) technologies. Energy payback time (EPBT) is a basic metric of this performance: The lower the EPBT, that is the time it takes for a PV system to generate energy equal to the amount used in its production, the lower will be the emissions to the environment because emissions mainly occur from using fossil fuel-based energy in producing materials, solar cells, modules, and systems. These emissions differ in different countries, depending on that country's mixture in the electricity grid, and the varying methods of material/fuel processing. Under average US and Southern European conditions (e.g., 1,700 kWh/m^2/year), the EPBT of mono- and multi-crystalline Si ground mounted PV systems were estimated respectively to be 1.4 and 1 years, while CdTe ground mounted PV systems range at 0.5 year, and CIGS at 0.7 year. Under US SW irradiation (e.g., Phoenix, AZ, 2,370 kWh/m^2/year at a fixed latitude tilt), the EPBT of ground-mount installations is estimated to be 1 year for sc-Si, 0.7 year for mc-Si, 0.4 year for CdTe, and 0.5 for CIGS, all ground mounted installations.

The environmental impacts of the life cycle of photovoltaics as assessed by the common metrics of GHG emissions, toxic emissions, and heavy metal emissions are very small in comparison to those of the power generation technologies they replace.

R and D Needs

The EPBT and GHG emissions of photovoltaics will keep decreasing as the efficiencies of modules, inverters, and material utilization all increase. Such improvements and new products entering the market necessitate frequent updates of the environmental performance of PV.

New LCAs are needed for CIGS and tandem PV as the published estimates are uncertain and outdated, correspondingly. The PV industry is dynamic and LCIs with associated LCAs would be needed, as established technologies keep improving and new technologies (e.g., perovskites) are being developed. Scaling up to commercial production LCI data collected in the laboratory is a challenge for new technologies.

The environmental issues related to the installation and operation phases of very large (e.g., thousands of acres) PV facilities need to be evaluated in a comparative context as PV are displacing fossil fuel life cycles.

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