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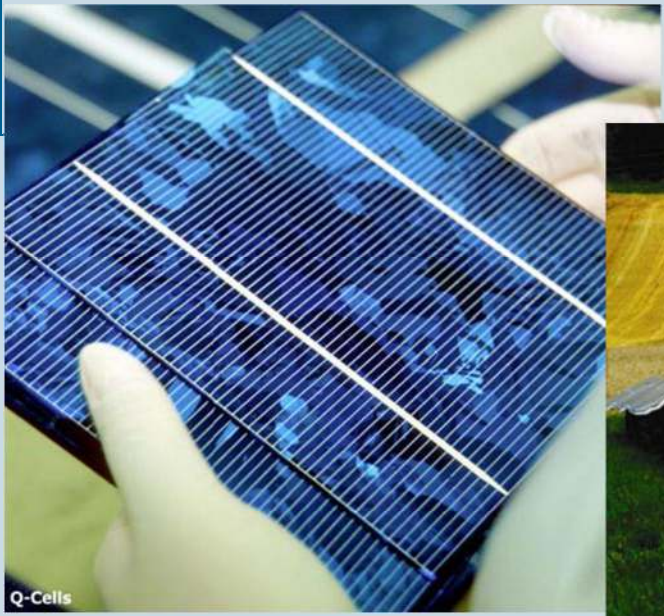
Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems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PVPS

PHOTOVOLTAIC
POWER SYSTEMS
PROGRAMME

Report IEA-PVPS T12-02:2011

INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems

IEA PVPS Task 12, Subtask 20, LCA
Report IEA-PVPS T12-02:2011

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Operating agent:

Vasilis Fthenakis, Brookhaven National Laboratory
Upton, New York, USA

Authors:

Vasilis Fthenakis, Hyung Chul Kim, Rolf Frischknecht, Marco Raugei, Parikhit Sinha and Matthias Stucki

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Executive Summary

Life Cycle Assessment (LCA) is a structured, comprehensive method of quantifying material- and energy-flows and their associated impacts in the life cycles of products (i.e., goods and services). One of the major goals of IEA PVPS Task 12 is to provide guidance on assuring consistency, balance, transparency and quality of LCA to enhance the credibility and reliability of the results. The current report presents the latest consensus LCA results among the authors, PV LCA experts in North America, Europe and Asia. At this time consensus is limited to four technologies for which they are well-established and up-to-date LCI data: mono- and multi-crystalline Si, CdTe and high concentration PV (HCPV) using III/V cells. The LCA indicators shown herein include Energy Payback Times (EPBT), Greenhouse Gas emissions (GHG), criteria pollutant emissions, and heavy metal emissions.

Life Cycle Inventories (LCIs) are necessary for LCA and the availability of such data is often the greatest barrier for conducting LCA. The Task 12 LCA experts have put great efforts in gathering and compiling the LCI data presented in this report. 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 from actual production and operation facilities. In addition to the LCI data that support the LCA results presented herein, data are presented to enable analyses of various types of PV installations; these include operational data of rooftop and ground-mount PV systems and country-specific PV-mixes. The LCI datasets presented in this report are the latest that are available to the public describing the status of 2005-2006 for crystalline Si, 2008 for CdTe, and 2010 for HCPV technology.

Foreword

The International Energy Agency (IEA), founded in November 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD) that carries out a comprehensive programme of energy co-operation among its member countries. The European Commission also participates in the work of the IEA.

The IEA Photovoltaic Power Systems Programme (PVPS) is one of the collaborative R & D Agreements established within the IEA. Since 1993, participants in the PVPS have been conducting a variety of joint projects in the applications of photovoltaic conversion of solar energy into electricity.

The mission of the Photovoltaic Power Systems Programme is "…to enhance the international collaboration efforts which accelerate the development and deployment of photovoltaic solar energy as a significant and sustainable renewable energy option". The underlying assumption is that the market for PV systems gradually is expanding from the niche-markets of remote applications and consumer products, to rapidly growing ones for building-integrated and centralised PV- generation systems. An Executive Committee composed of one representative from each participating country heads the overall programme: Operating Agents assume responsibility for managing individual research projects (Tasks). By the end of 2010, fourteen Tasks were established within the PVPS programme.

Task 12 aims at fostering international collaboration in safety and sustainability that are crucial for assuring that PV growth to levels enabling it to make a major contribution to the needs of the member countries and the world.

The overall objectives of Task 12 are to accomplish the following:

1. Quantify the environmental profile of PV in comparison to other energy- technologies;

2. Define and address environmental health & safety and sustainability issues that are important for market growth.

The first objective of this task is well served by life cycle assessments (LCAs) that describe the energy-, material-, and emission-flows in all the stages of the life of PV. The second objective will be addressed by assisting the collective action of PV companies in defining material availability and product-recycling issues, and on communicating "lessons learned" from incidents or potential ones in PV- production facilities. A third objective (i.e., dissemination) will be accomplished by presentations to broad audiences, producing simple fact sheets documented by comprehensive reports, and engaging industrial associations and the media in the spreading this information.

Within Task 12, there are three targets of Subtask 20 "Life Cycle Assessment": To quantify the environmental profile of electricity produced with PV systems (compared to that from other sources); to show trends in the improvement of PV's environmental profile; and, to assess this profile with the help of "external" costs, and other life-cycle-impact assessment methods.

Task 12 was initiated by Brookhaven National Laboratory under the auspices of the U.S. Department of Energy and is operated jointly by BNL and EPIA. Support from DOE and EPIA are gratefully acknowledged. Further information on the activities and results of the Task can be found at

http://www.iea-pvps.org and http://www.iea-pvps-task12.org

1. Introduction

Life Cycle Assessment (LCA) enables us to take into account the entire life cycle stages, from cradle to grave, in measuring environmental and resource sustainability. There has been continuous and remarkable progress in photovoltaic (PV) technologies during the last decade as governments and the industry stepped up investments in solar energy. Economies of scale and improvements in material utilization and process and module efficiencies have contributed to drastic reductions in production costs and to lower environmental footprints. In this report, we present major life cycle impact metrics (e.g., energy payback time and life cycle emissions) of commercial PV technologies for which detailed data are available. This report also includes the life cycle inventory data that were the building block of the reported LCA results. The results pertain to mono-and multi-crystalline Si, CdTe and high concentration (HC) PV for which up-to-date analyses have been performed. We also include in the report additional inventory data describing different mounting and system options. LCA results related to a-Si and CIGS technologies were not included as there are no LCI data available in the public domain supporting such. The LCA indicators we present in this report are: Energy Payback Times (EPBT), Greenhouse Gas (GHG) emissions, SO2, NOX and heavy metal emissions. Other indicators (e.g. resource availability, toxicity indicators) are relatively uncertain and lack consensus in the LCA community.

2. Life Cycle Assessment Overview

2.1 Life Cycle of PV

The life-cycle of photovoltaics starts from the extraction of raw materials (cradle) and ends with the disposal (grave) or recycling and recovery (cradle) of the PV components (Figure 1).

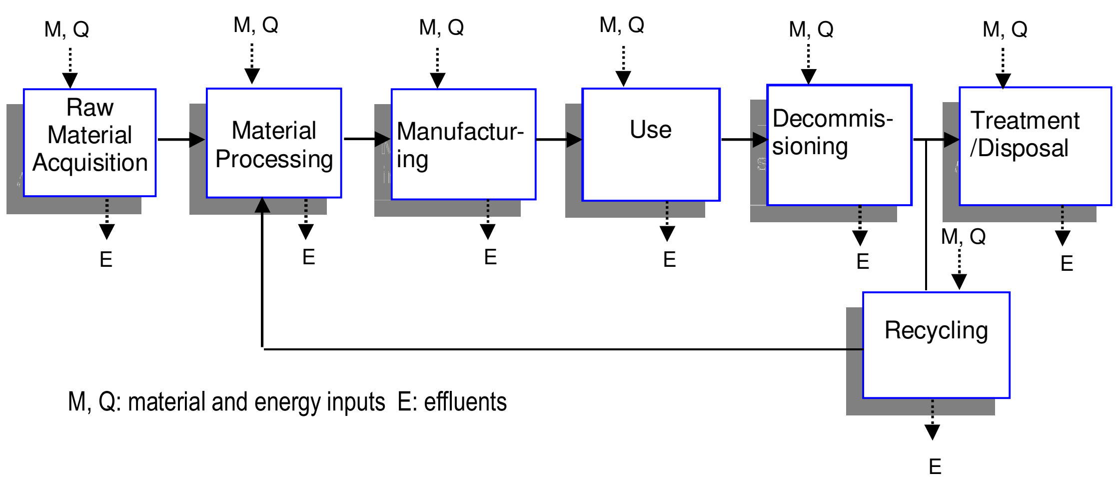

Figure 1: Flow of the life-cycle stages, energy, materials, and effluents for PV systems

The mining of raw materials, for example, quartz sand for silicon PVs, is followed by further processing and purification stages, to achieve the required high purities, which typically entails a large amount of energy consumption. The silica in the quartz sand is reduced in an arc furnace to metallurgical-grade silicon, which must be purified further into solar grade silicon (>99.9999%), typically through a modified-Siemens process. Metal-grade cadmium and tellurium for CdTe PV is primarily obtained as a byproduct of zinc and copper smelters respectively, and further purification is required for solar-grade purity (>99.999%). Similarly, metals used in CIGS PV are recovered as byproducts; indium and gallium are byproducts of zinc mining while selenium is mostly recovered from copper production.

The raw materials include those for encapsulations and balance-of-system components, for example, silica for glass, copper ore for cables, and iron and zinc ores for mounting structures. The manufacture of a bulk silicon PV device is divided into several steps, that is, wafer, cell, and module. In the wafer stage, solar-grade polycrystalline or single-crystal silicon ingots are sliced into ~0.2 mm thick wafers. During the cell stage, a p-n junction is formed by dopant diffusion and electric circuit is created by applying and sintering metallization pastes. In the module stage, cells are connected physically and electronically, and encapsulated by glasses and plastics. The manufacturing stage is relatively simple for thin-film PVs which typically rely on a series of semiconductor layer deposition followed by module fabrication steps (e.g., encapsulation) similar to those for silicon PVs. During the PV system installation stage, support structures are erected, PV systems are mounted, and PV modules, cables, and power conditioning equipment are integrated. At the end of their lifetime, PV systems are decommissioned and disposed with valuable parts and materials recycled.

2.2 Life Cycle Assessment Indicators and Interpretation

2.2.1 Primary Energy Demand

This is the cumulative primary energy demand throughout the life cycle of a PV system. 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 [1].

2.2.2 Energy Payback Time

Energy payback time 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.

Energy Payback Time (EPBT) = $(E_{mat}+E_{manuf}+E_{trans}+E_{inst}+E_{EOL}) / ((E_{agen} / \eta_G) - E_{aoper})$

where,

E_{mat} : Primary energy demand to produce materials comprising PV system

E_{manuf} : Primary energy demand to manufacture PV system

E_{trans} : Primary energy demand to transport materials used during the life cycle

E_{inst} : Primary energy demand to install the system
E_{EOL} : Primary energy demand for end-of-life management
E_{agen} : Annual electricity generation
E_{aoper} : Annual energy demand for operation and maintenance in primary energy terms
η_G : Grid efficiency, the average primary energy to electricity conversion efficiency at the demand side

Calculating the primary energy equivalent requires knowledge of the country-specific, energy-conversion parameters for fuels and technologies used to generate energy and feedstock. In the results presented in this report, the annual electricity generation (E_{agen}) is converted to the primary energy equivalent by means of the average conversion efficiency of 0.29 for the United States and 0.31 for Western Europe [2, 3].

2.2.3 Greenhouse Gas Emissions

The greenhouse gas (GHG) emissions during the life cycle stages of a PV system are estimated as an equivalent of CO2 using an integrated time horizon of 100 years; the major emissions included as GHG emissions are CO2 (GWP =1), CH4 (GWP=25), N2O (GWP=298) and chlorofluorocarbons (GWP=4750-14400) [4].

2.3 Literature Review

In early life-cycle studies, researchers estimated a wide range of primary energy consumption for Si-PV modules [5]: 2400-7600 and 5300-16500 MJ/m2 for multi-crystalline silicon (multi-Si) and mono-crystalline silicon (mono-si) modules. Besides the uncertainty in the data, these differences are due to different assumptions and allocation rules for modeling the purification and crystallization stages of silicon [5, 6]. Reject electronic-grade silicon collected during the Siemens process which produces silicon of over nine 9s purity (i.e. >99.9999999%), was often used for PV wafer manufacturing. This route was replaced by a dedicated solar-grade silicon purification process called modified-Siemens process in early 2000s, which requires far less energy than the former process. Allocating environmental burdens between off-spec electronic grade and on-spec solar grade silicon is debatable when both types of silicon are used in PV wafer. Selecting only those process steps needed to produce solar-grade silicon, Alsema estimated 4200 and 5700 MJ/m2 for multi- and mono-Si modules, respectively [5]. These values correspond to an energy payback time (EPBT, see section 2.1 for definition) of 2.5 and 3.1 years, and life-cycle GHG emissions of 46 and 63 g CO2-eq./kWh for rooftop mounted multi- Si PV with 13% efficiency and mono-Si with 14% efficiency, respectively, under Southern European (Mediterranean) conditions: insolation of 1700 kWh/m2/yr, and a performance ratio of 0.75. Meijer et al. [7] reported a slightly higher energy demand of 4900 MJ/m2 to produce a multi-Si module assuming that wafer is produced from electronic-grade silicon. With 14.5% cell efficiency, their corresponding EPBT estimate for the module was 3.5 years under the solar irradiation in the Netherlands (1000 kWh/m2/yr).

Jungbluth [8] reported the life-cycle metrics of various PV systems under environmental conditions in Switzerland assuming that the source of silicon materials was 50% from solar-grade silicon and 50% from electronic grade-silicon. For 300 µm-thick multi-Si and mono-Si PV modules with 13.2% and 14.8% conversion efficiency, respectively, this study arrived at 39-110 g CO2-eq./kWh of GHG emissions and 3-6 years of EPBT for the Swiss average insolation of 1100 kWh/m2/yr [6, 8], depending on configuration of PV systems (i.e., façade, slanted-roof, and flat-roof).

With material-inventory data from industry, Alsema and de Wild-Scholten [6] demonstrated that the life-cycle primary energy and greenhouse gas emission of complete rooftop Si-PV systems are much lower than those reported in earlier studies. Primary energy consumption is 3700 and 4200 MJ/m2, respectively, for multi- and mono- Si modules. Fthenakis and Alsema also report that the GHG emissions of multi- and mono-Si modules corresponding to 2004-2005 production are within a 37 and 45 g CO2-eq./kWh , with an EPBT of 2.2 and 2.7 years for a rooftop application under Southern European insolation of 1700 kWh/m2/yr and a performance ratio (PR) of 0.75 [9]. We note that in these estimates, the BOS for rooftop application accounts for 4.5-5 g CO2-eq./kWh of GHG emissions and 0.3 years of EPBT. De wild-Scholten [10] recently updated these estimates based on thinner modules and more efficient processes, reporting an EPBT of ~1.8 yrs and GHG emissions of ~30 g CO2-eq./kWh for both multi- and mono-Si PVs. Note that these figures include the effect of “take back and recycling” of PV modules but do not take into account the frame which is typically required for structural integrity in single glass modules.

There are fewer life-cycle studies of thin film PV technologies. Kato et al. (2001) in an early energy study of CdTe life cycle forecasted energy burdens of 1523, 1234, and 992 MJ/m2 for CdTe PV frameless modules with annual capacities of 10, 30, and 100 MWp , respectively[11]. However, these earlier estimates fall far short of present-day commercial-scale CdTe PV production that, unlike previously, now encompasses many large-scale production plants. Fthenakis and Kim (2006) 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 [9, 12]. The greenhouse-gas emissions (GHG) and energy payback time (EPBT) of ground-mounted CdTe PV modules under the average US insolation condition, 1800 kWh/m2/yr, were determined to be 24 g CO2-eq./kWh and 1.1 years, correspondingly. These estimates include 6 g CO2-eq./kWh of GHG and 0.3 year of EPBT contribution from the ground-mounted BOS [13]. Raugei et al. [14] estimated a lower primary energy consumption, ~1100 MJ/m2, and thereby less GHG emissions and lower EPBT than ours, based on the data of the year 2002 from Antec Solar’s 10 MWp plant in Germany. However, the latter estimates are obsolete as their plant ceased producing CdTe PV. Fthenakis et al. [18] recently updated these estimates 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.

Amorphous silicon (a-Si) PV has been installed mostly as building integrated configuration. An early study by Lewis and Keoleian (1999) reported that for a-Si thin-film PV integrated in a building, the life cycle GHG emissions corresponded to 187.8 g CO2/kWh while the EPBT was 5.14 yrs [15]. This study assumed a 20-yr lifetime operation under the condition of Detroit, MI with a zero tilt angle that receives 1400 kWh/m2/yr of solar irradiation. Pacca et al (2007) recently assessed the life cycle environmental impact of a-Si PV systems on a rooftop in Ann Arbor, Michigan [16]. The installed a-Si PV array facing the south with a 12° tilt angle receives a solar irradiation of 1359 kWh/m2/yr in this location. The life cycle CO2 emissions from the a-Si PV module with 6.3% efficiency corresponded to 34.3 g/kWh over a 20-yr lifetime. Note that this estimate takes into account an assumed degradation of module efficiency of 1.1% per year.

Note that this picture is not a static one and it is expected that improvements in material and energy utilization and recycling will continue to improve the environmental profiles. For example, a recently introduced recycling process for the sawing slurry used in the wafer cutting recovers 80-90% of the silicon carbide and polyethylene glycol [17]. Also, any increases in the electric-conversion efficiencies of the modules will entail a proportional improvement of the EPBT.

3. LCA of Current PV Technologies

With continuing efficiency growth and reduction of electricity use in the new production lines, Fthenakis et al (2009) updated CdTe PV's environmental indicators using new data from the plant in Perrysburg Ohio, and two studies based on data from the plant in Frankfurt-Oder, Germany [18]. Besides raising conversion efficiency, efforts have been made in reducing the thickness of silicon wafer used in PV modules to save expensive high grade silicon materials. De Wild-Scholten (2009) recently updated the EPBT and GHG emissions of bulk silicon PVs based on a new investigation under the Crystal Clear project [10]. In this study, the reduced thickness, enhanced conversion efficiency, and novel silicon feedstock and wafer processes were evaluated.

3.1 Energy Payback Time

Figure 2 presents the energy payback times (EPBTs) estimated from the currently-available in the public domain life cycle inventory (LCI) data (mostly 2006 status); these are shown in Tables 5.1.1 to 5.2.3 for modules and frames and in Tables 5.4.1 and 5.5.1.1 to 5.5.1.4 for balance of system (BOS) components. However, these LCI data do not represent the up-to-date EPBT status. For example, current technologies offer mono- and multi - Si wafers with a thickness of around 200 µm, while the 2006 LCI data describe wafers with 270-and 240-µm thicknesses, respectively. Figure 3 gives the latest EPBT estimates of three major commercial PV module types, i.e. mono-Si, multi-Si, and cadmium telluride (CdTe), by Fthenakis et al (2009) and de Wild Scholten (2009) [10, 18]. The LCI data corresponding to the new mono- and multi-Si PVs are not in the public domain. The poly silicon purification and multi-Si wafer production stage data are from REC Solar and may not be representative of industry averages. The wafer thickness for the analyzed system represents state-of-the-art designs corresponding to 180 and 200 µm for mono- and multi-crystalline Si. For CdTe, the estimate is an average of two studies based on data from First Solar's plant in Frankfurt-Oder, Germany. First Solar is by far the biggest CdTe PV manufacturer and therefore, their data are currently representative of the entire CdTe PV industry;

note that the current module efficiency (11.7%) is higher than the efficiency corresponding to figures 2 and 3. The ribbon-Si estimates were removed from the latest comparison lacking verified data. Take back and recycling stages have not been included. The latest EPBT typical rooftop installation in south Europe, (i.e., irradiation of 1700 kWh/m2/yr), correspond to 1.7, 1.7 and 0.8 yrs for mono-Si, multi-Si, and CdTe PV technologies, respectively.

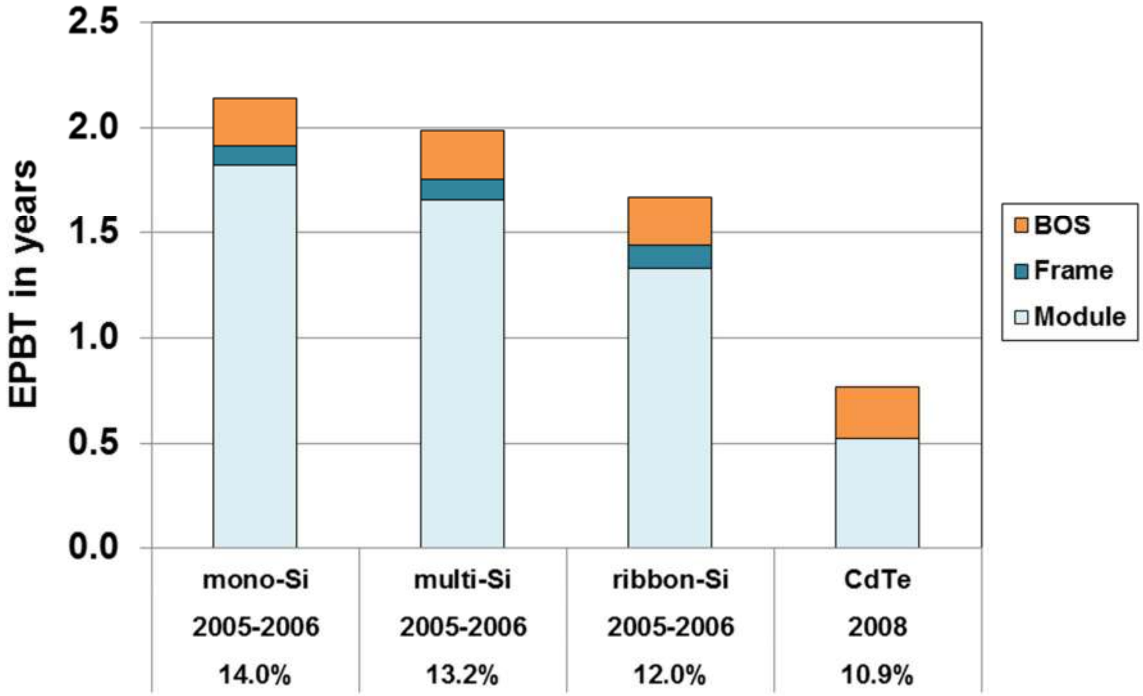

Figure 2: Energy payback time (EPBT) of rooftop mounted PV systems estimated from the currently available LCI data for European production and installation. The estimates are based on Southern European irradiation of 1700 kWh/m2/yr and performance ratio of 0.75. See Tables 5.1.1-5.2.3, 5.4.1, and 5.5.1.1-5.5.1.4 for the corresponding LCI data.

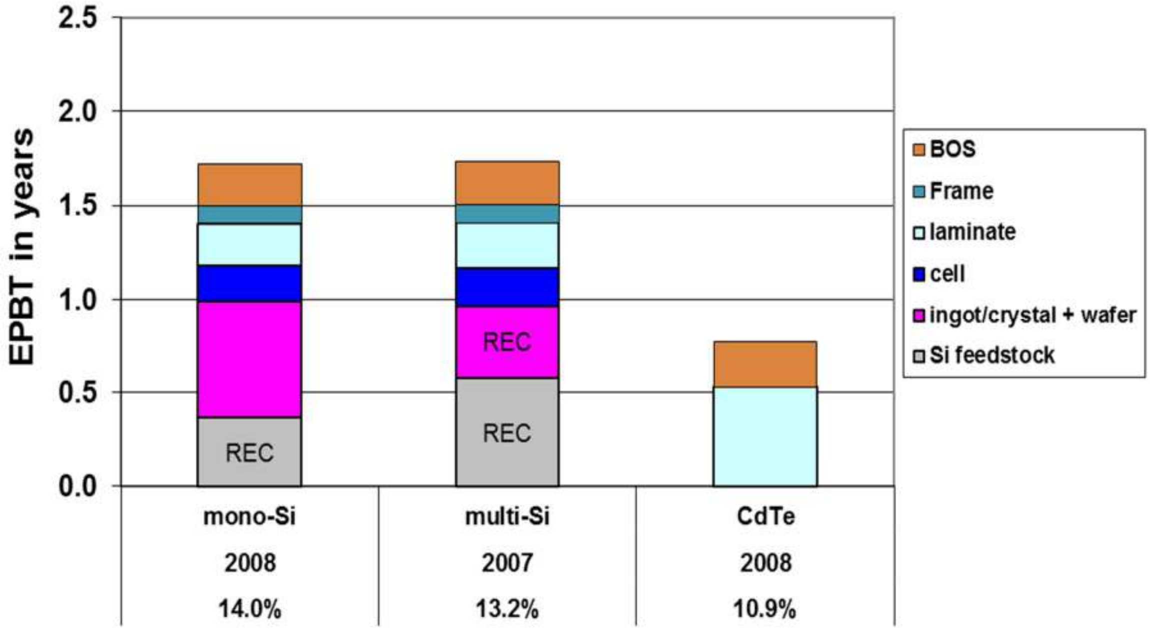

Figure 3: Energy payback time (EPBT) of rooftop mounted PV systems for European production and installation under Southern European irradiation of 1700 kWh/m2/yr and performance ratio of 0.75. Data adapted from de Wild Scholten (2009) and Fthenakis et al. (2009) [6, 18]. They were harmonized for system boundary and performance ratios, according to IEA Task 12 LCA Methodology Guidelines. REC corresponds to REC product-specific Si production; the corresponding LCI data are not publically available.

3.2 Greenhouse Gas Emissions

Figure 4 presents the GHG emissions per kWh generated for crystalline silicon and CdTe PV technologies estimated based on the same available LCI data under the same condition as for Figure 2, with an expected lifetime of 30 yrs [10, 18]. Note that the GHG estimates of 30-37 g CO2-eq./kWh for Si PV technologies do not represent the current level of carbon footprint for the same reason described above. Figure 5 gives the latest estimates by Fthenakis et al (2009) and de Wild Scholten (2009) [10, 18], which are 29, 28 and 18 g CO2-eq./kWh for mono-Si, multi-Si and CdTe respectively. These figures indicate that for silicon PV, 30-40% reductions in EPBT and GHG emissions from the previous estimates by Fthenakis and Alsema (2006) and Fthenakis et al (2008) [9, 12]. For CdTe, the EPBT is 35% lower while the GHG emissions are 30% lower than the previous estimates by Fthenakis and Kim (2006), reflecting the efficiency growth and reduction of electricity use in the new production lines [19].

Since the major parameters of the PV technologies including conversion efficiency, wafer thickness, material utilization are continuously improving, even the latest estimates in Figures 3 and 5 may not represent the current data, warranting timely updates of these indicators.

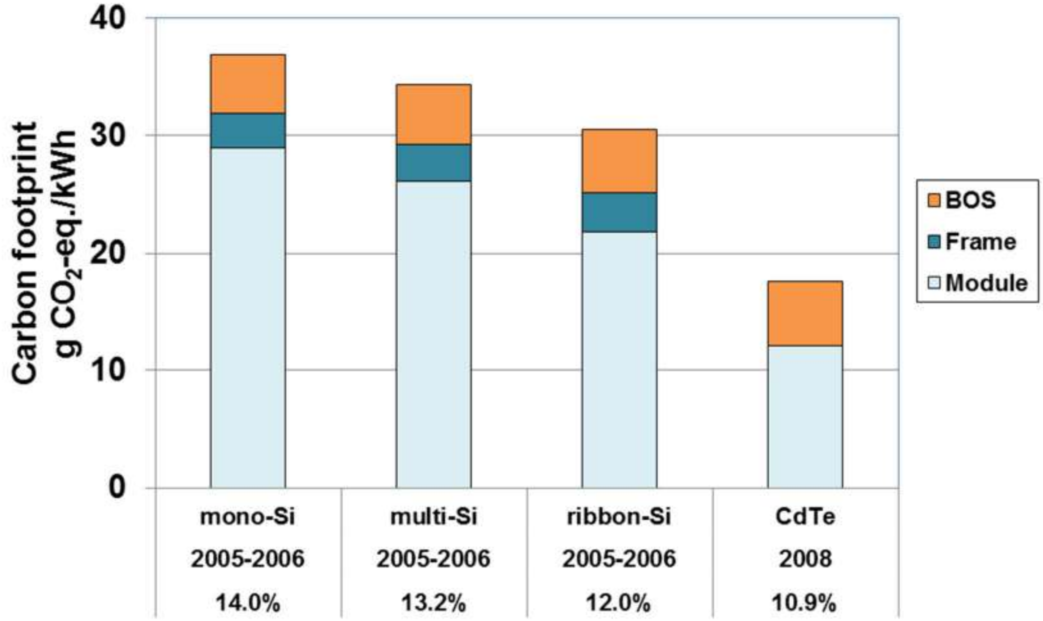

Figure 4: Greenhouse gas (GHG) emissions of rooftop mounted PV systems estimated from the currently available LCI data for European production and installation. The estimates are based on Southern European irradiation of 1700 kWh/m2/yr and performance ratio of 0.75. See Tables 5.1.1-5.2.3, 5.4.1, and 5.5.1.1-5.5.1.4 for the corresponding LCI data.

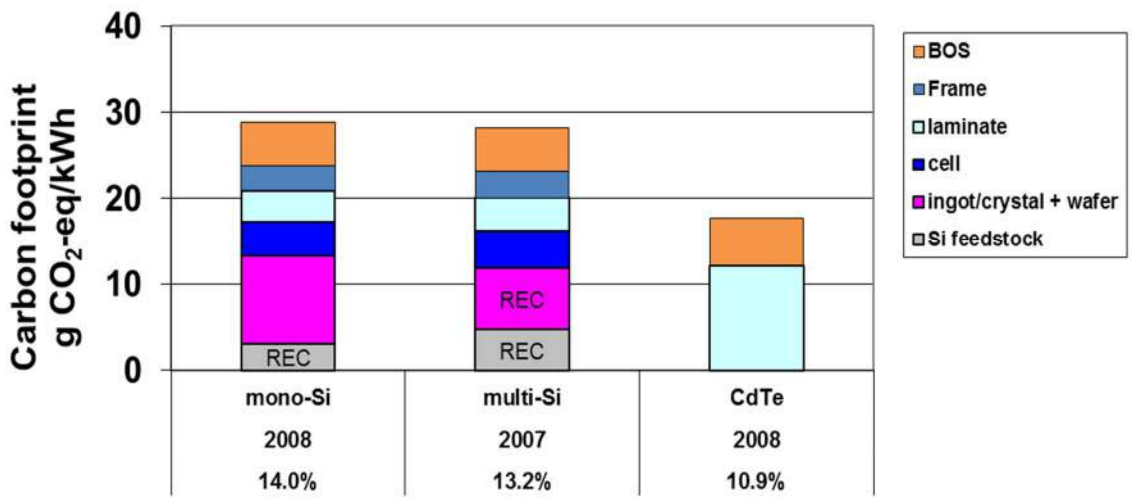

Figure 5: Life cycle GHG emissions from rooftop mounted PV systems for European production and installation under Southern European irradiation of 1700 kWh/m2/yr, performance ratio of 0.75, and lifetime of 30 yrs. Data adapted from de Wild Scholten (2009) and Fthenakis et al (2009) [10, 18]. They were harmonized for system boundary and performance ratios, according to IEA Task 12 LCA Methodology Guidelines. REC corresponds to REC product-specific Si production; the corresponding LCI data are not publically available.

It is noted that all these indicators strongly depend on the location of the PV system operation and the locations of the supply chain. For operation in the US-South west (e.g., irradiation 2400 kWh/m2/yr), all indicators per kWh would be lower, whereas for operation in central Europe (e.g., irradiation 1100 kWh/m2/yr), they will be higher.

The Sustainability Working Group of the European Photovoltaic Industry Association (EPIA) develops fact sheets aiming at dissemination of factual information on the contribution of PV to sustainable development. At the time of publication of this report, the Working Group had developed two fact sheets, one related to the Energy Payback Time [20] and one related to Greenhouse Gas Emissions [21].

3.3 *Criteria Pollutant Emissions*

The emissions of criteria pollutants (e.g., SO_2, NO_x, particulates) during the life cycle of a PV system are largely proportional to the amount of fossil fuel burned during its various phases, in particular, PV material processing and manufacturing; therefore, the emission profiles are close to those of the greenhouse gas emissions. Figure 6 shows the life-cycle NOx emissions of three major technologies and Figure 7 Shows the corresponding SO2 emissions. Toxic gases and heavy metals can be emitted directly from material processing and PV manufacturing, and indirectly from generating the energy used at both stages.

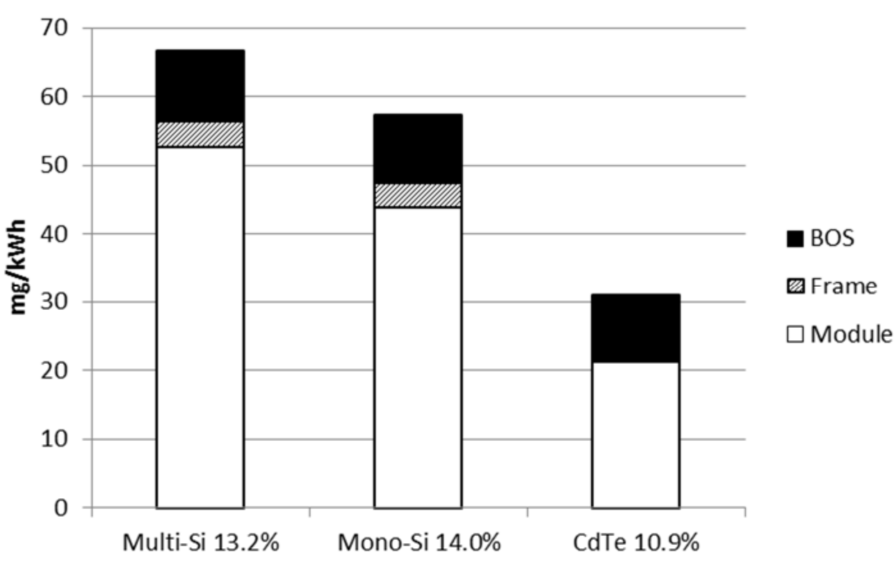

Figure 6: Life-cycle NO_x emissions from silicon and CdTe PV modules, wherein BOS is the Balance of System (i.e., module supports, cabling and power conditioning). The estimates are based on rooftop-mount installation, Southern European insolation, 1700 kWh/m2/yr, a performance ratio of 0.75, and a lifetime of 30 years. It is assumed that the electricity supply for all the PV system is from the European Network of Transmission System Operators for Electricity (ENTSO-E, former UCTE) grid.

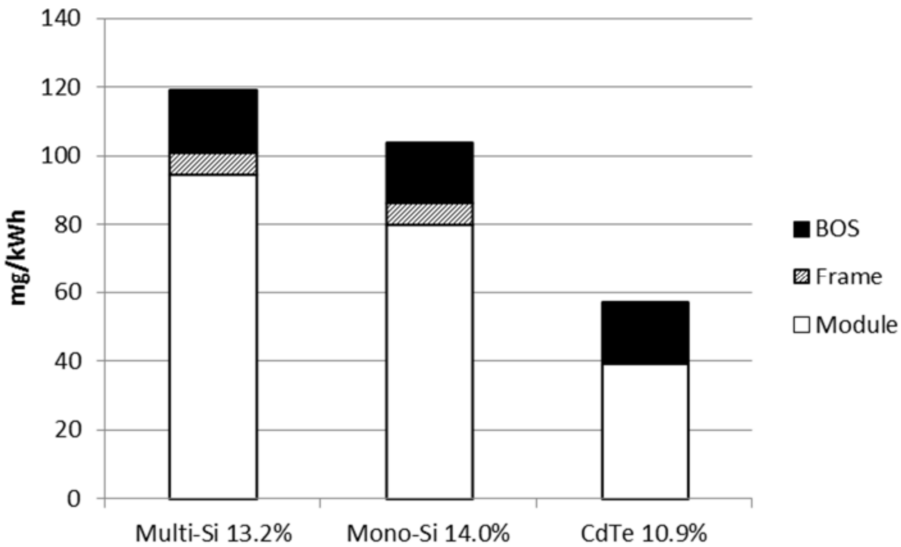

Figure 7: Life-cycle SO_2 emissions from silicon and CdTe PV modules, wherein BOS is the Balance of System (i.e., module supports, cabling and power conditioning). The estimates are based on rooftop-mount installation, Southern European insolation, 1700 kWh/m2/yr, a performance ratio of 0.75, and a lifetime of 30 years. It is assumed that the electricity supply for all the PV system is from the ENTSO-E grid.

Accounting for all the emissions is necessary to create a complete picture of the environmental impact of a technology. An interesting example of accounting for the total emissions is that of cadmium flows in CdTe and other PV technologies, as discussed next.

3.4 Heavy Metal Emissions

3.4.1 Direct Emissions

Direct emissions of heavy metals could occur during the mining and processing of precursor materials and during manufacturing of PV modules. Such emissions of cadmium in the life cycle of CdTe PV have been studied in detail by Fthenakis [19]. Cadmium is a byproduct of zinc and lead, and is collected from emissions and waste streams during the production of these major metals. The largest fraction of cadmium, with ~99.5% purity, is in the form of a sponge from the electrolytic recovery of zinc. This sponge is transferred to a cadmium-recovery facility, and is further processed through oxidation and leaching to generate a new electrolytic solution. After selectively precipitating the major impurities, cadmium of 99.99% purity is recovered by electrowinning. It is further purified by vacuum distillation to the five 9s purity required for CdTe PV manufacturing. The emissions during each of these steps are detailed elsewhere [22]. They total to 0.02 g per GWh of PV-produced electricity under Southern European condition. Gaseous cadmium emissions during the lifespan of a finished CdTe module are negligible; the only conceivable pathway of release is if a fire breaks out. Experiments at Brookhaven

National Laboratory that simulated fire conditions revealed that CdTe is effectively contained within the glass-to-glass encapsulation during the fire, and only minute amounts (0.4-0.6%) of Cd are released [23].

3.4.2 Indirect Emissions

The indirect emissions here are those emissions associated with the production of energy used in mining and industrial processes in the PV life cycle. Reporting indirect emissions separately from direct ones not only improves transparency in analyses but also allows calculating emissions for a certain mix of energy options as shown in a recent study by Reich et al (2011) [24]. Coal and oil-fired power plants routinely generate Cd during their operation, as it is a trace element in both fuels. 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 between 2 to 7 g of Cd/GWh into the atmosphere [25]. 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 1000 tons of CO_2, 8 tons of SO_2, 3 tons of NO_x, and 0.4 tons 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), because these plants do not have particulate-control equipment. Cadmium emissions also are associated with natural gas and nuclear fuel life-cycles because of the energy used in the associated fuel processing and material productions [2].

We accounted for Cd emissions in generating the electricity used in producing a CdTe PV system [32]. The assessment of electricity demand for PV modules and BOS was based on the life cycle inventory of each module and the electricity input data for producing BOS materials. Then, Cd emissions from the electricity demand for each module were assigned, assuming that the life-cycle electricity for the silicon- and CdTe-PV modules was supplied by the European Network of Transmission System Operators for Electricity (ENTSO-E) grid. The indirect Cd emissions from electricity usage during the life-cycle of CdTe PV modules (i.e., 0.2 g/GWh) are an order-of- magnitude greater than the direct ones (routine and accidental) (i.e., 0.016 g/GWh).

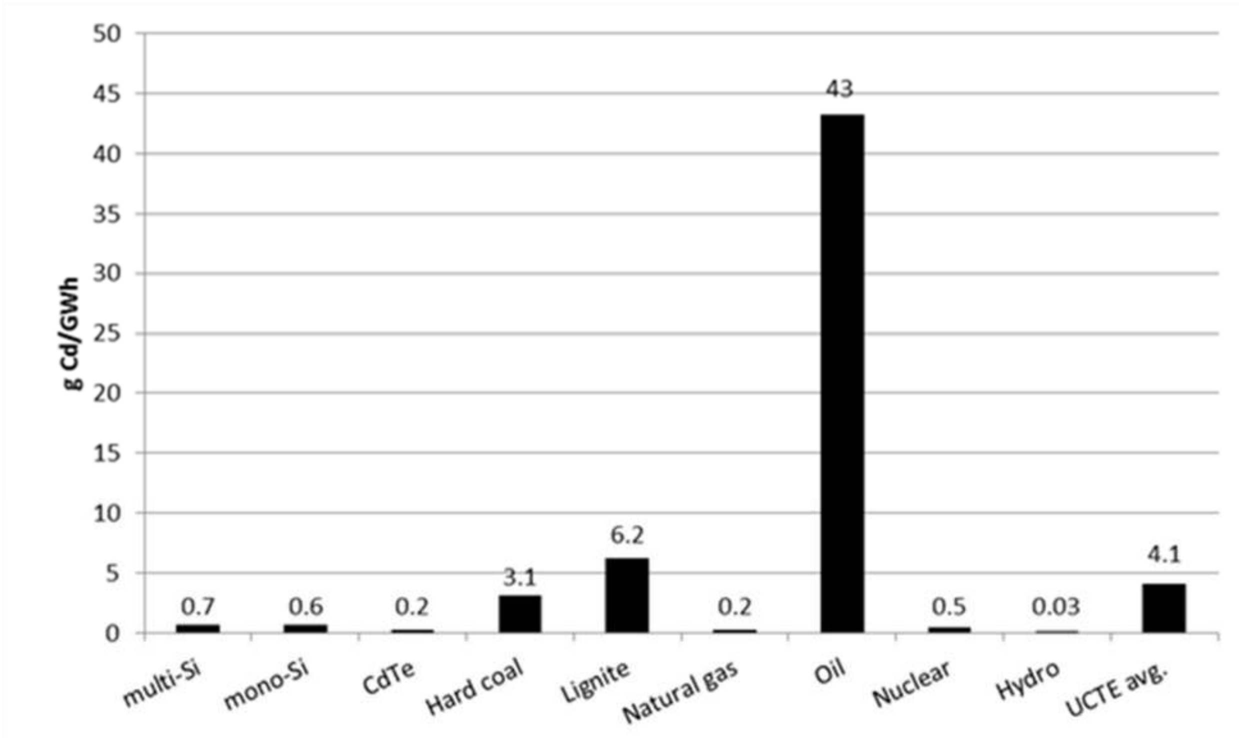

Figure 8: Life cycle atmospheric Cd emissions for PV systems from electricity and fuel consumption, normalized for a Southern Europe average insolation of 1700 kWh/m2/yr, performance ratio of 0.8, and lifetime of 30 yrs. A ground-mounted BOS is assumed for all PV systems [12].

The complete life-cycle atmospheric Cd emissions, estimated by adding those from the electricity and fuel demand associated with manufacturing and materials production for various PV modules and Balance of System (BOS), are compared with the emissions from conventional electricity generating technologies (Figure 8) [12]. Undoubtedly, displacing fossil-fuel-based power generation with Cd PV solar farms lowers the amount of Cd released into the air. Thus, every GWh of electricity generated by CdTe PV modules can prevent around 4 g of Cd air emissions if they are used instead of, or as a supplement to, the ENTSO-E grid. Also, the direct emissions of Cd during the life-cycle of CdTe PV are 10 times lower than the indirect ones due to electricity and fuel use in the same life-cycle, and about 30 times less than those indirect emissions from crystalline photovoltaics [9]. Furthermore, we examined the indirect heavy metal emissions in the life-cycle of the three silicon technologies discussed earlier, finding that, among PV technologies; CdTe PV with the lowest energy payback time has the fewest heavy metal emissions (Figure 9) [12].

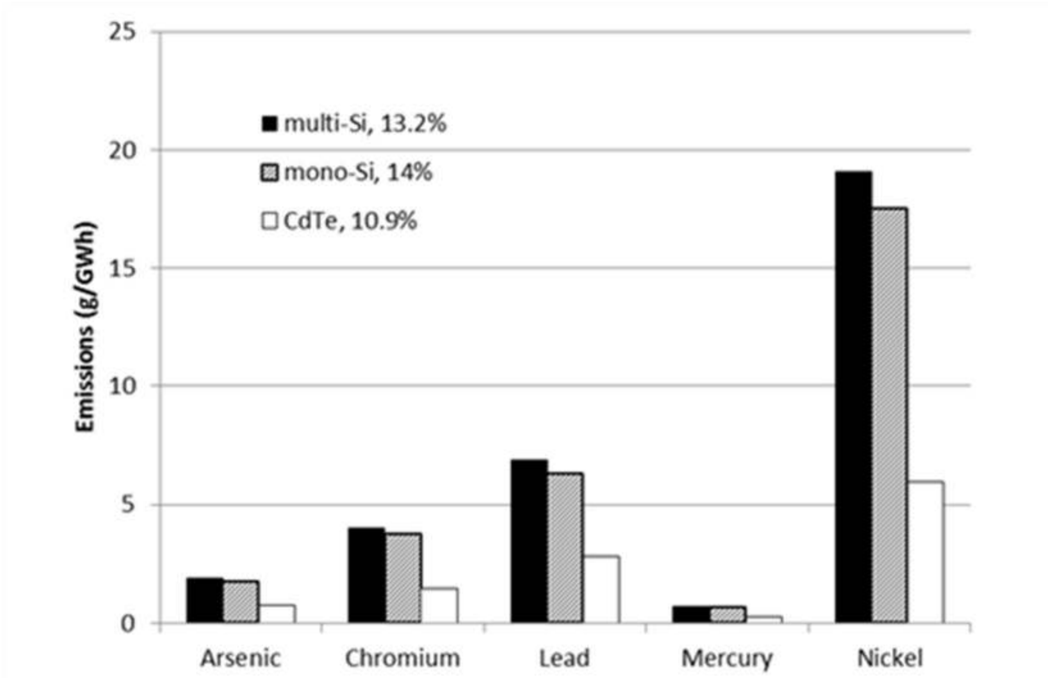

Figure 9: Emissions of heavy metals due to electricity use, based on European ENTSO-E average (ecoinvent database). Emissions are normalized for Southern European average insolation of 1700 kWh/m2/yr, performance ratio of 0.8, and lifetime of 30 yrs. Each PV system is assumed to include the ground-mounted BOS (Mason et al. [13]).

4. Life Cycle Inventories

4.1 Overview

The Life cycle inventory phase of LCA involves data compilation of materials and energy inputs, and emissions and product outputs for the complete life cycle of the system under analysis. For PV LCA these data are separately collected or modeled for the modules and the balance of system (BOS).

4.2 Modules

The material and energy inputs and outputs during the life cycles of Si PVs, viz., multi-Si, mono-Si, and also thin-film CdTe PV, were investigated in detail based on actual measurements from PV production plants. Alsema and de Wild-Scholten recently updated the life cycle inventory (LCI) for the technology for producing crystalline silicon modules in Western Europe under the framework of the Crystal Clear project, an European Integrated Project focusing on crystalline silicon technology, co-funded by the European Commission and the participating countries [6, 26].

The typical thickness of multi- and mono-Si PV is 200 and 180 µm, respectively; 60 individual cells of 243 cm2 (156 mm x156 mm) comprise a module of 1.6 m2 for all Si PV types. The conversion efficiency of multi- and mono-Si module is taken as 13.2%, and 14.0%, respectively. On the other hand, as of 2009, First Solar manufactures frameless, double-glass, CdTe modules of 1.2 m by 0.6 m, which are rated at 10.9% photon-to-electricity conversion efficiency with ~3 µm thick active layer. In 2010, conversion efficiency increased to 14.2%, 14.5%, and 11.3% for multi-Si, mono-Si, and CdTe modules, respectively.[1]

The data for Si PVs extend from the production stage of solar-grade Si to the module manufacturing stage, and those for CdTe PV correspond to the production of 99.999% CdTe, deposition of the CdTe film and the module's manufacturing stages.

4.2.1 Crystalline–Si PV

Detailed LCI of crystalline silicon modules for polycrystalline silicon feedstock purification, crystallization, wafering, cell processing, and module assembly for the status of 2005/2006 in Western Europe was completed within the "CrystalClear" European Commission project. The sources of LCI data for this project include 11 commercial European and U.S. photovoltaic module manufacturing companies supplemented by numbers from the literature. Such data are presented in this report (section 5. Life Cycle Inventory Data). However, we note that they do not represent the state-of-the art Si modules with a wafer thickness of ~200 µm.

The metallurgical-grade silicon that is extracted from quartz is purified into solar-grade polysilicon by either a silane (SiH4) or trichlorosilane (SiHCl3)-based process. The energy requirement for this purification step is significant for crystalline Si PV modules, accounting for ~30% of the primary energy used for fabricating multi-Si modules [27]. Two technologies are currently 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 US, silane- or trichlorosilane-gas is introduced into a thermal decomposition furnace (reactor) with high temperature (~1100-1200 °C) polysilicon rods [28-30]. The silicon rods grow as silicon atoms in the gas deposit onto them, up to 150 mm in diameter and up to 150 cm in length [27]. The data on Si PVs in Section 5.1 are based on averages over standard and modified Siemens reactors. The scenario involving the scrap silicon from electronic-grade silicon production is not considered as the market share of this material accounts for only 5% in 2005 [31].

4.2.2 CdTe PV

The LCI data were obtained at First Solar's CdTe PV manufacturing plant in Perrysburg, OH with a 25-MW production capacity for the period of Jan 1 - May 31, 2005 [19]. The electricity usage was updated in 2008 from data obtained at First Solar's plant in Frankfurt, Germany [18]. Chemicals and water data have also been updated since the first data collection. The CdTe module electricity conversion efficiency

[1] Source for Si PV: Mehta, S. 2010. PV Technology, Production and Cost Outlook: 2010 – 2015. GTM Research; Source for CdTe PV: First Solar. 2011. Key Quarterly Financial Data. (Available at: www.firstsolar.com)

was 9% in yr 2005, and 11% in 2010. The cadmium telluride (CdTe) absorber layer and cadmium sulfide (CdS) window layer in First Solar's production scheme are laid down by vapor transport deposition (VTD), based on subliming the powders and condensing the vapors on glass substrates. A stream of inert carrier gas guides the sublimed dense vapor cloud to deposit the films on glass substrates at 500–600 °C. Depositing layers of common metals followed by series of scribing and heat treatment forms interconnections and back contacts.

4.3 High Concentration PV (HCPV)

The LCI data for Amonix 7700 HCPV was compiled on February 2010 updating the previous LCI of previous 25 kW Amonix system. The Amonix 7700 HCPV system consists of seven concentrating module units called MegaModules mounted on a two-axis tracker. Sunlight is concentrated on to 7560 focal spots at a rate of 500:1. This system uses multi-junction GaInP/GaInAs/Ge cells grown on a germanium substrate rated at 37% efficiency under the test condition of $50W/cm^2$, 25°C, and AM 1.5D. With an aperture area of 267 m^2, the capacity of this unit corresponds to 53 kW_p AC power. While the measurements of the mass of manufactured parts were taken directly from the assembly line, the quantity of concrete used was calculated by the dimensions of the foundation. The detailed material compositions of electrical parts, i.e., motor, transformer, and inverter, were estimated from Mason et al (2006) [13]. The LCI includes materials used in scheduled maintenance over an expected lifetime of 30 years which include changing the hydraulic- and bearing-oils, cleaning the lens, and changing the air- and oil-filters.

4.4 Balance of System (BOS)

Little attention has been paid to the LCA studies of the balance of system (BOS), and so inventory data are scarce. Depending on the application, solar cells are either rooftop- or ground-mounted, both operating with a proper balance of system (BOS). Silicon modules need an aluminum frame of 2.6 kg per m2 for structural robustness and easy installation, while a glass backing performs the same functions for the CdTe PV produced in the US [6, 19]. For a rooftop PV application, the BOS typically includes inverters, mounting structures, cable and connectors. Large-scale ground-mounted PV installations require additional equipment and facilities, such as grid connections, office facilities, and concrete.

4.4.1 Mounting structures

Life cycle inventory datasets of the following types of photovoltaic mounting systems are established in compliance with the ecoinvent quality guidelines v2.2 as part of the Swiss contribution to the IEA PVPS Task 12:

- *Mounting on façade*
- *Integrating in façade*
- *Mounting on flat roof*
- *Mounting on slanted roof*
- *Integrating in slanted roof*
- *Mounting on open ground*

The inventory data are based on manufacturer information and literature. The amount of materials of each type of mounting system is weighted based on the average mass per type calculated from a European market overview in 2008. The open ground mounting systems considered have a foundation of profiles that are piled into the ground and not a concrete foundation [32]. The inventory data in this report are slightly simplified and do not reflect one-to-one the original ecoinvent datasets. In case of any uncertainties it is recommended to apply the original ecoinvent datasets.

4.4.2 Complete roof-top BOS

The LCI data of Balance-of-System components for year 2006 was collected by the project "Technologie-en Milieuverkenningen" with ECN project number 7.4750 financed by the Ministry of Economic Affairs, the Netherlands. De Wild-Scholten et al.[33] studied two classes of rooftop mounting systems based on a mc-Si PV system called SolarWorld SW220 with dimensions of 1001 mm x 1675 mm, 220 Wp: they are used for on-roof mounting where the system builds on existing roofing material, and in-roof mounting where the modules replace the roof tiles. The latter case is credited in terms of energy and materials use because roof tile materials then are not required. Section 5.4 details the LCI of several rooftop mounting systems, cabling, and inverters. Two types (500 and 2500 W) of small inverters adequate for rooftop PV design were inventoried. A transformer is included as an electronic component for both models. The amount of control electronics will become less significant for inverters with higher capacity (> 10 kW), resulting in less material use per PV capacity.

4.4.3 Complete ground mount BOS

A recent analysis of a large PV installation at the Springerville Generating Station in Arizona, USA [13] affords a detailed materials- and energy-balance for a ground-mounted BOS. The Springerville PV plant at the time of data collection had 4.6 MWp of installed PV modules, of which 3.5 MW were mc-Si PV modules. For this study, Tucson Electric Power (TEP) prepared the BOS bill of materials- and energy-consumption data for their mc-Si PV installations. The life expectancy of the PV metal support structures is assumed to be 60 years. Inverters and transformers are considered to last for 30 years, but parts must be replaced every 10 years, amounting to 10% of their total mass, according to well-established data from the power industry on transformers and electronic components. The inverters are utility-scale, Xantrex PV-150 models with a wide-open frame, allowing failed parts to be easily replaced. The life-cycle inventory includes the office facility's materials and energy use for administrative, maintenance, and security staff, as well as the operation of maintenance vehicles. Aluminum frames are shown separately, since they are part of the module, not of the BOS inventory; there are both framed and frameless modules on the market.

4.5 Medium-Large PV Installations in Europe

Within the framework of the ecoinvent database and the Swiss contribution to the IEA PVPS Task 12, life cycle inventory datasets of the following real photovoltaic installations are established:

- *93 kWp slanted-roof installation, single-Si laminates, Switzerland*
- *280 kWp flat-roof installation, single-Si panels, Switzerland*
- *156 kWp flat-roof installation, multi-Si panels, Switzerland*
- *1.3 MWp slanted-roof installation, multi-Si panels, Switzerland*
- *324 kWp flat-roof installation, single-Si panels, Germany*
- *450 kWp flat- roof installation, single-Si panels, Germany*
- *569 kWp open ground installation, multi-Si panels, Spain*
- *570 kWp open ground installation, multi-Si panels, Spain*

The inventory data are based on information from installers, operators, and literature. The inventories can be combined with information about mounting systems and silicon modules presented in this report [32]. The inventory data in this report are slightly simplified and do not reflect one-to-one the original ecoinvent datasets. In case of any uncertainties it is recommended to apply the original ecoinvent datasets.

4.6 Country specific photovoltaic mixes

Life cycle inventory datasets of 25 country specific photovoltaic electricity are established within the framework of the ecoinvent database and the Swiss contribution to the IEA PVPS Task 12. These are based on national and international statistics about the shares of different module technologies; the shares of different mounting systems, the share of centralized/decentralized installations, and country specific electricity yields that are dependent on solar irradiation[32].

The inventory data in this report are slightly simplified and do not reflect one-to-one the original ecoinvent datasets. In case of any uncertainties it is recommended to apply the original ecoinvent datasets.

5. Life Cycle Inventory Data

5.1 Crystalline Si PV

Authors:

M.J. de Wild-Scholten, Energy research Center of the Netherlands, Petten, The Netherlands m.dewild@ecn.nl

E.A. Alsema, Copernicus Institute for Sustainable Development and Innovation, Utrecht University, The Netherlands e.a.alsema@chem.uu.nl

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The set of LCI data of Balance-of-System components was collected by Mariska De Wild and Erik Alsema. Part of this work was carried out in the project "Technologie- en Milieuverkenningen" with ECN project number 7.4750 financed by the Ministry of Economic Affairs, the Netherlands

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Notes:

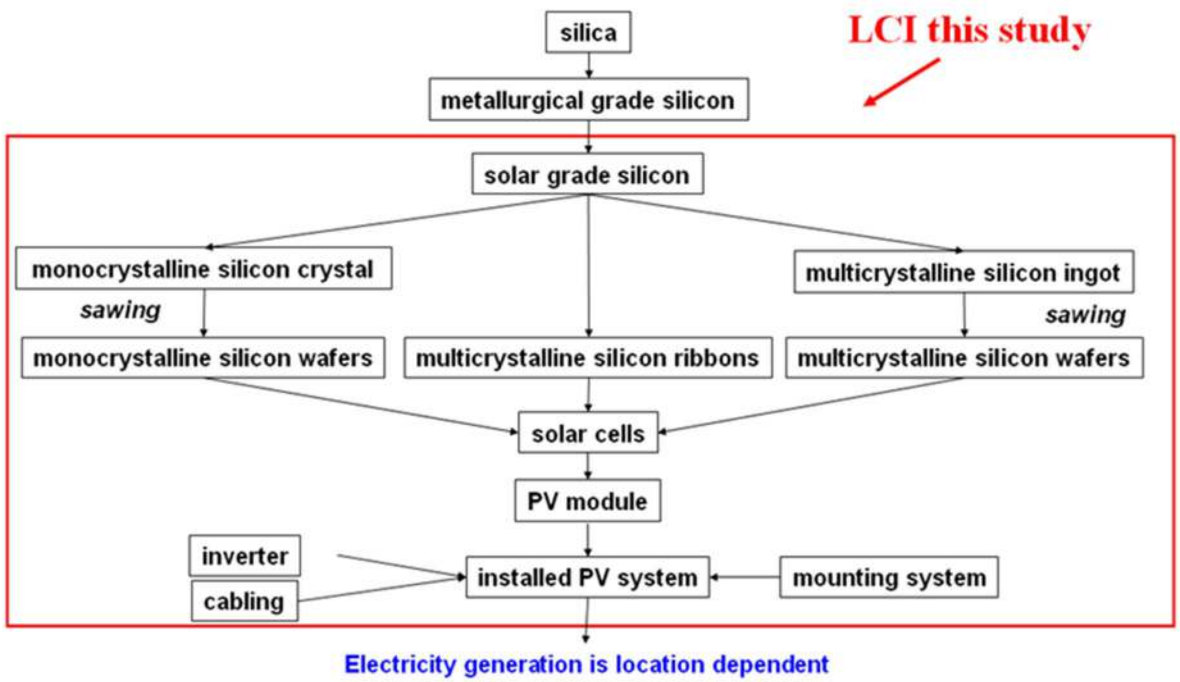
1) Input of **dissolved chemicals** follows convention applied in ecoinvent database: Input and output data for chemicals production refer to its active substance, but the carrier substance is stated in the name and considered as an input in the inventory. Thus the inventory for 1 kg "sodium hydroxide, 50% in H_2O, production mix, at plant" refers to the production of 2 kg NaOH with a water content of 50%. (i.e., 1 kg NaOH plus 1 kg H_2O).

2) Data on the mining of silica and the production of mg-Si can be found in for example the ecoinvent LCA database. Also LCA data on other commonly used materials (e.g. steel, aluminum, various chemicals) can be found here.

Disclaimer:

The authors have assembled this LCI data set to the best of their knowledge and in their opinion it gives a reliable representation of the crystalline silicon module production technology in Western-Europe in the year 2005/2006 and Balance-of-System components of the year 2006. However, most of the data were provided to us by the companies that helped us. Although we have cross-checked the data from different users we cannot guarantee that it does not contain any errors. Therefore we cannot accept any responsibility for the use of these data.

Scope:



Name	**High purity polycrystalline silicon, feedstock material for crystalline silicon ingots (Poly-Si)**
Time period	2004
Geography	Europe, Western and North America
Technology	Mixed data
Representativeness	Average of data from one company and estimated data from another company based on literature data
Date	12/15/2005
Collection method	Data collection by factory representative + literature data
Comment	Production with Siemens process either from $SiHCl_3$ or SiH_4. Partly with standard Siemens process and partly with modified Siemens ("solar grade") at reduced electricity consumption. Mix of electricity supply in accordance with actual conditions at considered production locations.

Table 5.1.1: LCI of Poly-Si Feedstock

Products	**Unit**	**Value**	**Comment**
Polycrystalline silicon, Siemens process	kg	1.00	high purity, for the photovoltaic industry
Materials			
MG-silicon	kg	1.13	metallurgical grade silicon
Inorganic chemicals, unspecified	kg	2.00	mix of NaOH, HCl and H_2
Heat from natural gas	MJ	185	for process heat
Electricity/heat			
Electricity, from combined cycle plant, gas-fired	kWh	45	actual sources of electricity vary with production location
Electricity, hydropower	kWh	65	mix of reservoir and run-of-river hydro

Name	**Mono-crystalline silicon wafer from poly-Si**
Time period	2005
Geography	North America + Europe, Western + Asia, former USSR
Technology	Mixed data
Representativeness	Average from 3 companies, total production 7.5E5 m^2 wafer area per year.
Date	11/6/2006
Data treatment	Averaging over 3 different assumed production locations
Comment	Includes both Czochralski crystal pulling and wafer cutting processes. Wafer thickness 270 um.

Table 5.1.2: LCI of Mono-Si Wafer

Products	**Unit**	**Amount**	**Comment**
mono-Si wafer	m^2	1.00	typical wafer: 156x156 mm^2 (0.0243 m^2), semisquare, thickness 270 um
Materials			
SOLIDS			
poly-Si	kg	1.15	polycrystalline silicon of semiconductor or solar grade quality. This value is the total silicon needed minus internally recycled silicon from crystal cut-offs and broken wafers.
quartz crucible	kg	0.36	for melting the silicon
glass	kg	0.01	for temporarily attachment of bricks to wiresawing equipment, assumed same as multi wafers
steel wire	kg	1.49	for wafer cutting, assumed same as multi wafers
silicon carbide (SiC), virgin	kg	2.14	for sawing slurry, assumed same as multi wafers
silicon carbide (SiC), from external recycling	kg	0.00	
GASES			
argon (Ar)	kg	6.20	for crystal growing
LIQUIDS			
polyethylene glycol (PEG), virgin	kg	2.60	for sawing slurry, assumed same as multi wafers
polyethylene glycol (PEG), from external recycling	kg	0.30	
dipropylene glycol monomethyl ether (DPM)	kg	0.30	for wafer cleaning
adhesive	kg	0.002	for temporarily attachment of bricks to wire-sawing equipment
tenside (concentrated)	kg	0.24	for wafer cleaning

Sodium hydroxide, 50% in H_2O	kg	0.015	see note 1, for wafer cleaning, assumed same as multi wafers
Hydrochloric acid, 30% in H_2O	kg	0.0027	see note 1, for wafer cleaning, assumed same as multi wafers
Acetic acid, 98% in H_2O	kg	0.039	see note 1, for wafer cleaning, assumed same as multi wafers
tap water	kg	0.006	for ingot sawing
water, deionised	kg	65	for wafer cleaning
factory area	m^2	4.30E-04	same as for multi-Si wafer; assuming 25 years life of factory
Electricity/fuel			
electricity, medium voltage	kWh	100	total electricity consumption including direct and indirect process energy and overhead energy
natural gas	MJ	77	general use + furnaces
Final waste flows			
Silicon waste (not recycled)	kg	0.11	unused part of crystal, estimate
Waste to treatment			
graphite crucibles	kg	0.36	
steel wire	kg	1.49	
waste slurry, to external recycling	kg	5.54	waste slurry containing SiC, PEG, silicon kerf loss and iron from wire; see worksheet "slurry recycling" for treatment

Name	**Multi-silicon wafer from poly-Si**
Time period	2005
Geography	Europe, Western
Technology	Average technology
Representativeness	Average from 3 companies, total production 2.6E6 m^2 wafer area per year
Date	11/6/2006
Collection method	Data collection by factory representatives
Comment	Includes both the ingot growth and wafer cutting processes. Average wafer thickness 240 um.

Table 5.1.3: LCI of Multi-Si Wafer

Products	**Unit**	**Amount**	**Comment**
multi-Si wafer	m^2	1.00	typical wafer area: 156x156 mm^2 (0.0243 m^2), average thickness 240 um
Materials			
SOLIDS			
poly-Si	kg	1.30	polycrystalline silicon of semiconductor or solar grade quality. This value is the total silicon needed minus internally recycled silicon from ingot cut-offs and broken wafers.
quartz crucible	kg	0.39	for ingot growing
glass	kg	0.01	for temporarily attachment of bricks to wire sawing equipment
steel wire	kg	1.49	for wafer cutting
silicon carbide (SiC), virgin	kg	0.49	for sawing slurry
silicon carbide (SiC), from external recycling	kg	2.14	for sawing slurry
GASES			
nitrogen (N_2)	kg	0.05	for ingot growing
argon (Ar)	kg	0.30	for ingot growing
helium (He)	kg	1.362E-04	for ingot growing
LIQUIDS			
polyethylene glycol (PEG), virgin	kg	0.11	for sawing slurry
polyethylene glycol (PEG), from	kg	2.60	for sawing slurry

external recycling			
dipropylene glycol monomethyl ether (DPM)	kg	0.30	for wafer cleaning
adhesive	kg	0.002	for temporarily attachment of bricks to wire-sawing equipment
tenside (concentrated)	kg	0.24	for wafer cleaning
Sodium hydroxide, 50% in H_2O	kg	0.01	see note 1, for wafer cleaning
Hydrochloric acid, 30% in H_2O	kg	0.0027	see note 1, for wafer cleaning
Acetic acid, 98% in H_2O	kg	0.039	see note 1, for wafer cleaning
tap water	kg	0.006	for ingot sawing
water, deionised	kg	65	for wafer cleaning
factory area	m^2	4.30E-04	2400 m^2 factory producing 30 MWp/yr (9 mln wafers); assuming 25 years life of factory
Electricity/fuel			
electricity, medium voltage	kWh	30	total electricity consumption including direct and indirect process energy and overhead energy
natural gas	MJ	4	for removing adhesive after sawing
Final waste flows			
silicon waste (not recycled)	kg	0.17	not recycled part of ingot (top), estimate
Waste to treatment			
quartz crucible	kg	0.39	
steel wire	kg	1.49	
waste slurry, to external recycling	kg	5.83	waste slurry containing SiC, PEG, silicon kerf loss and iron from wire; see worksheet "slurry recycling" for treatment

Name **Ribbon silicon wafer from poly-Si**
Time period 2005
Geography Europe, Western + North America
Technology Average technology
Representativeness Average from 3 specific processes of which one in pilot phase.
Date 11/6/2006
Collection method Data collection by factory representatives.
Comment Wafer thickness 200-300 um. Wafer area 120-156 cm^2.
Allocation rules NA

Table 5.1.4: LCI of Ribbon-Si Wafer

Products	**Unit**	**Amount**	**Comment**
ribbon Si wafer	m^2	1	
Materials/fuels			
SOLIDS			
poly-Si	kg	0.74	polycrystalline silicon of semiconductor or solar grade quality. This value is the total silicon needed minus internally recycled silicon from broken wafers.
graphite	kg	0.0066	
GASES			
argon (Ar)	kg	5.21	
factory area	m^2	4.30E-04	same as for multi-Si wafer; assuming 25 years life of factory
Electricity/fuel			
electricity, medium voltage, total	kWh	42.3	
Emissions to air			
argon	kg	5.21	
Waste to treatment			
graphite crucibles	kg	0.007	

Name	**Mono- or multi-crystalline silicon cells**
Time period	2005
Geography	Europe, Western
Technology	Average technology
Representativeness	Average from 5 specific processes and companies (4 multi + 1 mono)
Date	11/6/2006
Collection method	Data collection by factory representatives.
Comment	Wafer thickness 270-300 um

Table 5.1.5: LCI of Multi- or Mono Si cell

Products	Unit	Amount	Comment
multi- or mono-Si cell (243 cm2)	p	1	cell size 156 mm x 156 mm = 243 cm2; thickness can vary
Resources			
Water, cooling	m3	2.43E-02	cooling water
Materials/fuels			
SOLIDS			
multi/mono-Si wafer (156 cm2)	p	1.06E+00	+ 6% cell loss
phosphorus paste	kg	3.53E-05	for emitter formation. Example is Ferro FX99-014: hazardous components 1-5% P2O5, 40-90% organic chemicals.
front metallization paste	kg	1.80E-04	see worksheet "paste front" for composition
back contact metallization paste	kg	1.20E-04	see worksheet "paste back contact" for composition
back aluminum BSF metallization paste	kg	1.75E-03	see worksheet "paste back BSF" for composition
metallization paste			
polystyrene, expandable	kg	9.91E-06	for packaging
GASES			
nitrogen (N2)	kg	4.51E-02	
oxygen (O2)	kg	2.48E-03	
argon (Ar)	kg	6.25E-04	
Fluorinated compound mix (CF4, C2F6)	kg	7.68E-05	aggregate value for different fluorinated source gases
ammonia (NH3)	kg	1.64E-04	for silicon nitride deposition
silane (SiH4)	kg	2.95E-05	for silicon nitride deposition

LIQUIDS			
sodium hydroxide, 50% in H2O (NaOH)	kg	3.82E-03	
acetic acid, 98% in H2O (CH3COOH)	kg	6.88E-05	
hydrochloric acid, 30% in H2O (HCl)	kg	1.11E-03	
hydrogen fluoride (HF) 100%	kg	9.18E-04	
nitric acid, 50% in H2O (HNO3)	kg	6.49E-04	
POCl3 phosphoryl chloride	kg	5.28E-06	for emitter formation
phosphoric acid, industrial grade, 85% in H2O (H3PO4)	kg	1.85E-04	for emitter formation
sodium silicate	kg	1.82E-03	
calcium chloride (CaCl2)	kg	5.25E-04	
tetraisopropyltitanate (TPT, a titanium precursor)	liter	3.45E-08	for titanium dioxide antireflection coating deposition
isopropanol	kg	1.92E-03	
ethanol	kg	1.56E-05	
solvents, organic, unspecified	kg	3.49E-05	
water, deionised	kg	3.34E+00	
factory area	m2	7.40E-06	1600 m2 factory producing 30 MWp/yr (9 mln cells/yr); assuming 25 years life of factory
Electricity			
electricity, medium voltage	kWh	7.36E-01	
natural gas	MJ	1.16E-01	
fuel oil	liter	7.88E-04	
Emissions to air			
aluminum	kg	1.88E-05	
hydrogen chloride	kg	6.48E-06	
hydrogen fluoride	kg	1.18E-07	
lead	kg	1.88E-05	
particulates, unspecified	kg	6.48E-05	
silicon dioxide	kg	1.77E-06	
silver	kg	1.88E-05	
sodium hydroxide	kg	1.18E-06	
tin	kg	1.88E-05	

VOC, volatile organic compounds	kg	4.71E-03	
FC-gases (CF4, C2F6)	kg CO2-eq	6.87E-02	Emission in **kg CO2 equivalent,** estimate based on 30% emission of used FC gases
Final waste flows			
Photovoltaic cell waste	kg	6.71E-03	
Waste to treatment			
mono- or multi-Si cell, to recycling	p	1.76E-02	
neutral solution	m3	3.72E-03	
alkaline solution	m3	3.39E-04	
acid solution	m3	1.23E-03	
organic waste	liter	1.90E-04	

Name	Crystalline silicon PV module production
Time period	2005
Geography	Europe, Western
Technology	Mixed data
Representativeness	Average from 2 companies + literature data
Date	11/6/2006
Record	Erik Alsema (Utrecht University), Mariska de Wild (ECN)
Generator	Mariska de Wild (ECN), Erik Alsema (Utrecht University)
Collection method	Data collection by factory representatives and literature data
Data treatment	Only materials and energy use for module lamination and further assembly. Typical total area (excluding frame) efficiencies are 14.0% for mono-Si modules, 13.2% for multi-Si modules and 12% for ribbon-Si modules.

Number of cells, width:	6
Number of cells, length:	10
Cell size (length):	15.6 cm
Cell area factor:	1
Cell efficiency (encapsulated)	14.4%
Calculated parameters:	
Module width (w/o frame)	98.6 cm
Module length (w/o frame)	162 cm
Module area (w/o frame)	1.60 m2
Module perimeter (=frame length)	5.21 m
Number of cells:	60
Module power	210 Wp
Module efficiency (glass area, excl. frame)	13.2%

Table 5.1.6: LCI of Crystalline Si PV Module

Products	Unit	Amount	Comment
Module, c-Si	p	1	dimensions see above
Materials			
Solar cells	p	61.2	+2% cell loss
Aluminum	kg	4.2	for frame, may vary per manufacturer
Polyphenylenoxid	kg	0.3	junction box, may vary per manufacturer

Glass sheet, low iron, tempered	kg	16.1	assuming 4 mm glass thickness, varies from 3.2 to 4.0 depending on application, size and manufacturer, +1% loss, density 2.5 g/cm3
Ethyl Vinyl Acetate	kg	1.6	EVA consumption 0.96 kg/m2, +6% more than glass area
Back foil, for solar cell module	kg	0.83	350 micron thickness: 2x37 micron polyvinylfluoride, 250 micron polyethylene terephthalate; 0.488 g/m2, 7% cutting loss
Copper	kg	0.18	copper ribbons for cell interconnection
Tin	kg	0.009	Sn60Pb40 plating on tabbing material, Sn plating on interconnect/terminal ribbons
Lead	kg	0.005	Sn60Pb40 plating on tabbing material, some manufacturers use lead free.
Nickel	kg	0.00026	Ni plating on interconnect/terminal ribbons
Soldering flux	kg	0.013	soldering flux, 95% propanol, no halogens
Cleaning fluid	kg	0.0207	cleaning fluid 13 ml/m2
Silicone	kg	0.0038	for diaphragm of laminator
Silicone kit	kg	0.191	kit to attach frame and junction box
Cardboard	kg	1.75	packaging; estimation: 2 modules per cardboard box, 1 kg/m2 board, 2.2 m2 board per m2 module
Tap water	kg	34	for glass rinsing and general use
Factory area	m2	9.20E-04	4200 m2 factory producing 30 MWp/yr (180.000 modules); for 25 years factory life
Electricity			
Electricity, medium voltage	kWh	1.78	tabbing/stringing: 1.91E-2 kWh/cell of 125 mm x 125 mm
Electricity, medium voltage	kWh	8.87	lamination: 6.95 kWh per 1.25 m2 module area
Electricity, medium voltage	kWh	0.01	testing of module: 0.01 kWh/module of 1.25 m2
Electricity, medium voltage	kWh	**10.7**	total process energy
Final waste flows			
Solar cells waste	kg	0.012	2% loss, 10 g per cell, may be recycled
Waste to treatment			
Solar glass, low-iron, to recycling	kg	0.16	1% breakage loss assumed
Ethyl vinyl acetate, foil, to waste incineration	kg	0.06	4% cutting loss
Back foil, to waste incineration	kg	0.06	7% cutting loss

Name **Silicon carbide for wire sawing**
Time period 2006
Geography World
Technology Average technology
Representativeness Average from 4 companies.
Date 11/6/2006
Collection method Data collection by factory representatives and literature.
Data treatment Production capacities as weighting factor.

Table 5.1.7: LCI of Silicon Carbide

Products	**Unit**	**Amount**	**Comment**
silicon carbide (SiC)	kg	1	
Materials			
SOLIDS			
silica sand	kg	1.77	
petroleum coke	kg	1.09	
wood chips	m3	1.90E-04	wood chips and saw dust is not always used
sodium chloride	kg	0.007	sodium chloride is not always used
plant	p		taken from ecoinvent
transport	tkm		taken from ecoinvent
Electricity/fuel			
electricity, medium voltage	kWh	8.6	energy to make the crude SiC and the grains for wiring sawing
Emissions to air			
carbon dioxide, fossil	kg		taken from ecoinvent
Waste to treatment			
lost and rejected SiC	kg	0.2	

Name	**Slurry recycling**
Time period	2005
Geography	Europe, Western
Technology	Average technology
Representativeness	Average from 3 companies
Date	11/6/2006
Collection method	Data collection by factory representatives
Data treatment	Equal weighting of data of the 3 companies.
Comment	Recycles used sawing slurry from wafer cutting process, to recover SiC and PEG. This recycling is usually done off-site by the slurry supplier and therefore modeled separately. Silicon is generally not recycled.

Table 5.1.8: LCI of Silicon Carbide Slurry Recycling

Products	**Unit**	**Amount**	**Comment**
silicon carbide (SiC)	kg	0.62	
polyethylene glycol (PEG)	kg	0.64	
silicon carbide, silicon and iron mix	kg	0.14	Fine grained material, may be sold as raw material to the refractory business. For example as SiSiCar® ; patent of Metallkraft WO 02/40407
Materials			
LIQUIDS			
used slurry	liter	1	slurry produced during wire sawing of silicon (Spec. weight 1.75 g/cm3)
Electricity/fuel			
electricity, medium voltage	kWh	1.1	
Waste to treatment			
silicon carbide (SiC) unusable	kg	0.06	
polyethylene glycol (PEG) unusable	kg	0.10	
Si + Fe sludge	kg	0.19	Remaining Si and Fe waste material

Name	**Front metallization paste**
Time period	2006
Geography	Europe, Western
Technology	Average technology
Representativeness	Typical paste used.
Date	11/6/2006
Collection method	Chemical composition of typical pastes taken from Material Safety Data Sheets.

Table 5.1.9: LCI of Front Metallization

Products	**Unit**	**Amount**	**Comment**
metallization paste front	kg	1	
Materials/fuels			
silver	kg	0.83	
lead	kg	0.05	lead in glass frit
organic chemicals	kg	0.12	

Name	**Back contact metallization paste**
Time period	2006
Geography	Europe, Western
Technology	Average technology
Representativeness	Typical paste used.
Date	11/6/2006

Table 5.1.10: LCI of Back Contact Metallization Paste

Products	**Unit**	**Amount**	**Comment**
metallization paste back contact	kg	1	
Materials/fuels			
silver	kg	0.67	
bismuth	kg	0.08	bismuth in glass frit
organic chemicals	kg	0.25	

Name	**Back aluminum BSF metallization paste**
Time period	2006
Geography	Europe, Western
Technology	Average technology
Representativeness	Typical paste used.
Date	11/6/2006
Collection method	Chemical composition of typical pastes taken from Material Safety Data Sheets.
Comment	BSF = back surface field

Table 5.1.11: LCI of Back Aluminum BSF Metallization Paste

Products	**Unit**	**Amount**	**Comment**
metallization paste back Al BSF	kg	1	
Materials/fuels			
aluminum	kg	0.80	
quartz	kg	0.03	
organic chemicals	kg	0.17	

5.2 CdTe PV

Note:
1. All data unless otherwise noted is for the time period of January 1, 2005 through May 31, 2005, from First Solar's plant at Perrysburg, Ohio, US.
2. The energy data associated with manufacturing the module is for the time period of Jan 1 - Dec 31, 2008, from First Solar's plant at Frankfurt, Germany.

Table 5.2.1: LCI of CdTe Process

Products	**Unit**	**Amount**	**Comment**
CdTe PV Module	m2	1.00	
Materials			
Ethyl vinyl acetate	g	376.20	
Copper foil	g	14.24	Bussing and lamination
Acrylic polymer	g	3.44	
Acrylate polymer	g	8.79	
Polyester film	g	5.86	
Rosin core solder	g	1.35	
Acrylic tape	g	8.01	
Nylon	g	1.93	Cable tie
Poly carbonate	g	50.21	Cord plate set
Thermoplastic rubber	g	10.44	
Copper	g	8.19	Connectors
Silicone elastomer	g	12.60	
Glass -Clear float	g	9859	
Glass –Soda lime	9	9859	
Polyester	g	5.93	Product labels and tapes
Corrugated box	g	571	Corrugated container
Photoresist	g	26.10	
Back contact metals	g	5.29	

Helium gas	g	0.04	
Nitrogen gas	g	52.44	
Cadmium compound powder	g	0.72	
Cadmium sulfide	g	2.61	
Cadmium telluride powder	g	43.22	
Soda lime glass	g	9859	
Wire	g	193.88	Lead wire comprising tinned-copper conductor (38%)* and rubber insulation (62%)
Water	kg	219	
Energy			
Electricity	kWh	28.5	Electricity consumption data from First Solar Plant at Frankfurt, Germany in 2008

*the conductor can be represented as all copper (198.88*0.38) = 75.57 g/m2

Table 5.2.2: LCI of CdTe plant Chemical Usage

Products	**Unit**	**Amount**	**Comment**
CdTe PV Module	m2	1.00	
Materials			
Sulfuric Acid	g	39.6	50% sulfuric acid solution
Alcohol	g	2.2	90-100% isopropyl alcohol
Argon	g	16.2	100% argon gas
Multi Surface Polish	g	0.1	5-10% dimethylpolysiloxane
Biocide	g	0.3	1.1% 5-chloro-2-methyl-4-isothiazolin-3-one, 0.4% 2-methyl-4-isothiazolin-3-one
Cationic Coagulant	g	31.2	>1% aluminum chloride hydroxide
Caustic Soda	g	30.6	50% Caustic Soda
Degreaser	g	0.3	
Citrus pray	g	0.1	
Spot Cleaner	g	0.1	
Detergent	g	0.1	
Ethyl Alcohol	g	1.8	
Glass Cleaner	g	30.6	60-100% water, 1-5%, 2-butoxy ethanol, 0.5-1.5% 2-propanol, 0.1-1% ammonium hydroxide, 0.1-1% ethyl alcohol
Hydrogen Peroxide	g	44.1	20-51% hydrogen peroxide solution
Inhibitor	g	6.0	sodium benzotriazole
Hand Soap Cleaner	g	0.6	
Nitric Acid Reagent	g	0.2	<70% Nitric Acid, >30% Water
Anionic Emulsion	g	5.8	
Potassium Ferricyanide	g	17.2	
Soda Ash	g	15.1	
Sodium Bisulfite 38-40%	g	22.5	
Sodium Hydroxide Solution	g	0.9	
Nitric Acid Solution	g	253.8	20-30% nitric acid
Stainless Steel Cleaner Polish	g	0.01	
Water Softener Salt	g	57.6	
13% Nitrogen in Argon	g	1.8	
Helium	g	0.2	
Sodium Hypochlorite	g	0.4	

Table 5.2.3: LCI of CdTe Plant Hardware Usage

Products	**Unit**	**Amount**	**Comment**
CdTe PV Module	m2	1.00	
Materials			
Aluminum	g	2.6	Braided Strap, Shields, spacer
Copper	g	8.9	Pipes, wires, nuts, terminal
Plastics	g	70.3	Tapes, labels, gloves, drums
Paper	g	36.2	Towel, corrugated boxes
Steel	g	23.0	Nuts, pins, screws, washers, clamps
Ceramics	g	30.0	Pipes, insulation, sleeves
Graphite	g	48.0	Graphite blocks

5.3 Amonix 7700 High Concentration PV (HCPV)

Table 5.3.1: LCI for Manufacturing of Amonix 7700 HCPV

Product	**Unit**	**Amount**	**Comment**
Amonix 7700	p	1	aperture area: 267 m^2, capacity: 53 kW_p AC
Component			
Cells	kg	0.16	GaInP/GaInAs/Ge cells grown on a germanium substrate; dimension: 9.5 x 9 x 0.2 mm
Frame	kg	6566	4x12 sections, thickness: 5 mm, material: 18 GA. 55 ksi, G90 Pre-galvanized Steel
Fresnel Lenses	kg	1143	4x6 lenses for submodule; thickness: 4 mm; material: coated acrylic
Heat Sink	kg	3086	aluminum; 3 cm wide rod
Foundation	kg	3126	18’ deep, 42” diameter; concrete basis underground, 3000 PSI concrete
Hydraulic Drive	kg	2724	Steel
Pedestal/Torque tube	kg	11260	Tracker; 18 ft high Pedestal with 30 inch diameter steel pipe with outriggers
Fastener	kg	49	Stainless steel fastener for outriggers
Motor	kg	16	2 horsepower per system.
Inverter	kg	500	
Transformer	kg	100	500 kW
Cables	kg	35	Copper/PVC
Controller	kg	18	
Sensor	kg	1.4	
Anemometer	kg	0.14	
Energy			
Diesel	MJ	126	Used for assembly and installation
Electricity	kWh	1.5	Used for assembly and installation

Table 5.3.2: LCI for Maintenance of Amonix 7700 HCPV

Product	**Unit**	**Amount**	**Comment**
Amonix 7700	p	1	based on 30 yrs of operation and maintenance
Material			
Water	kg	106000	Lens cleaning
Hydraulic Oil	kg	900	
Lubricating Oil	kg	25	For bearing lubrication
Poly carbonate	kg	3	Desiccant Cartridge
Polyester	kg	60	Air filter
Polyurethane	kg	9	Air filter and desiccant cartridge
ABS (co-polymer plastic)	kg	40	Air filter guard
Poly amide	kg	1	Desiccant Cartridge
Silica gel	kg	9	Desiccant Cartridge
Stainless steel	kg	7	Hydraulic pressure filter
Glass fiber	kg	7	Hydraulic pressure filter

5. 4 Mounting Structures of PV Modules

Time period 2006
Geography Europe, Western
Technology Data from a specific process and company
Representativeness Data of one company
Date 9/1/2006
Collection method Data from system installers (Phönix, Schweizer, Schletter) and literature (Springerville)
Comment For roof top systems: 4 rows of 13 SolarWorld SW220 poly module with 6 x 10 multicrystalline cells of 156 mm x 156 mm. For ground-based systems see references below.

Table 5.4.1: LCI of Mounting Structures of PV Modules

Installation type		on-roof	on-roof	in-roof	in-roof	ground	ground	
Company		PhönixSonnenstrom AG	Schletter	Schletter	Schweizer	PhönixSonnenstrom AG	Springerville	
type of mounting system		TectoSun	Eco05+EcoG	Plandach5	Solrif			
framed (f) or unframed (u) modules		f	f+u	f+u	u	f	f	
Products	**Unit**	**Amount**	**Amount**	**Amount**	**Amount**	**Amount**	**Amount**	**Comment**
mounting structure	m2	1	1	1	1	1	1	m2 module area
Materials/fuels								
steel	kg	0	0	0	0	11.5	4.01	
stainless steel	kg	0.49	0.72	0.28	0.08	0.17	0	
aluminum	kg	0.54	0.97	1.21	1.71	1.26	0	
concrete	kg	0	0	0	0	0	8.03	
EPDM	kg	0	0	1.41	1.41	0	0	EPDM underlayer, thickness 1.14 mm
roof tiles (avoided)	kg	0	0	-40	-40	0	0	ceramic roof tiles
total without EPDM/roof tiles	kg	1.03	1.69	1.49	1.79	12.93	12.04	

References: [13, 33, 34]

Name	**Average mounting structures for installing modules to a roof or on the ground**
Time period	1992-2009
Geography	Europe
Technology	Average technology
Representativeness	Mixed data
Date	15/2/2009 and 9/2/2010
Collection method	Data from manufacturers, system installers and literature.
Comment	Manufacturer data is weighted with average mass per type of mounting system reported in a market survey.

Table 5.4.2: LCI of Average Mounting Structures

type of mounting system:		Façade mounted	Façade integrated	Flat roof mounted	Slanted roof mounted	Slanted roof integrated	Open ground	
Products	**Unit**	**Amount**	**Amount**	**Amount**	**Amount**	**Amount**	**Amount**	**Comment**
mounting structure	m2	1	1	1	1	1	1	m2 module area
Materials/fuels								
aluminium	kg	2.64E0	3.27E0	2.52E0	2.84E0	2.25E0	3.98E0	
corrugated board[1]	kg	4.03E-2	0	1.83E-2	1.33E-1	1.14E-1	8.64E-2	
ppolyethylene[1]	kg	7.32E-4	0	1.92E0	1.4E-3	2.82E-2	1.4E-3	
polystyrene[1]	kg	3.66E-3	0	8.30E-3	7.02E-3	6.02E-3	4.55E-3	
polyurethane[1]	kg	0	0	0	0	1.84E-2	0	
synthetic rubber[1]	kg	0	0	0	0	1.24E0	0	
steel low alloyed	kg	1.80E+0	0	2.67E-1	1.50E0	2.00E-1	7.21E0	
stainless steel	kg	0	0	0	0	0	2.47E-1	
concrete	m^3	0	0	0	0	0	5.37E-4	Fence foundation
Processes								
aluminium section bar extrusion	kg	2.64E0	3.27E0	2.52E0	2.84E0	2.25E0	3.98E0	
Steel sheet rolling	kg	1.1E-1	0	2.67E-1	1.50E0	0	0	
Steel section bar rolling	kg	1.69E0	0	0	0	2.00E-1	6.15E0	
Wire drawing	kg	0	0	0	0	0	1.06E0	Mesh wire fence
Zinc coating pieces	kg	0	0	0	0	0	1.56E-1	
Zinc coating coils	kg	0	0	0	0	0	1.09E-1	Fence

Transport	tkm							
Lorry	tkm	2.24E-1	1.64E-1	2.56E-1	2.25E-1	2.07E-1	2.17E-1	
Rail, freight	tkm	1.61E0	6.54E-1	1.05E0	1.50E0	8.52E-1	5.14E0	
Van	tkm	4.44E-1	3.27E-1	4.72E-1	4.34E-1	3.75E-1	1.14E0	
Land use	m^2a	0	0	0	0	0	1.42E0	

[1] includes manufacturing and disposal in municipal incineration

References: [32]

5.5. Electrical Components

5.5.1 Roof Top Installations

Name	**Electrical cabling for module interconnection and AC-interface**
Time period	2006
Geography	Europe, Western
Technology	Average technology
Representativeness	Mixed data
Date	11/6/2006
Collection method	For roof top systems: 4 rows of 13 SolarWorld SW220 poly module with 6 x 10 multicrystalline cells of 156 mm x 156 mm.
Data treatment	Scaled to 1 m2 of module area
Comment	For systems with modules in 150-170 Wp range and dimension of about 1 x 1.3 m2, connected to a 4.6 kW inverter. See ref 1.

Table 5.5.1.1: LCI of DC Cable (1)

Type of system		on-roof or in-roof	ground PhönixSonnenstrom	ground Springerville	
Products	**Unit**	**Amount**	**Amount**	**Amount**	**Comment**
DC Cabling	m2	1	1	1	per m2 module area
Materials/fuels					
copper	kg	0.10	0.62	0.64	2.2 m DC cable and 0.1 m AC cable
TPE = Thermoplastic elastomer	kg	0.06	0.25	0.48	
Electricity					
electricity, medium voltage	kWh	0.0	0.0	0.0	unknown
Emissions					unknown
Waste to treatment					Unknown

Note

1) Typical cable lengths for a roof top system are: 2.2 m DC cable and 0.1 m AC cable per m2 of module/array area

Reference: [33]

Date 9/1/2006
Collection method http://www.helukabel.de/download.php?lang=en&im=pdf/english/datenblatt/&fid=78990.pdf
Comment Helukabel Solarflex 101, 4 mm^2, ROHS compliant.
In a typical rooftop system, comprising modules of 1x1.7 m2, the DC cable length will be about 2.2 m per m2 of module area

Table 5.5.1.2: LCI of DC Cable (2)

Products	**Unit**	**Amount**	**Comment**
Cable DC 4 mm^2	m	1	
Materials/fuels			
SOLIDS			
copper	kg	0.038	Cu, Sn coated
TPE = Thermoplastic elastomer	kg	0.030	TPE
Electricity			
electricity, medium voltage, total	kWh	0.0	unknown
Emissions			unknown
Waste to treatment			unknown

Reference [33]

Name **Inverter 500 W-ac**
Time period 2000-2004
Geography Europe, Western
Technology Average technology
Representativeness Data from a specific component
Date 9/21/2006
Collection method Based on manufacturer specification for PSI 300, extrapolated to values for PSI 500. (Only upscaling of transformers and capacitors).

Table 5.5.1.3: LCI of 500 W-AC Inverter

Products	**Unit**	**Amount**	**Comment**
Inverter	p	1.00	Nominal output 2500 W AC
Materials			
Aluminum	g	682	casing
Polycarbonate	g	68	casing
ABS	g	148	casing
Poly Ethylene	g	1.4	
PVC	g	2	in cable
SAN (Styrene acrylonitrile)	g	2	in cable
copper	g	2	in cable
Steel	g	78	screws and clamps
Printed Circuit Board	cm2	596	double layered board, without components, weight 100 g
connector	g	50	
transformers, wire-wound	g	310	
coils	g	74	
IC's	g	6	
transistor	g	8	
transistor diode	g	10	
capacitor, film	g	72	
capacitor, electrolytic	g	54	
capacitor, CMC	g	4.8	
resistors	g	1	

Name	**Inverter 2500 W-ac**
Time period	2000-2004
Geography	Europe, Western
Technology	Average technology
Representativeness	Data from a specific component
Date	9/21/2006
Collection method	Disassembly of inverter and weighing
Comment	Based on data collected in 2001, based on the Mastervolt Sunmaster 2500

Table 5.5.1.4: LCI of 2500 W-AC Inverter

Products	**Unit**	**Amount**	**Comment**
Inverter	p	1.00	Nominal output 2500 W AC
Materials			
Steel	kg	9.8	casing
Aluminum	kg	1.4	casing
Transformers, wire-wound	kg	5.5	
Printed Circuit Board, with electronic components	kg	1.8	

5.5.2 Ground mount installations

Name	**Inverters + transformers 1 MW**
Time period	2000-2004
Geography	Europe, Western
Technology	Average technology
Representativeness	Data from a specific component
Date	9/21/2006
Data treatment	Data scaled to 1 MW DC
Comment	Based on data collected at the 4.6 MWp Springerville plant (Tucson, USA), scaled to 1 MW DC power. Inverters: Xantrex PV-150. Includes material for step-up transformers. See refs. 1,2 for details

Table 5.5.2.1: LCI of 1 MW Inverters + Transformers for Ground Mount Installation

Products	**Unit**	**Amount**	**Comment**
Inverters + Transformers	p	1.00	Nominal input power 1 MW DC
Materials			
steels	kg	9792	
aluminum	kg	894	
copper	kg	2277	
polyamide injection molded	kg	485	
polyester	kg	300	
Polyethylene, HD	kg	150	
Paint	kg	150	
Transformer oil (vegetable)	kg	6001	

References: [13, 35]

5.6 Medium-Large PV installations In Europe

Name	**Real photovoltaic power plants in Europe**
Time period	2004-2009
Geography	Europe
Technology	Mixed data
Representativeness	Individual real installations
Date	09.02.2010
Collection method	Data from system installers, operators and literature.
Comment	Photovoltaic power plants operating in Switzerland, Germany, and Spain Reference [30]

Table 5.6.1: LCI of PV Power Plants in Europe

capacity		93 kWp	280 kWp	156 kWp	1.3 MWp	324 kWp	450 kWp	569 kWp	570 kWp	
type of module		single-Si laminate	single-Si panel	multi-Si panel	multi-Si panel	multi-Si panel	single-Si panel	multi-Si panel	multi-Si panel	
type of mounting system:		Slanted roof integrate	Flat roof mounted	Flat roof mounted	Slanted roof mounted	Flat roof mounted	Flat roof mounted	Open ground	Open ground	
location		Switzerland	Switzerland	Switzerland	Switzerland	Germany	Germany	Spain	Spain	
Products	**Unit**	**Amount**	**Amount**	**Amount**	**Amount**	**Amount**	**Amount**	**Amount**	**Amount**	**Comment**
photovoltaic installation	unit	1	1	1	1	1	1	1	1	Refers to capacity above
electricity yield	kWh/ m^2*a	131	155	120	128	141	136	238	198	3.85 MJ converted solar energy per kWh
Components/fuels										
electricity consumption	kWh	7.13E+00	2.15E+01	1.19E+01	1.03E+02	2.48E+01	3.45E+01	3.60E+01	3.60E+01	Erection of plant
diesel consumption	MJ	0	0	0	0	0	0	7.66E+03	7.67E+03	
inverter weight	kg	123	2420	1590	6600	2600	3535	4675	4675	This amount is replaced every 15 years.
mounting system	m2	6.84E+02	2.08E+03	1.17E+03	1.01E+04	2.55E+03	3.38E+03	4.27E+03	4.27E+03	
photovoltaic module	m2	7.05E+02	2.14E+03	1.21E+03	1.04E+04	2.63E+03	3.48E+03	4.29E+03	4.40E+03	Including 2% replaces during life time and 1% rejects

Electric installations (excluding inverter)										
copper	kg	7.06E+01	3.18E+02	3.03E+02	3.87E+03	3.77E+02	3.81E+02	7.41E+02	7.41E+02	Drawn to wire
brass	kg	5.46E-01	1.02E+00	6.82E-01	7.50E+00	1.36E+00	1.36E+00	1.36E+00	1.36E+00	
zinc	kg	1.09E+00	2.05E+00	1.36E+00	1.50E+01	2.73E+00	2.73E+00	2.73E+00	2.73E+00	
Steel	kg	2.24E+01	4.12E+01	2.81E+01	2.90E+02	5.29E+01	5.29E+01	5.29E+01	5.29E+01	
nylon 61	kg	6.28E+00	1.18E+01	7.84E+00	8.63E+01	1.57E+01	1.57E+01	1.57E+01	1.57E+01	
polyethylene1	kg	6.07E+01	3.15E+02	2.80E+02	3.73E+03	4.12E+02	4.17E+02	7.09E+02	7.09E+02	
polyvinylchloride1	kg	8.69E-01	2.61E+01	2.17E+01	2.36E+02	4.17E+01	4.35E+01	4.49E+01	4.49E+01	
polycarbonate1	kg	5.46E-02	1.02E-01	6.82E-02	7.50E-01	1.36E-01	1.36E-01	1.36E-01	1.36E-01	
epoxy resin1	kg	5.46E-02	1.02E-01	6.82E-02	7.50E-01	1.36E-01	1.36E-01	1.36E-01	1.36E-01	
Transport	tkm									
lorry	tkm	4.23E+03	1.82E+04	9.64E+03	8.34E+04	2.10E+04	2.96E+04	3.51E+04	3.52E+04	500 km modules
transoceanic freight ship	tkm	1.69E+04	7.28E+04	3.86E+04	3.34E+05	8.14E+04	1.18E+05	1.41E+05	1.41E+05	2’000 km modules
van	tkm	8.91E+02	4.12E+03	2.24E+03	1.80E+04	4.72E+03	6.62E+03	7.96E+03	7.98E+03	100 km system

5.7 *Country specific photovoltaic mixes*

Name	**Country-specific photovoltaic electricity mixes**
Time period	2005-2009
Geography	World
Technology	Mixed data
Representativeness	Representative for selected countries
Date	9/2/2010
Collection method	National and international statistics.
Comment	Photovoltaic installations on buildings are considered with 3kWp installations, centralized installations are considered with open ground installations

Country		**Netherlands**	**Norway**	**Portugal**	**Spain**	**Sweden**	**United Kingdom**	**United States**	**Australia**	**Canada**	**Korea, Republic of**	**New Zealand**	**Turkey**
Product	kWh	1	1	1	1	1	1	1	1	1	1	1	1
converted solar energy	MJ	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0
tap water	kg	6.25E-3	6.27E-3	3.90E-3	3.14E-3	6.38E-3	7.04E-3	3.63E-3	4.37E-3	5.11E-3	5.45E-3	4.77E-3	4.05E-3
sewage	m3	6.25E-6	6.27E-6	3.90E-6	3.14E-6	6.38E-6	7.04E-6	3.63E-6	4.37E-6	5.11E-6	5.45E-6	4.77E-6	4.05E-6
569 kWp open ground installation, multi-Si	unit	-	-	2.19E-8	1.61E-8	-	-	-	-	-	-	-	-
570 kWp open ground installation, multi-Si	unit	4.83E-9	-	2.19E-8	1.93E-8	-	-	-	2.04E-9	7.26E-10	5.36E-8	-	-
3.5 MWp open ground installation, multi-Si	unit	-	-	-	-	-	-	1.09E-9	-	-	-	-	-
3kWp facade installation, single-Si, laminated, integrated	unit	1.59E-7	1.54E-7	-	-	1.63E-7	1.91E-7	9.14E-8	1.38E-7	1.40E-7	2.41E-8	1.37E-7	1.24E-7
3kWp facade installation, single-Si, panel, mounted	unit	6.36E-7	6.18E-7	-	-	6.52E-7	7.65E-7	3.65E-7	5.53E-7	5.59E-7	9.64E-8	5.46E-7	4.96E-7
3kWp facade installation, multi-Si, laminated, integrated	unit	2.42E-7	2.35E-7	-	-	2.48E-7	2.91E-7	1.39E-7	2.11E-7	2.13E-7	3.67E-8	2.08E-7	1.89E-7
3kWp facade installation, multi-Si, panel, mounted	unit	9.68E-7	9.41E-7	-	-	9.93E-7	1.17E-6	5.57E-7	8.43E-7	8.52E-7	1.47E-7	8.32E-7	7.55E-7
3kWp flat roof installation, single-Si, on roof	unit	8.77E-7	9.57E-7	-	-	9.68E-7	1.06E-6	4.41E-7	6.07E-7	7.56E-7	1.30E-7	7.09E-7	5.95E-7
3kWp flat roof installation, multi-Si	unit	1.34E-6	1.46E-6	8.90E-8	-	1.48E-6	1.61E-6	6.72E-7	9.24E-7	1.15E-6	1.98E-7	1.08E-6	9.06E-7
3kWp slanted-roof installation, single-Si, laminated, integrated	unit	1.10E-7	1.20E-7	-	-	1.21E-7	1.32E-7	5.52E-8	7.58E-8	9.45E-8	1.62E-8	8.86E-8	7.44E-8
3kWp slanted-roof installation, single-Si, panel, mounted	unit	2.85E-6	3.11E-6	-	-	3.15E-6	3.43E-6	1.43E-6	1.97E-6	2.46E-6	4.21E-7	2.30E-6	1.93E-6

3kWp slanted-roof installation, multi-Si, laminated, integrated	unit	1.67E-7	1.82E-7	-	-	1.84E-7	2.01E-7	8.40E-8	1.15E-7	1.44E-7	2.47E-8	1.35E-7	1.13E-7
3kWp slanted-roof installation, multi-Si, panel, mounted	unit	4.34E-6	4.74E-6	2.66E-7	-	4.79E-6	5.23E-6	2.19E-6	3.00E-6	3.74E-6	6.42E-7	3.51E-6	2.94E-6
3kWp slanted-roof installation, ribbon-Si, panel, mounted	unit	3.67E-7	4.00E-7	-	-	4.05E-7	4.42E-7	1.85E-7	2.54E-7	3.16E-7	5.42E-8	2.96E-7	2.49E-7
3kWp slanted-roof installation, ribbon-Si, laminated, integrated	unit	1.41E-8	1.54E-8	-	-	1.56E-8	1.70E-8	7.10E-9	9.75E-9	1.22E-8	2.09E-9	1.14E-8	9.56E-9
3kWp slanted-roof installation, CdTe, laminated, integrated, on roof	unit	6.12E-7	6.68E-7	-	1.73E-7	6.76E-7	7.38E-7	3.08E-7	4.24E-7	5.28E-7	9.05E-8	4.95E-7	4.15E-7
3kWp slanted-roof installation, CIS, panel, mounted	unit	7.25E-8	7.92E-8	-	-	8.01E-8	8.74E-8	3.65E-8	5.02E-8	6.25E-8	1.07E-8	5.86E-8	4.92E-8
3kWp slanted-roof installation, a-Si, laminated, integrated	unit	2.21E-8	2.41E-8	1.11E-8	-	2.44E-8	2.66E-8	1.11E-8	1.53E-8	1.90E-8	3.26E-9	1.78E-8	1.50E-8
3kWp slanted-roof installation, a-Si, panel, mounted	unit	5.74E-7	6.26E-7	2.37E-8	-	6.34E-7	6.91E-7	2.89E-7	3.97E-7	4.95E-7	8.48E-8	4.64E-7	3.89E-7
Heat, waste	MJ	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1
Global horizontal irradiation	kWh / m2	1045	967	1682	1660	980	955	1816	1686	1273	1215	1412	1697
Annual output, Roof-Top	kWh /kW_p	815	800	1276	1282	791	725	1390	1209	1000	921	1080	1287
Annual output, Facade	kWh /kW_p	562	620	789	813	588	500	839	663	676	620	701	772

Table 5.7.1: Country-Specific PV Electricity Mixes (Continued)

Country		**Austria**	**Belgium**	**Czech Republic**	**Denmark**	**Finland**	**France**	**Germany**	**Greece**	**Hungary**	**Ireland**	**Italy**	**Japan**	**Luxembourg**
Product	kWh	1	1	1	1	1	1	1	1	1	1	1	1	1
converted solar energy	MJ	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0
tap water	kg	6.25E-3	7.05E-3	6.81E-3	6.48E-3	6.67E-3	5.72E-3	5.85E-3	4.43E-3	5.65E-3	6.80E-3	5.41E-3	5.85E-3	6.45E-3
sewage	m3	6.25E-6	7.05E-6	6.81E-6	6.48E-6	6.67E-6	5.72E-6	5.85E-6	4.43E-6	5.65E-6	6.80E-6	5.41E-6	5.85E-6	6.45E-6
324 kWp flat-roof installation, multi-Si	unit	-	-	-	-	-	5.36E-9	7.16E-9	-	-	-	2.25E-9	-	-
450 kWp flat-roof installation, single-Si	unit	-	-	-	-	-	3.15E-9	4.17E-9	-	-	-	3.33E-9	-	-
570 kWp open ground installation, multi-Si, on open ground	unit	4.25E-9	-	-	-	-	6.60E-9	3.94E-9	-	-	-	2.05E-8	3.02E-10	-
3kWp facade installation, single-Si, laminated, integrated	unit	2.22E-7	1.93E-7	1.90E-7	1.70E-7	1.73E-7	1.93E-7	1.84E-8	1.34E-7	1.59E-7	1.79E-7	7.84E-7	1.64E-7	1.79E-7
3kWp facade installation, single-Si, panel, mounted	unit	8.89E-7	7.72E-7	7.60E-7	6.79E-7	6.92E-7	7.71E-7	7.35E-8	5.38E-7	6.35E-7	7.14E-7	5.03E-7	6.57E-7	7.15E-7

3kWp facade installation, multi-Si, laminated, integrated	unit	2.37E-7	2.94E-7	2.89E-7	2.59E-7	2.63E-7	2.37E-7	2.47E-8	2.05E-7	2.42E-7	2.72E-7	3.81E-7	2.50E-7	2.72E-7
3kWp facade installation, multi-Si, panel, mounted	unit	9.49E-7	1.18E-6	1.16E-6	1.03E-6	1.05E-6	9.46E-7	9.88E-8	8.19E-7	9.67E-7	1.09E-6	2.45E-7	1.00E-6	1.09E-6
3kWp flat roof installation, single-Si	unit	1.17E-6	1.06E-6	1.02E-6	9.80E-7	1.01E-6	5.18E-7	4.37E-7	6.52E-7	8.43E-7	1.03E-6	1.26E-6	8.68E-7	9.66E-7
3kWp flat roof installation, multi-Si	unit	1.25E-6	1.61E-6	1.55E-6	1.49E-6	1.54E-6	6.36E-7	5.87E-7	9.93E-7	1.28E-6	1.56E-6	6.12E-7	1.32E-6	1.47E-6
3kWp slanted-roof installation, single-Si, laminated, integrated	unit	1.47E-7	1.32E-7	1.27E-7	1.22E-7	1.26E-7	9.83E-8	8.17E-8	8.14E-8	1.05E-7	1.28E-7	2.03E-7	1.09E-7	1.21E-7
3kWp slanted-roof installation, single-Si, panel, mounted	unit	3.81E-6	3.43E-6	3.31E-6	3.18E-6	3.28E-6	2.52E-6	3.71E-6	2.12E-6	2.74E-6	3.34E-6	1.87E-6	2.82E-6	3.14E-6
3kWp slanted-roof installation, multi-Si, laminated, integrated	unit	1.57E-7	2.01E-7	1.94E-7	1.87E-7	1.92E-7	1.21E-7	1.10E-7	1.24E-7	1.60E-7	1.96E-7	9.88E-8	1.65E-7	1.84E-7
3kWp slanted-roof installation, multi-Si, panel, mounted	unit	4.07E-6	5.23E-6	5.04E-6	4.85E-6	5.00E-6	3.10E-6	4.98E-6	3.23E-6	4.17E-6	5.08E-6	9.10E-7	4.30E-6	4.78E-6
3kWp slanted-roof installation, ribbon-Si, panel, mounted	unit	-	4.42E-7	4.26E-7	4.10E-7	4.22E-7	3.54E-7	4.30E-7	2.72E-7	3.52E-7	4.29E-7	6.40E-8	3.63E-7	4.04E-7
3kWp slanted-roof installation, ribbon-Si, laminated, integrated	unit	-	1.70E-8	1.64E-8	1.58E-8	1.62E-8	1.36E-8	1.66E-8	1.05E-8	1.36E-8	1.65E-8	1.53E-8	1.40E-8	1.55E-8
3kWp slanted-roof installation, CdTe, laminated, integrated	unit	2.39E-7	7.38E-7	7.11E-7	6.84E-7	7.05E-7	5.91E-7	1.46E-7	4.55E-7	5.89E-7	7.17E-7	3.75E-7	6.06E-7	6.75E-7
3kWp slanted-roof installation, CIS, panel, mounted	unit	2.82E-8	8.74E-8	8.42E-8	8.10E-8	8.35E-8	7.00E-8	8.51E-8	5.39E-8	6.97E-8	8.49E-8	4.44E-8	7.18E-8	7.99E-8
3kWp slanted-roof installation, a-Si, laminated, integrated	unit	1.28E-7	2.66E-8	2.56E-8	2.47E-8	2.54E-8	2.13E-8	2.59E-8	1.64E-8	2.12E-8	2.58E-8	7.05E-8	2.18E-8	2.43E-8
3kWp slanted-roof installation, a-Si, panel, mounted	unit	4.94E-9	6.91E-7	6.66E-7	6.41E-7	6.60E-7	5.54E-7	6.73E-7	4.26E-7	5.51E-7	6.72E-7	2.94E-7	5.68E-7	6.32E-7
Heat, waste	MJ	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1
Global horizontal irradiation	kWh / m2	1108	946	1000	985	956	1204	972	1563	1198	948	1251	1168	1035
Annual output, Roof-Top	kWh/kW_p	833	725	752	782	759	905	744	1175	908	746	949	878	793
Annual output, Facade	kWh/kW_p	550	496	504	564	554	581	516	712	603	536	622	580	535

Reference: [32]

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