Title

A Cradle to Grave Framework for Environmental Assessment of Photovoltaic Systems

Authors

Zhang, Teresa
Dornfeld, David

Publication Date

2010-05-17

A Cradle to Grave Framework for Environmental Assessment of Photovoltaic Systems

Teresa W. Zhang and David A. Dornfeld

Abstract—**Environmental assessment of photovoltaic systems is a rich field, with representations of many technologies, regions and methodologies. This paper discusses some of the factors that strongly affect the outcomes of studies, encourages detailed reporting of normalization parameters and scope, and discusses a cradle to grave framework for benchmarking life cycle assessments of photovoltaic systems.**

Index Terms—**Photovoltaic, Life Cycle Assessment, Scope, Cradle to Grave.**

I. INTRODUCTION

Differences in assumptions, scope, and methodology are to be expected in life cycle assessment (LCA). Though there is the potential for "apples to oranges" comparisons, such differences are not inherently problematic. For example, Hocking and Lave et al. employ very different approaches to quantifying the energy use of paper and plastic drinking cups [1], [2]. The energy use reported by Lave et al. is dramatically higher than that reported by Hocking, but Lave et al. clearly explain the sources of the differences and why their results are not directly comparable.

In the PV arena, differences in assumptions, scope and methodology may not be as substantial, but the differences that do exist are not always addressed as explicitly. Results of disparate analyses are not uncommonly compared side-by-side by LCA practitioners and laypeople alike. In part, this may be because there are many parameters that factor into common environmental metrics. Yet, it is particularly important to compare like with like because of the importance the PV industry has placed on LCA results as a measure of technology performance.

Life cycle assessments of photovoltaic products, like most attributional LCAs, may serve many purposes. One major function is to drive development to reduce the environmental impacts of a product or service, by identifying the biggest contributors to environmental impact, identifying the biggest opportunities to reduce environmental impact, and predicting the impacts of specific design changes.

Another major function of life cycle assessment is to compare two or more options for fulfilling a given function. The environmental impacts of electricity generated by a particular PV system may be compared to electricity generated from other sources, such as coal, natural gas, or other PV technologies.

The aim of this paper is to aid in the comparative function of life cycle assessments for PV products in three ways: by (1) helping readers interpret the PV LCA literature, (2) encouraging researchers to be extremely explicit about the assumptions, scope, and methodology employed, and (3) suggesting a cradle to gave framework for environmental assessment of PV products. The next sections will review some important works in the recent literature, highlight parameters that strongly affect the outcome of LCA studies, and discuss how individual components of the PV life cycle may affect the environmental impacts of the system.

II. LITERATURE REVIEW

Many researchers have assessed the environmental impacts of photovoltaic products. Environmental studies of PVs mostly fall into five categories: (1) comparisons of greenhouse gas (GHG) emissions from PVs and other power generation technologies, (2) life cycle assessments of PV modules and/or balance of systems (BOS), (3) reports of emissions of specific toxins, (4) evaluations of PV land use requirements, and (5) economic studies of PVs (which we omit in this discussion). The impacts most commonly reported are energy payback time (years) and greenhouse gas emissions (gCO_2eq/kWh), though researchers also report energy use, GHG emissions, ecotoxicity, acidification, or other environmental impacts in terms of yield ratio or on a per area, per module, per system, per W_{peak}, or per kWh basis.

Comparisons to Other Power Generation Technologies: Numerous studies show that PV compares favorably in terms of GHG emissions compared to coal and natural gas power generation [3], [4], [5]. PV GHG emissions are generally higher than that of nuclear and wind power, though the results are far less unequivocal [3], [6].

Reviews: Both Pacca et al. and Sherwani et al. reviewed and summarized numerous life cycle studies of PVs in the literature [7], [8]. Bankier and Gale compiled low and high estimates of energy payback time from the literature, covering many types of roof-mounted PVs [9]. Knapp and Jester graphed energy payback times reported by numerous previous studies as functions of insolation and production energy intensity [10]. Richards and Watt reviewed the history of energy payback times, and advocated energy yield ratio as the de facto metric for PV systems [11].

Modules and/or BOS: Meijer et al. compared the production of multicrystalline silicon (mc-Si), InGaP and InGaP/mc-Si

This work was supported in part by the U.S. National Science Foundation Center for Scalable and Integrated Nanomanufacturing (SINAM).

T. W. Zhang is with the University of California at Berkeley, CA 94720-1740 and Applied Materials, Inc., Santa Clara, CA 95054 (e-mail: resa@berkeley.edu or teresa_zhang@amat.com).

D. A. Dornfeld is with the University of California at Berkeley, CA 94720-1740 (e-mail: dornfeld@berkeley.edu).

PV modules in terms of six impact indicators [12], whereas Mohr et al. extended that work to include GaInP/GaAs modules [13]. Raugei et al. evaluated CdTe modules with respect to mc-Si and CIS modules using a slightly different set of impact indicators [14]. Alsema assessed the energy payback time and greenhouse gas emissions of mc-Si and thin film amorphous silicon PV modules, as well as BOS components for both distributed roof-mounted and centralized ground-mounted PV systems [6]. Ito et al. modeled the energy use and GHG emissions of six types of phototvoltaics, from mining to operation [15], whereas Kannan et al. did so for a mc-Si PV system in Singapore from material production to decommissioning and recycling [16]. Pacca et al. reported energy payback time and net energy ratio (or energy yield ratio) as functions of energy conversion efficiency, insolation, lifetime, and manufacturing energy use [7]. De Wild-Scholten et al. focused on balance of system components, evaluating a multicrystalline silicon module installed under six BOS scenarios in Southern Europe [17]. Mason et al. showed reduced BOS impacts for a plant in Arizona [18].

Toxic Emissions: Fthenakis et al. reported that though toxicity is a major concern for some thin film PV technologies, the cadmium emissions to air on a per kWh basis are higher from coal and the European energy mix [19], [20].

Land: Denholm and Margolis quantified the amount of land needed to meet the electricity requirements of US states on a per capita basis [21]. Fthenakis and Kim compared the life cycle land requirements of electricity generation from coal, nuclear, natural gas, solar, wind, hydroelectric and biomass sources [22]. Tsoutsos et al. discussed the relative land requirements of solar thermal, centralized PV, and distributed PV systems [23].

Semiconductor: Due to the many similarities between PV manufacturing and semiconductor manufacturing in terms of materials use, equipment, processes and facilities, life cycle studies of semiconductor products may be useful resources [24], [25], [26].

The results of these and other studies are reliant on the assumptions and scope chosen by the authors. In the next two sections, we will discuss the parameters that directly influence system performance and the life cycle scope components that comprise a cradle to grave framework for PV products.

III. NORMALIZATION PARAMETERS

Many parameters affect the calculation of the environmental impacts of photovoltaic systems. In this section, we will forgo discussion of detailed factors such as wafer thickness, deposition efficiency, and processing times in favor of parameters that are directly proportional to the normalized environmental performance of a PV module or system. These parameters include energy conversion efficiency, performance ratio, insolation, and lifetime.

Models may reflect a range of measured, calculated, or assumed values. While it is generally desirable to use measured values when available in life cycle assessments, it is common to see assumed values of energy conversion efficiency rather than or in addition to measured values. This is done to keep pace with rapid efficiency gains observed in the industry. Many studies report environmental impacts today, given current energy conversion efficiency, alongside future impacts, given projected energy conversion efficiency. The PV LCA literature has also seen a convergence around certain normalization parameter values. This may aid in benchmarking different PV products across studies but attention must also be paid to difference in scope, which strongly influence the outcomes of studies.

Performance ratio (PR), the ratio of actual to theoretical output of a PV system, has been improving over the years. According to a report from the International Energy Agency, PV plants built up to 1995 have an average PR of 66% whereas plants built from 1996 to 2002 have an average PR of 70% [27]. An assumed PR value of 75% is most frequently seen in recent literature, though measured values as high as 83.5% have also been used [28].

The US National Aeronautics and Space Administration (NASA) is an excellent resource for average annual insolation values of any given location [29], [30]. Values typically seen in the literature range from 900 $kWh/m^2/yr$, representing Northern Europe, to 2370 $kWh/m^2/yr$, representing Arizona, though the most commonly used value is 1700 $kWh/m^2/yr$, representing Southern Europe or the Gobi Desert.

The lifetime of PV systems may be very long. Raugei and Frankle modeled modules with lifetime values ranging from 15 years to 40 years [5], though lifetimes of 20, 25, or 30 years are much more common. Note that BOS components may not be so long lived. Inverters are commonly modeled as lasting 10-15 years, requiring at least one replacement during the lifetime of the PV system.

IV. CRADLE TO GRAVE FRAMEWORK

Though the values selected for normalization parameters vary, the values are typically well defined. Studies also vary in their treatment of scope, with significant implications for the outcome of a study. However, the details of what is included in a study are not always explained to the extent possible.

This is true in many areas, but it is particularly important for PVs because direct comparisons between technologies are so frequently desired. Without explicit explanation of the scope included, readers tend to draw comparisons, whether or not the comparisons are fair.

While life cycle inventories maybe intellectually sensitive, much can be done to delineate which areas have been covered in an inventory. Table 1 is a worksheet that is intended to streamline the definition process for LCA practitioners and help readers evaluate the comparability of different studies.

This section will discuss the components of a cradle to grave framework that may or may not be addressed in any given study. It is not our intention to suggest at all studies follow this framework, as it may not be feasible or required to reach the goals of many studies. The framework is suggested as a point of comparison in an area that has demonstrated need for such a marker.

Where available, we also discuss the potential contribution of each component based on studies in the literature, and possible means of how to calculate the environmental impacts of each component.

TABLE 1. PV PARAMETER AND SCOPE WORKSHEET, INTENDED FOR USE BY READERS TO EVALUATE STUDIES IN THE CURRENT LITERATURE AND BY LCA PRACTITIONERS TO AID IN THE DEFINITION OF IMPORTANT ASSUMPTIONS.

Normalization Parameters	Energy Conversion Efficiency: ________% Performance Ratio: ________________% Insolation: ________________kWh/m^2/yr Lifetime: ______________________ years	☐ Measured ☐ Measured ☐ Measured ☐ Measured	☐ Calculated ☐ Calculated ☐ Calculated ☐ Calculated	☐ Assumed ☐ Assumed ☐ Assumed ☐ Assumed
Materials	Group 1: ________________ ________________ ________________ ________________ ________________ ________________	Source: ☐ Database: ________________ ☐ EIO-LCA: ________________ ☐ Literature: ________________	Scope: ☐ Mining/Extraction ☐ Processing ☐ Transportation ☐ Packaging ☐ Other: ________________	Note/Modification: ☐ Purity ☐ Energy Mix ☐ _____% Recycled ☐ By-/Co-products ☐ Other: ________________
Manufacturing Electricity Characteristics	Region: ________________ ________________	Energy Intensity of Electricity Produced: ______________MJ/kWh Energy Intensity of Electricity Consumed: _____________MJ/kWh GHG Intensity of Electricity Consumed:___________gCO$_2$eq/kWh		
Manufacturing Facilities /Overhead	Calculation: ☐ Top-down ☐ Bottom-up ☐ Extrapolated ☐ Other: ________________	Scope: ☐ HVAC ☐ Water Cooling ☐ DI Water ☐ Clean Dry Air ☐ Nitrogen	☐ Abatement ☐ Exhaust ☐ Scrubbers ☐ Waste Water Sys. ☐ Pumps ☐ Conveyors	☐ Lights ☐ Offices ☐ Warehouses ☐ Restrooms ☐ Grounds ☐ Labor
Infrastructure	☐ Equipment: ________________ ________________ ________________ Lifetime: _____yr Treatment at EOL: ________________	Source: ☐ Database: ________________ ☐ EIO-LCA: ________________ ☐ Literature: ________________	☐ Building/Roads: ________________ ________________ ________________ Lifetime: _____yr Treatment at EOL: ________________	Source: ☐ Database: ________________ ☐ EIO-LCA: ________________ ☐ Literature: ________________
Transportation	Scope: ☐ To Manufacturing: Mode: _________ ☐ To Installation: Mode: _________ ☐ To End of Life: Mode: _________	 Distance: ________ Distance: ________ Distance: ________	Source: ☐ Database: ________________ ☐ EIO-LCA ________________ ☐ Literature ________________	Note/Modification: ☐ Packaging Incl. ☐ Other: ________________ ________________ ________________ ________________
Installation /BOS	☐ Distributed ☐ Ground Mounted ☐ Building Integrated	☐ Centralized ☐ Roof Mounted	Scope: ☐ Inverter ☐ Cables	☐ Other Electronics ☐ Structural Support ☐ Labor
Operations, Maintenance, Transmission	☐ No Tracking ☐ 1 Axis Tracking ☐ 2 Axis Tracking	Scope: ☐ Cleaning ☐ Replacement Parts	☐ Transmission Line ☐ Labor	☐ Other: ________________
End of Life	☐ Recycling ☐ Processing ☐ Recovered Material: ______________		☐ Disposal ☐ Municipal Waste ☐ Hazardous Waste	☐ Database ☐ EIO-LCA ☐ Literature

A. Materials

Researchers are generally very thorough with regards to materials used in PV manufacturing because materials comprise a significant portion of the impacts of PV products. However, common sources of environmental data for feedstock materials do not always include transportation, packaging, or other elements of the material supply chain. Environmental data from LCA databases and EIO-LCA typically include transportation and packaging, but may not reflect the level of purity of materials used in PV manufacturing.

Purity is of particular concern in PV and semiconductor studies. Krishnan et al. correlated increasing purity requirements of bulk gases (nitrogen, oxygen, helium, hydrogen and argon) with considerable increases in energy use compared to standard grade or crude materials [31]. This is because high purity materials must be additionally processed to reach desired levels of purity. Krishnan et al. describe a method of estimating the additional energy requirements of purification using cost of ownership modeling and Economic Input-Output LCA.

B. Manufacturing Electricity Use

Like materials, manufacturing processes are typically well addressed in life cycle assessments of PVs, but the specifics of what is included may vary a great deal, particularly regarding the treatment of electricity use.

Bankier and Gale point out that some studies do not consider the energy consumed in electricity generation and distribution, instead only quantifying the direct electricity use of manufacturing processes [9]. While most studies do consider the additional energy use of electricity generation and distribution, they may do so differently.

For example, a study of PVs manufactured in Europe may choose to model the characteristics of the Union for the Co-ordination of Production and Transmission of Electricity (UCTE), the country, or region. Additionally, some studies assume that solar power is used to power the manufacturing facility [14], [32].

Few studies distinguish between the energy intensity of electricity generated and the energy intensity of electricity generated and distributed to the point of use. The former corresponds to the primary energy consumption offset by the use of a PV system whereas the latter corresponds to the primary energy used to provide electricity to PV manufacturing.

The International Energy Agency Energy Balance Reports are excellent resources for electrical distribution losses observed in most countries [33]. For the United States in 2007, approximately 6% of total generated electricity was lost in distribution [33].

C. Manufacturing Facilities and Overhead

The environmental impacts of manufacturing facilities and overhead may not be included in many studies of photovoltaics. De Wild-Scholten and Alsema explicitly state that they do include facilities and overhead impacts [34] but most do not offer more detail than “manufacturing” or “module processing”.

Manufacturing facilities provide utilities to the process tools, including climate control, de-ionized water, nitrogen, clean dry air, and exhaust. It is known that facilities impacts may account for almost half the total environmental impacts of semiconductor manufacturing [25]. Due to the similarities between semiconductor and PV manufacturing, the facilities impacts of PV manufacturing are likely to be significant as well.

Peharz and Dimroth reported a measured value for clean room energy use of 4.2 GJ for a 6 kW_p concentrator PV system [35]. This corresponds to 5.2% of the total energy use of the installed system, which also includes the energy used to transport the system from manufacturing to installation. Other facilities systems, which may be just as significant, are not explicitly addressed in the analysis.

Manufacturing overhead may include offices, warehouses, restrooms and other necessary elements of a manufacturing plant. Some researchers group facilities and overhead together. Based on many papers in the literature, Alsema found the facilities and overhead costs of thin film solar manufacturing to be in the range of 80-800 MJ/m^2 [6]. A “best estimate” value of 250 MJ/m^2 for facilities and overhead corresponds to 21% of the energy use of a manufacturing a frameless module.

D. Manufacturing Infrastructure

We define manufacturing infrastructure as the one time costs of PV manufacturing, including equipment manufacturing and building construction. The contribution of the manufacturing infrastructure is directly proportional to the functional life of the infrastructure. Manufacturing equipment is extremely long lived and technology obsolescence may occur prior to equipment failure. The functional life of buildings may depend on many factors including climate and maintenance.

Few researchers explicitly discuss the manufacturing equipment. PV manufacturing equipment may use large amounts of monolithic materials, as well as many motors, pumps, and mechanical components. Alsema reported that the energy requirement of equipment manufacturing may be 150 MJ/m^2 or 13% of the energy requirement of a frameless amorphous silicon module [6].

E. Transportation

Given the global supply chain for finished PV products, large quantities of materials may be transported very long distances via shipping and trucking. At the end of life, modules must be transported again for disposal, recycling or remanufacturing.

Peharz and Dimroth evaluated a concentrator PV system including transportation from manufacturing in Germany to installation in Spain. This transportation accounted for 10% of the life cycle energy use of the installed PV system [35]. Though it is not considered in this study, a similar amount of material must also be transported to manufacturing and from installation to end of life. Excellent source of information on the environmental impacts of freight transportation include [36], [37], and [38].

F. *Balance of Systems and Installation*

Many detailed studies in the literature document the impacts of balance of system components. The impacts of a PV system depend on the choice of installation and corresponding structures needed. Assessments of ground-mounted systems generally include the concrete foundations whereas roof-mounted support structures do not include the construction of the building or roof. Readers must take care to isolate the contribution of the mounting system from performance of the technology.

Installation can add 50% to the cost of a PV module, depending on type of installation [39]. The cost of installation includes the inverter, other materials and labor. Labor is one of the biggest costs of installation yet it is generally not addressed in life cycle assessments. New methods of quantifying the energy and GHG impacts of labor can be used to assess labor-intensive processes like installation [40], [41].

G. *Operations, Maintenance and Transmission*

Quantifying the environmental impacts of operations is particularly important for PV systems employing trackers, because of the direct electrical use of the trackers and the potential maintenance requirements of the moving components. While it is very important that PV collectors are kept clear of obstruction to sunlight, once installed, PV maintenance costs are fairly minimal.

Ito et al. reported that the impacts of a 100 km transmission line contribute approximately 10% to the mining-to-operation impacts of a PV system [12]. However, they are unique in considering transmission lines within the scope of assessment.

H. *End of Life*

Due to the long functional life of PV products and the lack of established recycling pathways, few have evaluated the end of life (EOL) impacts of PVs. Numerous studies discuss different means of recycling PV modules [42], [43]. Studies that focus on quantifying the environmental impacts of PV recycling show the impacts may vary significantly. Muller et al. reported that producing multicrystalline silicon modules with recycled wafers reduces manufacturing energy use by half, corresponding to a change in energy payback time of 1.7 years [44]. Raugei evaluated the decommissioning of CdTe modules, including recycling of glass, copper, iron, steel and alminum but not the reuse of Cd or Te, finding a net energy cost corresponding to an increase in energy payback time of 17 days [45].

If disposal is selected over recycling, the disposal pathway will vary based on the concentration of specific materials and the local regulations. U.S. Environmental Protection Agency regulations include the Toxicity Characteristic Leaching Procedure (TCLP), whereas California abides by a stricter set of standards including the Total Threshold Limit Concentration (TTLC) and the Soluble Threshold Limit Concentration (STLC). In Europe, the Restriction of Hazardous Substances Directive (RoHs) specifically exempts PV products, though this may change in later revisions [46]. Finally, end of life processing choices will strongly influence end of life transportation requirements.

V. CONCLUSION

We have provided a review of recent studies in the literature pertaining to the environmental impacts of PV systems, and provided information about normalization parameters with the hope of helping readers objectively evaluate results from various sources. We have also outlined a cradle to grave framework for the environmental life cycle assessment of PV systems. It is not the intention of this paper to suggest that all future studies abide by the comprehensive scope discussed, since studies may serve a wide vary of goals. However, we strongly suggest that researchers be explicit about which components of a comprehensive scope are addressed in any given study so that comparisons between studies can be made in a fair and realistic fashion.

ACKNOWLEDGMENT

This work is funded in part by the NSF Center for Scalable and Integrated NanoManufacturing (SINAM). The authors would like to thank Stan Hughes, Bruce Klafter, and Jim Cushing, for making this work possible, and the anonymous reviewers who provided valuable feedback and analysis.

REFERENCES

[1] M.B Hocking, “Paper versus Polystyrene: A Complex Choice.” *Science*, vol. 251, pp 504-505, February 1, 1991.

[2] L.B. Lave, E. Cobas, C. Hendrickson, F.C. McMichael, “Using Input-Output Analysis to Estimate Economy Wide Discharges,” *Environ. Sci. Technol.*, vol. 29 (9), pp 153-161, 1995.

[3] S. Pacca and A. Horvath, “Greenhouse Gas Emissions from Building and Operating Electric Power Plants in the Upper Colorado River Basin”, *Environ. Sci. Technol.*, vol. 36, no.14, pp. 3194-3200, 2002.

[4] L. Gagnon, C. Bélanger, Y. Uchiyama, "Life-cycle assessment of electricity generation options: The status of research in year 2001", *Energy Policy,* vol. 30, no.14, 1267-1278, 2002.

[5] M. Raugei and P. Frankle, “Life cycle impacts and costs of photovoltaic systems: Current state of the art and future outlooks”, *Energy*, vol. 34, pp 392-299, 2009.

[6] E.A. Alsema, “Energy Pay-back Time and CO2 Emissions of PV Systems,” *Prog. Photovolt. Res. Appl.* 8, 17-25, 2000.

[7] S. Pacca, D. Sivaraman, G.A. Keoleian, “Parameters affecting the life cycle performance of PV technologies and systems,” *Energy Policy*, vol. 35, pp. 3316–3326, 2007.

[8] A.F. Sherwani, J.A. Usmani, Varun, “Life cycle assessment of solar PV based electricity generation: A review,” *Ren. & Sust. Energy Reviews,* vol. 14(1), pp. 540-544, 2009.

[9] C. Bankier and S. Gale, “Energy Payback of Roof Mounted Photovoltaic Cells,” *Energy Bulletin,* June 16, 2006. Available: http://www.energybulletin.net/node/17219

[10] K.E. Knapp and T.L. Jester, “An Empirical Perspective on the Energy Payback Time for Photovoltaic Modules,” *Proceedings of the Solar 2000 Conference*, Madison, WI, June 16-21, 2000.

[11] B.S. Richards and M.E. Watt, “Permanently dispelling a myth of photovoltaics via the adoption of a new net energy indicator,” *Ren. & Sust. Energy Reviews*, vol. 11(1), pp. 162-172, 2007.

[12] A. Meijer, M.A.J. Huijbregts, J.J. Schermer, L. Reijnders, “Life-cycle assessment of photovoltaic modules: Comparison of mc-Si, InGaP and InGaP/mc-Si solar modules,” *Prog. Photovolt: Res. Appl.*, vol. 11(4), pp. 275–287, 2003.

[13] N. Mohr, A. Meijer, M.A.J. Huijbregts, L. Reijnders, “Environmental impact of thin-film GaInP/GaAs and multicrystalline silicon solar modules produced with solar electricity,” *Int. J. Life Cycle Assess.,* vol. 14, pp. 225-235, 2009.

[14] M. Raugei, S. Bargigli, S. Ulgiati, “Energy and life cycle asssement of thin film CdTe photovoltaic modules,” *Proceedings of the 20th European Photovoltaic Solar Energy Conference*, Barcelona, June 6-10, 2005.

[15] M. Ito, K. Komoto, K. Kurokawa, “Life-cycle analyses of very-large scale PV systems using six types of PV modules,” *Current Applied Physics*, vol. 9, 2009.

[16] R. Kannan, K.C. Leong, R. Osman, H.K. Ho, C.P. Tso, “Life cycle assessment study of solar PV systems: An example of a 2.7 kWp distributed solar PV system in Singapore,” *Solar Energy*, vol. 80, pp. 555–563, 2006.

[17] M.J. de Wild-Scholten, E.A. Alsema, E.W. ter Horst, Manfred Bächler, V.M. Fthenakis, “A cost and environmental impact comparison of grid connected rooftop and ground-based PV systems,” *Proceedings of the 21st European Photovoltaic Solar Energy Conference,* Dresden, Germany, September 4-8, 2006.

[18] J.E. Mason, V.M. Fthenakis, T. Hansen, H.C. Kim, “Energy Pay-Back and Life Cycle CO2 Emissions of the BOS in an Optimized 3.5 MW PV Installation,” *Prog. Photovolt: Res. Appl.,* vol. 14(2), pp. 179–190, 2006.

[19] V.M. Fthenakis, “Life cycle impact analysis of cadmium in CdTe PV production,” *Ren. & Sust. Energy Reviews,* vol. 8, pp. 303-334, 2004.

[20] V.M. Fthenakis, H.C. Kim, “CdTe photovoltaics: Life cycle environmental profile and comparisons,” *Thin Solid Films*, vol. 515, pp. 5961–5963, 2007.

[21] P. Denholm and R. M. Margolis, “Land-use requirements and the per-capita solar footprint for photovoltaic generation in the United States,” *Energy Policy*, vol. 36 (9), pp. 3531-3543, 2008.

[22] V.M. Fthenakis, H.C. Kim, “Land use and electricity generation: A life-cycle analysis”, *Ren. & Sust. Energy Reviews*, vol. 13, pp.1465-1474, 2009.

[23] T. Tsoutsosa, N. Frantzeskakib, V. Gekas, “Environmental impacts from the solar energy technologies,” *Energy Policy*, vol. 33, pp. 289–296, 2005.

[24] S.B. Boyd, A. Horvath, D.A. Dornfeld, “Life-Cycle Energy Demand and Global Warming Potential of Computational Logic,” *Environ. Sci. Technol.*, vol. 43 (19), pp. 7303–7309, 2009.

[25] N. Krishnan, S. Boyd, A. Somani, S. Raoux, D. Clark, D. Dornfeld, “A Hybrid Life Cycle Inventory of Nano-Scale Semiconductor Manufacturing,” *Environ. Sci. Technol.*, vol. 42 (8), pp. 3069–3075, 2008.

[26] E. Williams, “Energy Intensity of Computer Manufacturing: Hybrid Assessment Combining Processand Economic Input−Output Methods, *Environ. Sci. Technol.*, vol. 38 (22), pp 6166–6174, 2004.

[27] L. Clavadetscher, “Country Reports on PV System Performance,” Report of the International Energy Agency Photovoltaic Power Systems Programme, T2-05, December, 2004. Available: http://www.iea-pvps.org/products/download/rep2_05.pdf

[28] V.M. Fthenakis, E. Alsema, “Photovoltaics Energy Payback Times, Greenhouse Gas Emissions and External Costs: 2004–early 2005 Status,” *Prog. Photovolt: Res. Appl.,* vol. 14, pp. 275–280, 2006.

[29] C. E Whitlock, NASA Surface Meteorology and Solar Energy Data Set for Renewable Energy Industry Use (Release 3), 2000. Available: http://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?uid=3030

[30] Average annual and monthly insolation reprinted from [29] for many common locations are available: http://www.apricus.com/html/solar_collector_insolation.htm.

[31] N. Krishnan, E.D. Williams, S.B. Boyd, “Case studies in energy use to realize ultra-high purities in semiconductor manufacturing,” *Proceedings of the IEEE International Symposium on Electronics and the Environment,* San Francisco, May, 2008.

[32] V.M. Fthenakis, H.C. Kim and E. Alsema “Emissions from Photovoltaic Life Cycles,” *Environ. Sci. Technol*, vol. *42* (6), pp. 2168–2174, 2008.

[33] IEA, “Energy Balances of OECD Countries – 2009 Edition” and “Energy Balances of Non-OECD Countries – 2009 Edition”, *Publications of the International Energy Agency,* Paris, 2009. Available: http://www.iea.org/stats/index.asp

[34] M.J. de Wild-Scholten, E. Alsema, “Environmental Life Cycle Inventory of Crystalline Silicon Photovoltaic Module Production - Excel file,” *ECN Solar Energy Report*, January, 2006. Available: http://www.ecn.nl/publications/default.aspx?nr=c06002.

[35] G. Peharz and F. Dimroth, “Energy Payback Time of the High-concentration PV System FLATCON”, *Prog. Photovolt: Res. Appl.*, vol. 13, pp. 627–634, 2005.

[36] C. Facanha, A. Horvath, “Evaluation of Life Cycle Air Emission Factors of Freight Transportation,” *Environ. Sci. Technol.* vol. 41, pp. 7138–7144, 2007.

[37] A. Horvath, C. Facanha, “Environmental Assessment of Freight Transportation in the U.S,” *Int. J. LCA,* vol. 11, pp. 229–239, 2006.

[38] M. Spielmann, R. Scholz, “Life Cycle Inventories of Transport Services”, *Int. J. LCA*, vol. 10(1), pp. 85-94, 2005.

[39] R. Wiser, G. Barbose, C. Peterman, “Tracking the Sun: The Installed Cost of Photovoltaics in the US from 1998-2007,” *Lawrence Berkeley National Laboratory,* February 2009. Available: http://eetd.lbl.gov/ea/emp/reports/lbnl-1516e.pdf.

[40] T. Zhang and D. Dornfeld, “Quantifying the Environmental Impacts of Labor,” *Presented at the IEEE Int. Sym. on Electronics & the Environment*, San Francisco, May 19-21, 2008.

[41] M. Xu, E. Williams, B. Allenby, “Assessing environmental impacts embodied in manufacturing and labor input for the China-U.S. trade,” *Environ. Sci. Technol.*, vol. 44 (2), pp. 567-573, 2010.

[42] W. Berger, F.-G. Simon, K. Weimann, E.A. Alsema, “A novel approach for the recycling of thin-film photovoltaic modules,” *Resources, Conservation and Recycling,* in press, 2009.

[43] V.M. Fthenakis, “End-of Life Management and Recycling of PV Modules,” *Energy Policy*, vol. 28, pp. 1051-1058, 2000.

[44] A. Muller, K. Wambach, and E. Alsema, “ Life Cycle Analysis of Solar Module Recycling Process”, Proc. of *Mater. Res. Soc. Symp.,* 2006.

[45] M. Raugei, “Life Cycle Assessment of CdTe PV Decommissioning”, *Proc. of the 24th European Photovoltaic Solar Energy Conference and Exhibition,* 2009.

[46] H. Kundert, “Proposed Changes to RoHs May Adversely Affect PV Industry,” *Photovoltaics World*, March 2, 2010. Available: http://www.electroiq.com/index/display/photovoltaics-article-display/9949654853/articles/Photovoltaics-World/equipment-and_materials/esh/2010/march/proposed-changes_to.html.