Title
Producer-Focused Life Cycle Assessment of Thin-Film Silicon Photovoltaic Systems

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Publication Date
2011

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by

Teresa Weirui Zhang

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Mechanical Engineering

and the Designated Emphasis

in

Energy Science and Technology

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor David Dornfeld, Chair
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Spring 2011

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Abstract

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Life cycle assessment (LCA) is a powerful environmental management and decision- making tool that has served the needs of many individual and institutional consumers. Using the example of a thin-film amorphous silicon photovoltaic system, this dissertation work adapts life cycle assessment to best meet the design-for-environment needs of producers.

The producer-focused LCA helps to minimize to the environmental impacts of products by (1) identifying opportunities to reduce environmental impacts, (2) tracking and communicating the impacts of design changes, and (3) benchmarking the environmental performance of products with respect to other options on the market. To meet these goals, this dissertation introduces and demonstrates two unique life cycle assessment features - facilities integration and scenario functionality.

Facilities integration is a realistic and dynamic method of attributing the impacts of facilities systems to the corresponding process steps. This is important because facilities impacts are otherwise treated as fixed. This features significantly expands design space available to producers for minimizing environmental impacts in manufacturing.

Scenario functionality is a flexible model structure that allows end users to select from and evaluate a number of different technology, manufacturing, implementation, and model

scope options. The feature is useful for two main purposes: (1) to analyze and compare any number of life cycle scenarios, and (2) to adapt model assumptions and scope to mimic that of other studies so that their results can be compared more meaningfully.

This dissertation presents the most comprehensive environmental assessment of thin film silicon photovoltaic (PV) systems to date, employing measured process data of unprecedented resolution. The cumulative energy demand (CED) and global warming potential (GWP) emissions of an example case, in which manufacturing and installation occur in the United States and the scope includes processes from raw materials to recycling at the end of life, are 2.5 GJ/m^2 and 202 kg CO_2 eq/m^2, corresponding to payback times of 23 and 31 months, respectively. Approximately half the total life cycle impacts occur due to downstream processes, including balance of system components, transportation, and end of life processing.

A set of results, representing a range of values for 17 different manufacturing and system parameters, is used to identify scenarios yielding the fastest and slowest energy and global warming potential payback times. Thirteen of the parameters are evaluated in a sensitivity analysis, showing that the parameters having the greatest influence on the payback times of the system are energy conversion efficiency, system performance ratio, and characteristics of electricity offset during the life of the PV system. The characteristics of electricity offset are parameters that are not widely recognized as having such great influence, and if recognized, may persuasively illustrate the advantages of adopting PV and other renewable energy technologies in areas utilizing inefficient or highly polluting energy sources.

Finally, this dissertation presents a robust, top-down methodology for quantifying the environmental impact of a worker-hour of industrial human labor. Labor is a necessary component of any manufacturing system, and a major source of economic and logistical variance, yet is typically omitted as a factor in the environmental impacts of manufacturing systems. The methodology is applied to quantify the energy consumption, global warming potential, and water withdrawals of an industrial worker-hour in the US as 63 MJ, 4.6 kg CO_2 eq, and 82 gallons per worker-hour, respectively. Energy and GWP costs per worker-hour are given, including and excluding the effects of international trade, for 20 major manufacturing countries.

To all who fight for justice, especially when it is not the norm.

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Acknowledgments

I'd like to give my thanks to my esteemed committee members for providing such thought provoking comments and suggestions, and to Dave Dornfeld, especially, for tremendous support and guidance over the years. I owe a huge debt of gratitude to Ryan Williams, Chao Zhang, Yuyan Wang, Barbara Vivino, Marcia Gee Riley, Donna Craig, and Oliver O'Reily, whose unwavering and prudent moral support is entirely responsible for the completion of this work. I'd like to show my boundless appreciation for the incredible depth of knowledge and gracious availability that many experts in the field have shared with me, including Sarah Boyd, Eric Masanet, Arpad Horvath, Eric Williams, Scott Matthews, Jeff Dahmus, Jackie Isaacs, Nikhil Krishnan, and especially Tim Gutowski and Dara O'Rourke for also providing me with such a fine introduction to life cycle assessment and environmentally benign manufacturing practices. I'd like to express my gratitude to Mark Denome and everyone at Applied Materials for championing design-for-environment design processes and for showing, and encouraging me to take on, great confidence in my abilities. Particularly, I'd like to thank my team in the Environmental Health and Safety group, including Stan Hughes, Bruce Klafter, Lauren Crane, Marty Gothberg, John O'hehir, Curt Layman, Danha Doan-Nyugen, and Mike Truong, for unparalleled technical and professional support. This work could not have been completed without the help of Jim Cushing, Andreas Kalomiris, Michael Rogerson, Kevin Cunningham, Phil Naughton, Gary Sepherd, Belynda Filipo, Tzu-Fang Huang, Jon Dahm, Sali Schille and all the other very capable people from the Solar Business Group, who not only granted me exceptional access to information but sincere encouragement as well. I'd like to thank Andreas Neuber, Parth Sethia and Denis David in Applied Global Services for sharing their valuable time and immense knowledge, pertaining to semiconductor manufacturing and beyond. I feel extremely fortunate to have benefited from the instruction of some of the most excellent teachers in the fields of life cycle assessment and green energy technology, including Arpad Horvath, Dan Kammen, Van Carey, Cyrus Wadia, and Alex Farrell. I'm very happy to thank Juli Rubin and Melissa Varian who graciously offered their support at a critical juncture in the completion of my dissertation work. And finally, I'd like to acknowledge all the members of the Laboratory for Manufacturing and Sustainability (LMAS), past, current, and future for pushing the envelop of green manufacturing.

Chapter 1

Introduction

Life cycle assessment (LCA) aids consumers in making environmentally preferable purchasing decisions and, through consumers, encourages the development of environmentally benign products. This dissertation adapts life cycle assessment methodology to specifically help producers to evaluate and improve the environmental performance of products, in pace with, or even prior to, commercial utilization.

Relative to the influence that they wield, producers are underserved by the LCA community. While consumers may reduce their environmental impacts by making informed purchasing choices, producers are responsible for generating the purchasing choices available to consumers. To ensure the availability of environmentally benign goods, producers need tools that evaluate environmental performance during, rather than following, the product development process.

Life cycle assessment has encouraged the development of green products, albeit through a distended feedback loop. Just as solid modeling and finite element analysis have enabled the development of higher functioning mechanical goods, producer-focused life cycle assessment engages producers to streamline the technology development cycle and accelerate the emergence of ever more sustainable products.

1.1 Objectives

The primary objective of this work is to enable producers of thin-film silicon (TF-Si) photovoltaic (PV) systems to minimize the environmental impacts of their products. In order to do so, producers need to (1) identify opportunities to reduce environmental impacts, (2) track and communicate the impacts of specific design changes, and (3) benchmark the environmental impacts of their products with respect to other options on the market.

Another objective that is addressed in this dissertation is the ephemeral and scenario-dependent nature of LCA results. Life cycle assessments are often said to describe a single snapshot in time, space, and technology. Studies of more established technologies may accurately represent a product for some time and over a wide range of geographical locations, but this is not the case in the photovoltaic industry. Technological development in the PV industry happens at a particularly quick pace, highlighting the need for dynamic LCA modeling.

The LCA model described in this dissertation accomplishes these objectives through two unique features that are discussed in detail in Chapter 3. While this dissertation is focused on one type of product, the same ideas may be applied to other manufactured goods and industries. Other industries employing significant facilities systems (such as the pharmaceutical industry) or undergoing rapid development and deployment (such as the personal electronics or nanotechnology industries) may particularly benefit from the producer-focused LCA features introduced in this dissertation.

1.2 Background

Solar power is an especially promising source of clean, renewable power. Yet, solar technologies are not without their own environmental costs, particularly in the manufacturing life cycle. Manufacturing plants are often heavy consumers of electricity, fuels, and water. According to the US Energy Information Agency, the industrial sector consumes more energy than the commercial, residential or transportation sectors (EIA, 2005). Additionally, many photovoltaic materials are known to be energy-intensive to produce (ex: solar-grade silicon), scare (ex: tellurium), or toxic (ex: cadmium).

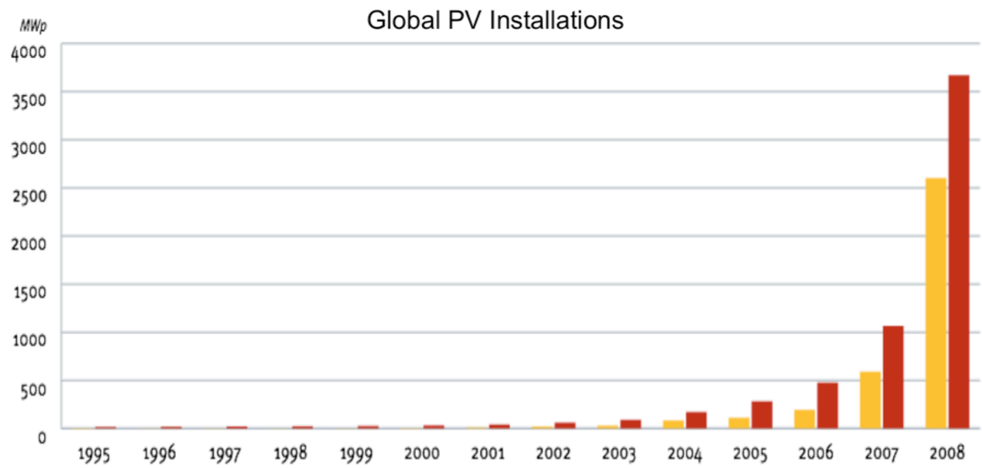


Figure 1.1: Annual and cumulative installed power from photovoltaic systems worldwide from 1995 to 2008 (Lenardic, 2008).

As the PV industry grows at a breakneck pace (Figure 1.1), increased production should be met with increased efficiency. Energy conversion efficiencies have been steadily climbing (Figure 1.2), but energy conversion efficiency is only one factor in the environmental performance of a PV system. Other factors include insolation at installation, system performance ratio, system functional life, and energy mix consumed during manufacturing. Assumptions about these and other factors that affect the outcome of an LCA study tend to vary significantly in the literature.

1.2.1 Literature Review

There has been tremendous activity in the PV LCA community with hundreds studies of PV systems ranging from crystalline silicon to thin film to concentrator PV system, in locations as diverse as Spain, Mongolia, and Brazil. Practitioners have taken various approaches to the specificity and boundary conditions of their studies, with significant influence on the results of the studies. An example of the differences in the life cycle stages and environmental impacts included within the boundary conditions of 12 notable PV LCA studies, is illustrated in Table 1.1.

The PV LCA field, like many other LCA fields, is unfortunately troubled by studies that fail to explicitly state sources of data, model completeness and/or modeling methods.

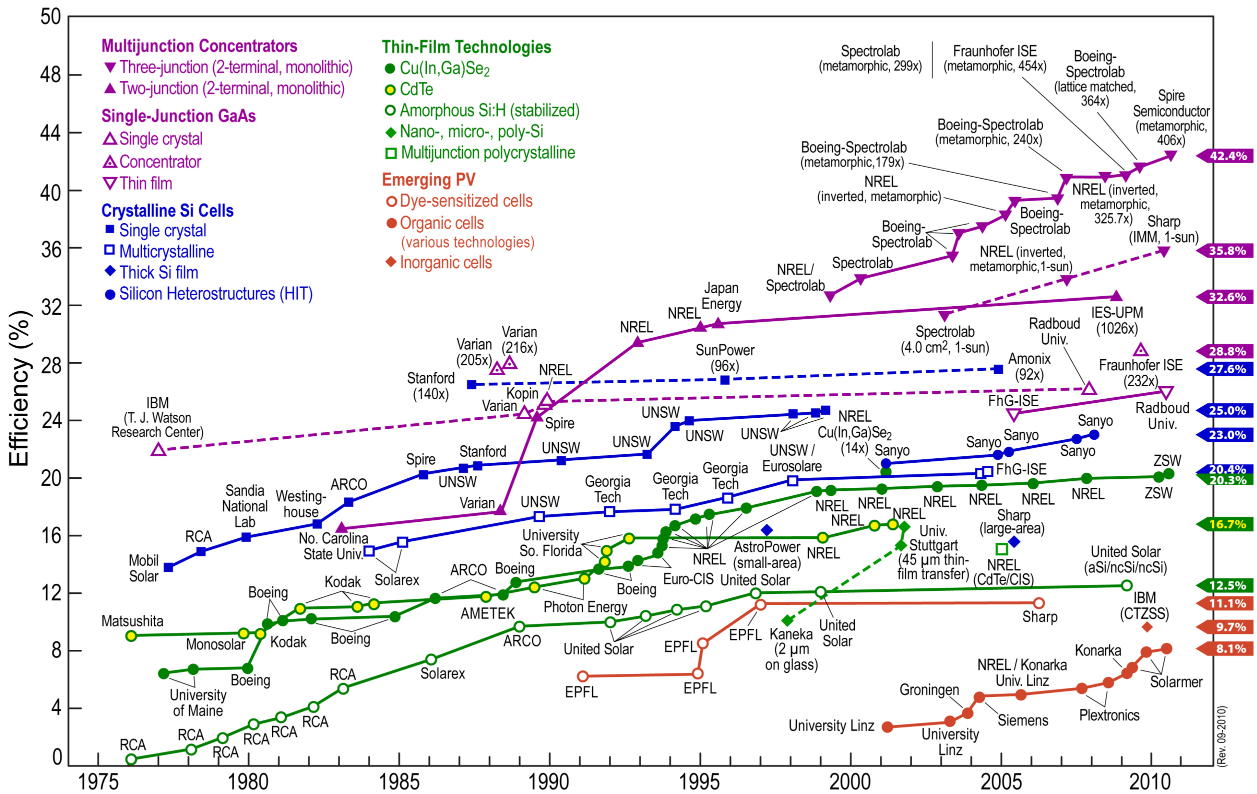


Figure 1.2: Best research photovoltaic efficiencies (Kazmerski, 2011).

Because of this, it is difficult to correlate the wide range of quantitative findings in the PV LCA literature. Figure 1.3shows a large spread of energy payback times from a number of notable PV LCA studies . Some of the range may be attributed to the type of photovoltaic system evaluated or technology development as indicated by time, but overwhelmingly, there is little discernible pattern when looking across multiple studies due to differences in scope and other assumptions made by researchers.

These substantial differences have been recognized by the PV LCA community as a limitation to the field and to the utility of individual studies. Efforts have been made to minimize methodological differences in future publications and are discussed in Section 1.2.2.

Despite the many differences, some commonality has emerged. For example, primary energy use and GWP, in terms of m^2, W$_p$, and/or payback time, are invariably included. Payback times are particularly appealing metrics of environmental performance to industry and the public at large. Some, including Richards and Watt (2007) advocate the use of

Impact Category	Materials Extract./Process.	Transportation to Mfg	Mfg Equipment	Mfg Processes	Mfg Overhead	Transportation to Install	Installation	Operation & Maintenance	End of Life (EOL)
Energy Use	A, B, C, F, G, I, J, K, L	L	A	A, B, C, E, F, G, I, J, K, L	A, J	C, G, L	C	A, B, G, K	B, H, I, K
GHG Emissions	A, F, K, L	L	A	A, F, K, L	A	L	L	K	H, K
Toxic Releases	D, L	L		D, L		L	L		H

A. Alsema, 2000	E. de Wild-Scholten, 2006	I. Muller, 2006
B. Meijer, 2003	F. Fthenakis, 2006	J. Knapp, 2000
C. Pacca, 2007	G. Peharz, 2005	K. Kannan, 2006
D. Fthenakis, 2004	H. Raugei, 2009	L. Keoleian, 1997

Table 1.1: Illustration of the range of life cycles and impacts covered in a small sample of the PV LCA literature.

energy yield ratio as de facto metric for PV systems instead of energy payback time. Energy and GWP yield ratios are valuable because they also consider the functional lifetimes of photovoltaic systems, whereas payback times do not.

In addition to these basic metrics, different technologies necessitate the inclusion of different environmental impact categories. For example, analysis of photovoltaic systems containing potentially toxic materials, like cadmium, must include some assessment of toxicity. Fthenakis approximates toxicity with the life cycle releases of toxic materials such as Cd.

Water use (withdrawals or consumption) is an important impact category for the power sector, given that half of water withdrawals in the U.S. are used to cool thermo-electric power

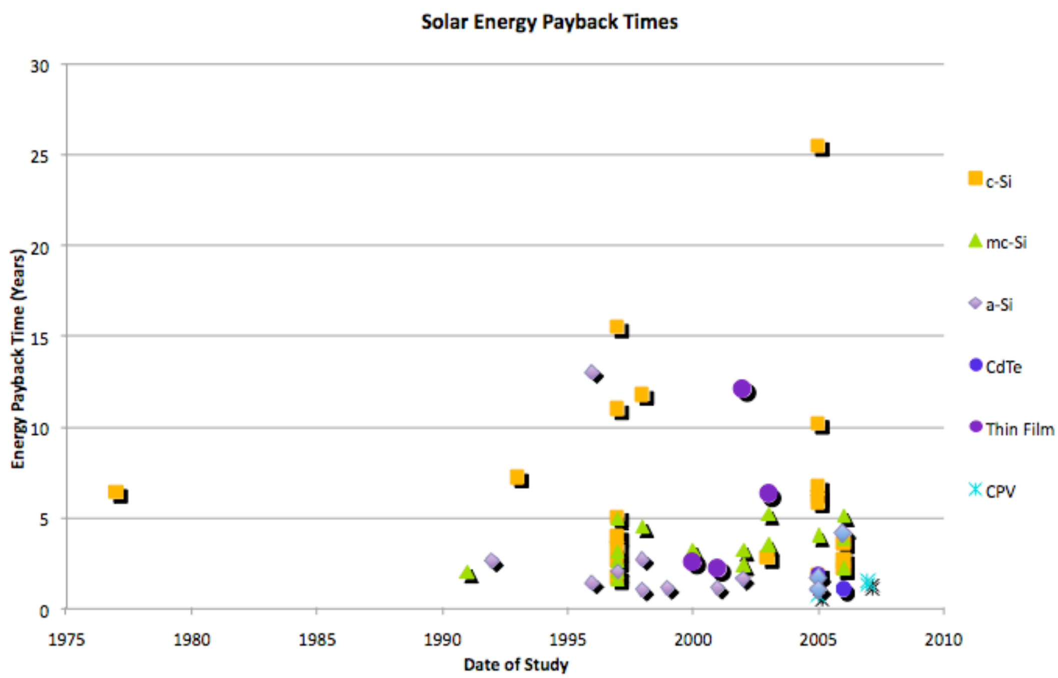


Figure 1.3: Graph of energy payback times as a function of time for numerous types of photovoltaic systems.

plants (Kenny et al., 2009). Relative to coal, natural gas, combined heat and power, or nuclear sources of power, photovoltaic systems represent a significant water savings (Younos et al., 2009).

Land use, or land use change, has both quantitative and qualitative aspects of environmental impact. Fthenakis and Kim (2009) have found that despite the concerns over land use of photovoltaics, the life cycle land use of electricity from photovoltaic sources is significantly less than that of electricity from surface mined coal sources. Other studies discuss the nature of land use change associated with PV systems, which may take on different characteristics relative to other sources of energy. For example, Denholm and Margolis (2008) estimates that two-thirds of US electricity demand could be met using ”zero-impact” land in the from of residential and commercial rooftop space.

The majority of PV LCA studies are centered around crystalline silicon photovoltaics, which has the largest market share of all photovoltaic technologies. Many studies compare various implementations of crystalline silicon solar cells (including Alsema, 2000) or compare a typical single-crystalline or multi-crystalline silicon photovoltaic system to other sources of electricity (Gagnon et al., 2002),(Pacca and Horvath, 2002). A small number of studies, including Tsoutsos et al. (2005), compare different solar technologies, such as solar thermal power, centralized PV, and distributed PV systems. Meanwhile, a growing number of studies are evaluating the environmental impacts novel or specialty PVs, such as multijunction (Mohr et al., 2003), dye-sensitized (Veltkamp and de Wild-Scholten, 2006), or concentrator photovoltaic systems (Peharz and Dimroth, 2005).

Across the PV LCA literature, process-based methods dominate over economic input-output (EIO) or hybrid assessments. Most authors employ a combination of original process data and data from established LCA databases. Modeling using the Simapro software package and the Ecoinvent database is particularly popular, with traction amongst many of the most prolific PV LCA authors including Erik Alsema, Vasilis Fthenakis, and Mariska de Wild-Scholten. Pacca and Hovarth (2002) are among few authors in the PV LCA who have employed hybrid EIO process-based methods to evaluate PV life cycles.

A number of studies have focused specifically on the balance of system (BOS) components such as the inverter, mechanical mountings, and cables needed to implement a PV system (Mason et al., 2006). These studies are important because many studies directly employ the Ecoinvent values for roof-mounted photovoltaic installation, which suffer from lack of resolution given that BOS components may contribute as much as a half of the environmental impacts of an installed PV system. Finally, a number of studies are have evaluated end-of-life processing, particularly that of CdTe photovoltaic systems, for which end-of-life toxcity is a major environmental concern.

Many authors, including Pacca (2007), Sherwani(2009)(Sherwani et al., 2009), and Raugei (2009)(Raugei and Frankle, 2009) have reviewed and summarized numerous life cycle studies of PV systems in the literature. Bankier and Gale (2006) compiled low and high estimates of energy payback time from the literature, covering many types of roof-mounted PVs. However, due to many difference in the assumptions and system parameter values chosen, it is difficult to extract conclusions across studies. Knapp and Jester (2000) recognized the influence of two such parameters (insolation and production energy intensity) in their meta-analysis of energy payback times.

Finally, it is important to take note of the semiconductor LCA literature. Highly detailed studies by Boyd et al. (2009), Krishnan et al. (2008a), and Williams (2004)(Williams. and

E., 2004) may be useful resources as there are many similarities between PV and semiconductor manufacturing in terms of materials use, equipment, processes and facilities.

1.2.2 PV LCA Guidelines

Differences in assumptions, scope, and methodology are to be expected in life cycle assessment. Though there is the potential for apples to oranges comparisons, such differences are not inherently problematic. For example, Hocking et al. (1995) and Lave et al. (1995) employ very different approaches to quantifying the energy use of paper and plastic drinking cups. The energy use reported by Lave et al. is dramatically higher than that reported by Hocking et al., 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, and even slight differences in scope may have significant consequences (de Koning et al., 2006). Results of disparate analyses are commonly compared side-by-side, both by LCA practitioners and laypeople alike. In part, this may be because there is a large number parameters that influence 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.

There is great need for better definition of breadth, depth, specificity, and standardization of PV-specific parameters, including for energy conversion efficiency, installation performance ratio, insolation, location, and lifetime. Manufacturing location and transportation requirements are two factors that are assumed to be static in many assessments, when in fact, they do vary and they influence results. Just as manufacturing location influences the energy mix consumed during manufacturing, the installation location influences the energy mix offset by the output of the photovoltaic system.

A number of influential LCA practitioners recently defined a set of guidelines that expand on the general guidelines defined by ISO 14040 and 14044 explicitly for LCA studies of photovoltaic systems in a document called Methodology Guidelines on Life Cycle Analysis of Photovoltaic Electricity (Alsema, 2009). Tables 1.2 and 1.3 summarize the recommendations the document makes regarding model and physical system characteristics, respectively.

<table>
<tr><th>Subject Area</th><th colspan="2">Recommendation</th></tr>
<tr><td>Functional Unit</td><td colspan="2">Impact per kWh electricity or m² laminate.</td></tr>
<tr><td rowspan="5">System Boundaries</td><td>State</td><td>Location, module technology, and voltage output</td></tr>
<tr><td>Include</td><td>Panel, mounting system, cabling, inverter, and any other components necessary to produce electricity to the grid. Energy and material flows associated with manufacturing processes, climate control, ventilation, production hall lighting, on-site abatement, and waste treatment systems.</td></tr>
<tr><td>Optional</td><td>Equipment (list separately)
Transmission/distribution losses</td></tr>
<tr><td>No opinion</td><td>Administration, research</td></tr>
<tr><td>Exclude</td><td>Commuting</td></tr>
<tr><td>Methods</td><td colspan="2">EIO not specifically recommended</td></tr>
<tr><td rowspan="2">Energy Mix</td><td>PV production</td><td>Present energy mix</td></tr>
<tr><td>Comparison of PV output</td><td>Future energy mix</td></tr>
<tr><td rowspan="3">Impact Categories</td><td>Include</td><td>GHG, CED, human toxicity, ecotoxicity, radionuclide emissions, nuclear waste generation, air pollutant emissions (NOx, SO2, PM10)</td></tr>
<tr><td>No consensus</td><td>Land use
Water use</td></tr>
<tr><td>Do not include</td><td>Resource depletion (due to lack of data for scarce metals such as indium, gallium, and tellurium).</td></tr>
<tr><td rowspan="2">Reporting Characteristics</td><td>State</td><td>Goals and commissioner of study.
Intended purpose and audience.
Module technology/efficiency, voltage output, irradiation, manufacturing location, and assumptions regarding materials, mounting, and balance of systems.
GWP time horizon, CED description, EPBT calculation, and primary energy to electricity conversion factor.</td></tr>
<tr><td>Results</td><td>Mid-point indicators: GHG, CED, AP, ODP, etc.</td></tr>
</table>

Table 1.2: Model recommendations made by the IEA PV LCA committee. Adapted from Alsema, 2009.

These recommendations still allow for many differences in PV LCA studies, but will hopefully help develop cohesion in the key areas they address. At minimum, these recommendations raise awareness of the need for thorough documentation of influential system and model parameters.

Lifetime	Mature encapsulation technologies	30 yr
	Cabling	30 yr
	Structures, roof-mount	30 yr
	Structures, ground-mount	30-60 yr
	Inverters	15 yr
Performance Ratio	Site specific value	
	Roof-mount	75%
	Ground-mount	80%
Irradiation	Industry average	**Optimal orientation/tilt**
	Best case studies	
	Installed systems	Actual irradiation
Degradation	80% of initial efficiency at end of life, with linear degradation over 30 yrs	

Table 1.3: Physical system recommendations, adapted from Alsema, 2009.

One of the features of this producer-focused model, scenario functionality discussed in Chapter 3, and these recommendations are both motivated by the same observations of disparate and incomparable studies in the literature. This work is influenced by these recommendations to highlight physical variables of the PV life cycle, namely the PV lifetime, performance ratio and degradation. In Chapter 5, the sensitivity of the model to these physical variables will be presented, thereby quantifying the importance of these physical variables.

The guideline also highlights the need for producer-focused life cycle assessment because it states that PV LCA studies should specify their goals as one of the following.

- **Retrospective LCA**: Reporting of environmental impacts of PV currently installed in a utility's network.
- **Short-term Prospective LCA**: Choice of a PV electricity supplier, comparison of PV systems, or comparison of electricity generating technologies.
- **Long-term Prospective LCA**: Long-term energy policy, comparison of future PV systems or comparison of future electricity generating technologies.

While these three goals are important to utilities, consumers, and policy makers, respectively, a perhaps even more important application of LCA remains overlooked and unexploited. This dissertation work serves to fill the needs of producers, guiding them toward continuous environmental improvement in the design, manufacture, and deployment of the real-world PV systems.

1.3 Scope of the Study

This work expands the capabilities of LCA for PV systems in two ways: (1) a scenario functionality is employed to better understand impacts of the installed system, and (2) the impacts of manufacturing utilities are correlated to the process steps that consume them to better understand impacts of individual process steps.

This dissertation identifies the primary energy and global warming potential impacts of all materials, processes and utilities that are consumed in the manufacture of thin-film silicon (TF-Si) photovoltaic systems under numerous technological, manufacturing, and installation parameters.

The LCA model is unique in the literature in that it allows users to evaluate any combination of 6 technology versions, 12 manufacturing locations, 18 installation locations, and numerous other user-selected parameters. The model also allows users to easily add additional choices for any of the parameters. This scenario functionality is important as the PV industry is an extraordinarily globalized industry, with China and Taiwan now producing 50% of world production according to the European Commission (2010).

The thin-film silicon PV system is a tandem junction thin film silicon PV system consisting of amorphous and microcrystalline silicon junctions. The technology is widely adopted; currently fourteen 60-100 MW manufacturing plants worldwide employ the materials and processes evaluated in this study, while many others use very similar technologies.

The LCA model discussed in this dissertation largely follows the model recommendations summarized in Tables 1.2-3.Though they are listed as optional, this dissertation includes and discusses the impacts of manufacturing equipment and transmission and distribution losses. However, due to the unique geography-specific and detailed manufacturing-specific features of this LCA model, many common midpoint indicator data sources were not available or not judged to be of high enough quality, and were therefore omitted from the analysis.

The remainder of this dissertation introduces life cycle assessment (Chapter 2), explains the mechanisms and contributions of producer-focused life cycle assessment (Chapter 3), describes the PV system in detail (Chapter 4), quantifies and communicates the environmental impacts of thin-film silicon photovoltaic systems (Chapter 5), and illustrates some of the lessons learned and new questions posed by this work (Chapter 6). Chapter 7 expounds on one typically neglected but important aspect of this and all manufacturing systems: the environmental impacts of labor. Finally, Chapter 8 discusses the conclusions and future implications of this work.

Chapter 2

Life Cycle Assessment

2.1 Definition

Life cycle assessment (LCA) is a holistic method of evaluating the environmental impacts of products. A holistic method is important and necessary to ensure that changes taken to reduce the environmental impact of a product are not displaced by increased impacts elsewhere in the life cycle of the product. A shift from steel to light weight aluminum car bodies, for example, can reduce energy use during the operation of the vehicle, but the savings must outweigh any additional energy costs up to and during manufacturing.

Life cycle assessment developed from early material flow analysis (MFA), and was formalized by the Society of Environmental Toxicology and Chemistry (SETAC) starting in the 1980s (Bretz, 1998). Since then, the United Nations Environmental Program (UNEP, 1999) and the United States Environmental Protection Agency (US EPA, 1993) have produced informative guides to life cycle assessment.

The most recognized definition of LCA comes from the International Standards Organization (ISO) 14040 and 14044 standards, which describe life cycle assessment as the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle (ISO, 2006). As defined by ISO, and shown in Figure 2.1, LCA is comprised of 4 major steps: (1) goal and scope definition, (2) life cycle inventory, (3) life cycle impact assessment, and (4) interpretation.

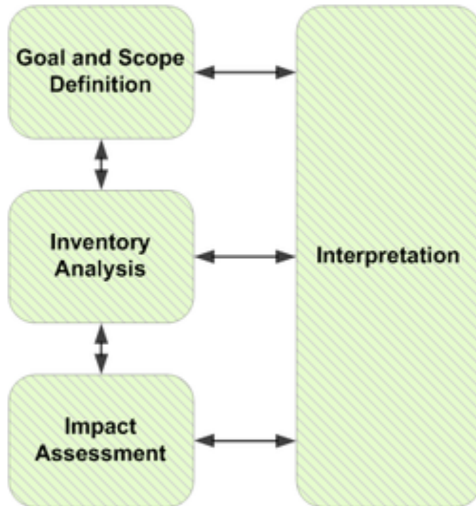


Figure 2.1: Four phases of life cycle assessment as described by ISO 14040.

2.1.1 Goal and Scope Definition

The first and most important step in any life cycle assessment is to establish the goals, scope, and functional unit. LCA practitioners have many choices when it comes to the intended audience, intended application, and scope of the study; many choices are discussed in detail in Section 2.2.

The functional unit of a study is a quantity of good or service to which environmental impacts can be attributed. A study may evaluate dissimilar products if they serve similar functions and can be correlated to the same functional unit. For example, one passenger-mile often serves as the functional unit of studies evaluating airplanes, trains, and personally owned automobiles.

The goal and scope definition step is also the opportunity to decide the environmental metrics relevant to the study, whether they are global, regional, or local. If needed, allocation procedures, data assumptions, and data quality requirements should be determined and stated prior to other LCA steps.

2.1.2 Inventory Analysis

Life cycle inventory (LCI) is the collection of data concerning the material and energy flows within the scope of the study. Inventory data may come from practitioner-collected process data, published studies in the literature, LCI databases, or a combination of sources. Table 2.1lists a number of LCI databases and their characteristics.

LCI database	Region	Data Focus	Datasets	Fee
Ecoinvent	Switzerland/ EU/Global	General	>1000	€ 1,800 per user
GaBi	Germany/ Global	General	>1000	> € 2,460
Spine	Sweden/ Global	General	>100	>$37 per dataset
EIO-LCA	US	Input-Output	>100	Free
BEES	US	Building Materials	>100	Free
Athena	US	Construction	>100	> $1,000 per user
GREET	US	Transportation	>100	Free

Table 2.1: Popular life cycle inventory databases.

A main distinction exists in inventory structure between process-flow or process-tree structure, which correspond to process-based methods, and matrix structure, which correspond to input-output methods, both of which are discussed in Section 2.3.

2.1.3 Impact Assessment

Inventory flows must then be transformed into one or more environmental impacts (see Section 2.2) via the following mandatory and optional impact assessment steps:

Mandatory

- *Classification:* Inventory flows must be classified into relevant impact categories. For example, N2O is a greenhouse gas while NO2 is a criteria air pollutant.
- *Characterization:* The quantity of each inventory flow is converted to a unit of impact through characterization. For example, N2O has a characterization factor for global warming potential of 310 g CO_2 eq. over a 100-year time horizon (IPCC, 2007).

Optional

- *Normalization:* To normalize an environmental impact is to compare it to a reference quantity of impact. A reference quantity can be the impact of another product, a household, a region, or of the resources available. For example, the ecological footprint methodology normalizes land use impacts of a particular product or lifestyle to the amount of land that is available to each person if distributed evenly (Wackernagel and Rees, 1996). Normalization is useful for conveying the significance of otherwise nebulous environmental metrics.
- *Weighting:* Dissimilar environmental impacts may be aggregated into a single metric of impact though weighting. By necessity, one must assign a relative importance or weight to each impact category evaluated. There is no standard way of weighting impacts, though many common schemes exist. Priorities in weighting may shift due to practical, social or political factors over time and from region to region. For example, water use may be weighted much higher than other impacts in arid regions, particularly during periods of drought.

2.1.4 Interpretation

Finally, results of inventory and impact assessment is interpreted to extract conclusions and recommendations. Sensitivity and uncertainty analysis is an important aspect of interpretation, as it informs the conclusions and recommendations. ISO 14040 further recommends undergoing a peer review process, particularly if the results are to be made public.

In addition to these LCA authorities discussed above, both the World Resources Institute (WRI, 2008) and the British Standards Institution (BSI, 2008) have developed guidelines to formalize life cycle greenhouse gas (GHG) accounting. The WRI Greenhouse Gas Protocol and the BSI Publicly Available Standards 2050, known as PAS 2050, characterize this particularly popular subset of life cycle assessment. They differ from most life cycle analyses in their focus on greenhouse gas emissions as the sole indicator of environmental impact. The scope of GHG accounting tends to be more focused on direct emissions and is defined as follows by the WRI Greenhouse Gas Protocol (WRI, 2007):

- Scope 1 All direct GHG emissions.
- Scope 2 Indirect GHG emissions from consumption of purchased electricity, heat or steam.
- Scope 3 Other indirect emissions, such as the extraction and production of purchased materials and fuels, transport-related activities in vehicles not owned or controlled by the reporting entity, electricity-related activities not covered in Scope 2, outsourced activities, waste disposal, etc.

The remainder of this introductory chapter explains major LCA concepts, including the goals and attributes of LCA studies, process-based and input-output methodologies, and LCA limitations. Finally, Section 2.4 discuses specific guidelines for environmental analysis of photovoltaic systems.

2.2 Goals and Attributes

Life cycle analyses are useful for a number of purposes; they can be used to help consumers compare the impacts of similar or dissimilar products, to better equip designers make informed choices, and to track changes in impacts over time or with technology development. LCA is a basic component of any carbon trading or eco-labeling program. Ultimately, it provides producers and consumers a quantitative method for measuring and managing environmental impacts.

Life cycle studies examine at least two life cycle stages and evaluate at least one indicator of environmental impact. Studies vary tremendously in terms of breadth, depth, specificity, and the environmental impacts deemed relevant. There is not a single right way to perform an LCA, as the purposes can be extremely varied. Rather, the attributes of a particular LCA depend on the intended goals of the study.

2.2.1 Breadth

The LCA literature is comprised of studies ranging from narrowly focused to panoptic. Panoptic studies are often desirable because they can ensure a higher level of accuracy by addressing every area of impact that may be associated with a product. However, there are practical limitations to the scope and level of precision that is possible with an all-encompassing study. (In many countries, economic input-output tables have been combined with environmental data to address the so-called boundary problem of life cycle assessment. Economic input-output life cycle assessment (EIO-LCA) is discussed in more detail in Section 2.3.2.)

For these reasons, narrowly focused studies play an important role. Rather than evaluating the full life cycle of a finished consumer good, such as a car, an LCA practitioner may instead choose to evaluate the life cycle impacts of a small sub-component, such as an injection molding process (Thiriez, 2006). Other examples of focused studies that contribute to knowledge in the LCA community include studies of electronic components (Boyd, 2006), transportation (Facanha, 2006), and labor (Zhang, 2007). The results of these studies may be applied as a modular component in other, broader studies.

2.2.2 Depth

By many definitions, an LCA must convert every economic or physical flow over the entire life cycle of a product to an environmental inventory or impact (Guine, 2002). There are practical limitations to this, and ad-hoc, rather than quantitative, cut-off criteria are often used. Nevertheless, life cycle analyses are often long, detailed works of Ph.D. dissertations.

However, they are not so necessarily. A back-of-the-envelope calculation is often enough to answer a simple question. For example, consider the greenhouse gas emissions of a simple steel widget that is redesigned to be lighter, but becomes more prone to failure. If the material and transportation GHG emissions are reduced by 1/3, but the functional life of the widget is reduced by 1/2, then the redesign is not environmentally beneficial.

Such exploratory studies are becoming more common, especially as LCA moves increasingly beyond the academic community. Businesses, non-governmental organizations, and policy makers are embracing and utilizing LCAs of various depth and scope in their decision-making.

2.2.3 Specificity

On one end of the spectrum, practitioners can choose to examine a specific technology, at a particular point in time and in space. For example, a study may focus on one specific make and model car that is produced at a particular factory, using a known local power mix. Or, a study may instead take an average car produced by the automotive industry, assuming a regional or national power mix.

Some of these differences, towards more or less specificity, may be motivated by data availability. However, there are also practical benefits to choosing one type versus another. Very specific studies can be used to make decisions, regarding process steps, material choices, or transportation options within the life cycle of a product. Whereas general studies, which better represent an average product, may be more consistent with the literature and may allow consumers a more direct comparison of one product class against another.

As a side note, it is common to see data representing a certain region used in studies of products of another region. Much of the Ecoinvent LCA database, for example, represents Swiss or European production, but is commonly used for studies of products made in the US. Such choices may be motivated by the availability, representativeness, or timeliness of data. (See Sections 2.4 and 5.4 for more discussion of data quality.)

2.2.4 Relevant Impacts

Cumulative energy demand (CED) and global warming potential (GWP) are two of the most commonly tracked environmental impacts. Depending on the study, a much wider set of impacts may be relevant, including human toxicity, ozone layer depletion, climate change, photochemical smog, acidification and eutrophication.

	CML 2001 (Netherlands)	EDIP 2003 (Denmark)	Eco-Indicator 99 (Netherlands)	IMPACT+ 2002 (Switzerland)	TRACI (US)
Acidification Potential	x	x	x	Aquatic, Terrestrial	Air
Ecotoxicity	Freshwater, Marine, Terrestrial		x	Aquatic, Terrestrial	Air, Soil, Water
Eutrophication Potential	x	Aquatic, Terrestrial	Aquatic, Terrestrial	Air, Water	
Global Warming Potential	x	x	x	500 yr	x
Human Health/ Toxicity	x		Carcinogens, Ozone Depletion, Radiation, Respiratory	Carcinogens, Non-carcinogens, Respiratory	Cancer, Non-cancer, Criteria Air Pollutants
Land Use/ Conversion			x	x	
Photochemical Smog	Ozone	Ozone			x
Ozone Lay Depletion	x	x		Ionizing Radiation	x
Radioactive Radiation	x				
Resource Use	Abiotic Depletion		Fossil Fuels, Minerals	Non-renewable Energy, Minerals	

Table 2.2: Impact categories included in major life cycle impact assessment methods.

While many specific sets of impacts are commonly used in the literature and by major LCIA methods (see Table 2.2), it is important to note that none are complete. The impacts that are included are ones that are relatively well understood by the scientific community, but many others may emerge in importance as our understanding grows. Some impacts of growing importance may include fresh water depletion, pollination, or habitat loss.

2.3 LCA Methods

Three major types of life cycle assessment methods are (1) process-based, (2) economic input-output (EIO), and (3) hybrid economic input-output methods. The following sections discuss the pros and cons of each LCA method.

2.3.1 Process-based LCA

Process-based assessments, in which the inputs and outputs for each process are analyzed individually, are most common. Process-based assessments are based on a process-flow or process-tree inventory structure, and are considered as bottom-up studies.

This type of assessment may be very time and labor intensive, depending on the attributes of the study. Process-based assessments may be facilitated by life cycle assessment software such as GaBi, Simapro, and Umberto, and databases such as those listed in Table 2.1.

Process-based assessments are generally recognized as the most precise method of conducting a life cycle assessment. However, for practical reasons, process-based assessments must focus on finite set of processes that are most commonly determined by non-quantitative means. Without having performed the assessment, one cannot be certain which processes are most important. Repeated iteration is important to ensure inclusion of consequential process flows and accurate results.

The sum of many small processes may be very significant and in certain cases, even more significant than the larger processes that are included (Matthews, 2008). Therefore, process-based assessments suffer from an inherent boundary problem that may affect the accuracy of results (see Figure 2.2).

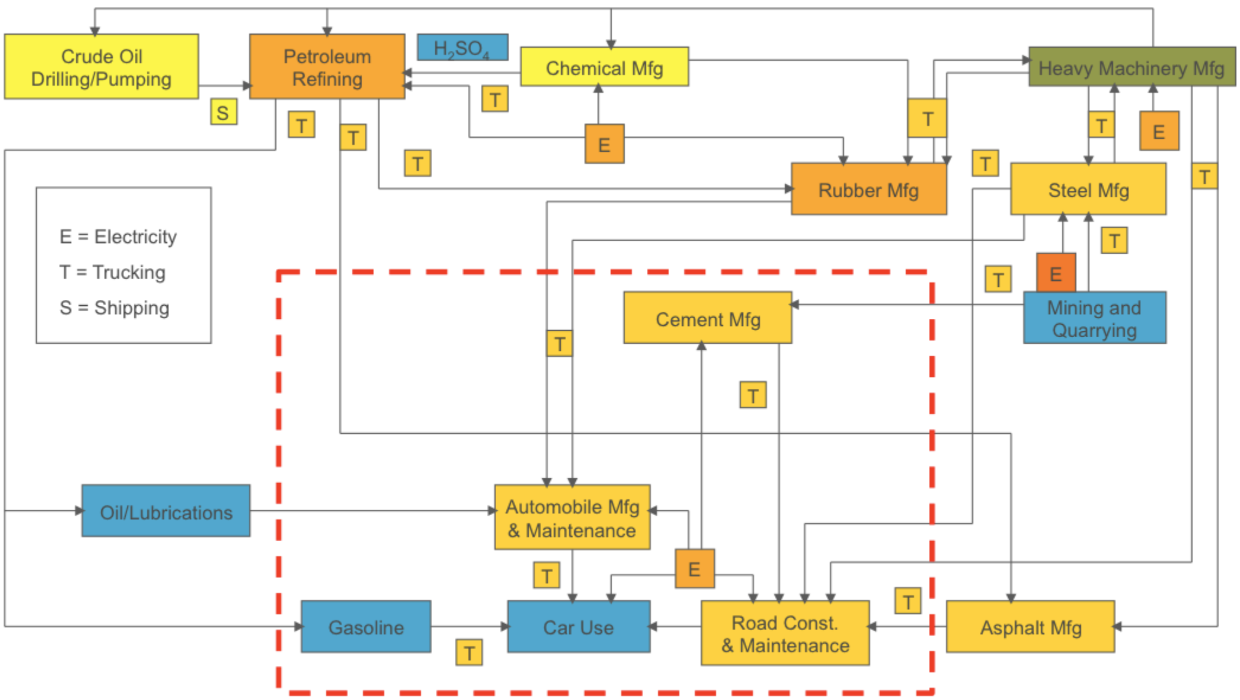


Figure 2.2: Sample boundary conditions for an LCA study of car use.

2.3.2 Economic Input-Output LCA

Economic input-output LCA (EIO-LCA) is a very comprehensive but imprecise LCA method that is based on economic activity. The US Bureau of Economic Analysis (BEA) publishes regularly publishes input-output (IO), or Leontif, tables which comprehensively document the economic activity of each sector of the economy with each other sector of the economy. These tables document the suppliers to any given industry, not only to the first or second level suppliers, but also to the nth level supplier, encompassing all activity within a national economy. (See Appendix Dfor more information on the formulation of EIO-LCA tables.)

Environmental vectors then document, for example, the GWP emissions per dollar of economic activity in the steel industry. Impact categories may vary from model to model; the latest US EIO-LCA model includes greenhouse gases, energy use, water use, and toxic releases. EIO-LCA models are currently available in the US, Germany, Spain, China, and Canada (GDI, 2011).

EIO-LCA is a comprehensive, economy wide assessment method because the underlying EIO model traces the consumption of every sector from every other sector. One of the main advantages of the EIO-LCA method is that it eliminates the need to establish arbitrary boundary condition as all impacts, economy-wide, are included. Furthermore, EIO-LCA captures circularity, or own-use, effects, such as the power consumed by the power generation sector. EIO-LCA is particularly powerful for quickly assessing goods that are not easily represented by their constituent materials or processes, like individual screws, or financial services. Finally, EIO-LCA model are publicly available, and as a consequence, the results of EIO-LCA studies are significantly more reproducible than the results of process-based studies.

The main drawback of EIO-LCA method is that sectors may be too highly aggregated to offer the resolution that may be desired. Surveys of industries are not equally complete, meaning that some industries are better represented than others. Moreover, the US EIO-LCA model is available for census years only. For very established industries, like the steel manufacturing industry, the results may be accurate. However, emerging and quickly developing industries such as the personal electronics industry will not be accurately represented. Finally, it is important to take note that EIO-LCA models imports as having the same impacts as products made domestically.

2.3.3 Hybrid EIO-LCA

The are pros and cons to both process-based and EIO-LCA methods. To take advantage of pros from either method, they may be combined into one of three hybrid forms. The forms of hybrid EIO-LCA described by Suh et al. (2004) as follows:

- Tiered hybrid analysis: Employs process based data for the most part, with EIO-LCA components employed to fill in gaps in the process flow.
- Input-output based hybrid analysis: Disaggregates input-output sectors where possible to best describe process-specific data.
- Integrated hybrid analysis: Employs a commodity-based, rather than economic sector-based, input-output matrix.

Of these, the tiered hybrid analysis is most commonly used, as it offers practitioners great flexibility in implementation with process-based components. The input-output based hybrid method is essentially a matrix-based EIO-LCA assessment that is augmented with process-based data for specific sectors. Integrated hybrid analysis on the other hand, is another form of EIO-LCA where economic flows are grouped by commodity type rather than by economic sector.

2.4 Limitations of Life Cycle Assessment

Life cycle assessment is a powerful technique, but each individual study is limited by the researchers choice in attributes described in Section 2.2. One must make a trade off between breadth and precision, between depth and reproducibility, and between specificity and comparability.

Furthermore, life cycle analyses may not definitively distinguish one product as a the better environmental choice than another; LCA studies may only compare products in terms of well understood and predefined environmental impact indicators such as global warming potential, acidification, and ecotoxicity.

Regardless of the choices made, a life cycle assessment study generally faces problems of consistency with the literature due to the wide range of practices in use today. As the LCA field develops and formalizes further, a wide range of practices may continue to flourish, but consistency problems may be ameliorated through improved classification and communication standards, such as those described in section 1.2.2.

In general, the LCA field as a whole is limited by data availability and data quality. Data must be precise, complete and, though practically diametrically opposed, both temporally and geographically representative. There are wide variations in the collection of data, as well as known and unknown data gaps.

Problems of data are often times related to the still nascent nature of the field. Environmental process data is not typically collected in most industries, though this is quickly changing. However, environmental data may not be made publicly available in unaggregated form or in any form due to the sensitivity of the data itself or the intellectual property that may be disclosed with the data.

Another important limitation in LCA has to do with the choice of impacts reported. Product A may have lower global warming potential emissions than product B, but product B may be deemed the better environmental option if photochemical smog is weighed more highly or is the sole metric of environmental impact chosen. There are additionally many categories of environmental impacts, like pollination or habitat loss, that are not currently a part of LCA methodology because we lack the understanding needed to quantitatively correlate actions with impacts.

Even within a single impact category, there may be differences in environmental rankings. For example, a CdTe photovoltaic system releases far less toxic material per kWh of electricity produced using a coal-fired power plant(Fthenakis, 2004). However, the concentration of emissions for the CdTe PV system may be much higher than for the coal-fired power plant. The toxicity of Cd releases may be calculated as a function of the quantity, concentration, or both quantity and concentration of emissions. Finnveden (2000) is a good resource for a numerous other limitations of LCA, including problems of allocation, persistent emissions, and differences in characterization.

Finally, life cycle assessment as described herein is what is considered attributional LCA as opposed to consequential LCA, which deals with the macro effects of a specific technology or activity. Attributional LCA may be described as a study of the environmental characteristics of a static system, whereas consequential LCA aims to quantify the future or marginal impacts of choices taken today (Weidema, 1999).

These two forms of LCA may yield significantly different results. For example, a new process for making steel may reduce the energy demand of steel, while simultaneously decreasing the price of steel and increase the rate of production. The consequence of this attributionally beneficial process may be a rebound effect, an increased consumption of steel, which may more than offset the initial savings. Consequential LCA is an emerging subfield of LCA, and faces even greater problems of data availability, uncertainty, comparability, and reproducibility.

Chapter 3

The LCA Model

The LCA model described here is a tiered hybrid EIO-LCA cradle-to-grave model, based on extremely detailed and high quality manufacturing data. The primary intended audience for the model is design and manufacturing engineers. There are two primary features of the model that make it particularly well suited for design for environment purposes: facilities integration and scenario functionality. Sections 3.1-3.2 describe the characteristics and applications of these producer-focused features.

3.1 Facilities Integration

This model is unique in sorting out the environmental impacts of individual processes, including the utilities consumed by each process step. This is in stark contrast to studies, which evaluate the manufacturing life cycle as a static black box. The tendency to do so is great, as the impacts of any particular manufacturing step are often distributed over the factory facilities. Therefore, one of the most significant innovations of this model is its ability to correctly attribute the electricity demand of manufacturing utilities to the processes that consume the utilities, rather than to the factory facilities systems that produce utilities.

This allows for manufacturing processes to be assessed in a holistic manner, analogous to what LCA does for products. Not all life cycle assessments in the literature account for the full impacts of a process, though it is the only way we can meaningfully compare one process to another.

Facilities integration represents more than a simple expansion of system boundaries. Many other studies do include the facilities impacts of processes, but no others in the PV LCA literature do so dynamically and with such great detail. Facilities integration correlates the environmental impacts of manufacturing facilities to the utility consumption of manufacturing process tools. Whereas, the facilities are typically views as static entities, this functionality more accurately models the activity of manufacturing facilities as a function of the process tools that they support.

3.1.1 Electricity Use

SEMI is an industry organization, which in 2008, published SEMI S23-0708 - Guide for Conservation of Energy, Utilities and Materials Used by Semiconductor Manufacturing Equipment. SEMI S23, as it is known, outlines a set of energy conversion factors (ECFs), shown in Table 3.1, that correlate utility use and electricity consumption for each utility system (SEMI, 2008). Note that while SEMI S23 is intended to be a comprehensive guide based in LCA methodology, the scope of the current version is limited to electricity use within factories. Therefore, ECFs more accurately refers to electricity conversion factors than to energy conversion factors.

SEMI S23 ECFs are derived from measured data from SEMI member facilities, including many from members of the Japan Electronics and Information Technology Industries Association (JEITA). The accuracy and applicability of the ECFs vary with the utility; some ECFs (such as heat burden) are recognized as accurate and applicable for a wide range of facilities, while others indicate a value within the distribution. Though SEMI S23 does not account for them, regional factors such as humidity and the quality of the municipal water supply will affect the true environmental cost of each unit of utility.

This dissertation presents a version of SEMI S23 for PV manufacturing facilities. The details of the PV-specific facilities integration model are discussed in Section 4.2.1. Electricity use in the life cycle inventory based on facilities integration and other data sources are then correlated to cumulative energy demand and global warming potential for each scenario, as described in Section 3.2.

Utility	Energy Conversion Factor	Units
Direct Electrical Power	1	kWh/kWh
Ultra Pure Water ($\leq 25°C$)	9.0	kWh/m^3
Ultra Pure water ($> 85°$)	92.2	kWh/m^3
Process Cooling Water ($< 25°C$)	0.258ΔT + 0.273	kWh/m^3
Process Cooling Water ($\geq 25°$)	0.26	kWh/m^3
Bulk Nitrogen	0.25	kWh/m^3
Clean Dry Air ($\leq 120psi$)	0.147	kWh/m^3
Clean Dry Air ($120 - 150psi$)	0.175	kWh/m^3
House Vacuum	0.06	kWh/m^3
Exhaust	0.0037	kWh/m^3
Heat Burden	0.287	kWh/m^3
Heat Removal via Air	3.24×10^{-4}ΔT	kWh/m^3
Heat Removal via Water	1.16ΔT	kWh/m^3

Table 3.1: SEMI S23 energy conversion factors (ECFs).

3.1.2 Water Use

Water is an increasingly scarce resource in many manufacturing areas, and as a result, equipment providers and factory operators are seeking more water-efficient manufacturing methods. Equipment suppliers can better contribute to these reductions if they understand how their products contribute to overall water-use.

The amount of feedwater that a factory uses to support the operation of a process tool is a function of both the factory and the tool itself, as shown in Figure 3.1. A process tool consumes feedwater in three ways: by 1) direct use of feedwater at the tool, 2) by direct use of processed feedwater in the form of ultra-pure water (UPW) and 3) by indirect use of feedwater needed to provide cooling for the tool and for the facilities systems supplying utilities to the tool.

These factors in turn depend on the amount of energy and non-electrical utilities that are used by the tool. This is directly analogous to SEMI 23 for electricity. In fact, the facilities integration model for water requires the same process tool utility use data as SEMI S23, with the addition of direct feedwater use.

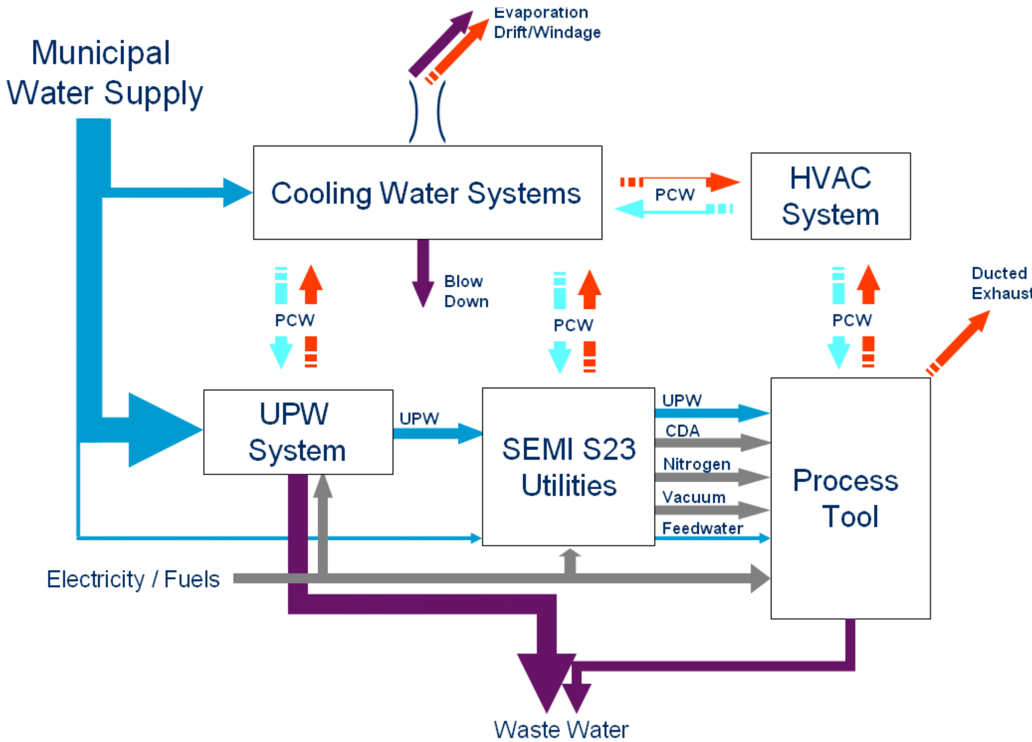


Figure 3.1: Water model overview.

However, facilities water systems are very complex and may vary more significantly in design and operation than other utilities systems. Therefore, water conversion factors (WCFs) are not static, but based on 15 water system operating variables. Default values of the variables and brief definitions are given in Table 3.2.

These variables account for differences in cooling water systems and in UPW system design, feedwater quality, recycling rates and re-use rates (note that values may be zero for some variables). WCFs based on default values for these variables can be used for basic analysis and comparative benchmarking. The operating variables may be modified to create custom WCFs to estimate process tool feedwater requirements under specific factory conditions.

It is desirable to consider water and energy together because 1) energy and water use are often related, 2) both can be estimated from the same inputs and 3) considering water and energy use together allows design and process engineers to understand interactions between the two.

As with electricity, the supply system efficiency for water subject to regional differences. However, unlike electricity systems, the system information available for water is extremely limited (Stokes, 2009). Regional differences make it hard to know what the life cycle water impacts of our activities are, and so this analysis is limited to the direct water requirements of manufacturing.

Ultra Pure Water System Variable	Default Value	Definition of Variable
Loop Ratio	3.0	Ratio of UPW polishing loop flow vs. consumption
UF Recovery	95%	Percent yield of ultra filtration (UF) treatment
UF Reject Reuse	95%	Percent ultra filtration reject retreated for reuse
RO Recovery	80%	Percent yield of reverse osmosis (RO) treatment
RO Reject Reuse	60%	Percent RO reject that is retreated for reuse
PT Water Loss	3%	Percent lost in pretreatment (PT)
IEx Water Loss	0%	Percent lost in pre-RO ion exchange (IEx) systems
Recyc. Uncont. Water	30%	Percent UPW consumption directly retreated for reuse
Recyc. with RO	30%	Percent UPW consumption recycled with RO
Recyc. RO Recovery	90%	Percent UPW recycled with RO recovered
Recyc. with IEx	0%	Percent UPW consumption recycled with IEx
Recyc. IEx Recovery	95%	Percent UPW recycled with IEX recovered
Feedwater / UPW	0.58	Units feedwater needed per unit of UPW consumed
Cooling Water System Variable	**Default Value**	**Definition of Variable**
Reclaimed MUW	0%	Percent make-up water from reclaimed sources
Cycles of Concentration	4	Ratio of mineral conc. of circulating vs. make-up water
Feedwater Intensity	2.13	Liters feedwater needed to remove every kWh of heat

Table 3.2: Water system variables, default values, and resulting water intensity per unit of ultra pure water and per kWh of heat load.

The two main components of manufacturing water use are the ultra-pure water and cooling water systems, as the volume of direct feedwater use is diminishingly small.

Ultra-pure water, which is also known as deionized or DI-water, is used for numerous wash steps. UPW is so pure than even spent UPW is significantly less contaminated than feedwater from most municipal water supplies. As a result, the feedwater that enters a UPW

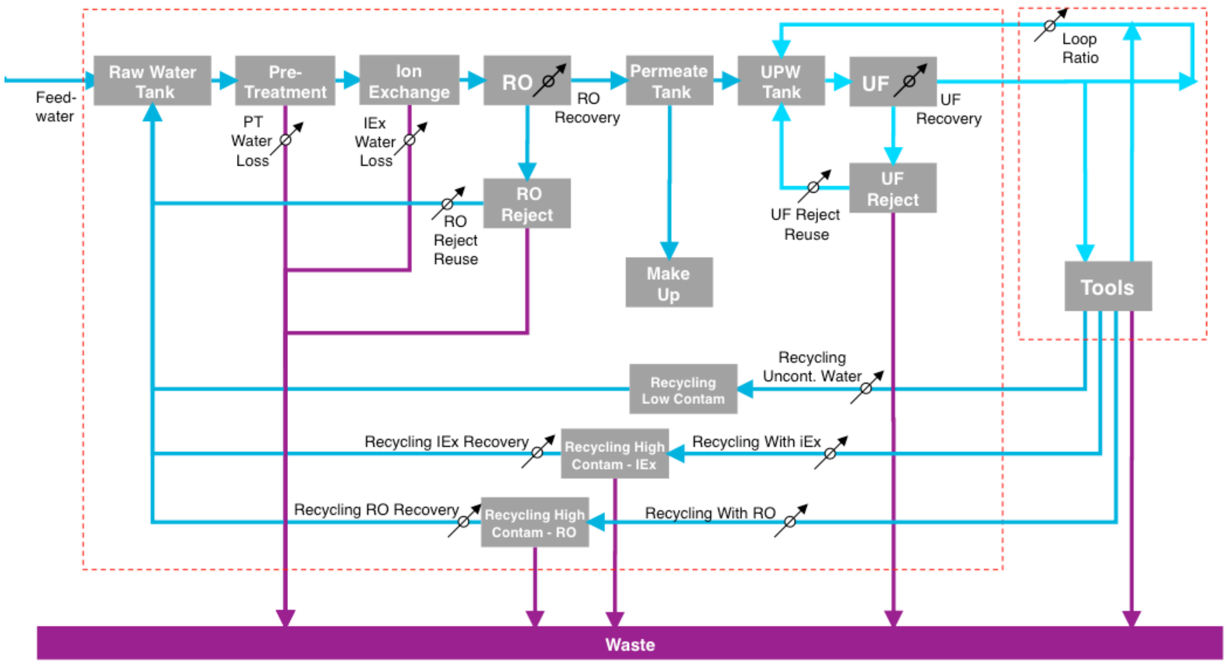


Figure 3.2: Schematic of an ultra-pure water system and operating variables affecting water use.

system is typically recirculated in some capacity. Figure 3.2shows a schematic of a generic UPW system and the 13 variables that affect water consumption (terms are defined in Table 3.2).

Cooling water systems are much simpler in comparison. An evaporative cooling tower removes heat from the factory and factory facilities via cooling water loops. Though cooling water loops are closed systems, they consume significant quantities of water through the cooling systems. The amount of water use, M, depends on the amount of heat, Q, the specific heat of water, H_v, the cycles of concentration of the system, C_r, and the reclamation rate, Re. Re refers to water from other sources within the factory or factory facilities, such as reverse osmosis reject water from UPW treatment.

Of these, Q and H_v are known while C_r and Re are measured quantities. The cycles of concentration refers to the concentration of minerals in the cooling tower circulating water relative to that of the make-up water, M. For a certain quality of make-up water, higher C_r means that less water needs to be blown down or bled to maintain a relatively higher concentration of minerals in the circulating water.

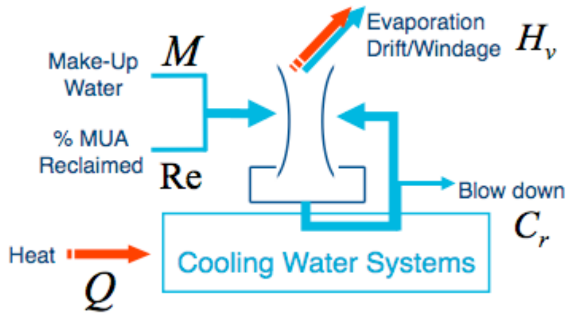


Figure 3.3: Schematic governing the quantity of make up water required for cooling systems.

$$M = Q \times \frac{1}{H_v} \times \frac{C_r}{C_r - 1} \times (1 - Re) \tag{3.1}$$

Note that the term water use refers to water withdrawals, rather than water consumption (though water consumption can also be calculated from this model). Water withdrawal is to water supplied to a system from a reservoir of water, while water consumption is water withdrawn but not returned to a reservoir. By this definition, withdrawals correspond to the water inputs to the UPW and cooling water systems (the municipal water supply in Figure 3.3), while consumption corresponds to evaporative and drift (or windage) losses of the water tower only.

Tools typically consume more water through the facilities than they do directly, and these models help quantify the direct and facilities water use of any tool just as the facilities integration model does for electricity use. This technique may provide equipment and process designers with valuable insight into tool feedwater requirements, an important aspect of the environmental performance of their products.

3.2 Scenario Functionality

This model is unique in its adaptability to a number of manufacturing and operating parameters. Six different versions of the technology, each with slight differences in materials and processes, are included in the model. Users may select any one of the existing versions or input additional versions based on future developments. Likewise, users may select fro among 12 pre-defined manufacturing countries or regions, 18 pre-defined installation locations, or input additional user-generated scenarios. The origins of the values built into the model are explained in the sections below. Users may also input alternate values for module lifetime, efficiency degradation, performance ratio, and transportation distances by road, rail or oceanic freight.

3.2.1 Technology Version

The TF-Si PV system has undergone numerous revisions. Some aspects of each technology version are shown in Table 3.3. In addition to the parameters shown, many of the costs of materials inputs also vary, typically decreasing with later versions, both due to technology improvements and increased production volume.

Technology Version	SunFab 1.0-85	SunFab 1.0-85 Module 2.0	SunFab 2.0-85 Module 2.0	SunFab Module 4.0 SnO	SunFab Module 4.0 ZnO	SunFab 4.0 ZnO 100MW
Efficiency (%)	8.5%	8.5%	8.5%	9.0%	10%	10%
Availability (hr/yr)	7000	7000	7200	7450	7450	7450
Throughput (panels/hr)	20	20	20	20	20	25
Yield (%)	0.95	0.95	0.95	0.96	0.96	0.96
CapEx Lifetime (yr)	7.0	7.0	7.0	7.0	7.0	5.0
TCO Line In-house	No	No	No	No	Yes	Yes

Table 3.3: Existing technology versions included in the LCA model.

The ability of the model to accurately reflect numerous options dramatically expands the utility of the model by enabling users to quantify the environmental impacts of numerous design, production and installation options. This allows users to make informed decisions between existing options and to communicate the significance of proposed changes.

For example, a major design variable is the source of the transparent conductive oxide (TCO) coating that functions as a top contact for each cell. SnO coated glass can be purchased or untreated glass may be coated with ZnO in-house. This model quantifies the tradeoffs between the additional equipment and processing requirements of in-house ZnO with higher performance (transparency 90%, resistivity 10-4 cm) during the life of the resulting PV module (see Section 5.2).

3.2.2 Geographic Data

The impacts of electricity production and consumption vary with the power grid mix from country to country, and from region to region. Weber et al demonstrate that different choices in geographic groupings may result in dramatically different emissions factors (Weber, 2010). Therefore, users may select from pre-defined impact factors corresponding to national averages included in the model or add other countries or sub regions, and corresponding energy and emissions factors.

This feature further allows users to distinguish between existing average power grid characteristics and marginal power grid characteristics. LCA studies of PV systems typically only compare the PV output to that of the existing power grid, particularly for energy payback time analysis. However, as new capacity becomes tends towards clean and renewable power sources, it may become important to compare the environmental characteristics of any power supply option against other viable options rather than against a simple average of the existing power supply mix.

The primary energy use and greenhouse gas impacts per unit of electricity are calculated from (IEA, 2010d). The greenhouse gas emissions of electricity production for each country are directly reported by the IEA (2010b).

A careful distinction is made between the primary energy use of electricity produced and electricity consumed; the latter defined as the electricity produced minus distribution losses and the energy sectors own use of electricity. These values are reported by the IEA Energy Statistics for all countries under study. The total primary energy inputs to electricity generation are calculated as the sum of inputs to electricity plants and combined heat and power plants as reported by the IEA Energy Balances.

The primary energy intensity of electricity produced, $pe_{production}$, is defined for any region or country by Equation 3.1:

$$pe_{production} = \frac{\sum(PE_{Elec.} + PE_{CHP})}{kWh_{Total}} \tag{3.2}$$

where $PE_{Elec.}$ is the primary energy input to electricity plants, PE_{CHP} is the primary energy input to combined heat and power plants (CHP), and kWh_{Total} is the total electricity output of the country or region. This calculation slightly overestimates the primary energy of electricity production because it assumes all the primary energy consumed in combined heat and power plants goes to producing power rather than heat. This assumption is made acceptable because the amount of energy consumed by CHP plants is zero or diminishingly small relative to electricity plants in most regions.

The primary energy intensity of electricity produced must be distinguished from the primary energy intensity of electricity consumed, $pe_{consumption}$, which is also considers the electricity consumed by the power generation plant or own use, kWh_{OU}, and the electricity lost in distribution, kWh_{DL}. The primary energy of electricity consumed corresponds to the electricity that is consumed in manufacturing, while the primary energy of electricity produced corresponds to the electricity that is offset by solar power.

$$pe_{production} = \frac{\sum(PE_{Elec.} + PE_{CHP})}{kWh_{Total} - kWh_{OU} - kWh_{DL}} \tag{3.3}$$

This distinction is more significant in areas with less efficient power systems such as India. However, even in areas with highly efficient power systems, such as Spain and the US, the difference between $pe_{production}$ and $pe_{consumption}$ is non-negligible (15%). Despite this, and the recent recommendations of the IEA, few PV LCA studies make any distinction between the electricity used in manufacturing and the electricity offset by PV operation.

Twelve manufacturing countries are included in the producer-focused model and their primary energy intensity values and global warming intensity values are shown in Figures 3.1 and 3.2, respectively. Global warming intensity of electricity produced comes from the IEA, while global warming intensity of electricity consumed is extrapolated based on the proportion of kWh_{OU} and kWh_{DL} to kWh_{Total} found in the calculation of Equation 3.2.

Data on human toxicity and other environmental impacts is available for materials produced in certain regions from LCA databases Ecoinvent and Gabi, and for industries for countries with EIO-LCA databases. Unfortunately, data on toxicity and other environmental impacts are not known or documented to the precision found in International Energy Agency reports.

Insolation, or incoming solar radiation, data comes from (NASA, 2011) for specific locations or commonly accepted values for certain regions, as shown in Table 3.4.

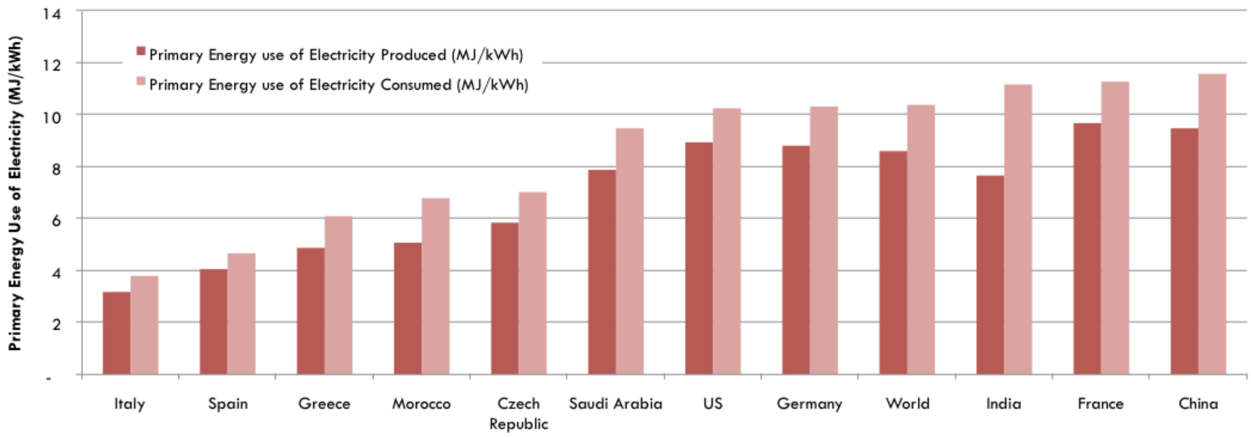


Figure 3.4: Primary energy use of electricity produced and consumed of select countries for the year 2007.

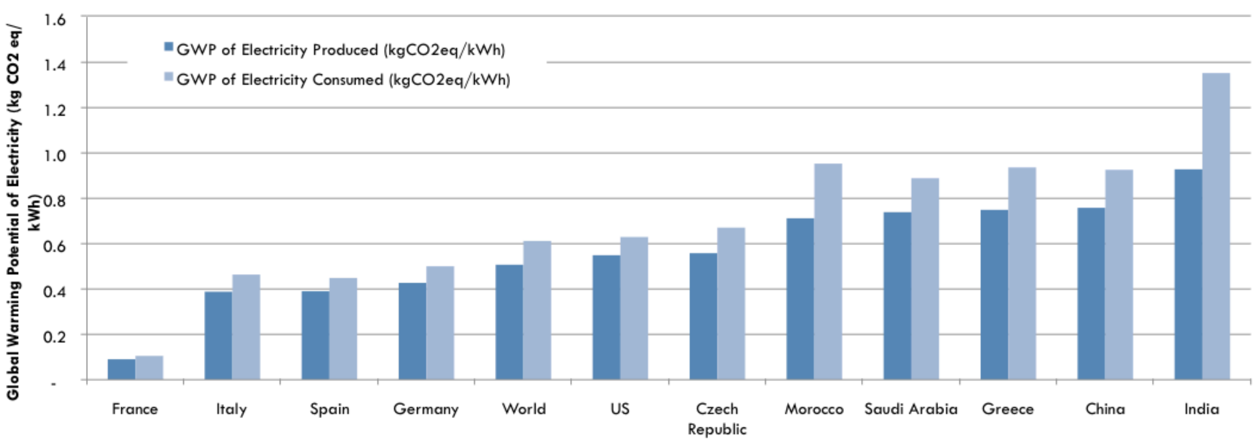


Figure 3.5: Global warming potential of electricity produced and consumed of select countries for the year 2007. Per portion of own use and distribution losses are assumed to be equivalent to that for primary energy use of electricity.

3.2.3 U.S. Example Case

Of the parameters available in the model, a US example case is described by production of the technology version described as SunFab 4.0 ZnO 100MW, with the manufacturing attributes listed in Table 3.5. The functional unit of this study is one 5.72m^2 tandem junction PV module that is manufactured in the US using a US average energy grid and

Location	Insolation (kWh/m^2/yr)
Middle Europe	1,000
Munich, Germany	1,100
Boston, MA	1,307
Detroit, MI	1,307
Toulouse, France	1,370
Shanghai, China	1,460
Sicily, Italy	1,635
Madrid, Spain	1,686
South Europe	1,700
San Francisco, CA	1,785
US Average	1,825
Miami, FL	1,920
Mumbai, India	1,927
Las Vegas, NV	1935
Phoenix, AZ	1,960
Los Angeles, CA	1,970
Riyadh, Saudi Arabia	2,106
Honolulu, HI	2,175

Table 3.4: Installation location and insolation values included in the LCA model.

installed in Pheonix, AZ. The module is modeled as functioning for 30 years, with linear degradation of 20% by the end of life, an average performance ratio of 80%, and 1000 miles of freight transportation by truck (700 miles to installation and 300 miles to end of life).

Just as users of the LCA model may select to evaluate any number of manufacturing and installation options, they may also easily opt to evaluate or omit subcomponents of the full life cycle. This feature allows users to more accurately compare the results of this LCA study to other studies in the literature. Table 3.6 lists the subcomponents that are included or excluded in the U.S. example case study.

Chapter 5 reports the cumulative energy demand and global warming potential of this U.S. example case, along with analysis of a sample technology change and numerous manufacturing/installation location scenarios.

Fab/Module Version:	SunFab 4.0 ZnO 100MW	
Efficiency (%)	10.0%	
Availability (hr/yr)	7,450	
Throughput (sheets per hour)	25	
Yield (%)	96%	
CapEx Lifetime (yr)	5.0	
TCO Line In-house	Yes	
Manufacturing Location:	US	
Primary Energy use of Electricity Consumed (MJ/kWh)	10.26	
GWP Intensity of Electricity Produced (kgCO2eq/kWh)	0.549	
Use Phase Location:	Phoenix, AZ	
Insolation (kWh/m2/yr)	1960	
Primary Energy use of Electricity Produced (MJ/kWh)	8.95	
GWP Intensity of Electricity Produced (kgCO2eq/kWh)	0.549	
Additional Assumptions:		
Module Lifetime (yr)	30	
Degradation at End of Life	20%	
Performance Ratio	80%	
Module and BOS Transportation Distance by Truck	1,000	Miles
Module and BOS Transportation Distance by Rail	-	Miles
Module and BOS Transportation Distance by Ocean Freight	-	Miles

Table 3.5: Screen shot of parameters available for users selection, with U.S. example case selections shown.

Transportation to Mfg	No
Mfg Equipment	Yes
Mfg Infrastructure	Yes
Mfg Labor	No
Mechanical BOS	Yes
Inverter	Yes
Other BOS	Yes
Installation Labor	No
Installation Equip.	No
Transportation to Installation/EOL	Yes
Use phase Maintenance	No
End of Life (EOL)	Yes

Table 3.6: Screen shot of life cycle subcomponents that are selected for inclusion and exclusion in the U.S. example case.

Chapter 4

System Description

This chapter describes each component of an operational thin-film silicon PV system and the associated life cycle inventory. The photovoltaic module under study is a tandem junction amorphous-silicon/microcrystalline-silicon thin-film module, with a cross Section as shown as in Figure 10. The amorphous-silicon (a-Si:H) and microcrystalline-silicon layers absorb wavelengths from 300-700nm and 450-1000nm, respectively. Each full sized module measures 5.72 m^2 (2.3m x 2.6m), approximately 8 times larger than most PV modules on the market. The production line is largely automated as the size and quality control requirements of the modules call for a high level of precision.

One of the strengths of this study is data of unprecedented quality in the PV LCA literature. Measured process data from volume production is documented by the Applied Materials Consumption Data List (CDL) for the 157 manufacturing processes that constitute the amorphous silicon PV production line.

Other data sources include the 2.3 Ecoinvent LCA database, 2002 US Economic Input-Output Life Cycle Assessment (EIO-LCA) database, and recent publications from the LCA literature. Users of the LCA model may select the life cycle inventory data sources for specific materials, where both multiple data sources are available.

While EIO-LCA is known to be more comprehensive and generally report higher impact values, there are exceptions. In the case of uncoated glass, the mass-based energy impact is significantly higher than the EIO-based energy impact, resulting in a 600 MJ difference. In

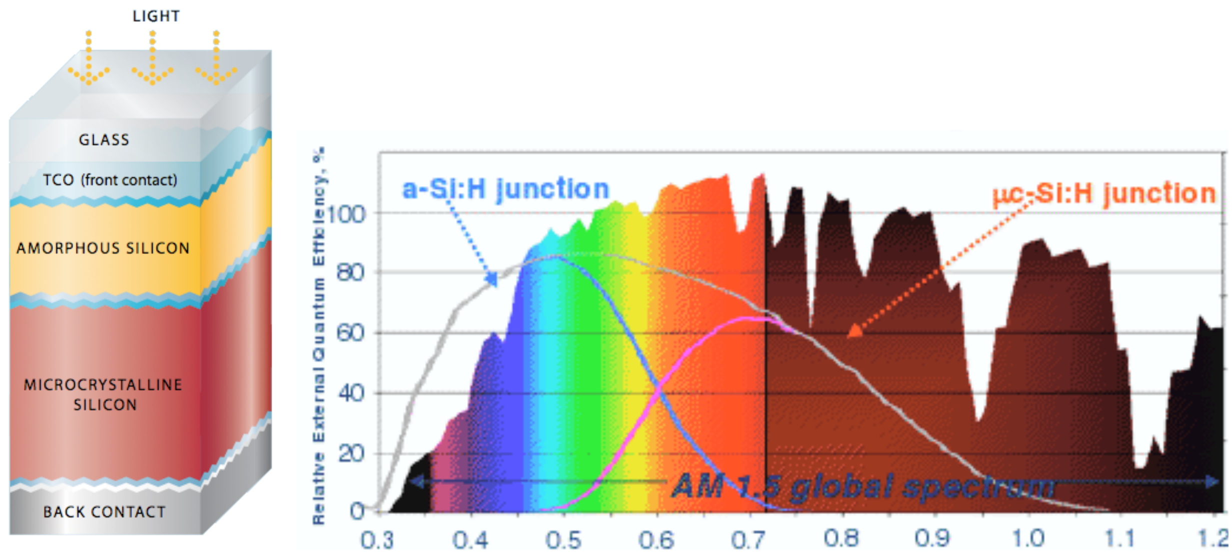


Figure 4.1: A) Cross Sectional schematic of a tandem junction amorphous-silicon/microcrystalline-silicon photovoltaic cell, B) range of wavelengths absorbed by each junction. Images curtesy of Applied Materials.

each case, the data source with the best technological fit was selected as the model default. Occasionally, the lower of the values was selected as the default, but most frequently, and with the higher impact components, it was the higher value that best represented the materials employed.

The impacts of PVs are known to be concentrated in the manufacturing life cycle. With that in mind, this chapter is divided into three main Sections: upstream activity, module manufacturing, and downstream activity. Upstream activity includes the major materials consumed in manufacturing as well as the capital equipment and infrastructure used for manufacturing. Module manufacturing utilities include electricity, clean dry air, and cooling systems that are used in manufacturing but do not contribute to the composition of the finished product. Module manufacturing emissions takes a close look at the emissions of greenhouse gases and other wastes. Finally, downstream activity examines post-manufacturing life cycle stages, particularly the use and recycling of the modules.

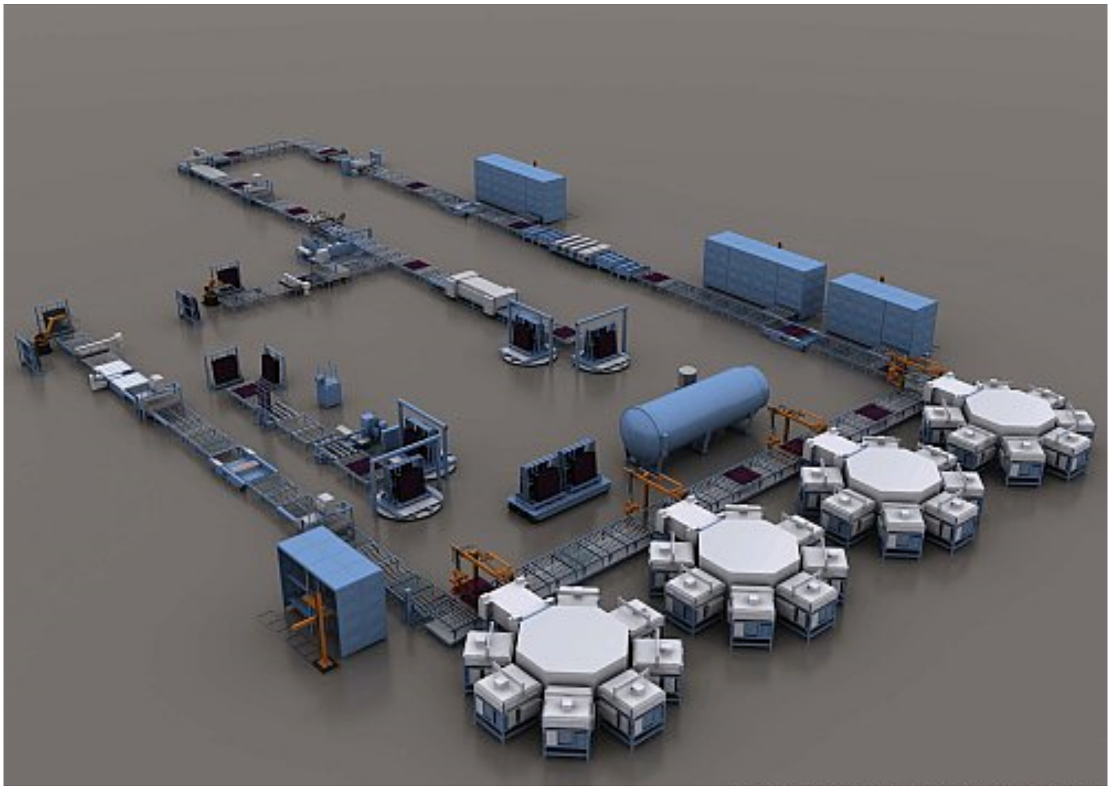


Figure 4.2: Manufacturing equipment used in the production of thin film silicon PV modules. Image curtesy of Applied Materials.

4.1 Upstream Activity

The materials that are consumed to produce photovoltaic systems are divided into the glass, laminate, process gases, target materials, other consumables and equipment and infrastructure. The treatment of each of these materials is discussed in the following Sections.

4.1.1 Glass

The substrate comprises the majority of the mass of thin film photovoltaic modules. Soda lime float glass is typically used as the back and front glass in single junction amorphous solar cells. However, tandem junction amorphous silicon/microcrystalline silicon solar cells evaluated in this study, absorb light at the same wavelength as iron in soda lime glass, and so low iron float glass, sometimes called solar glass, is used in place of the soda lime front glass.

Both soda lime float glass and low iron float glass are well characterized by the Ecoinvent and GaBi LCA databases. Some module versions use low iron float glass that is pre-coated with a tin (II) oxide (SnO) transparent conductive oxide. Because SnO is not characterized by LCA databases, the US 2002 economic input-output model for sector "327211: Flat glass manufacturing" and version-specific cost data are used to model modules employing TCO pre-coated glass.

4.1.2 Laminate

Thin film photovoltaic modules employ a laminate to bind the substrate to the top and bottom glass and to seal out contaminants. The amorphous Si thin film PV under study employs polyvinyl butyral (PVB) as a laminate though ethylene vinyl acetate (EVA) is also a common choice.

While EVA is well characterized by LCA databases, PVB is not. PVB is especially resistant to heat and moisture, and is the most commonly used laminate in automotive glass. Due to the prevalent nature of this material within its industrial sector, the US 2002 EIO model for sector "325211: Plastics material and resin manufacturing" is used to characterize the PVB laminate used.

4.1.3 Process Gases

Eleven process gases are used, mostly during deposition processes to form and dope the semiconductor active layers, and to clean the deposition chamber. The Applied Materials consumption data list describes the consumption of each process gas in terms of the following metrics:

- Connected Flow [standard liters/min]
- Max Flow [sl/min]

- Average Flow [sl/min]
- Pressure [bar absolute]
- Purity [%]

This data combined with information on the duration of flow for each tool produces the following inventory of each process gas (Table 4.1).

With the exception of nitrogen trifluoride (NF_3) and trimethyl boron (TMB), the process gases are characterized by LCA databases, and impact factors are taken from the Ecoinvent 2.3 database. One major caveat of using established LCA databases is that they do not reflect the high purity requirements of these and other gases used in the solar industry. The purity of certain bulk semiconductor gases has been shown to correlate with the energy requirements of purifying the gases, though the exact nature of the relationship is not well known (Krishnan, 2008b).

Process Gas	Purity	Consumption
Hydrogen (H_2)	0.99999%	155 g/m^2
Natural Gas		124 g/m^2
Nitrogen trifluoride (NF_3)	0.999%	97 g/m^2
Argon (Ar)	0.999997%	37 g/m^2
Silane (SiH_4)	0.999997%	34 g/m^2
Nitrogen (N_2)	0.99999%	2.0 g/m^2
Oxygen (O_2)	0.99995%	1.9 g/m^2
Methane (CH_4)	0.9997%	0.3 g/m^2
Helium (He)	0.999%	0.2 g/m^2
Phosphine/Hydrogen (0.05%PH_3/H_2)	0.99999%/0.9999%	0.1 g/m^2
Trimethyl Boron/Hydrogen (0.05%TMB/H_2)	0.995%/0.900999%	0.1 g/m^2

Table 4.1: Process gases consumed in manufacturing.

NF_3 is a silicon etchant that is used to clean deposition chambers between process steps. NF_3 can be produced by direct reaction of ammonia and fluorine gas or electrolysis of ammonia and hydrogen fluoride. This study models NF_3 as produced by the reaction of ammonia and fluorine. Stoichiometry shows that 0.24 kg of NH3, 1.6kg of F2, and 12.4 MJ are required to produce each kg of NF_3. The actual energy use of producing NF_3 is much higher, and estimated to be 25 kWh per kg (Ortelli, A., personal communication, March 10, 2010). HF is produced as a byproduct but is not assumed to be utilized commercially. The characterization factors for NF_3 also account for a 90% production yield and 1.5% fugitive emissions of NF_3 during production and distribution (Fthenakis, 2010).

$$NH_3 + 3\,F_2 + heat \rightarrow NF_3 + 3\,HF \tag{4.1}$$

TMB is a specialty gas used in extremely small quantities (less than 3.5 mg per m^2) as a dopant. It is modeled as formed by the reaction of boric oxide and methanol. The energy for formation is not considered in this assessment as the contribution of this process gas to the energy use and GWP of the module is diminishingly small. Again, the hydrogen byproduct is not assumed to be utilized commercially.

$$B_2O_3 + 6\,CH_3OHF \rightarrow 2\,C_3H_9B + 3\,H_2 \tag{4.2}$$

4.1.4 Targets

Target are deposited via physical vapor deposition to form the back or front and back contacts, in the case of in-house TCO processing. The amounts of target material consumed per module are calculated based on the dimensions of the targets and the change frequency. With the exception of vanadium, all the materials are well characterized by LCA databases. Data for vanadium is extrapolated from a life cycle study of vanadium redox batteries utilizing secondary vanadium collected from boiler soot (Rydh, 1999). As with the process gases, the data sources do not reflect the high purity and crystal structure requirements of PV targets.

4.1.5 Other Consumables

Other materials include those used to clean the module components during manufacturing and those used to form connections with balance of system components. These include the junction box, pottant, sealant, flux, tape, label, detergent, and other cleaning agents.

Target Materials	CAS Number	Consumption
Zinc Oxide (ZnO)	1314-13-2	17 g/m^2
Silver (Ag)	12595-26-5	2.9 g/m^2
Nickel Vanadium (NiV)	7440-02-0/7440-62-2	0.9 g/m^2
Silicon (Si)	90337-93-2	0.9 g/m^2
Aluminum Oxide (Al_2O_3)	1344-28-1	0.1 g/m^2

Table 4.2: Target materials consumed in manufacturing.

With the exception of HCl and cerium oxide, materials are characterized using EIO-LCA due to the availability of detailed cost data and their poor fit with LCA databases. The buswire, junction box and detergents are well characterized by 2002 EIO sectors "335920: Communication and energy wire and cable manufacturing", "334417: Electronic connector manufacturing", and "325610: Soap and cleaning compound manufacturing", respectively.

4.1.6 Transportation to Manufacturing

Ecoinvent data generally describes the environmental impacts of materials at plant, meaning that the impacts of transportation to the location of use is not included. In this study, the impacts of transportation of materials to manufacturing are explicitly calculated in one of two classes of materials: IEC certified and non-IEC certified materials.

The International Electrotechnical Commission (IEC) is a governing body that may certify specific vendors as providers of materials meeting certain performance requirements. Certification is required for the most critical materials, such as the targets and buswire, but not required for 70% of materials by weight. The distances traveled by IEC certified materials can be calculated for any location, though distances will vary with manufacturers locations, purchasing decisions, and with the certification of additional vendors.

Therefore, a typical travel distance of 1,000 miles for IEC certified materials and 500 miles for non-IEC certified materials is chosen for the U.S. example case. Again, these are parameters that users may easily vary or update over time. The impacts per ton-km are taken from Ecoinvent, due to the comprehensiveness and excellent documentation of the data (Spielmann, 2005).

4.1.7 Manufacturing Equipment and Infrastructure

The capital equipment used for manufacturing photovoltaic systems can be extremely long-lived. Like many other types of manufacturing equipment, PV manufacturing equipment may be refurbished and continue to operate far past the original intended use. Not accounting for secondary uses of the equipment, the original functional life of the equipment is 5 or 7 years, depending on the version of the technology selected and corresponding production rate. The impacts of infrastructure are amortized over a functional life of 25 years, which assumes the facility will continue to be utilized for manufacturing even as manufacturing equipment is replaced.

Figure 4.3: A plasma enhanced chemical vapor deposition (PECVD) tool. Image curtesy of Applied Materials.

The manufacturing equipment is characterized by large scale, high degree of automation, detailed production cost data, and a good fit of the equipment to the 2002 US economic sector “333295: Semiconductor machinery manufacturing”. Though the equipment studied is produced by Applied Materials, a US-based company, the manufacture of some equipment is sourced globally.

Manufacturing infrastructure is modeled using the 2002 US economic sector “230102: Nonresidential manufacturing structures” as the cost of the infrastructure is well known and documented for numerous locations. Geographical differences introduce a source of uncertainty into the study that is discussed in Chapter 5.

4.2 Module Manufacturing

The module manufacturing process is comprised of 157 discrete process steps, 42 of which are unique. The process flow is described generally as follows: (1) front contact preparation and patterning, (2) photovoltaic material deposition, (3) back contact formation, (4) panel encapsulation, and (5) external wiring and panel power rating. See Figure 13 for an overview of the manufacturing floor layout including these main processing groups.

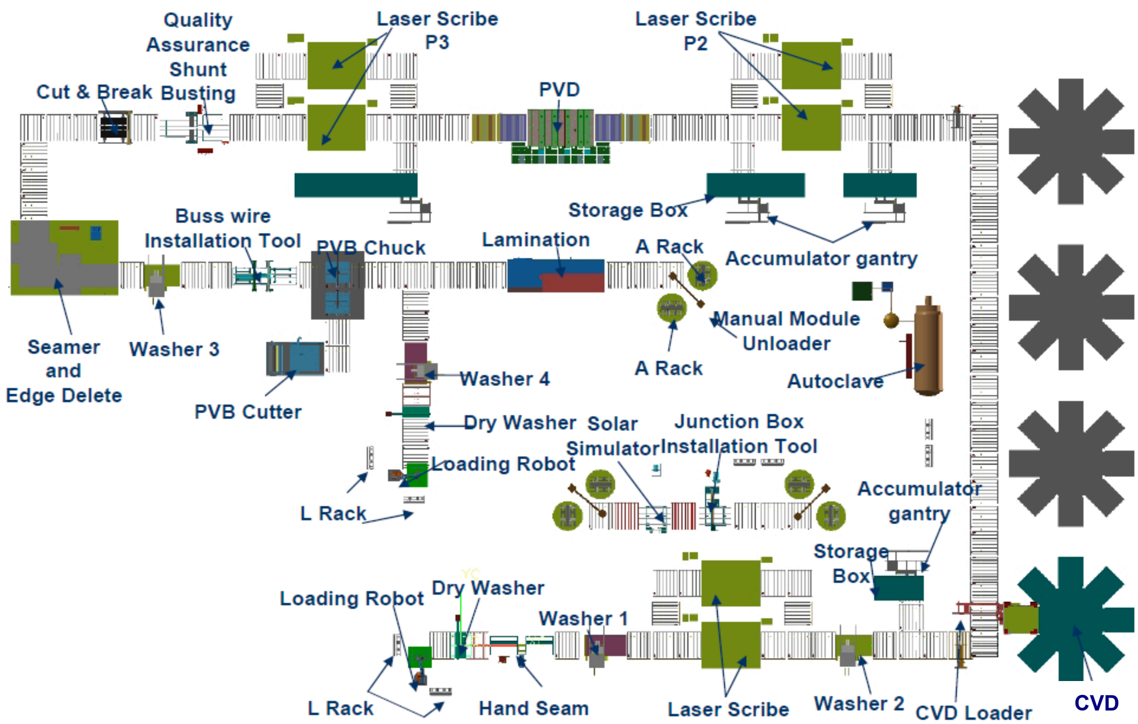


Figure 4.4: Module manufacturing layout. Image curtesy of Applied Materials.

Front contact preparation includes seaming, washing and scribing steps, and in the case of in-house TCO processing, the physical vapor deposition of the transparent conductive oxide. All processes occur in a linear fashion with the exception of the deposition processes of photovoltaic materials, which occur in parallel due to longer processing times relative to the line. As shown in Figure 14, a single plasma enhanced chemical vapor deposition (PECVD) tool deposits the top cell (amorphous silicon layers) while another three PECVD tools deposit thicker bottom cell (microcrystalline silicon layers).

Each PECVD tool consists of 8 chambers. The first chamber is a load lock (LL), or an isolation chamber. The second chamber deposits the p-junction. Every substrate moves through the first and second chambers before moving on to one of the remaining chambers for the deposition of intrinsic and n-junction. Each of these processes takes approximately six times longer than the p-junction deposition process. Each PECVD deposition chamber is served by a scrub-and-burn abatement system.

The back glass is then cleaned and prepared for physical vapor deposition of the back contacts and scribed to form individual cells. Buswires are attached, and the assembly is laminated and annealed in an autoclave. Finally, a junction box and mounting rails are attached and the finished product undergoes final inspection. All processing, material handling and auxiliary steps are included in the model.

The utilization factor (the percentage of time manufacturing tools are processing, idle, or off) is an important factor in the consumption of utilities. Most utilities are consumed in smaller quantities during idle than during processing. A major exception is the abatement equipment for the PECVD processes, which consume utilities only during the idle phase of chemical vapor deposition.

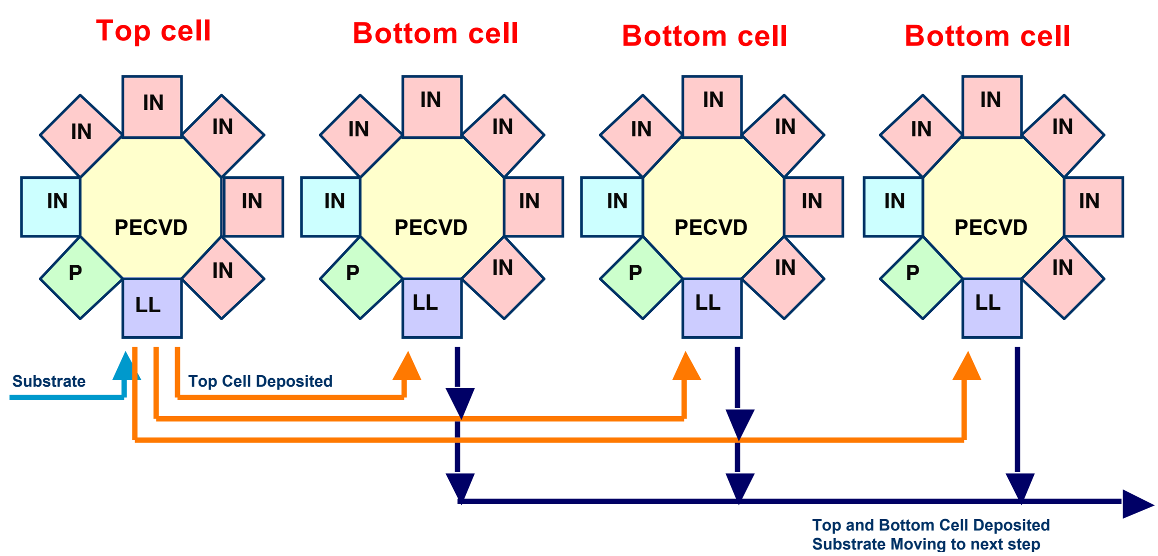


Figure 4.5: Process sequence across four PECVD tools.

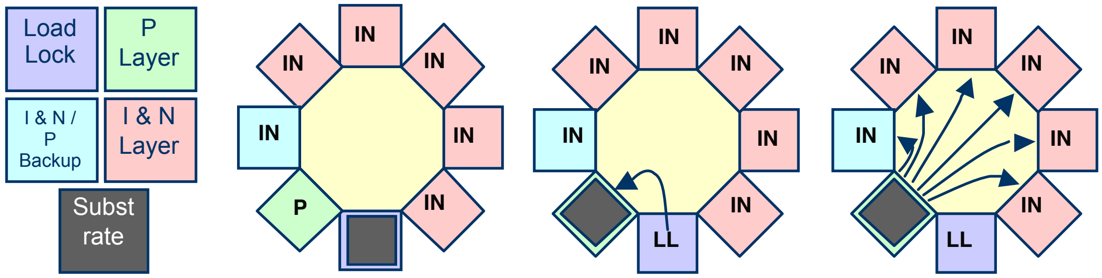


Figure 4.6: Process sequence within each of the four PECVD tools.

4.2.1 Manufacturing Utilities

One of the defining characteristics of this analysis is unprecedented detail in the manufacturing processes. The maximum and average consumption of electricity, utilities, and chemicals is documented in the Applied Materials Consumption Data List (CDL). Numerous versions of the CDL have been released over time; each reflecting measured process data from a number of production facilities. The CDL documents the utility consumption rates and conditions shown in Appendix A for 157 processes.

This level of resolution is not necessary to quantify the environmental impact of a module, but it is necessary to distinguish environmentally significant components of module manufacturing so that they may be targeted for improvement. For example, with information on how much clean dry air (CDA) is consumed by each process tool, it is possible to allocate the impacts of the CDA system to the individual processes that are responsible for the consumption. This resolution significantly expands the capabilities of the LCA model from static accounting to dynamic process design and optimization.

Due to the similarities between semiconductor and photovoltaic manufacturing, some utility energy conversion factors are taken from the SEMI S23 Standard (2008), a widely utilized guide for calculating the electricity consumption of manufacturing equipment in the semiconductor industry.

The purity and precision requirements of semiconductor manufacturing are generally much higher than those of PV manufacturing. As there are costs to increased purity (Krishnan, 2008b), SEMI S23 values may overestimate the impacts of PV manufacturing. Therefore, the electricity use of certain PV facilities is calculated using a modified form of the

SEMI S23 standard. A third category of utilities that SEMI S23 characterizes with static or no energy conversion factors is described for PV manufacturing by the electricity consumption of the pumps and/or the cooling systems. A summary of the treatment of each utility is shown in Table 4.3.

SEMI S23 Standard	Modified SEMI S23	Pumps and/or Cooling Systems
Clean Dry Air (CDA) Scrubbed Exhaust Environmental Heat Load	Ultra Pure Water (UPW) General Exhaust	Cooling Water Loops (CWL) Industrial City Water (ICW) Reclaimed DI Water Wastewate

Table 4.3: Treatment of PV manufacturing utilities.

4.2.2 SEMI S23 Standard

The solar utilities accurately described by SEMI S23 are clean dry air (CDA), scrubbed exhaust, and environmental heat load. The equipment used to generate these utilities is similar from plant to plant, with similar energy requirements. SEMI S23 energy conversion factors are based on member supplied data. However, members of the SEMI organization have correlated the ECFs to meaningful operational parameters for each utility (Cohen, R, personal communication, October 11, 2010).

4.2.3 Modified SEMI S23

Of all the SEMI S23 utilities, ultra pure water (UPW) is recognized as one that is not so easily characterized. UPW systems may employ reverse osmosis or reverse osmosis and deionization processes, and there are numerous operating variables in UPW generation that will affect the environmental cost of each unit of UPW.

Facilities experts recognize the ultra pure water ECFs in the current version of SEMI S23 as overestimates for most production plants, particularly so for production plants that reclaim spent UPW (Naughton, P., personal communication, June 6, 2010). Spent UPW water is typically cleaner than municipal city water, and so, reclaiming and retreating spent

DI water may reduce energy use, water loss during treatment, and feedwater per unit of UPW produced relative to treating 100% municipal city water (See Figure 8).

The ECF for cold UPW (T 25 C) was reduced based on the observations of facilities engineer, energy expert, and SEMI S23 co-creater Phil Naughton in accordance with the quantity of water entering the UPW treatment system from municipal versus reclaimed sources at operational TF-Si PV plants. Hot UPW (T ¿ 85 C) is not used in the process flow studied, but it is suggested to modify the ECF for hot UPW as follows.

$$ECF'_{HotUPW} = ECF_{HotUPW} + C_p\Delta T \tag{4.3}$$

C_p is the specific heat of water at constant pressure, P, and ΔT is the change in temperature from ambient.

Pumps and Cooling Systems

Pumping energy is calculated as the product of the flow rate, pressure, and pump and motor efficiency. A typical pump and motor efficiency of 60% is selected. As documented by the CDL, the pumping pressure of the cooling water loops average 5 bar, while the pumping pressure of the industrial city water, reclaimed water, and waste water average 3 bar.

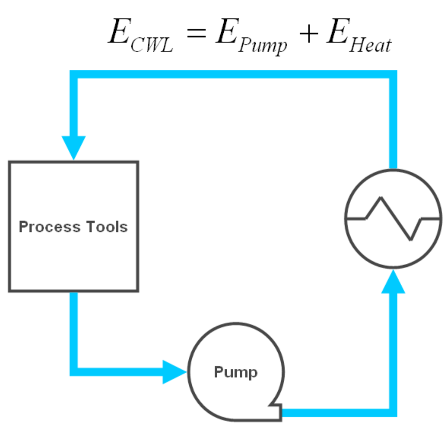


Figure 4.7: Schematic of the calculation of energy use in cooling water loops.

$$E_{Pump} = \frac{\dot{m} \times P}{\eta_{Pump}} \times t \tag{4.4}$$

$$E_{Heat} = \dot{q} \times R \times t \tag{4.5}$$

E_{CWL} is the electricity demand of each cooling water loop. E_{Pump} is the energy it takes to pump a flow rate of water, $\dot{m}$, at pressure, P, over time, t, with pump efficiency, η_{Pump}. E_{Heat} is the energy needed to cool a heat transfer rate, q, for specific power ratio, R, over time, t. Processing time is 2.5 minutes for mainline processes and 1.2 minutes for TCO processes. The specific power ratio is 0.1 kW/ton of refrigeration for flows cooled directly using a cooling tower and 0.7 kW/ton of refrigeration for flows cooled using a chiller.

Cooling Water Loops

Cooling water loops (CWLs) providing process cooling water (PCW) is a utility that varies greatly in energy intensity as a function of inflow and outflow temperature and pressure, pump efficiency, pump motor efficiency, chiller power, and chiller or cooling tower efficiency.

The energy use of pumping the water, and the energy use of the chiller or cooling tower are modeled using typical specific power ratios of 1 kW/ton for Cooling Water Loop 2 (chilled water) and 0.1 kW/ton for all other cooling water loops. A ton of refrigeration is equal to 12,000 BTU/hr or 3.5 kW.

Industrial City Water

Industrial city water (ICW), or municipal city water (MCW), is modeled as consuming only the energy of pumping the water due to the vast differences in municipal water supply systems across the world. In general, very little water data is available, though this is changing, particularly in areas of water scarcity (Cloony, 2009). Excellent sources of information on the energy and greenhouse gas impacts of water in specific regions include publications by Stokes (2009) and Pfister (2009).

Reclaimed UPW

The amount of UPW reclaimed impacts the energy and water intensity of producing UPW, as described above. Reclaimed UPW is individually characterized in terms of the energy use to pump water from the point of use to the treatment system, as described above and in Figure 4.7. Though it is not ideal, the system effects of reclaimed UPW are grouped with the treatment of UPW generation.

Waste Water

The energy required to pump wastewater is quantified as a process while the contaminants in wastewater are categorized as emissions of manufacturing, and are addressed in the following section. The energy required to pump wastewater is calculated in the same way as the energy required to pump industrial city water and reclaimed UPW.

4.2.4 Manufacturing Emissions

Module manufacturing produces exhaust, wastewater, and abatement waste in addition to the module itself. The cumulative energy demand and global warming potential associated with the production of these exhaust streams, such as the impacts of producing facilities nitrogen or clean dry air and of pumping exhaust gases through a facility, are discussed in the previous sections.

There are four types of exhaust in amorphous silicon PV manufacturing: exhaust air to the production hall (from washers, laser scribes, cooling stations), general exhaust (from washers and pumps), direct exhaust to the atmosphere (from the autoclave) and scrubbed exhaust. Of the four, the first three exhaust streams are benign; consisting of spent air from the production hall, clean dry air and/or facilities nitrogen. General exhaust and direct exhaust to the atmosphere mainly differ in the temperature of exhaust gases.

Scrubbed exhaust systems a characterized by SEMI S23. The standard values are likely to represent the high end of the spectrum of values that may be observed in operation. In this case, the difference is mainly due to differences in local air quality requirements (and corresponding scrubbed exhaust equipment specifications) rather than due to differences in the requirements of semiconductor and PV manufacturing. This section is primarily focused on the scrubbed emission from chemical vapor deposition (CVD) abatement and contaminants in washer wastewater.

Abatement Emissions

Between each deposition step, the CVD chamber needs to be cleaned to ensure product quality and reliability. The clean gas of choice in the industry is nitrogen trifluoride (NF_3), a gas with a very high global warming potential characterization factor (17,200 for a 100-year time horizon, IPCC, 2007). Weiss et al. (2008) discussed the strong correlation of atmospheric NF_3 to NF_3 production quantities reported by the chemical industry.

NF_3 is used to clean films of amorphous Si from the chamber walls between each deposition process. NF_3 is dissociated into fluorine radicals in a remote plasma source (RPS) system and then treated with a point of use (POU) wet thermal abatement system. Greater than 99.9% of the NF_3 is dissociated between these two processes. An additional 0.5% of all NF_3 consumed is lost to the environment during synthesis, packaging, and transportation (Fthenakis, 2010).

NF_3 and other chemicals are broken down in a wet-burn abatement process prior to release. Natural gas is burned during abatement to break down a majority of NF_3 to fluorine and nitrogen gas. Carbon dioxide is also produced through the combustion of natural gas. Table 4.4 shows the species and amounts of chemicals emitted post-abatement from chemical vapor deposition of the four active semiconductor layers. Of these emissions, NF_3 and CO_2 are global warming gases according to the IPCC Fourth Assessment Report (2007).

Emissions (g/m^2)	CO_2	H_2	SiO_2	CO	SiH_4	NF_3	SiF_4	F_2
Top Cell P Layer	10	0.037	0.49	0.34	0.0049	0.0004	0.0002	
Top Cell IN Layer	63	1.4	5.8	2.0	0.058	0.0094	0.0045	0.0001
Bottom Cell P Layer	31	1.1	0.29	1.0	0.0028	0.0012	0.0005	
Bottom Cell IN Layer	190	20	14	6.1	0.13	0.043	0.021	0.0002
Total PECVD Processes	290	22	20	9.5	0.20	0.054	0.026	0.0003

Table 4.4: Post-abatement chemical emissions of each of the four chemical vapor deposition steps.

Abatement is necessary to reduce the GWP impacts of CVD processes, but it is not required or regulated by law for PV manufacturers. If abatement is neglected, then direct CO_2 emissions are reduced (since natural gas is burned during abatement) but a significant amount of the NF_3 that is consumed during processing will be released to the environment. In this case, 99% of NF_3 consumed is generally dissociated into fluorine radicals in the remote plasma system prior to deposition, leaving up to 1% to be emitted to the environment (Fthenakis, 2010). The global warming impact of operating PECVD processes without abatement processes is significant and must be avoided.

Solid Waste

Scribe steps to form individual cells on the module also remove a small amount of photovoltaic and contact materials. Most of this material is filtered and disposed of as a non-hazardous solid. The amount of municipal solid waste produced from these sources is on the order of 3 g/m^2 (for the U.S. example case introduced in Section 3.2.3). Packaging materials for glass, gases and other materials are assumed to be reused and are therefore omitted from this assessment. Damaged work in progress (WIP) is modeled as recycled rather than disposed of as municipal solid waste.

Wastewater Contaminants

The remaining amounts of material removed during scribe steps are washed off the panels during numerous washing steps, and removed via wastewater. The concentrations of all wastewater contaminants are well under 10 ppb and typically do not approach the limits of regional wastewater standards.

As with water supply, municipal wastewater management systems dramatically vary from location to location and are omitted in this analysis.

4.3 Downstream Activity

Downstream activity includes the impacts of transportation, balance of systems (BOS), and end-of-life in the form of recycling. Downstream life cycle impacts are calculated using

Contaminant	Concentration
Amorphous Silicon (a-Si)	6.7 ppb
Silver (Ag)	2.4 ppb
Transparent Conductive Oxide (SnO or ZnO)	0.74 ppb
Nickel (Ni)	0.51 ppb
Zinc Oxide (ZnO)	0.3266 ppb
P+	0.053 ppb
N-	0.053 ppb

Table 4.5: Concentrations of wastewater contaminants.

a combination of process-based and EIO-LCA data, with EIO-LCA data used many of the BOS components.

4.3.1 Transportation

Transportation distances of the module and BOS components from manufacturing to installation via road, rail, and shipping are user-defined variables in the LCA model. The U.S. example case assumes 1,000 miles of freight transportation by road only. The mass of each module is 120 kg, and a module-share of BOS components is 90 kg. The impact per ton-kilometer of transportation is taken from Spielmann (2005), which includes the life cycle impacts of freight transportation via rail, road, or water. Transportation impacts of materials used in manufacturing are based on the locations of suppliers, and are calculated in the same manner as discussed in Section 3.1.

4.3.2 Balance of Systems

The TF-Si PV structure is well established, with many manufacturers worldwide, but the scale of the PV modules is unique to this production process. Highly automated installation equipment and systems have been developed to streamline the installation process.

The large scale of the photovoltaic modules in this study lend to large commercial or utility scale installations. The balance of systems (BOS) is a ground-mounted system comprised of three main subsystems: the mechanical mounting, the power electronics, and the installation processes. Detailed cost data is available for all BOS components in addition to physical product specifications.

Figure 4.8: Mechanical mounting system. Image curtesy of Applied Materials.

The impacts of the mechanical bill of materials are calculated by mass using Ecoinvent for the galvanized steel rails, posts, purlin, and supports. Ecoinvent is also the source of data for the inverter, as it is the source most frequently used in the literature.

The functional life of mechanical components is modeled as 30 years to match that of the module. Realistically, the components may last significantly longer. The functional life of the inverter is modeled as 15 years, requiring a one-time replacement during the 30-year life span of the installed system. This is a departure from the study of BOS that Mason et al (2006) conducted, which finds significantly lower values for the impacts of the inverter based on the main constituent materials (steel, aluminum, copper and plastics) in an inverter and a 30 year inverter life.

US 2002 economic sectors describe all other mechanical and electrical components, listed in Table 4.6. This is a significantly more product-specific assessment of BOS part production than is currently available in the literature or in LCA databases.

The installation of photovoltaic modules is a labor-intensive process that is not typically included in life cycle analyses. The LCA community has yet to recognize labor as having non-zero impacts, though a number of studies have begun to quantify what those impacts may be (Xu, 2009), (Alfredsson, 2004). This LCA model gives users the option of including

Balance of System Component	U.S. Economic Sector
Washers, Screws, Nuts, Flanges	332720: Turned product and screw, nut, and bolt manufacturing
Combiner Boxes, Enclosure	334419: Other electronic component manufacturing
Transformer, Monitoring Equip.	335311: Electric power and specialty transformer manufacturing
Electrical Cables	335920: Communication and energy wire and cable manufacturing

Table 4.6: Economic input-output classification for balance of system (BOS) components.

the impacts of installation labor on a per worker-hour basis. This methodology is discussed in much greater detail in Chapter 6.

The other component of installation is the installation equipment. This is typically not included in assessments of PV BOS, but detailed cost data was available which was then mapped to environmental impacts using the US 2002 EIO-LCA model for sector "532400: Commercial and industrial machinery and equipment rental and leasing".

4.3.3 End of Life

End of life (EOL) environmental impacts are a major concern for many species of photovoltaic systems, particularly for those containing lead, cadmium, hexavalent chromium, or brominated fire retardants according to a report from the Silicon Valley Toxics Coalition (Mulvaney et al., 2009). Thin film silicon systems evaluated in this study do not have the same toxicity problems of many other types of photovoltaic systems, and may be recycled via common glass recycling processes according to the SVTC.

The thin film silicon PV modules evaluated in this study may be recycled or disposed of as non-hazardous waste. This study assumes that all PV modules are recycled, as it is the manufacturers' recommended method of disposal. Table 4.8 shows that the concentrations of hazardous materials in the PV module; all are non-detectable or well below US Toxicity Characteristic Leaching Procedure (TCLP) or California Soluble Threshold Limit Concentration (STLC) and Total Threshold Limit Concentration (TTLC) standards.

PV modules may be recycled using much of the same machinery and processes as used to recycle cathode ray tube (CRT) monitors or laminated automotive glass. The process

		Sample Concentrations		Limit Concentrations (Should exceed sample concentrations)		
Composition	Mass (g)	Theoretical Maximum (mg/L)	Analytical Results (mg/L)	TCLP (mg/L)	STLC (mg/L)	TTLC (mg/kg)
Low-Iron Float Glass	92,000	97,000				
Polyvinyl Butyral (PVB)	2,800	2,900				
Copper (Cu)	43	45	1.4		25	2500
Silicon (Si)	28	29				
Tin Oxide (SnO)	23	24				
Silver (Ag)	11	12	Non Detect	5.0	5.0	500
Tin (Sn)	11	11				
Zinc Oxide (ZnO)	3.1	3.3			250	5000
Nickel Vanadium (NiV)	2.5	2.6			Ni: 20/V:24	2000/2400
Polypropylene (PP)	1.9	2.0				
Aluminum Oxide (Al_2O_3)	0.064	0.067				

Table 4.7: Concentrations of materials in PV modules relative to US and CA limit concentration standards.

steps employed by ECS Refining, a recycler of PV modules made by Applied Materials, are as follows:

1. Transport to recycler
2. Remove from packaging
3. Shred to 5 inch or smaller
4. Manually remove plastic or metal pieces
5. Shred to 2.5 inch or smaller
6. Package for shipment

Shredding processes require the use of hammer mill, shredder, or glass pulverizer equipment, with dust control systems. The operation of shaker tables and motor transfer conveyors is included in this assessment. The impacts of the recycling processes are calculated based on the electricity consumption of the process tools as the material, labor and maintenance requirements of the processes are minimal.

Packaging materials are repeatedly reused and are therefore not included in this assessment. Glass products are transported to one of three major smelters in North America for use as a fluxing agent in ore smelting. No materials are sent to landfill. Current demand for silica exceeds the supply of recycling processes (Gregory, H., ECS Refining, personal communication, May 14, 2009).

It is assumed that all panels, including those that fail to meet quality standards in manufacturing, undergo this recycling process, with a yield of 90%. Chapter 5 will show that value of recycling output approximately offsets the cumulative energy demand and global warming potential impacts of the recycling processes.

Chapter 5

Results

The life cycle assessment model described in Chapters 3 and 4 produces values of environmental impact for any combination of design, manufacturing, and installation options selected or entered by users of the model. It is not practical to include results for every possible scenario, and so detailed results are presented for a single U.S. example in Section 5.1.

Section 5.2 presents additional results, comparing (1) options for transparent conductive oxide coating and (2) a number of manufacturing and installation location scenarios. The power mix consumed or displaced at each location, not just differences in insolation, drive differences in the environmental performance of each scenario.

It is with great caution that Section 5.3 compares the results of this model to other results in the literature. As was discussed in the background chapters, there is a wide range of boundary conditions and methodologies that have been adopted by PV LCA practitioners, making it very difficult to make meaningful comparisons between studies. In these cases, the scenario functionality of the model served to produce as similar model inputs as possible.

Finally Sections 5.4 and 5.5 discuss the sensitivity and uncertainties of this LCA model via parameter elasticity and the LCA pedigree matrix.

Fab/Module Version:	SunFab 4.0 ZnO 100MW	
Efficiency (%)	10.0%	
Availability (hr/yr)	7,450	
Throughput (sheets per hour)	25	
Yield (%)	96%	
CapEx Lifetime (yr)	5.0	
TCO Line In-house	Yes	
Manufacturing Location:	US	
Primary Energy use of Electricity Consumed (MJ/kWh)	10.26	
GWP Intensity of Electricity Produced (kgCO2eq/kWh)	0.549	
Use Phase Location:	Phoenix, AZ	
Insolation (kWh/m2/yr)	1960	
Primary Energy use of Electricity Produced (MJ/kWh)	8.95	
GWP Intensity of Electricity Produced (kgCO2eq/kWh)	0.549	
Additional Assumptions:		
Module Lifetime (yr)	30	
Degradation at End of Life	20%	
Performance Ratio	80%	
Module and BOS Transportation Distance by Truck	1,000	Miles
Module and BOS Transportation Distance by Rail	-	Miles
Module and BOS Transportation Distance by Ocean Freight	-	Miles

Table 5.1: The parameter values of the selected U.S. example case are reproduced here for convenience.

5.1 U.S. Example Case

Given the U.S. example case conditions shown above, Table 5.1 shows the cumulative energy demand and global warming potential impact of a thin film silicon PV system on a per square meter (m^2) and per watt-peak (W_p) basis, as well as the energy payback time (EPBT) and global warming potential payback time (GWP-PBT).

Please note the Scope column of Table 5.2, which indicates which of the optional life cycle components in the model are included in the U.S. example case. The selections made in the example case are meant to reflect a superset of what is common in the literature.

Results Summary	Scope	MJ/m^2	MJ/W$_p$	EPBT (month)	kgCO$_2$ eq/m^2	kgCO$_2$ eq/W$_p$	GWP-PBT (month)
TOTAL		**2,464**	**24.6**	**23.4**	**202**	**2.0**	**31.4**
UPSTREAM ACTIVITY	**YES**	**366**	**3.7**	**3.5**	**56**	**0.6**	**8.7**
Top Glass	Yes	65	0.7	0.6	9	0.1	1.4
Bottom Glass	Yes	42	0.4	0.4	8	0.1	1.2
Laminate	Yes	53	0.5	0.5	3	0.0	0.5
Process Gases	Yes	129	1.3	1.2	31	0.3	4.8
Targets	Yes	22	0.2	0.2	1	0.0	0.2
Other Consumables	Yes	4	0.0	0.0	0	0.0	0.0
Transportation to Mfg	No	-	-	-	-	-	-
Equipment	Yes	49	0.5	0.5	3	0.0	0.5
Infrastructure	Yes	3	0.0	0.0	0	0.0	0.0
MODULE MANUFACTURING	**YES**	**853**	**8.5**	**8.1**	**56**	**0.6**	**8.7**
Electricity	Yes	393	3.9	3.7	21	0.2	3.3
Other Utilities	Yes	461	4.6	4.4	26	0.3	4.0
Labor	No	-	-	-	-	-	-
Emissions	Yes	0	0.0	0.0	10	0.1	1.5
DOWNSTREAM ACTIVITY	**YES**	**1,245**	**12.4**	**11.8**	**90**	**0.9**	**14.0**
Mechanical BOS	Yes	452	4.5	4.3	41	0.4	6.4
Inverter	Yes	709	7.1	6.7	39	0.4	6.0
Other BOS	Yes	34	0.3	0.3	2	0.0	0.3
Installation Labor	No	-	-	-	-	-	-
Installation Equip.	No	-	-	-	-	-	-
Transportation to Intstallation/EOL	Yes	44	0.4	0.4	8	0.1	1.2
End of Life	Yes	7	0.1	0.1	0	0.0	0.1

Table 5.2: Cumulative energy demand and global warming potential for the cradle-to-grave life cycle of an example PV system manufactured and installed in the US.

5.1.1 Cumulative Energy Demand

Each 5.72 m^2 module requires 14 GJ over its cradle-to-grave life cycle. This corresponds to 2.5 MJ/m^2 or 25 MJ/Wp. Materials and other upstream activity consume only 13% of the cumulative energy demand of the installed system. Downstream activity, on the other hand, sums to 49% of the installed cumulative energy demand. Figure 18(A) shows that the balance of system impacts are very significant, with the inverters comprising the largest single contributor to life cycle CED.

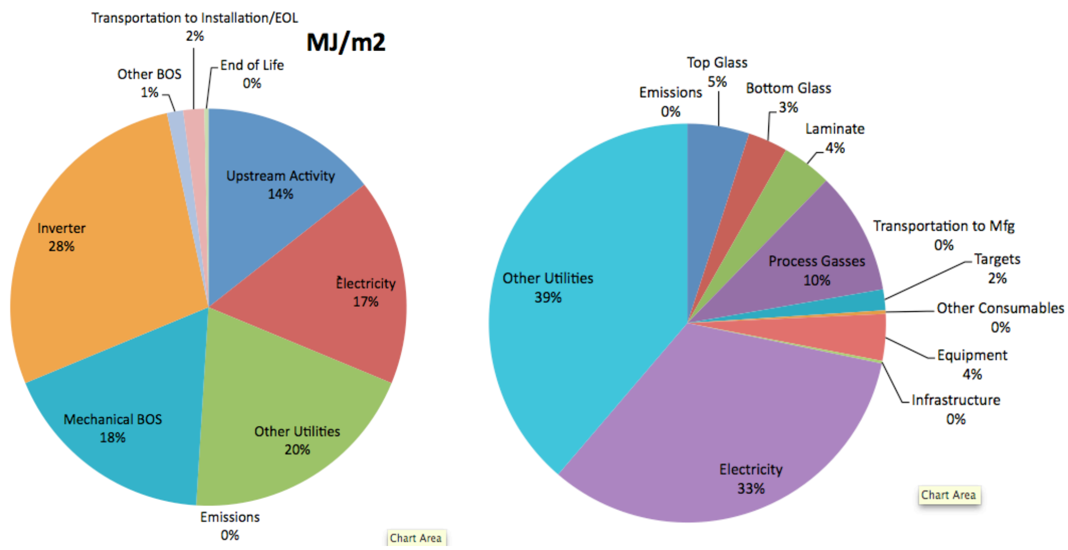


Figure 5.1: Contribution of all components to the cumulative energy demand of (A) an installed system, and (B) an uninstalled module.

Removing the downstream energy impacts, the cumulative energy demand of the module itself is 7.3 GJ per module. Approximately one third of the energy use occurs at the process tool, one third of the energy use is distributed across facilities systems in the factory, while another third corresponds to upstream activities. Figure 18(B) shows that process gases are the most energy intensive upstream component.

Figure 19 further breaks down the cumulative energy demand of the manufacturing processes, showing 10 of the top most energy intensive process steps. Note that processes that occur multiple times in the production line are grouped together, as a change to one process may apply to all others in the group. This information allows process designers to quickly pinpoint areas where efforts to reduce energy consumption will have the greatest impact.

Figure 20 is a subset of Figure 19, showing only the CED corresponding to the direct electricity consumption of each tool. This illustrates the utility of the facilities integration model in accurately and holistically representing each process, thereby significantly changing the energy use ranking, and design for environment priorities, for the process tools.

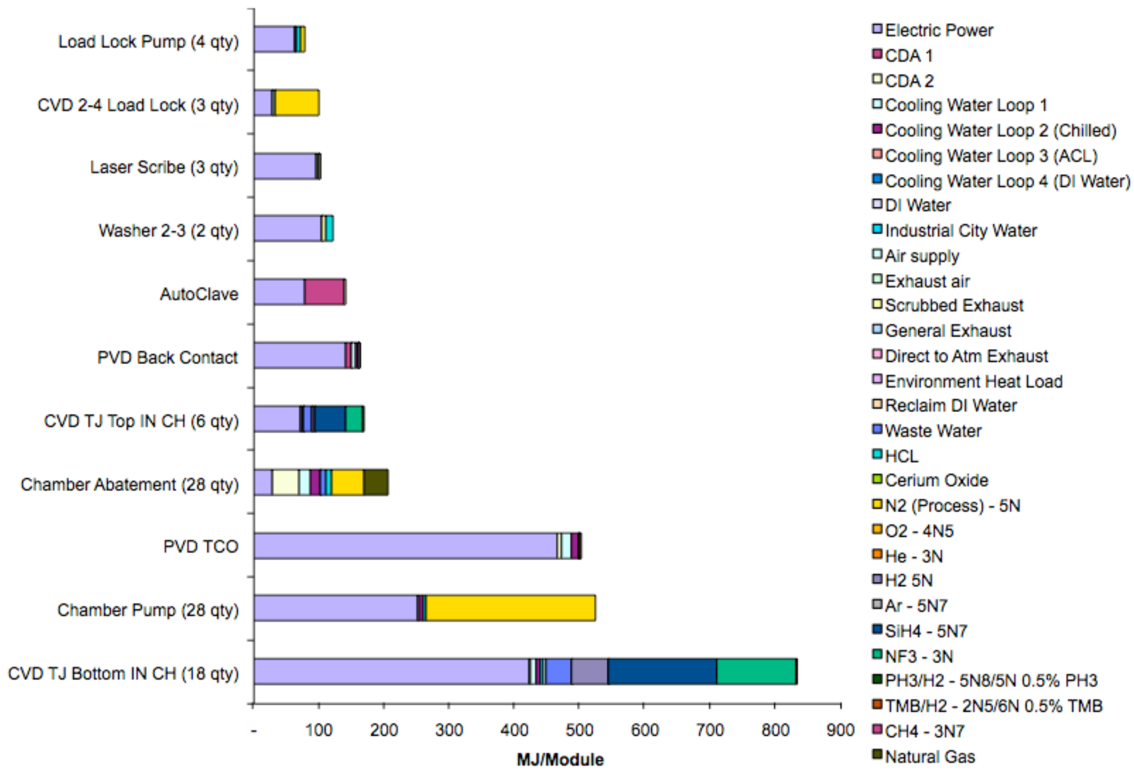


Figure 5.2: The top 10 most energy intensive process steps.

5.1.2 Global Warming Potential

The life cycle global warming potential impact of a 5.72 m^2 module is 1.2 tons CO_2 equivalent emissions. This corresponds to 200 kg CO_2 equivalent per m^2, or 2.0 kg CO_2 equivalent per Wp. Global warming potential characterization factor are based on the recommendations of the IPCC fourth assessment report (2007) assuming a 100-year time horizon.

The GWP impact of electricity and other utilities is markedly a smaller proportion of the life cycle GWP impact. This is in part, a reflection of the GWP intensity of the electricity mix in the US. If the example case were based in India, the relative impact of these components would be much higher (or lower, in the case of France). Section 5.5 discusses the uncertainty surrounding the upstream and downstream data sources.

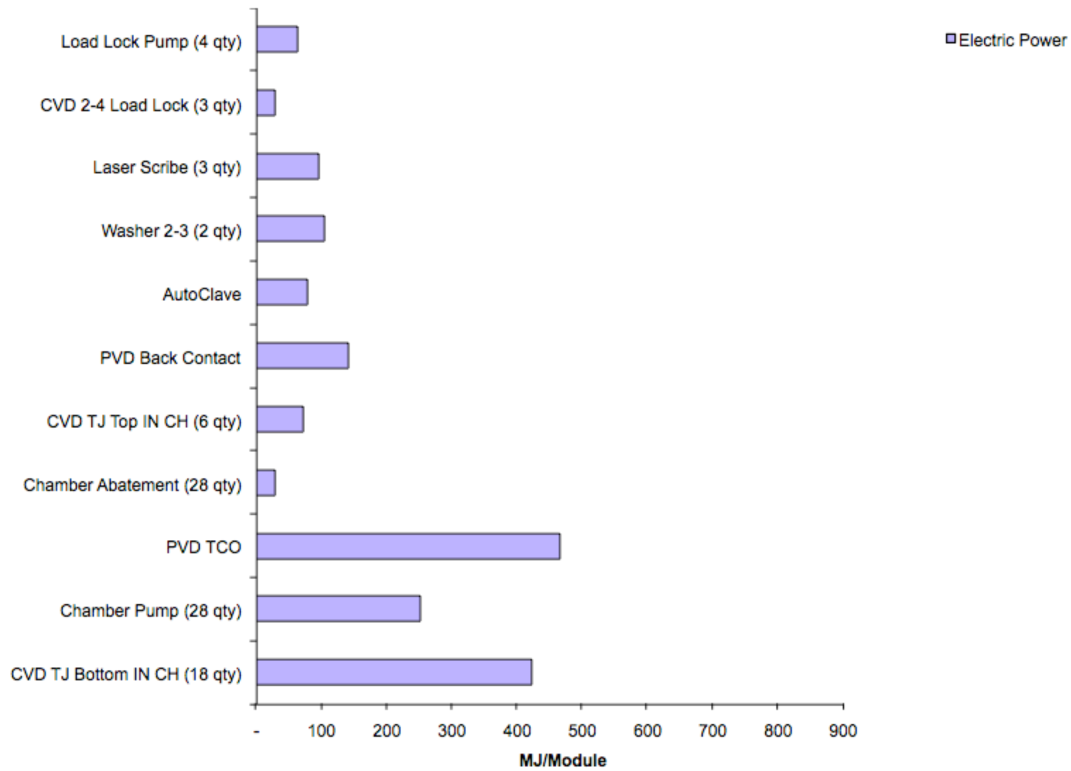
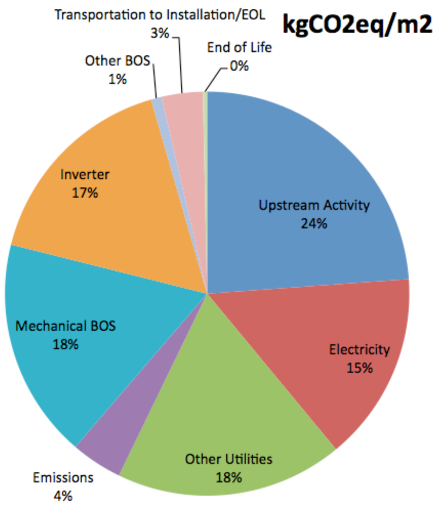


Figure 5.3: The top 10 most energy intensive process steps, with only direct electricity consumption shown.

5.1.3 Human Toxicity

Life cycle environmental data was collected for all materials from Ecoinvent or the US EIO-LCA database in the same manner as was done for CED and GWP. However, the human toxicity results are not presented because the data sources seem to be incompatable for hybrid analysis. Toxicity results are heavily dominated by EIO-LCA sources, and process based values were insignificant. There is not sufficient confidence in the data sources to present the results.

In general, toxicity of TF-Si is proportional to its consumption of electric power, upstream materials, and downstream materials. The concentrations of toxic materials in the PV module is not sufficiently high to be classified as hazardous in the US or CA (see Appendix E). This is in stark contrast with many other types of thin film PV systems that are based on neurotoxic or carcinogenic photovoltaic materials such as cadmium and arsenic (SVTC,



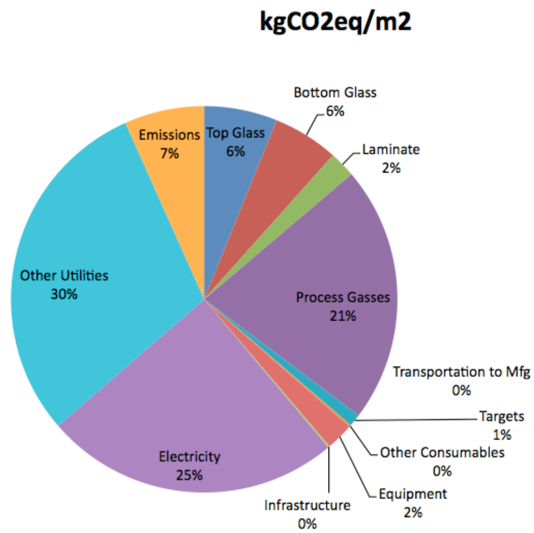


Figure 5.4: Contribution of all components to the global warming potential of (A) an installed system and (B) an uninstalled module.

2009).

5.2 Product Options

5.2.1 Transparent Conductive Oxide

As with any thin film photovoltaic system, a transparent conductive oxide is needed to form a front contact, to conduct electricity from cell to cell. Factories can choose to purchase SnO-coated solar glass or to purchase plain low-iron float glass that is then coated in house with ZnO.

The ZnO process results in higher energy conversion efficiency but adds an extremely energy intensive process step. The strength of the scenario functionality of the model is extremely clear when evaluating the TCO options. Table 5.3 shows that for the system parameters given in Table 5.1, the ZnO coating will require 700 MJ of additional processing energy requirements over the SnO coating, but will produce more than 10,000 MJ of additional electricity over the operational life of the module.

	Upstream/Production Energy Requirements	Generated Energy
Tin Oxide (SnO)	300 MJ	128,000 MJ
Zinc Oxide (ZnO)	1,000 MJ	142,000 MJ
Δ (SnO $\rightarrow$ ZnO)	-700 MJ	14,000 MJ

Table 5.3: Comparison of cumulative energy demand and generated energy relating to choice of transparent conductive oxide.

Please note that energy consumption of SnO-coated glass is based on the US 2002 EIO-LCA model for sector “327215: Glass Product Manufacturing Made of Purchased Glass while the energy consumption of ZnO-coated glass is based on EIO-LCA for sector “327211: Flat glass manufacturing and measured manufacturing process data. Also note that electricity consumed and electricity produced are not equivalent. In the US, 15% of electricity produced is lost prior to final consumption (IEA, 2010a).

5.2.2 Geographic Options

A ZnO-coated module with 10% energy conversion efficiency was evaluated under a number of different manufacturing and installation locations. Transportation distances are not varied in each case, in order to maintain focus on geographic factors, specifically electricity supply characteristics and insolation. See Section 3.2 for graphs of energy and GPW intensity and a table of insolation values by geographic location.

The U.S. example case conditions shown in Section 5.1 was repeated for a number of current and potential manufacturing and installation locations, the results of which are shown in Table 5.4. These tables, modeled after the work of Ortelli (2009), highlight the importance of the energy mix consumed during manufacturing and the energy mix offset over the life of the PV system. Insolation at the installation location is widely known to be an important factor in PV performance; however, this analysis demonstrates that energy mix, particularly at installation, may have an even more significant impact.

Locations are ordered from lowest primary energy demand per kWh (Spain: 4.7 MJ/kWh consumed, 4.1 MJ/kWh produced) to highest (China: 11.6 MJ/kWh consumed, 9.5 MJ/kWh produced), from left to right for manufacturing locations, and from top to bottom for instal-

Installation Location	Insolation ($kWh/m^2/yr$)	Manufacturing Location					
		Spain	US	Germany	India	France	China
Madrid, Spain	1686	*49*	*60*	*60*	*62*	*62*	*63*
Phoenix, US	1960	**19**	**23**	**24**	24	24	25
Madrid, Spain	1686	*49*	*60*	*60*	*62*	*62*	*63*
Munich, Germany	1100	34	42	42	44	43	44
Mumbai, India	1927	**23**	28	28	29	29	29
Toulouse, France	1370	25	31	31	32	32	32
Shanghai, China	1460	**24**	30	29	31	31	30

Table 5.4: Energy payback times (months) for installed amorphous silicon PV modules as a function of manufacturing and installation location. Bold font represents less than 24 month payback time, italic font represents greater than 48 month payback time.

lation locations. Note that a diagonal axis indicates the energy payback time of a system manufactured and installed within the same country.

Table 5.4shows that there is a factor of 2.6 difference in energy payback time between manufacturing in China and installation in Madrid, Spain versus manufacturing in Spain and installation in Shanghai, China. Assuming installation locations in China and Spain with equal insolation, there is a factor of 3 difference in energy payback time.

Note that the primary energy demand of the power source only varies in this analysis within the manufacturing facility. The majority of primary energy demand does not vary with module manufacturing location as it corresponds to fixed sources of data (Ecoinvent and EIO-LCA) for upstream materials, BOS materials, and other life cycle components.

The dependency of GWP payback time is even more dependent on regional power supply factors, as a greater variation exists than for cumulative energy demand (a factor of 10 difference in the GWP intensity of the six countries included in this analysis, versus a factor of 2 difference in the CED intensity). France, for example, has a significantly lower GWP/kWh than other countries in this comparison due to its high percentage of power from nuclear sources.

Table 5.5 is likewise organized from lowest (France: 100 g CO_2 eq/kWh consumed, 90 g CO_2 eq/kWh produced) to highest (India: 1400 g CO_2 eq/kWh consumed, 930 g CO_2 eq/kWh produced) GWP intensity per kWh. GWP payback times vary by a factor of

Installation Location	Insolation ($kWh/m^2/yr$)	Manufacturing Location					
		France	Spain	Germany	US	China	India
Toulouse, France	1370	*221*	*256*	*260*	*274*	*298*	*317*
Madrid, Spain	1686	42	48	*49*	*51*	*56*	*59*
Munich, Germany	1100	*58*	*67*	*68*	*72*	*78*	*83*
Phoenix, US	1960	25	29	30	31	34	36
Shanghai, China	1460	25	29	29	31	33	35
Mumbai, India	1927	**15**	**18**	**18**	**19**	**21**	**22**

Table 5.5: Global warming potential payback times (months) for installed amorphous silicon PV modules as a function of manufacturing and installation location. Bold font represents less than 24 month payback time, italic font represents greater than 48 month payback time.

20, from 15 months for manufacture in France and installation in India to 317 months for manufacture in India and installation in France. Keeping insolation constant, the range of power mix GWP intensities observed above can result in a factor of 15 difference in GWP payback times.

Analysis of the results reveals that the quickest energy and global warming potential payback times are found when the electricity used in manufacturing has lower energy and GWP intensity than the electricity that is offset during the use phase of the system. This result is significant because most PV systems are not manufactured and installed under such circumstances. Global PV production is rapidly growing in India and China, where the CED and GWP intensity of electricity are the highest, respectively, while many countries and municipalities with relatively efficient energy mixes are major consumers of photovoltaic products.

5.3 Comparisons to Other Power Sources

Chapter 1 discussed current limitations of the PV LCA literature, least of which is the difficulty in comparing results of different studies due to differences in scope, data sources, and LCA methodology. Therefore, it is with great caution that the following comparisons between thin film silicon PV systems and other power sources based on existing PV studies are presented.

Efforts have been made to minimize differences using the scenario functionality feature of the model. However, any conclusions drawn from these comparisons may be attributed to model differences rather than technological differences.

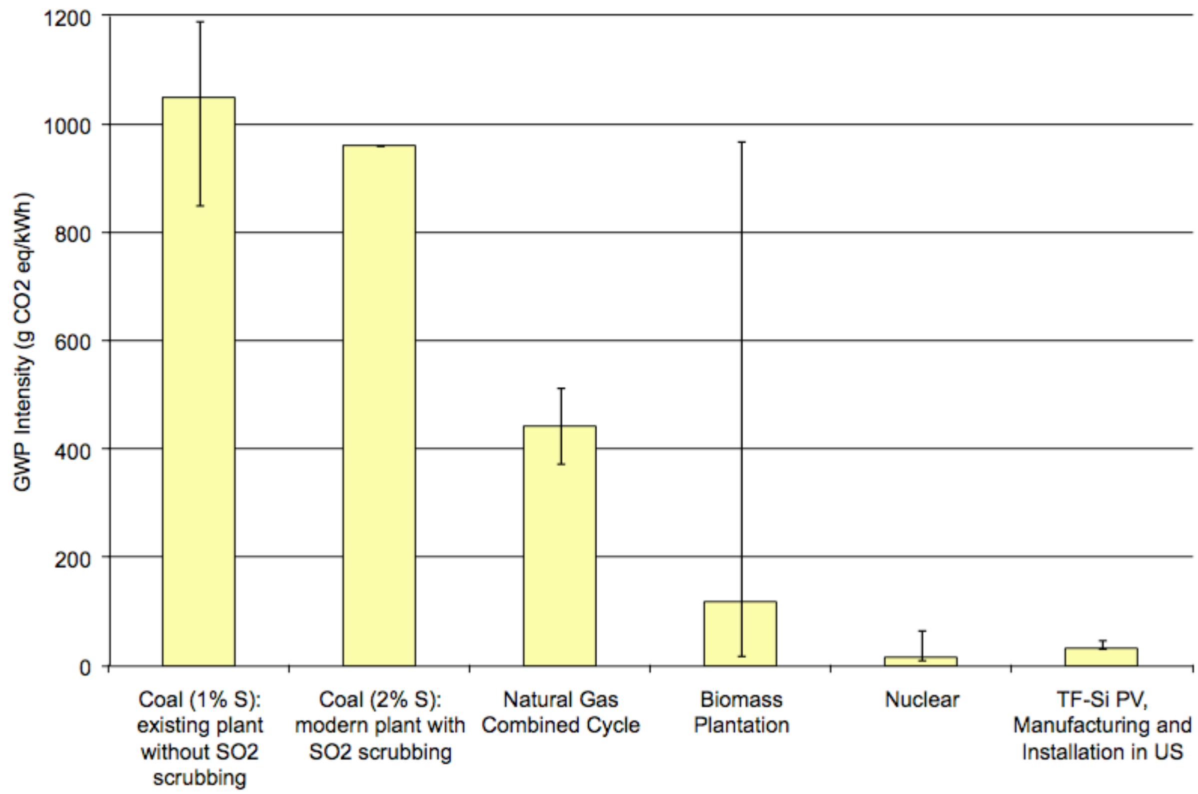


Figure 5.5: Comparison to major sources of power, typical of conditions in North America.

Section 5.2.2 demonstrated that environmental performance is a function of location, and so any comparison of power sources is location specific. Pacca et al. (2002), for example, compared hydro, solar, and fossil fuel sources of power in the CO river basin. Gagnon et al. (2002) compared a number of different power sources for typical conditions in North America that are reproduced on Figure 5.5 next to the GWP intensity of a TF-Si PV system. The base value represents the U.S. example case presented in Section 5.2, while the error bar reflects the range of insolation values found in major cities in the U.S.

Like many other PV technologies, TF-Si compares favorably to traditional sources of power, particularly coal and natural gas. However, the comparison to power from nuclear and biomass sources falls within the margins of error.

Figure 5.6 shows how the GWP intensity of TF-Si compares to existing energy mixes in eight countries. Of these, the biggest benefits of implementing such PV technology may be found in India, China, and Saudi Arabia. However, it may be surprising that a move to TF-Si represents a GWP savings even in France, where a large proportion of electricity generation comes from nuclear sources.

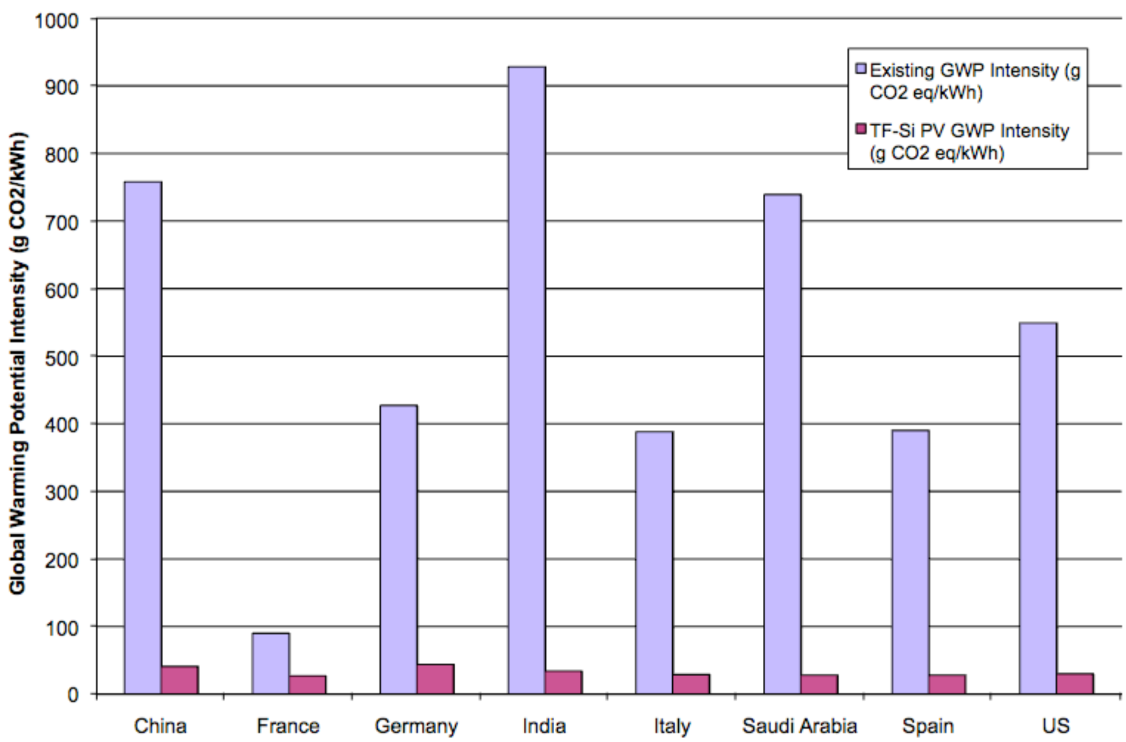


Figure 5.6: The GWP intensity of power from TF-Si sources compared to existing power mixes, adapted from IEA, 2010b.

In terms of energy payback time, TF-Si appears to compare favorably relative to other silicon PV technologies but compares unfavorably relative to other thin film technologies. However, as was discussed previously, the toxicity and end of life options for TF-Si are substantially more environmentally benign than for other TF PV systems.

Data for the comparison to other silicon PV technologies shown in Figure 5.7 comes from a very detailed study conducted by Alsema et al. (2006). Data for the comparison to other thin film PV technologies shown in Figure 5.8 comes from the office of technology development at Applied Materials (Haas, D., personal communication, June 19, 2010).

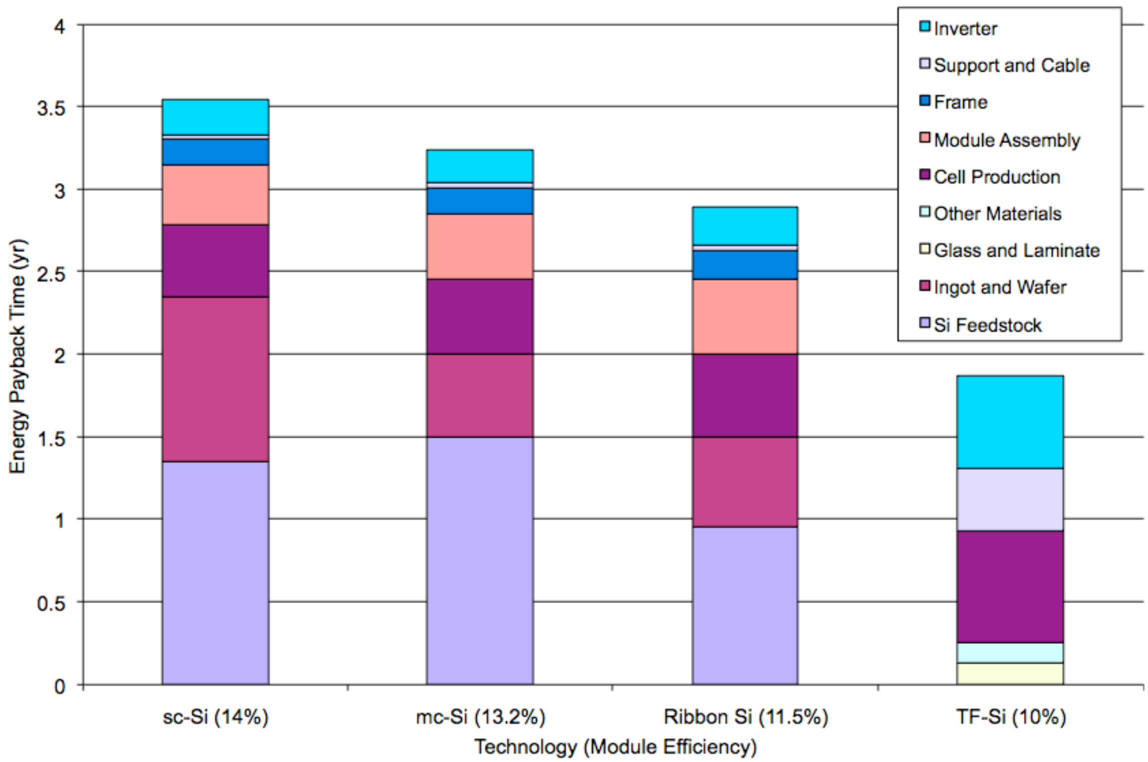


Figure 5.7: TF-Si has faster energy payback times than bulk Si photovoltaic systems.

It cannot be overstated that Figures 5.7-8 reflect a specific set of scenarios that, while realistic at one point in time and space, are likely to become dated quickly.

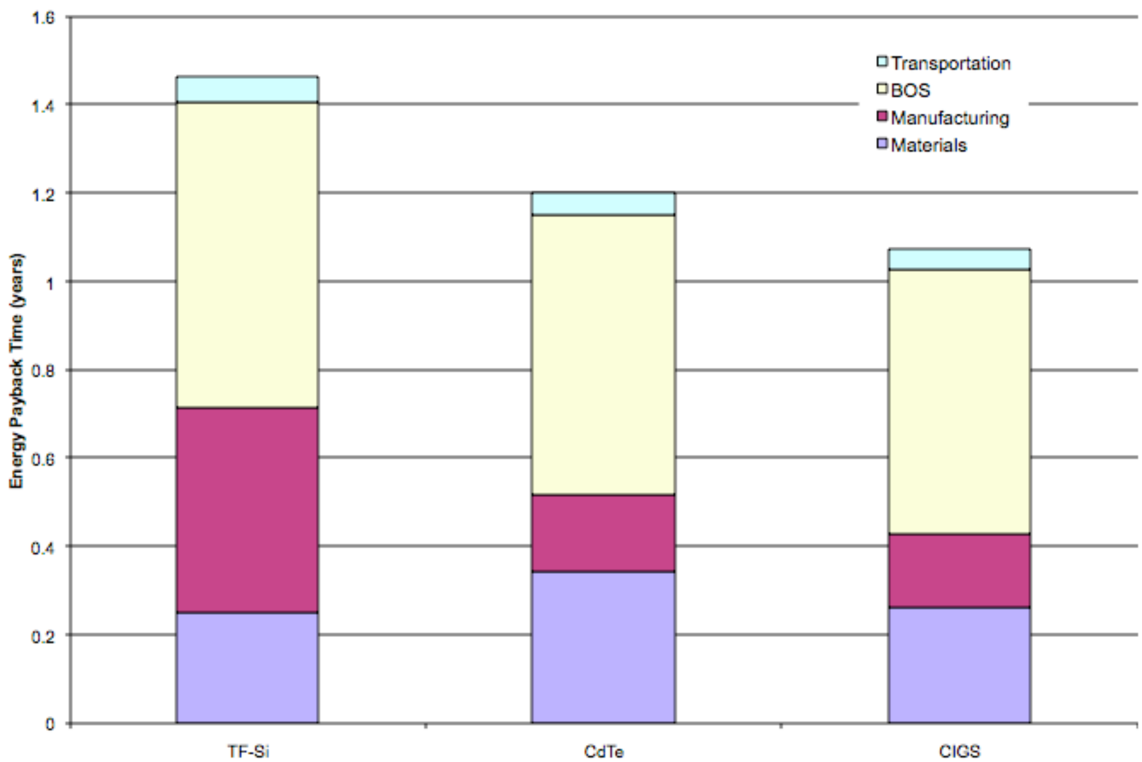


Figure 5.8: Comparison of the energy payback of a a-Si thin film PV system compared to CdTe and CIGS thin film PV systems.

Chapter 6

Analysis and Discussion

6.1 Sensitivity

The beginning of Chapter 5 discussed the dependence of LCA results on manufacturing and installation parameters. The results given in Section 5.1 represent only a single snapshot in time, space and technology. It is much more valuable to understand the degree to which each parameter influences the environmental impact of the cradle-to-grave system.

The goal of this section is to quantify the elasticity of results to specific model parameters. Each of the following parameters in Table 18was varied by 5% relative to the values given in Table 2 to find the effect on the percent change in energy payback time.

Note that the inverter lifetime and module lifetime parameters are not linearly related to the energy or GWP payback times because of the need for a whole number of inverters. For the sensitivity analysis only, the nonlinear relationship is modeled as linear, assuming that portions of the lifetime of the inverter may be used over the lifetime of the module.

The energy payback time found by the model is most sensitive to energy conversion efficiency, performance ratio, and primary energy use of electricity offset in the location of operation. This suggests that improving system performance ratios and installing PV systems to offset inefficient power sources should receive an equal degree of attention as the current intense drive to improve energy conversion efficiency.

	Parameter	% Change in EPBT	% Change in GWP-PBT
Technology Characteristics	Energy Conversion Efficiency (%)	4.8%	4.8%
	Performance Ratio (%)	4.8%	4.8%
	Inverter Lifetime (yr)*	1.4%	.92%
	Module Lifetime (yr)*	-1.4%	-.96%
	Degradation at End of Life (%)	-0.6%	-0.56%
Manufacturing Characteristics	Yield (%)	2.1%	1.4%
	Throughput (sheets/hr)	1.9%	1.3%
	Manufacturing Availability (hr/yr)	0.1%	0.11%
	Primary Energy Intensity of Elec. Consumed (MJ/kWh)	-1.8%	NA
	GWP Intensity of Elec. Consumed (kg CO_2 eq./kWh)	NA	-1.3%
Post-Mfg	Primary Energy Intensity of Elec. Offset (MJ/kWh)	4.8%	NA
	GWP Intensity of Elec. Offset (kg CO_2 eq./kWh)	NA	4.6%
	Transportation by Truck (Miles)	-0.1%	-0.19%

Table 6.1: Percent change in energy payback time (EPBT) and global warming potential payback time (GWP-PBT) corresponding to a 5% change in each parameter while holding all others constant. A positive value means that payback occurs more quickly as the parameter value increases. * indicates a nonlinear relationship that is modeled as continuous and linear for this analysis only.

6.1.1 Marginal versus Average Electricity Offset

The environmental characteristics of electricity offset is a predominant factor in the life cycle environmental performance of this and other electricity producing technologies. It is therefore important to note that electricity offset by new energy producing technologies is approximated, and may not accurately represented, by the average electricity production (AEP) in any given region. Rather, as new capacity is brought online, it will offset marginal electricity production (MEP).

Marginal electricity production has considerably different composition and characteristics relative to average electricity production. There are both build and operating aspects to marginal energy production (Callaway and Fowlie, 2009). Build margin refers to the power plants that may be built or decommissioned, while operating margin refers to the power plants that may be turned on or off, in response to increased need for or availability of power.

Build Margin

The species and efficiency of power plants vary with age. Of the 104 nuclear power plants operating in the US, for example, none were built starting after 1974 (Wald, 2010). From 2008 to 2009, the electricity generation of coal-fired power plants in the US declined by 12% while electricity generation from renewable sources saw double digit growth (Dorjets, 2011).

Many older plants are considerably less efficient than plants built today due to technological and environmental policy development. Power plants built following the Clean Air Act of 1977 are required to adopt emission control equipment but power plants built prior to the regulation are exempt. Many of these older power plants are kept online much longer than originally intended specifically because they are exempt from regulation that may introduce additional operating costs.

The calculation of marginal electricity production can be extremely complex and the results variable from location to location. However, due to a general trend towards developments in power generation technology and more stringent environmental regulations, it is likely that approximating build MEP with AEP will result in a less favorable assessment of the environmental performance of new electricity capacity.

Operational Margin

By definition, AEP is comprised of a mix of base load, peaking, and intermediate load-following power plants. Base load plants often utilize coal or nuclear energy sources because they must dependably produce electricity at a constant rate and at relatively low cost. Peaking power plants, on the other hand, operate only to meet peak demand, typically during afternoon hours and/or summer months. Peaking power plants generally employ gas turbines to burn natural gas, though diesel and hydroelectric power plants may also function as peaking power plants.

Because of data availability constraints, this study approximates the power offset by photovoltaic systems as the average electricity production in a given region. However, photovoltaic systems tend to produce power during periods of high, or even peak, demand. It is therefore more accurate to model the power offset by photovoltaic systems as a mix that includes more peaking power plants than the simple average of power plants.

Depending on the composition of average electricity production, such a power mix could have lower or higher environmental impact intensity than that of the AEP, i.e. a negative or positive marginal operational emissions rate (MOER). For example, peaking power plants will have a higher GWP intensity than base load power plants in regions, like France, where nuclear power is prevalent. In such a situation, the mix of power sources offset during the hours of PV availability would be considerably more GWP intensive than that produced during night hours. Conversely, in regions, like China, where coal power is prevalent, the GWP intensity of power offset by PVs may be less GWP intensive than that produced during night hours.

As with build MEP, operational MEP is dependent on many different factors and is difficult to calculate. However, it is important to devote attention to marginal electricity production because of the significance of the characteristics of electricity offset in the environmental performance of PV systems.

Under these circumstances, the strength of the scenario functionality of the LCA model become apparent. Though the model currently approximates the electricity offset by photovoltaic systems as average electricity production, users of the model may easily add additional data points, representing marginal electricity production or an availability-specific mix power sources, to more accurately represent the characteristics of the electricity mix offset.

6.1.2 Centralized versus Distributed Installation

The large scale (5.72m^2) of the thin-film silicon modules evaluated in this study are particularly well suited and specifically designed for centralized utility-scale installations. However, the technology can be easily adapted to, or even cut into, smaller scale modules for distributed installation. Under these circumstances, it is important to address the role that the distribution of installation makes in the environmental performance of a PV system.

Utility scale installations my benefit from lower BOS costs and higher system performance ratios, however they experience distribution losses simply by virtue of their distance from end users. Table 6.2 list the percent of distribution and own use losses of the 12 manufacturing regions built into the LCA model.

Country	% Distribution Losses	% Own Use Losses
Germany	4.6%	10%
Spain	5.0%	8.1%
France	5.5%	8.6%
Czech Republic	5.6%	11%
China	6.0%	12%
US	6.1%	6.7%
Italy	6.7%	9.5%
Saudi Arabia	7.4%	9.7%
Greece	7.7%	12%
World	8.4%	8.8%
Morrocco	19%	6.7%
India	25%	6.7%

Table 6.2: Percent of distribution and own use losses relative to total electricity production (IEA, 2010d).

Distributed installations, on the other hand, produce power in close proximity to final consumption. In certain cases, the distribution losses may be essentially zero and electricity production would appear as negative demand. The environmental performance of distributed PV systems will be higher than that of centralized utility-scale installations.

6.2 Uncertainty

Chapter 2 discussed some of the many limitations of life cycle assessment. Like any other model, LCA models represent a simplification of reality. As such, inaccuracies and uncertainties will always exist and our confidence in the results is only as strong as our understanding of the uncertainties associated with the results. Therefore, this section seeks to highlight and explain sources of uncertainty in both the data sources and in the LCA model itself.

6.2.1 Data Uncertainty

The data quality employed in this study is high, particularly within manufacturing. However, even within the manufacturing process data, there may be error and uncertainty in measurement equipment and systems.

Table 6.3 is a LCA pedigree matrix that indicates the quality of data used in the three main sections of the model in terms of reliability, completeness, and temporal, geographic and technological correlation. A value of 1 indicates the highest data quality while a value of 5 indicates the lowest. See Weidema and Wesnaes (1996) for precise definitions of values for each metric of quality in the LCA pedigree matrix.

	Reliability	Completeness	Temporal Correlation	Geographic Correlation	Technological Correlation
Top and Bottom Glass	1	1	1	3	2
Laminate	3	1	3	1	4
Process Gasses	1	1	1	3	4
Targets	1	1	1	3	3
Other Consumables	1	1	1	1	1
Transportation	3	5	2	2	2
Equipment	1	1	1	1	3
Infrastructure	1	1	1	1	3
Module Manufacturing	2	1	1	1	1
BOS	1	1	1	1	1
Transportation	3	5	2	2	2
End of Life	2	4	1	1	1

Table 6.3: LCA pedigree matrix, modeled after Weidema and Wesnaes (1996).

The life cycles with the poorest overall correlation are transportation and end of life. The impact of these life cycles, however, is relatively small. The greatest uncertainty in this study is regarding the technological correlation of high purity materials. There is a lack of sufficient environmental data for high purity and specialty materials. While the PV industry does not employ the level of purity required by the semiconductor industry, the materials are still significantly more pure than those found in typical LCA databases. Short of custom process-based data for each individual chemical, both industries could benefit for the formulation equations describing the environmental costs of purification processes.

Ideally, the offset energy mix is the sum of marginal energy from the time of installation to the time of decommissioning. However, there is very high uncertainty surrounding the future energy mixes since it is dependent on current and future social, political, and ecological factors. For these reasons, and those discussed in Section 6.1.1, current energy mixes are used to approximate future energy mixes offset by PV systems.

Additionally, there may be significant uncertainty in the measurement of current energy mixes. There are differences in the statistics each country collects and in how they may report their findings to the International Energy Agency. For example, many countries do not explicitly report the amount of primary energy consumed by combined heat and power (CHP) plants. For any given country this may be due to differences in grouping energy consumption or it may simply reflect a lack of combined heat and power plants.

6.2.2 Model Uncertainty

Standard energy conversion factors are used in facilities integration rather than measured values for each factory. For certain utilities, this is a very fair simplification, as equipment for producing HVAC, vacuum, and facilities nitrogen are very similar from factory to factory. Measured ECF values tend to match the standard ECF values very well for most utilities. However, ultra pure water is a major exception, as many different purification technologies, with different performance characteristics, are used worldwide.

To a lesser extent, process cooling water ECFs also vary based on site-specific factors. However, the standard ECFs are used even in the case of ultra pure water or process cooling water because of the lack of measured site-specific data in most locations. This is true as well of waste treatment systems, which do vary from location to location, reflecting local environmental standards or conditions.

For example, little water is used during manufacturing because of the costs of water and wastewater management in the face of poor infrastructure. In certain cases, where wastewater infrastructure is not available, wastewater is evaporated to produce solid waste, which can be disposed of more easily (Sypherd, G., personal communication, November 28, 2009).

The hybrid methodology employed may introduce model uncertainty. Where data is available from both process based and EIO sources, both sets of values are built into the model. The source with the best fit is selected as the default, though users may simple toggle between choices.

Though efforts have been made to accommodate regional energy mixes and insolation, there are more regional differences than are modeled. For example, upstream materials, downstream materials, equipment, infrastructure, and labor requirements are all region dependent and are currently modeled as static.

Finally, all equipment is modeled as produced in the U.S. since Applied Materials, the equipment producer, is a U.S. based company. Realistically, Applied Materials is a global company, with research and manufacturing distributed across three continents. The resource intensity of processing tools produced in other areas may differ from that of tools produced in the U.S.

Chapter 7

Environmental Impacts of Labor

Life cycle assessment is by definition a holistic approach to environmental modeling. However, an important component, the environmental impacts embodied in human labor, is most frequently omitted. Labor is a necessary requirement for any production system. Workers, in turn, require housing, healthcare, education, and directly or indirectly, every output of the economy. Some portion of the impacts of this consumption should be attributed to the production system, as labor can replace equipment that does contribute to life cycle inventories. Kakela (1978), Pindyck (1979), Hannon (1978), Welsch (1996), and Kemfert (2000) thoroughly document the substitutions of energy, labor and/or capital equipment that occur under various scenarios.

This chapter presents a straightforward method of estimating the energy, global warming potential, and water use demands of an hour of industrial labor based on readily available national statistics. In the United States, this estimate yields 58 MJ of primary energy use, 82 gallons of water use, and 4.6 kg of CO_2 equivalent emissions. These results can be applied to inform and expand the applications of process-based and hybrid economic input-output life-cycle assessment. The energy use of labor enables us to quantify and inform decisions that introduce or reduce workers, deal with the location of a plant, or involve labor-intensive process steps. Detailed examples of such applications are given in Section 5.3.

Boustead and Hancock (1979) discuss the energy use of labor in the form of caloric content of food consumed. Calculated as such, they ultimately conclude that the energy contribution of human labor to energy use is negligible.

However, just as evaluating only the direct energy consumption of a manufacturing tool and omitting the impacts of the infrastructure leads to an incomplete assessment, so to must the energy associated with human labor include the energy of infrastructure in addition to that of food. Infrastructure includes housing, transportation, health care, education, government services, agricultural infrastructure, and so on. If defined in this way, the energy use of labor can be a significant contributor to manufacturing energy use.

7.1 Calculating the Impacts of Labor

Many scientists have discussed the environmental cost and particularly the energy cost of labor, but it has not entered standard practice in the LCA community. In part, this is due to concerns of model complexity, variability, double counting, and attribution. The methodology presented here addresses each of theses concerns.

7.1.1 Model Complexity and Variability

Like economic input-output (EIO) LCA, the methodology presented herein aims to quantify environmental impacts that may not be included in process-based LCA. Because both EIO-LCA and the energy use of labor take a top-down approach, presenting averages for an industry or country, they do so without tremendously increasing the work of LCA practitioners.

7.1.2 Double Counting

Energy use of labor and EIO-LCA should not be applied to the same component of analysis because many sources of energy use would be double counted. However, energy use of labor can be very effective if incorporated into hybrid EIO-LCA, as shown in Figure 7.1, where EIO-LCA is used to assess activity upstream of the process-based analysis. The energy use of labor enriches the horizontal scope of process-based LCA, while EIO captures vertical supply chain impacts.

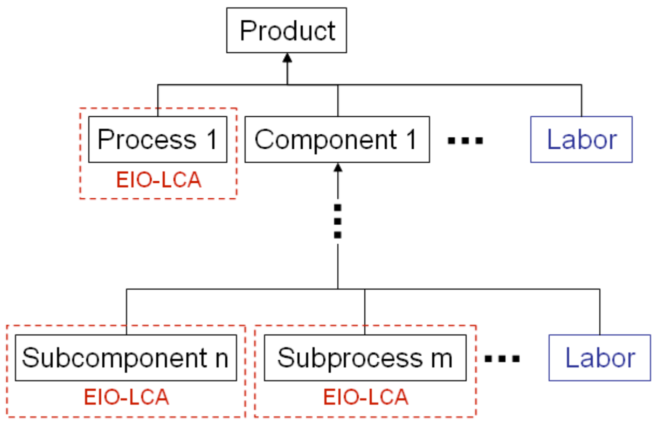


Figure 7.1: Schematic of process-based LCA and energy use of labor applied in series with economic input-output LCA.

An upper bound estimate is given by amortizing a country or regions energy supply across its population and over the number of hours in a year.

Odum used the same method to calculate the national fuel share per person (Odum, 1996). Based on 1993 data, he concluded that 967 MJ are expended per worker-day or 40 MJ per worker-hour. In comparison, 2004 data reveals that 37 MJ of primary energy are expended per worker-hour. This difference indicates rising energy efficiency per capita, possibly as a result of population growth or differences in data collection.

Note that allocating energy use over the entire population gives us a better estimate than allocating energy use over the workforce alone. Just as a machine tool must be manufactured and have an end of life, a worker must have a childhood and an end of life.

This upper bound estimate considers all the infrastructure and services that go into supporting a worker in terms of primary energy. Primary energy is measured in the units of tons of oil equivalent (TOE). Unlike final consumption in the form of refined fuels or electricity, primary energy captures all transformation and distribution losses.

However, energy use per worker-hour calculated based on primary energy cannot be used as a component of process-based life-cycle assessment because this method double counts industrial energy use. A better estimate of energy use per worker-hour for the industrial sector is derived from non-industrial energy supply, which includes all primary energy except that supplied to industry, as given by Equation 7.1.

$$e_{wk-hr} = \frac{TPES - IPES}{P_{wk} \times H} \tag{7.1}$$

where $TPES$ is a country or regions total primary energy supply and IPES is industrial primary energy supply. P_{wk} is the worker population in the region, and H is the number of hours in a year. $IPES$ can be replaced with primary energy supply to other sectors of the economy or specific industrial sectors, such as the petrochemical sector, to reflect a particular product or process.

Energy use per worker-hour, in terms of primary energy, captures the energy mix and efficiencies in transformation and distribution for a given region. However, $IPES$ is not always readily available, so I approximate it using industrial final consumption (IFC) and total final consumption (TFC) of energy as follows

$$IPES = TPES \times \frac{IFC}{TFC} \tag{7.2}$$

This assumes the ratio of final consumption to primary energy supply for industry is representative of the ratio of final consumption to primary energy supply for the country. Countries with industries that consume disproportionately more primary energy than the country at large are penalized by this assumption, resulting in a larger value of EPWH.

The International Energy Agency (IEA) regularly compiles and publishes values for TPES, IFC, and TFC from each country or region in its purview (IEA, 2010c), (IEA, 2010d). Though there are disparities in what each country reports, the IEA make efforts to standardize where possible. As defined by the IEA, the industrial sector includes mining, smelting and construction but does not include transportation used by industry.

This method of calculating the energy use of a worker- hour suitable for use in life cycle assessment can be expanded to water use and greenhouse gas (GHG) emissions. The environmental impact of a worker-hour is defined as:

$$i_{wk-hr} = \frac{I_{tot} - I_{st}}{P_{wk} \times H} \tag{7.3}$$

where i_{wkhr} is the impact per worker-hour, I_{tot} is the total annual impact reported in the nation or region, I_{st} is the annual impact assessed by the study, using process-based or hybrid economic input-output life cycle assessment.

I assume only the impacts of working hours, generally 21% of total impacts, are attributed to the production system. By amortizing impacts over the worker population, I account for the life cycle of the worker.

For simplicity, I can approximate the impacts of the study with the impacts of the entire industrial sector to produce a lower-bound estimate that is constant across studies. However, this may underestimate the impact per worker-hour up to the percent contribution of the industrial sector to total reported impact.

	Contribution of Industrial Sector to Total Impact	Impact per Industrial Worker-Hour	
Primary Energy Use	19%	63	MJ/wk-hr
GPW Emissions	28%	4.6	kg CO_2 eq/wk-hr
Water Use	23%	82	gal/wk-hr

Table 7.1: Environmental impacts per US worker-hour in 2005.

7.2 Applications

The contribution of labor to LCA is important to quantify, particularly for labor-intensive processes, such as equipment maintenance and electronics assembly, or for labor-intensive industries such as recycling and textiles. The inclusion of labor may reduce discrepancies between environmental and economic assessments, in which labor factors heavily.

Assessments including the impact of labor allow us to compare process technologies employing varying levels of automation. The impacts of labor across manufacturing countries, along with the impacts of transportation and power supply, may be used to site production facilities.

7.2.1 Evaluating Labor-Intensive Processes

Without quantifying the energy use of labor, it is easy to underestimate the environmental impacts of labor-intensive processes, such as those used in installation, maintenance, repair, and recycling.

For example, energy payback time analyses for photovoltaic systems often do not consider panel installation, even though it is a major component of their financial cost. Evaluating the energy use of labor is necessary to determine the impact of expensive and labor-intensive solar cell installation on energy payback time.

Labor-intensive sorting processes for recycling are another important application of the energy use of labor. It is important to know the degree to which the energy expended in sorting processes counteracts the energy savings of recycling. There many benefits to recycling outside of energy savings, but the ratio of energy inputs, including that of labor, to energy savings can serve as a measure of efficiency for recycling operations.

7.2.2 Evaluating Labor-Intensive Industries

The degree of labor required between industries can vary dramatically. Agriculture, handcraft, textile, and service industries are especially labor-intensive. These industries have typically not been the subject of life cycle assessment, even though their products are consumed in relatively large quantities. Process-based LCA would in fact grossly underreport the environmental costs of a service or an entirely handmade product.

It is also interesting to note that new industries, such as the renewable energy and nanotechnology industries, typically employ more workers per unit output than more established industries (Kammen, 2004). Emerging industries may present problems for LCA practitioners seeking to perform comprehensive assessments. As EIO-LCA data is not yet available for the industry in question, new technologies must be assessed using process-based or hybrid EIO-LCA. Evaluating the energy use of labor is therefore especially valuable to accurately assess the environmental impacts of new technologies and industries.

7.2.3 Decisions Regarding Automation

Though there are significant differences between the capabilities of a worker and a machine tool, it is an interesting exercise to compare their relative energy demands. In the US, electricity production from primary energy is approximately 35% efficient (EIA, 2005). This conversion factor is used to compare primary EPWH with machine tool electricity use.

As shown in Figure 7.2, the 6.2 kWh of electricity equivalent EPWH that equates to 63 MJ of primary EPWH is comparable to the power consumption of an automated milling machine but is considerably less than that of a production scale machining center (Dahmus, 2004).

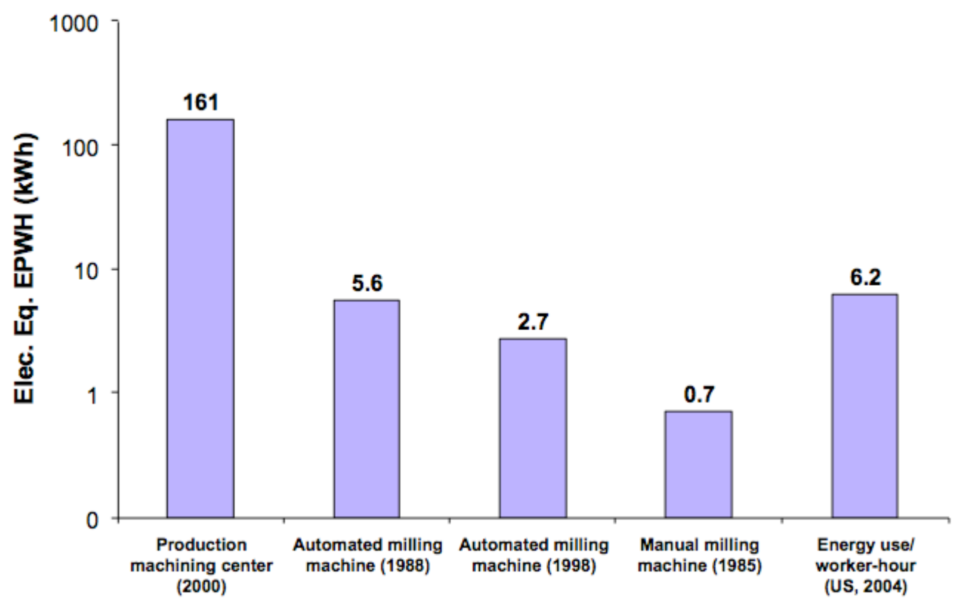


Figure 7.2: Electricity equivalent energy use per worker-hour in the US based on 2004 data as compared to the hourly electricity requirements of four common milling machines produced in the years indicated, adapted from Dahmus, 2004. Note the semi-log scale.

Dahmus presents a thorough analysis of machining, including material production, cutting fluid preparation, and operation of all components of the milling machine itself. I can obtain an even more complete assessment of total energy use by expanding the analysis to include labor.

Assuming the manual milling machine requires one worker to operate, a worker-hour

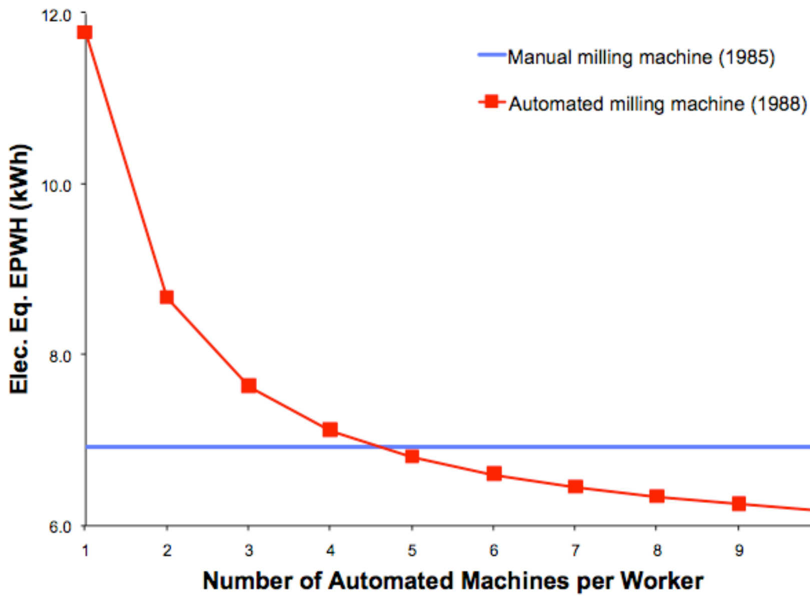


Figure 7.3: Electricity equivalent energy use, including labor and machine operation, for manual and automated machine configurations.

contributes 6.2 kWh to the 0.7 kWh the machine consumes directly each hour. The actual energy impact of manual milling is almost 10 times greater than previously thought. As a component of process-based LCA, this higher energy use may be reflected in a wide range of products and services.

A decision-making application of energy use per worker-hour is shown in Figure 7.3 for Dahmus milling machines. If a worker is able to operate four or more machines at a time, it is advantageous from an energy point of view to employ the automated milling machine even though it directly uses four times more energy per hour than the manual milling machine. Energy use per part will scale with production rate for each machine.

Though many researchers have documented substitutions of labor and energy in practice, until now, the degree to which these substitutions should occur has not been possible to ascertain.

7.2.4 Decisions Regarding Location

The methodology discussed in Section 5.1 can be easily applied to any region with records of total and industrial environmental impacts such as those reporting to the International Energy Agency. Major manufacturing countries demonstrate a wide range of energy use per worker-hour values, as shown in Table 7.2.

These differences can be attributed to a complex set of factors. A very important factor is undoubtedly population. With the exception of the United States, the five most populous countries evaluated represent the countries with the lowest values for energy per worker-hour.

Country	Total Primary Energy Supply	Industrial Final Consumption	Total Final Consumption	Population (million)	EPWH (MJ)
	(EJ/year)				
Brazil	8.6	2.9	7.2	85	7.0
China, Peoples Republic of	67	18	44	614	7.4
Chinese Taipei	4.4	0.93	2.7	11	30
France	12	1.6	7.2	25	41
Germany	15	2.2	11	37	36
India	24	4.0	17	520	4.0
Indonesia	7.3	1.1	5.5	95	7.0
Japan	22	4.3	15	64	29
Korea	8.9	1.6	6.0	23	33
Malaysia	2.4	0.61	1.6	11	15
Mexico	6.9	1.1	4.4	41	14
United Kingdom	9.8	1.4	6.9	28	31
United States	97	13	67	142	63

Table 7.2: Data for the year 2004. Exajoule (EJ) = $10^{1}2$ MJ.

There is also an inverse relationship between impact per worker-hour and ratio of industrial final consumption to total final consumption. For the countries evaluated, this ratio ranges from 19% for the United States to 41% for China. In general, the more a country expends in manufacturing, the less energy is expended per worker-hour. These trends may suggest relationships between service and manufacturing economies and development, or they may simply be attributed to the calculation of impact per worker-hour.

These results do not consider geographic differences in the number of workers employed for any given task, purchasing power and related energy consumption of industry workers compared to the general population, or unemployment rates.

The necessity of excluding industrial energy use from the calculations, as discussed in Section 2.3, is observed when comparing net importers and net exporters. For example, consider the $214 billion trade deficit between the United States and China in 2006. Energy used in China to manufacture goods for sale in the United States does not contribute to the Chinese EPWH. Meanwhile, energy the United States imports in the form of products can be captured by process-based LCA.

Figures 7.4-5 reflect primary energy and global warming potential per worker-hour if trade between countries is considered. Data on trade comes from the International Monetary Fund (IMF) Direction of Trade Statistics (DOT, 2005) database for 168 countries. Primary energy use and global warming potential per dollar of economic activity are calculated for each country, and it is assumed that for every dollar of exports, a corresponding amount of primary energy use or global warming potential is exported.

$$i_{wk-hr,TA,i} = \frac{I'_i - \sum_{i=1}^{168}\sum_{j=1}^{168}(I'_j \times \frac{T_{ij}}{GDP_i}) + \sum_{i=1}^{168}\sum_{j=1}^{168}(I'_j \times \frac{T_{ji}}{GDP_j})}{P_{wk,i} \times H} \tag{7.4}$$

where I'_i refers to non-industrial impacts of country i, T_{ij} is exports of country i to country j, and GDP_i is the gross domestic product of country i. This assumes that the impact intensity of imports correspond to the national average impact intensity of the source of the imports. Relatively few of the 168 countries explicitly report their ratio of industrial to total national primary energy use or industrial to total national global warming potential, so world average values are employed for consistency. World industrial primary energy use comprises 32% of total world primary energy use while world industrial global warming potential comprises 36% of total world global warming potential.

Due to this simplification, the values shown in Figure 7.4 are slightly different from those

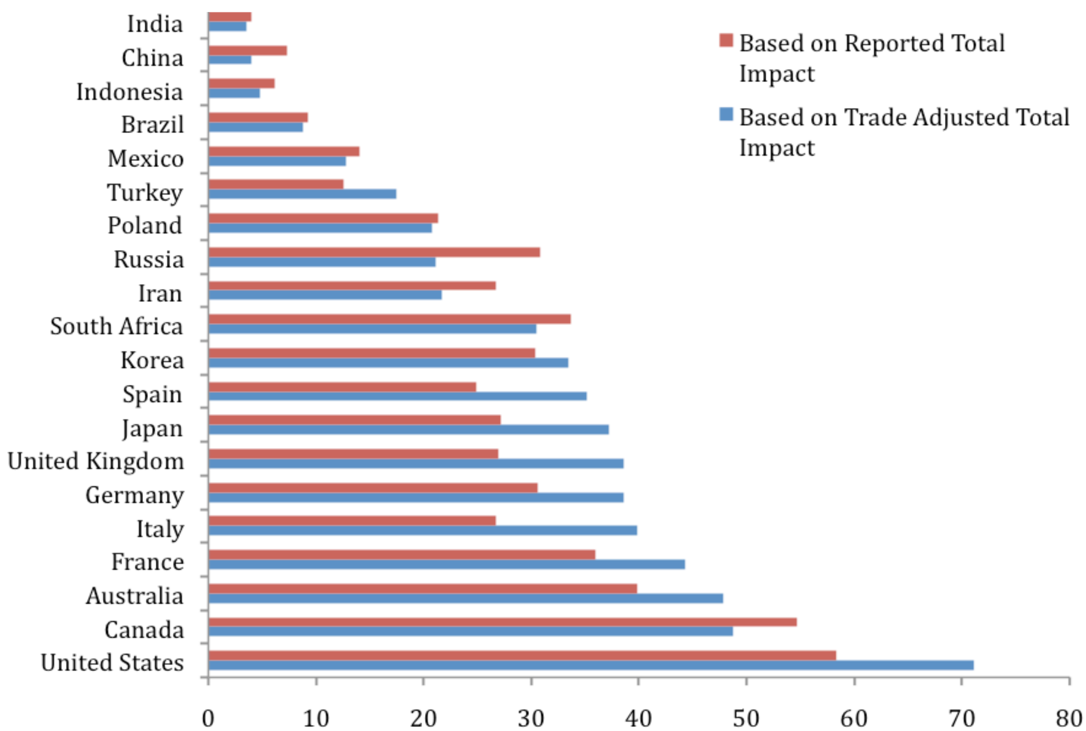


Figure 7.4: Energy use per worker-hour for major manufacturing countries with and without adjustment for trade in 2005.

shown in Table 7.2. This calculation underestimates the impact per worker-hour for the United States, with a ratio of industrial final consumption to total final consumption of 19%, and overestimates impact per worker-hour for China with a ratio of 41%.

7.2.5 Other

The prices of various forms of energy are well documented and understood. It is interesting from an economic and social point of view to understand how labor of a given sector is priced with respect to other forms of energy.

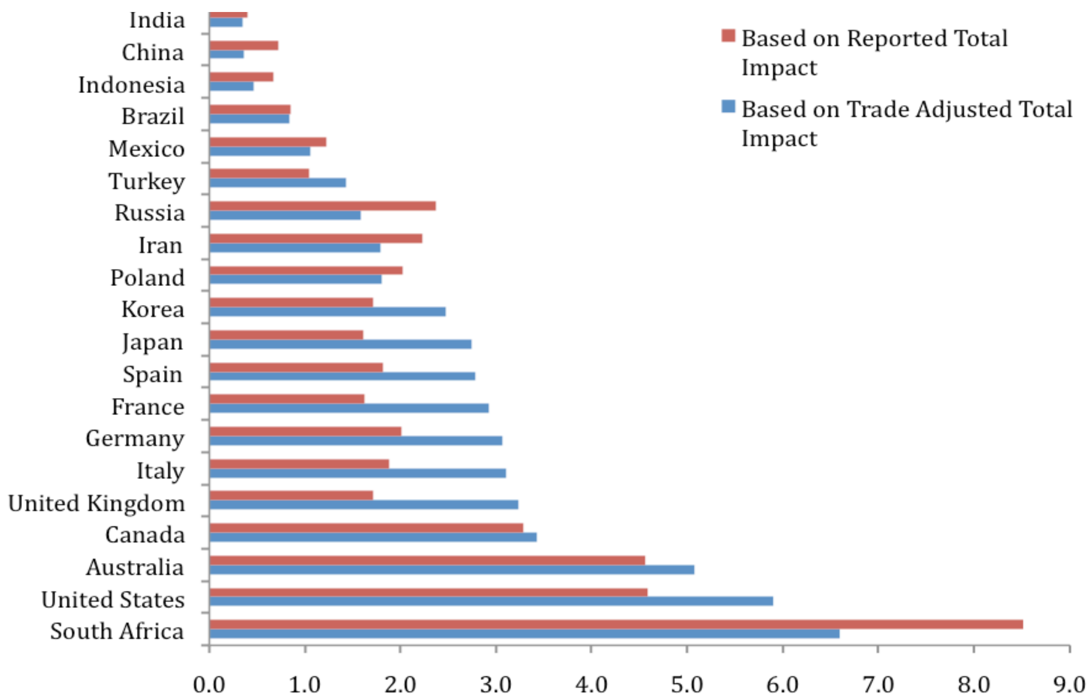


Figure 7.5: Global warming potential per worker-hour for major manufacturing countries with and without adjustment for trade in 2005.

7.3 Discussion

The energy use of labor consequently helps address the disparities between environmental and economic accounting. Environmental analysis largely ignores labor, while the cost of labor factors very heavily into economic analysis. Evaluating the energy use of labor can help reduce the gap between those who prioritize environment and those who prioritize economics.

Finally, human capital, like environmental capital, has externalities that can be passed from a manufacturing system to society at large. For example, manufacturers who pay workers less than a livable wage rely on social programs to support their workforce. The energy use of labor is a tool with which we can begin to account for the environmental externalities of labor.

Amortizing non-industrial energy supply produces a simple estimate of energy use per worker-hour. However, there are questions regarding how to apply this information. At first glance, Figures 7.4-5 appear to present a strong argument for the exportation of labor-intensive industries. Yet, energy savings in labor can be easily overturned by energy use in transportation. Intercontinental shipping can consume 1.1 MJ per container-km, based on industry standard emissions of 85 g CO_2 per container-km (Brutsaert, K., Maritime Engineer, personal communication, February 11, 2007). An average container truck may expend 2.3 MJ/ton-km (Spielmann, 2005), in addition to the energy use of the operator. Energy analysis may be a useful tool for choosing the location of manufacturing facilities, but the energy requirements of both labor and transportation must be considered.

However, industrial final consumption does not include industrial transportation. This means that the energy use of industrial transport is not subtracted from Equation 7.1, and is therefore encompassed by energy use per worker-hour. If used in conjunction with process-based LCA, energy use per worker-hour double counts the energy use of industrial transportation. This is a major drawback of this technique and must be addressed if used with process-based transportation inventories.

It is also not entirely straightforward to decide the number of worker-hours to evaluate in life-cycle assessment. An employee may work eight hours a day, but he or she will continue to expend energy outside of work. Manufacturers reap the rewards of the energy expended during worker-hours in the form of value added to their products and should be responsible for a proportional amount of energy. For the purposes of process-based life-cycle assessment, I recommend calculating the energy corresponding to the number of hours actually worked.

However, one can argue that employers, as a whole, are responsible for the economic activity and corresponding energy consumption employees enjoy outside of work as a result of their hours worked. While the economic activity of both employer and employee are required to sustain manufacturing, consider a factory that employs all workers for only four hours a day. Twice the numbers of workers are needed compared to an identical factory employing workers for eight hours a day. Though these half-time employees would be compensated less and enjoy less economic activity, it is doubtful that their energy demands would be half of that of their full-time colleagues.

Another factor to consider is the effect of feedback. A facility built in a low energy use per worker-hour area may find that its presence spurs economic activity, development, and in turn, increased energy use per worker-hour. It is important to note that energy use, industrial activity, and population can change over time. To be meaningful, energy use per worker-hour should reflect up-to-date statistics.

Evaluating energy use per worker-hour is a simple and effective way to improve the accuracy and scope of life-cycle energy analysis. This dissertation makes note of energy use per worker-hour as it compares to a machine tool and to worker-hours in other major manufacturing regions. The potential applications of the energy use of labor in life-cycle assessment are exceedingly broad.

Chapter 8

Conclusions

Life cycle assessment is a valuable tool of environmental management and a vector for sustainable development. The value of life cycle assessment must not be limited to consumers, especially considering the power that producers wield to directly improve the environmental impact of purchasing choices that are available.

This study aims to aid producers in the design-for-environment process. The LCA tool described in this dissertation provides information to producers so that they may identify opportunities for environmental improvement, track and communicate the impacts of specific design changes, and finally, meaningfully compare the environmental performance of a given product to others on the market.

This dissertation introduces two unique producer-focused LCA features: facilities integration and scenario functionality. Facilities integration is a way of correctly attributing the environmental impacts of manufacturing facilities to the process steps that put demands on the facilities systems. The impacts of manufacturing facilities are often seen as static, when in fact, they dynamically respond to the demands of process tools. By modeling the impacts of the facilities systems as variable, this tool broadens the design space available to producers.

Scenario functionality is a feature of the tool that allows users to select from, and model the environmental impacts 17 model and PV system parameters. Additionally, users may individually add new parameter values and select to include or exclude each component in the life cycle of the PV system. The comprehensive and flexible nature of the model allows engineers and business people alike to evaluate real-world technology, manufacturing, and installation options.

Amongst the life cycle components that can be included or excluded from the analysis are labor used in manufacturing and labor used in installation. Labor is not yet a part of the mainstream LCA methodology but it becomes increasingly important as economies move to service industries and as manufacturing becomes more polarized between highly automated and labor-intensive paradigms.

This dissertation introduces a top-down method of quantifying the environmental impacts of industrial labor in terms of "x per worker-our". The method is applied to quantify energy use, global warming potential, and water use of a worker-hour in the US, though the same method may be applied to any metric of environmental impact. The energy and global warming potential of 20 countries are also shown, with and without accounting for trade between 168 countries.

8.1 Implications of Results

This research is fairly unique in the PV LCA literature in that it recognizes the strong influence of many system and model parameters to the results of the study. Life cycle assessments are known to be vulnerable to parameter and scope choices, leading to problems of comparability and reproducibility. This is especially true with photovoltaic life cycle assessments, as the field is populated by a wide range of technologies that are manufactured and implemented under dramatically different yet realistic situations.

Despite industry efforts to standardize assessments, there is a great deal of variability in the scope definition of PV life cycle assessments. Particularly because this field garners the attention of many outside the LCA community, it is important to avoid using results of dissimilar studies to draw unwarranted or inappropriate conclusions.

Of the parameters evaluated, the environmental intensity of electricity offset during the life of the installed PV system is one that emerges as one of great importance. The energy conversion efficiency, and to a lesser extent, the installation performance ratio are widely recognized as important parameters in the environmental performance of a PV system. However, few studies explicitly compare a number of installation locations and the corresponding characteristics of electricity offset.

The characteristics of electricity offset is as important as energy conversion efficiency to the environmental performance of the PV system. In contrast to the current state of affairs, the most environmentally benign PV life cycles would consume an efficient source of power during manufacturing and offset inefficient power sources during the use phase of the system.

Average energy and GWP intensity of power vary across major manufacturing countries. Furthermore, as discussed in Section 6.1.1, the electricity offset by solar typically does not offset an average mix of power, but rather a marginal mix of power. Because PV systems generate power during daylight hours, they may offset a greater proportion of dirty but agile peaking plants than is indicated by the national average.

The weight of this parameter suggests the need for better data on marginal electricity production. Due to the lack of such data, this study approximates the electricity offset with national average energy production with potentially significant impacts on the results. The characteristics of both build and marginal electricity production will vary over a wider range of values, by region and time, compared to the characteristics of average electricity production.

8.2 Suggestion for Practice and Policy

The results of this study suggest several courses of action for the photovoltaic industry and policy makers, finding that the current global PV industry is not operating at top environmental performance. Rather, PV modules are largely manufactured in countries using electricity of high impact intensity and then installed in countries offsetting electricity of low impact intensity. This mismatch severely impacts the environmental payback times for photovoltaic systems.

This work suggests that the industry and policy makers should strongly encourage PV installation to offset dirty sources of power, such as power from diesel generators. Leapfrogging cleaner, intermediate sources of power, such as natural gas, will produce the greatest environmental benefit in the shortest time.

It is also important that PV production consume efficient sources of power, whether by virtue of the power mix available via the regional power grid or via photovoltaic installations at the manufacturing plant. So called "breeder plants" are not explored in this dissertation, but offer a means of improving the environmental performance of PV products at a fixed location or within a fixed electricity supply system.

8.3 Significance of Findings

This research illustrates the value that life cycle assessment brings to the design-for-environment processes. Concurrent environmental assessment, or that which occurs during product development process, may shorten the environmental performance feedback loop, accelerating the development of environmentally benign products and potentially bypassing or otherwise avoiding environmentally costly products.

Many aspects of this life cycle assessment model may be applied to other photovoltaic products and other electricity producing technologies, such as wind, hydro, geothermal, or tidal sources of power. Furthermore, the facilities integration feature can be modified to address any production system with extensive facilities systems, such as in the chemical or pharmaceutical industries.

Most significantly, this work highlights the many parameters that describe and impact the findings of an LCA study. Prioritizing particularly influential parameters will give producers greater and more direct access to improving environmental performance. The model also demonstrates that life cycle assessment tools may be flexible to produce results reflecting a wide range of technology, manufacturing and installation choices.

8.4 Limitations the Study

A major limitation of the model, as with any LCA model, is data quality. The energy use and global warming potential data collected for the PV module manufacturing is of exceptionally high quality, but the data on upstream and downstream components is hindered by limited data availability for specialty materials and products, particularly those of unusually high purity.

Insufficient data is currently available to accurately assess the human toxicity and water consumption of the PV system. Data limitations also include gaps due to technology fit, geographic fit, and marginal electricity characteristics.

Geographic fit is particularly a limitation for processes evaluated using the 2002 US EIO-LCA model, as many components of the PV life cycle occur outside the US. EIO-LCA treats imports as having the same impacts as products produced domestically, but this is an approximation that may be misleading under certain situations.

This highlights another benefit of scenario functionality. As improved data becomes available, the user may easily manually input additional parameter values, thereby extending the utility of such an LCA tool.

The facilities integration model offers sufficient resolution to make many decisions, but there are aspects of the model that are lacking. For example, though the scrubbers employed at the 14 manufacturing locations vary significantly, due to differences in national and regional environmental regulations, they were modeled as performing as industry standard based on the SEMI S23 standard due to lack of data on the individual scrubbers.

8.5 Future Work

As with all life cycle assessments, more work will need to be done to improve the resolution of the study. The data limitations, such as regarding the performance of the range of scrubbers in use today, are the primary areas in need of future work.

One of the LCA limitations addressed by this study is the ephemeral validity of life cycle assessment results. Additional work is also needed to maintain the utility of the model. To maintain the current level of accuracy, the user must update values for many system and model parameters, such as the manufacturing throughput rate, and module lifetime.

The BOS components, equipment and infrastructure are modeled using EIO-LCA. Future iterations of this model will evaluate the manufacturing equipment in process-based detail. The equipment is an especially good candidate because process-based data is available and because EIO-LCA may not accurately represent the globally sourced nature of the manufacturing equipment.

The significance of the sensitivity analysis results warrants additional evaluation, ideally using Monte Carlo methods. As mentioned previously in Section 6.1.1, the true impact of a photovoltaic system is unknown without knowledge of marginal electricity production and it's environmental characteristics.

Finally, the most significant future work that must be undertaken is the application of producer-focused LCA methodology to other products and services. The value of life cycle assessment is far too great for manufacturers and producers to disregard, especially as awareness of the environmental impacts of manufactured products continue to grow. This dissertation is a showcase and call to action for both the life cycle assessment community and producers of ever more environmentally benign goods.

Appendix A

Acronyms

AEP – Average Electricity Production

AP – Acidification Potential

BOS – Balance of Systems

CDA – Clean Dry Air

CDL – Consumption Data List

CED – Cumulative Energy Demand

CWL – Cooling Water Loops

DI – De-Ionized

DFE – Design-for-Environment

ECF – Energy Conversion Factor

EIO-LCA – Economic Input-Output Life Cycle Assessment

EOL – End of Life

EPBT – Energy Payback Time

GHG – Greenhouse Gases

GWP – Global Warming Potential

GWP-PBT – Global Warming Potential Payback Time

ICW – Industrial City Water

IEx – Ion Exchange

IFC– Industrial Final Consumption

IPES – Industrial Primary Energy Supply

LCA – Life Cycle Assessment, or sometimes, life cycle analysis

LCI – Life Cycle Inventory

LCIA – Life Cycle Impact Assessment

LL – Load Lock

MCW – Municipal City Water

MEP – Marginal Electricity Production

MOER – Marginal Operational Emissions Rate

MUW – Make Up Water

PCW – Process Cooling Water

PECVD – Plasma-Enhanced Chemical Vapor Deposition

POU – Point of Use

PVB – Poly Vinyl Butyral

PVD – Physical Vapor Deposition

RO – Reverse Osmosis

RPS – Remote Plasma Source

STLC – Soluble Threshold Limit Concentration

TCLP − Toxcity Characteristic Leaching Procedure

TCO − Transparent Conductive Oxide

TFC− Total Final Consumption

TOE − Tons of Oil Equivalent

TPES − Total Primary Energy Supply

TTLC − Total Threshold Limit Concentration

UF − Ultra Filtration

UPW − Ultra Pure Water

WCF − Water Conversion Factor

WIP − Work in Progress

Appendix B

Consumption Data List (CDL)

Utility	Metrics
Electricity	Equip Peak Load [kW] Equip Average Load [kW]
CDA 1 (>120 psi)	Compressed air Max flow [Sl/min] Compressed air average flow [Sl/m] CDA pressure [bar absolute]
CDA 2 (<120 psi)	Compressed air Max flow [Sl/min] Compressed air average flow [Sl/m] CDA pressure [bar absolute]
Cooling Water Loop1	Max Cooling water flow [m^3/h] Avg Cooling water flow [m^3/h] Heat Load Max [kW] Heat Load Average [kW] Cooling Water Temperature [C] Cooling Water temp. drop Delta T [C] Cooling water supply pressure [bar absolute] Cooling water back pressure [bar absolute] Pressure difference inlet / outlet [bar]

continued on the next page

Utility	Metrics
Cooling Water Loop2 (Chilled)	Max Cooling water flow [m^3/h] Avg Cooling water flow [m^3/h] Heat Load Max [kW] Heat Load Average [kW] Quality [uS/cm] Cooling Water Temperature [C] Cooling Water temp. drop Delta T [K] Cooling water supply pressure [bar absolute] Cooling water back pressure [bar absolute] Pressure difference inlet / outlet [bar]
Cooling Water Loop 4 (DI Water)	DI-H2O for Cooling Max flow [m^3/h] DI-H2O for Cooling Average [m^3/h] DI-H2O for Cooling Max Heat Load [kW] DI-H2O for Cooling Average Heat Load [kW] DI-Water Temperature C DI-Water Cooling Quality [uS/cm] DI-H2O Cooling Water temp. drop Delta T [K] DI-Water inlet pressure [bar absolute] Pressure difference inlet / outlet [bar]
DI-Water	DI-H2O Connected flow [m^3/h] DI-H2O Max flow [m^3/h] DI-H2O average [m^3/h] DI-Water Quality [uS/cm] DI-Water pressure [bar]
Industrial City Water	ICW Connected [m^3/h] ICW Max [m^3/h] ICW Avg [m^3/h] ICW Pressure [bar]
Air supply (from production hall)	Flow Rate [m^3/h] rel. humidity [% RH] Pressure [bar] Temperature [C]

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Utility	Metrics
Exhaust air (to production hall)	Loaded flow (m^3/h) Loaded temperature (C) Unloaded flow (m^3/h) Unloaded temperature (C)
Scrubbed Exhaust	Exhaust [m^3/h] Exhaust temperature (C) Discharge pressure [bar gauge]
General Exhaust	Exhaust [m^3/h] Exhaust temperature (degrees C) Discharge pressure [bar gauge]
Environment Heat Load	Heat Load Max [kW] Heat Load Average [kW]
Reclaim DI Water	Connected flow [m^3/h] Peak flow [m^3/h] Average flow [m^3/h] Temperature [C] pH-Value [pH] Contaminants
Waste Water	Waste Water Connected [m^3/h] Waste Water Max [m^3/h] Waste Water average [m^3/h] Waste Water (AA) Connected = max [m^3/h] Waste Water (AA) average [m^3/h] Waste Water F- Connected = max [m^3/h] Waste Water F- average [m^3/h] pH-Value [pH] Temperature [C]

Table B.1: Utilities and parameters documented by the consumption data list (CDL).

Bibliography

Alfredsson, E. (2004). green consumption no solution for climate change. *Energy*, 29:513–524.

Alsema, E. (2000). Energy pay-back time and CO_2 emissions of pv systems. *Progress in Photovoltaics: Research and Applications*, 8:17–25.

Alsema, E., de Wild-Scholten, M., and Fthenakis, V. (2006). Environmental impacts of PV electricity generation - a critical comparison of energy supply options. In *Proceedings of the 21st European Photovoltaic Solar Energy Conference*, Dresden, Germany, 4-8 September.

Alsema, E., Fraile, D., Frischknecht, R., Fthenakis, V., Held, M., Kim, H., Plz, W., Raugei, M., and de Wild-Scholten M. (2009). IEA PVPS task 12. methodology guidelines on life cycle analysis of photovoltaic electricity, subtask 20 lca. Technical report, International Energy Agency Photovoltaic Power System Programme.

Bankier, C. and Gale, S. (2006). Energy payback of roof mounted photovoltaic cells.

Boustead, I. and Hancock, G. (1979). *Handbook of Industrial Energy Analysis*. Wiley and Sons, New York.

Boyd, S., Dornfeld, D., and Krishnan, N. (2006). Life cycle inventory of a cmos chip. In *Proceedings of the 2006 IEEE International Symposium on Electronics and the Environmen*, San Francisco.

Boyd, S., Horvath, A., and Dornfeld, D. (2009). Life-cycle energy demand and global warming potential of computational logic. *Environmental Science and Technology*, 43(19):7303–7309.

Bretz, R. (1998). Setac lca workgroup: data availability and data quality. *The International Journal of Life Cycle Analysis*, 3(3):121–123.

Callaway, D. and Fowlie, M. (2009). Greenhouse gas emissions reductions from wind energy: Location, location, location? Preliminary.

Cloony, C. (2009). Lca finally takes water into account. *Environmental Science and Technology*, 10:3986.

Dahmus, J. B. and Gutowski, T. G. (2004). An environmental analysis of machining. In *Proceedings from the ASME International Mechanical Engineering Congress*, Anaheim, CA.

de Koning, A., Schowanek, D., Dewaele, J., Weisbrod, A., and Guine, J. (2006). Uncertainties in a carbon footprint model for detergents; quantifying the confidence in a comparative result. *International Journal of Life Cycle Assessment*, 15(1):79–89.

de Wild-Scholten, M., Alsema, E., ter Horst, E., Bchler, M., and Fthenakis, V. (2006). A cost and environmental impact comparison of grid connected rooftop and ground-based pv systems. In *Proceedings of the 21st European Photovoltaic Solar Energy Conference*, Dresden, Germany.

Denholm, P. and Margolis, R. (2008). Land-use requirements and the per-capita solar footprint for photovoltaic generation in the united states. *Energy Policy*, 36(9):3531–3543.

Dorjets, V. (2011). Form EIA-860: Annual electric generator report. Technical report, Energy Information Administration.

DOT (2005). Direction of trade statistics. Technical report, International Monetary Fund.

EC (2010). PV status report 2010: Research, solar cell production and market implementation of photovoltaics. European Commission.

EIA (2005). Annual energy review 2005. Technical report, Energy Information Administration, US Department of Energy (DOE).

Facanha, C. and Horvath, A. (2006). Environmental assessment of freight transportation in the u.s. *International Journal of Life Cycle Assessment*, 11(4):229–239.

Finnveden, G. (2000). On the limitations of life cycle analysis and environmental systems analysis tools in general. *International Journal of Life Cycle Assessment*, 5(4):229–238.

Fransen, T., Bhatia, P., and Hsu, A. (2007). Measuring to manage: A guide to designing ghg accounting and reporting programs. Technical report, World Resources Institute.

Fthenakis, V. (2004). Life cycle impact analysis of cadmium in cdte pv production. *Renewable and Sustainable Energy Reviews*, 8:303–334.

Fthenakis, V. and Alsema, E. (2006). Photovoltaics energy payback times, greenhouse gas emissions and external costs: 2004early 2005 status. *Progress in Photovoltaic Research and Applications*, 14:275–280.

Fthenakis, V., Clark, D.O.. Moalem, M., Chandler, P., Ridgeway, R., Hulbert, F., Cooper, D., and Maroulis, P. (2010). Life-cycle nitrogen trifluoride emissions from photovoltaics. *Environmental Science and Technology*, 44(22):8750–8757.

Fthenakis, V. and Kim, H. (2007). Cdte photovoltaics: life cycle environmental profile and comparisons. *Thin Solid Films*, 515:5961–5963.

Fthenakis, V. and Kim, H. (2009). Land use and electricity generation: a life-cycle analysis. *Renewable and Sustainable Energy Reviews*, 13:1465–1474.

Gagnon, L., Belanger, C., and Uchiyama, Y. (2002). Life-cycle assessment of electricity generation options: the status of research in year 2001. *Energy Policy*, 30(14):1267–1278.

Guine, J., , Gorre, M., Heijungs, R., Huppes, G., Kleijn, R., Koning, A. d., Oers, L. v., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H., Bruijn, H. d., Duin, R. v., and Huijbregts, M. (2002). *Handbook on Life Cycle Assessment. Operational guide to the ISO standards.* Kluwer Academic Publishers, Dordrecht.

Hannon, B., Stein, R. G., Segal, B. Z., and Serber, D. (1978). Energy and labor in the construction sector. *Science*, 202:837–847.

IEA (2010a). *CO_2 Emissions from Fuel Conbustion*. Stedi Media, Paris, France.

IEA (2010b). Energy balances of non-oecd countries. Technical report, International Energy Agency, Organization for Economic Co-operation and Development (OECD), Paris, France.

IEA (2010c). Energy balances of oecd countries. Technical report, International Energy Agency, Organization for Economic Co-operation and Development (OECD), Paris, France.

IEA (2010d). *Key World Energy Statistics*. Stedi Media, Paris, France.

IPCC (2007). *Fourth Assessment Report: Climate Change 2007 (AR4)*. Cambridge University Press, Cambridge and New York, 4th edition.

ISO (2006). Environmental management - life cycle assessment - requirements and guidelines. Technical report, International Organization for Standardization.

Kakela, P. J. (1978). Iron ore: Energy, labor, and capital changes with technology. *Science*, 202:1151–1157.

Kammen, D. M., Kapadia, K., and Fripp, M. (2004). Putting renewables to work: How many jobs can the clean energy industry generate? Technical report, Renewable and Appropriate Energy Laboratory, University of California, Berkeley.

Kannan, R., Leong, K., Osman, R., Ho, H., and Tso, C. (2006). Life cycle analysis study of solar pv systems: an example of a 2.7 kwp distributed solar pv system in singapore. *Solar Energy*, 80:555–563.

Kazmerski, L. (2011). Best research-cell efficiencies. National Renewable Energy Laboratory.

Kemfert, C. and Welsch, H. (2000). Energy-capital-labor substitution and the economic effects of co2 abatement: Evidence for germany. *Policy Modeling*, 22:641–660.

Kenny, J. F., Barber, N. L., Hutson, S. S., Linsey, K. S., Lovelace, J. K., and Maupin, M. A. (2009). *Estimated Use of Water in the United States in 2005*. Number 1344 in Circular. United States Geological Survey, Reston, VA.

Keoleian, G. and Lewis, G. (1997). Application of life-cycle energy analysis to photovoltaic module design. *Progress in PhotovoltaicsF*, 5:287–300.

Knapp, K. and Jester, T. (2000). An empirical perspective on the energy payback time for photovoltaic modules. In *Proceedings from the Solar 2000 Conference*, Madison, WI.

Krishnan, N., Boyd, S., Somani, A., Raoux, S., Clark, D., and Dornfeld, D. (2008a). A hybrid life cycle inventory of nano-scale semiconductor manufacturing. *Environmental Science and Technology*, 42(8):3069–3075.

Krishnan, N., Williams, E., , and Boyd, S. (2008b). Case studies in energy use to realize ultra-high purities in semiconductor manufacturing. In *Proceedings of the IEEE International Symposium on Electronics and the Environment*, San Francisco.

Lenardic, D. (2008). *Large-Scale Photovoltaic Power Plants: Annual and Cumulative Installed Power Output Capacity*. PV Resources, Jesenice, Slovenia.

Mason, J., Fthenakis, V., Hansen, T., and Kim, H. (2006). Energy pay-back and life cycle co_2 emissions of the bos in an optimized 3.5 mw pv installation. *Progress in Photovoltaics: Research and Applications*, 14(2):179–190.

Meijer, A., Huijbregts, M., Schermer, J., and Reijnders, L. (2003). Life-cycle assessment of photovoltaic modules: comparison of mc-si, ingap and ingap/mc-si solar modules. *Progress in Photovoltaics: Research and Applications*, 11(4):275–287.

Mohr, N., Meijer, A., Huijbregts, M., and Reijnders, L. (2003). Environmental impact of thin-film gainp/gaas and multicrystalline silicon solar modules produced with solar electricity. *International Journal of Life Cycle Assessment*, 14:225–235.

Muller, A., Wambach, K., and Alsema, E. (2006). Life cycle analysis of solar module recycling process. In *Proceedings of the Material Research Society Symposium*.

Mulvaney, D., Bolam, V., Cendejas, M., Davis, S., Ornelas, L., Kim, S., Mau, S., Rowan, W., Sanz, E., Satre, P., Sridhar, A., and Young, D. (2009). Towards a just and sustainable solar energy industry. Technical report, Silicon Valley Toxics Coalition, San Jose, CA.

NASA (2011). Insolation at specified location. atmosphere-ocean model. Technical report, US National Aeronautics and Space Administration.

Odum, H. T. (1996). *Environmental Accounting: Energy and Environmental Decision Making*. Wiley and Sons.

Ortelli, A. (2009). Analyse de cycle de vie de la technologie photovoltaque “tandem thin film”. Master’s thesis, Ecole des Mines d’Ales.

Pacca, S. and Horvath, A. (2002). Greenhouse gas emissions from building and operating electric power plants in the upper colorado river basin. *Environmental Science and Technology*, 36(14):3194–3200.

Pacca, S., Sivaraman, D., and Keoleian, G. (2007). Parameters affecting the life cycle performance of pv technologies and systems. *Energy Policy*, 35:3316–3326.

Peharz, G. and Dimroth, F. (2005). Energy payback time of the high-concentration pv system flatcon. *Progress in Photovoltaics: Research and Applications*, 13:627–634.

Pfister, S., Koehler, A., and Hellweg, S. (2009). The water shoesize vs. footprint of bioenergy. *Environmental Science and Technology*, 43(11):4098–4104.

Pindyck, R. S. (1979). Interfuel substitution and the industrial demand for energy: An international comparison. *The Review of Economics and Statistics*, 61(2):169–179.

Raugei, M. and Frankle, P. (2009). Life cycle impacts and costs of photovoltaic systems: current state of the art and future outlooks. *Energy*, 34:392–399.

Richards, B. and Watt, M. (2007). Permanently dispelling a myth of photovoltaics via the adoption of a new net energy indicator. *Ren. and Sust. Energy Reviews*, 11(1):162–172.

Rydh, C. (1999). Environmental assessment of vanadium redox and lead-acid batteries for stationary energy storage. *Journal of Power Sources*, 80(1-2):21–29.

SEMI (2008). Semi s23-0708 - guide for conservation of energy, utilities and materials used by semiconductor manufacturing equipment. Technical Report S23-0708, SEMI Safety Guidelines.

Sherwani, A., Usmani, J., and Siddhartha, V. (2009). Life cycle analysis of solar pv based electricity generation: a review. *Ren. and Sust. Energy Reviews*, 14(1):540–544.

Spielmann, M. and Scholz, R. W. (2005). Life cycle inventories of transport services: Background data for freight transport. *International Journal of Life Cycle Assessment*, 10(1):85–94.

Stokes, J. and Horvath, A. (2009). Energy and air emission effects of water supply. *Environmental Science and Technology*, 43(8):2680–2687.

Suh, S., Lenzen, M., Treloar, G. J., Hondo, H., Horvath, A., Huppes, G., Jolliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard, J., and Norris, G. (2004). System boundary selection in life-cycle inventories using hybrid approaches. *Environmental Science and Technology*, 38(3):657–664.

Thiriez, A. and Gutowski, T. (2006). An environmental analysis of injection molding. In *Proceedings of the 2006 IEEE International Symposium on Electronics and the Environment*, San Francisco.

Tsoutsos, T., Frantzeskaki, N., and Gekas, V. (2005). Environmental impacts from the solar energy technologies. *Energy Policy*, 33:289–296.

Veltkamp, A. and de Wild-Scholten, M. (2006). Dye sensitised solar cells for large-scale photovoltaics; the determination of environmental performances. In *Proceedings of the Renewable Energy 2006*, Chiba, Japan.

Wackernagel, M. and Rees, W. (1996). *Our ecological footprint: reducing human impact on the earth*. New Society Publishers.

Wald, M. L. (2010). Nuclear renaissance is short on largess. *The New York Times*.

Weidema, B., Frees, N., and A-M., N. (1999). Marginal production technologies for life cycleinventories. *Int. J. Life Cycle Assess*, 4(1):48–56.

Weidema, B. P. and Wesns, M. S. (1996). Data quality management for life cycle inventoriesan example of using data quality indicators. *Journal of Cleaner Production*, 4:167–174.

Weiss, R., Mhle, J., Salameh, P., and Harth, C. (2008). Nitrogen trifluoride in the global atmosphere. *Geophysical Research Letters*, 35.

Welsch, H. (1996). Recycling of carbon/energy taxes and the labor market. *Environmental and Resource Economics*, 8:141–155.

Williams. and E. (2004). Energy intensity of computer manufacturing: hybrid assessment combining process and economic input-output methods. *Environmental Science and Technology*, 38(22):6166–6174.

Xu, M., Allenby, B., and Chen, W. (2009). Energy and air emissions embodied in china-u.s. trade: Eastbound assessment using adjusted bilateral trade data. *Environmental Science and Technology*, 43(9):3378–3384.

Younos, T., Hill, R., and Poole, H. (2009). Water dependency of energy production and power generation systems. Technical report, Virginia Water Resources Research Center. Special Report No. SR46-2009.

Zhang, T. and Dornfeld, D. (2007). Energy use per worker- hour: Evaluating the contribution of labor to manufacturing energy use. In *Proceedings of the 14th CIRP Conference on Life Cycle Engineering*, Tokyo.