Life Cycle Assessment of Photovoltaic Manufacturing Consortium (PVMC) CIGS Cells:

REVISED REPORT

Submitted to
New York State Energy
Research and Development Authority
Agreement No. 30191
Task Work Order No. 2

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July 20, 2015

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List of Acronyms

AC: alternating current

Al:ZnO: aluminum-doped zinc oxide

a-Si: amorphous silicon

BOS: balance of system

CdS: cadmium sulfide

CdTe: cadmium telluride

CIGS: copper indium gallium (di)selenide

CIS: copper indium (di)selenide

CNSE: Colleges of Nanoscale Science and Engineering

CTU e/h: comparative toxicity unit (ecotoxicity/health)

DC: direct current

DF: degradation factor

DR: degradation rate

E: solar cell efficiency

EOL: end-of-life

EPBT: energy payback time

ETFE: ethylene tetrafluoroethylene

EVA: ethylene vinylacetate

GHG: greenhouse gas

GWP: global warming potential

ISO: International Organization for Standardization

i-ZnO: intrinsic zinc oxide

LCA: life cycle assessment

LCI: life cycle inventory

LCIA: life cycle impact assessment

LT: solar cell lifetime

mono-Si: monocrystalline silicon

multi-Si: multi-crystalline silicon

NREL: National Renewable Energy Lab

NYSERDA: New York State Energy Research and Development Authority

PET: polyethylene terephthalate

poly-Si: polycrystalline silicon

PPE: polyphenylene ether

PR: performance ratio

PTFE: polytetrafluoroethylene

PVMC: Photovoltaic Manufacturing Consortium

R&D: research and development

SENSE: Sustainability Evaluation of Solar Energy Systems

SI: solar irradiation

TCO: Transparent Conducting Oxide

TPE: thermoplastic elastomer

TRACI: Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts

x-Si: poly/mono/multi- crystalline silicon

Zn(O,S): zinc oxysulfide

Executive Summary

The photovoltaic (PV) industry is rapidly evolving as demand for renewable energy sources continues to grow. Although the PV industry is currently dominated by traditional silicon-based technology, next generation thin-film PV cells are gaining traction due to their potential for lower costs, better reliability, and higher efficiency.

This report presents the results of a life-cycle assessment (LCA) study of thin film PV cells – *copper indium gallium (di)selenide (CIGS)* – currently being researched and developed by the Photovoltaic Manufacturing Consortium (PVMC). Based in New York State (NYS), PVMC is an industry-led consortium of industry, university, and government stakeholders working to advance next generation PV cells (PVMC, 2014). Since the CIGS cell technology shows promise for significant growth, PVMC sought support to identify potential opportunities to reduce human health and environmental impacts of the product system using an LCA approach.

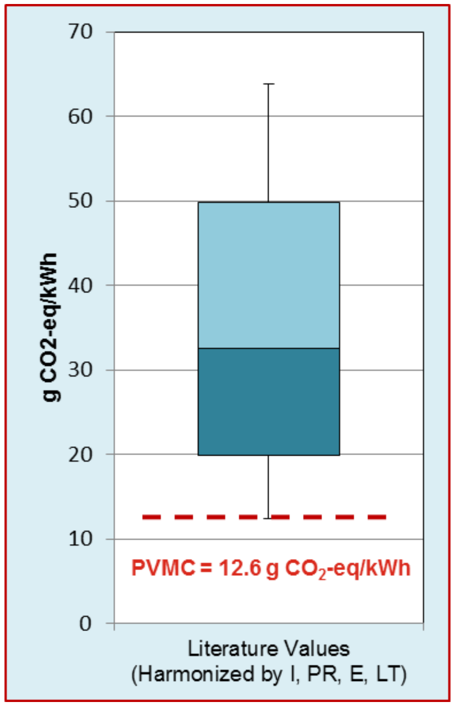

Figure ES- 1. PVMC CIGS Global Warming Impacts Compared to Harmonized Results of Published

The study, which entailed a cradle-to-gate LCA (i.e., material extraction to processing and product manufacture stages) due to limited end-of-life disposition data, identified the following key drivers of impacts: (i) silver used in several components of the cell (stringer and screen printing process), (ii) metals comprising the CIGS layer (copper, indium, gallium, and selenium), (iii) surface washing of the stainless steel substrate, and (iv) copper in the cable used in the balance of system. In addition, the study found that the zinc oxysulfide alternative had lower overall impacts compared to cadmium. Based on these key results, potential opportunities PVMC may wish to consider to reduce impacts include recycling more of the waste materials (including metals and water), using recycled metals to reduce the impact of virgin materials, considering substitution of the cadmium sulfide with the zinc oxysulfide alternative, and researching additional alternative metals that may have lower impacts, while maintaining similar properties.

Comparison of the overall life cycle impact results of PVMC's CIGS PV system to similar systems in published studies, which focused primarily on greenhouse-gas emissions, found that it fell in the lower end of the range of estimated global warming impact data (see Figure ES-1). This is likely due to PVMC's use of a stainless steel rather than glass substrate and the location of its manufacturing facility in NYS, which relies on a more renewable-based energy grid.

Additional research should be considered to further inform material and process choices that would yield a more sustainable CIGS cell. In particular, although the study found that the zinc oxysulfide alternative had lower overall impacts compared to cadmium sulfide, additional analysis of the alternatives should be conducted using data on the disposition of the filters containing the cadmium contaminants and potential emissions at the end-of-life stage. Also, given the impacts of metals, an LCA comparing different metal choices in the CIGS cell (e.g., using copper instead of silver) should be studied. Finally, a life cycle costing analysis would further inform material selection decisions to ensure that these decisions not only reduce impacts, but are also cost-competitive.

The LCA study was conducted consistent with the International Standards Organization (ISO) 14040 series and follows the Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity developed by International Energy Agency (ISO, 2006; Fthenakis, 2011a).

1 Goal and Scope Definition

An LCA is a comprehensive method for assessing impacts across the full life cycle of a product system, from materials acquisition to manufacturing, use, and final disposition. The International Standards Organization stipulates four phases of an LCA: (i) goal and scope definition, (ii) life-cycle inventory (LCI) collection, (iii) life-cycle impact assessment (LCIA), and (iv) interpretation of results (ISO, 2006). Consistent with these standards and the first phase of the analysis, the following section describes the purpose and goals of the study (Section 1.1), summary of previous LCA studies of PV cells, including CIGS cells (Section 1.2), the product system (Section 1.3), function unit (Section 1.4), and system boundaries (Section 1.5).

1.1 Purpose and Goals

Overall, the need for this study stems from the anticipated growth of CIGS cells coupled with the limited understanding of potential impacts of these cells on human health and the environment throughout the life cycle of the product. The goal of the study, therefore, is to provide information to facilitate improvements to CIGS photovoltaic systems by identifying which materials or processes within the product's life cycle are likely to pose the greatest impacts or potential risks to public health or the environment. The study also assessed some specific alternative materials choices being considered by PVMC to further inform their material selection decisions as the technology evolves and grows.

The target audience for the LCA study includes PVMC and other CIGS photovoltaic manufacturers, CIGS suppliers, and PV recyclers. Additional stakeholders include potential consumers and investors of CIGS cells and federal, state, and local agencies with an interest in promoting renewable energy sources, including the New York State Energy Research and Development Authority (NYSERDA).

1.2 Previous Research

Thousands of LCA studies on photovoltaic (PV) technologies have been published since their emergence with wide-ranging results (NREL, 2013). These studies have primarily assessed traditional silicon-based technology, which was the first type of PV technology to emerge. Although this technology continues to dominate the market, thin film PV systems are gaining traction due to lower cost and better performance (Kim et al., 2012). Thin film PV systems include amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium (di)selenide (CIGS or CIS).

The PV LCA studies have focused primarily on greenhouse gas (GHG) emissions from the raw material extraction to the manufacturing and use stage. Energy payback time (EPBT), the amount of time it takes for PV systems to generate the quantity of energy used in their life cycle, is another commonly used metric. Results from these studies, however, vary significantly due to different boundary conditions, modeling assumptions and data sources. The National Renewable Energy Lab (NREL) undertook a study to determine the key sources of variability in order to harmonize and compare results across studies (NREL, 2013). Kim et al. (2012) conducted a similar harmonization study with a focus on thin film PV modules. The harmonization methodology for both studies began with a review of the LCA literature of PV systems. The identified literature sources were screened based on the completeness of the results, data quality, age of data, and relevance to present day technologies (Kim et al., 2012; NREL, 2013). Of the screened studies, the following key parameters were identified that affect the energy output of the solar cells and LCA results:

- **Solar irradiation (kWh/m^2/year)** is the amount of solar energy incident upon a unit area of collector in the solar field during one year. NREL (2013) found that the solar irradiation assumption for LCA studies of PV cells varied from 900 - 2,143 kWh/m^2/year.
- **Operating lifetime (years)** is the useful life of operating systems assumed in LCA studies, which varied from 20 to 30 years for the CIGS cells (Kim et al., 2012).

- **Module conversion efficiency (%)** is the ratio of the annual electrical output of a solar cell to the input (solar irradiation). For CIGS PV cells, Kim et al. (2012) found the module efficiencies ranged from 9 to 11.5%.
- **Performance ratio (%)** is the ratio between the actual and theoretical energy outputs. The performance ratio for CIGS cells ranged from 75 to 91.2 percent (Kim et al., 2012).
- **Installation type** is either roof or ground mounted, which impacts the balance of system (BOS) and frame and materials needed to mount the cells (Kim et al., 2012).

The results from the screened studies were harmonized by adjusting key parameters and applying a common system boundary. For example, Kim et al. (2012) applied a solar irradiation level of 1,700 kWh/m^2/year for Southern Europe and 2,400 kWh/m^2/year for the Southwestern U.S., a module efficiency of 11.5% for CIGS, and a useful life of 30 years. The harmonized results found GHG emissions ranged from 14 to 36 g CO_2-eq/kWh for ground-mounted PV systems and 14 to 38 g CO_2-eq/kWh for roof top PV systems. These ranges were attributed to differences and assumptions regarding the type of PV technology, the manufacturing location, energy grid-mix, and the balance of system. Most of the GHG emissions occurred before the operational (use) phase (NREL, 2013) and were sensitive to the upstream grid-mix and production capacity (modules produced per year) (Kim et al., 2012).

Kim et al. (2012) found that of the LCA studies completed on thin film technology, most focused on a-Si and CdTe systems, as they have been in development longer than CIGS and other thin film technology. Of the 109 thin film LCA studies screened, 21 studies reviewed CIGS. Of these, only *two* met the screening requirements for data quality, relevance, and completeness. The first study by Raugei et al. (2007) relied upon "prototype batch production" data of copper indium (di)selenide (CIS) cells and "standard production data" of CdTe cells from 2004. In addition to GHG emissions, aquatic toxicity, and acidification potential were also assessed. Based on these impact categories, in comparison to poly-silicon based cells, the study found thin film technology to be more environmentally preferable, with a preference toward CdTe cells (Raugei, 2007).

The second study, a European Commission (EC) project titled Sustainability Evaluation of Solar Energy Systems (SENSE, 2008), assessed three types of thin film PV technologies (CIGS, a-Si, and CdTe). The data for the CIGS cells were based on production data from Wurth Solar from 2003 to 2006. The report concluded that power use in the "absorber simultaneous deposition" and the metal frame production caused the largest environmental impacts. The production capacity was also found to significantly influence results. The study also considered impacts from recycling of the cells based on laboratory experiments of different recycling strategies. Although data were limited, the study found recycling the CIGS and CdTe modules by thermal treatment to be favorable (SENSE, 2008).

Another recent study by Einsenberg et al. (2013) assessed the toxicity of materials in CIGS cells available commercially in 2010. Given the wide variety in manufacturing methods and emergence of new materials, the study highlighted the importance of evaluating the use of hazardous materials in the modules. Einsenberg et al. (2013) relied upon the Green Screen for Safer Chemicals and the Toxic Potential Indicator to assess the toxicity hazards associated with the alternative materials in CIGS cells. For each key component (p-type absorber, junction partner, transparent conducting oxide, and encapsulant layer) the study identified several materials and processes that are less hazardous. For example, for the p-type absorber, the study found that the $CuInS_2$ type absorber deposited by spray pyrolysis is preferable compared to the other materials evaluated (Einsenberg et al., 2013). However, the study did not follow a life cycle assessment approach.

A recently published Master's Thesis for the Norwegian University of Science and Technology by Kristine Bekkelund (2013) conducted a comparative LCA of four types of solar cells, including two multi-crystalline silicon based cells, and two thin film technologies (CdTe and CIGS). The study found the thin film cells had lower impacts than the silicon based cells. The study relied upon secondary data sources from published studies including Jungbluth et al. (2012), Alsema et al. (2006) and de Wild-Scholten et al. (2006) as well as Ecoinvent 2.2 data. In addition, it suggested that the dominant drivers of global warming impacts for CIGS cells include the glass for the module and aluminum for the frame.

Peng et al. (2013) prepared the most recent review of LCA studies on thin film cells. Although the technology and installation parameters (e.g., solar irradiation levels, efficiency, etc.) varied among the 5 studies reviewed, the results provided a starting point for comparison between PV technologies. The study found that GHG emissions from CIGS production and use ranged from 10.5 to 95 g CO_2-eq/kWh while energy payback times ranged from 1.45 to 2.9 years (time to produce the energy used throughout production and installation). In addition, the study found that CdTe PV systems had the lowest average GHG emission rate followed by CIGS, multi-Si, mono-Si, and thin-film a-Si.

Despite the emergence of recent CIGS LCA studies, some challenges remain when quantifying the impacts of the balance of system (BOS) needed to complete the photovoltaic installation. The BOS refers to all components external to the PV module required to collect usable electricity. This includes solar panel frames, cables and wires, and inverters needed to convert DC current to AC current. SENSE (2008) and de Wild-Scholten et al. (2013) found the inverter (which converts the direct current output from the PV modules to alternative current) contributes about 10% of the total global warming potential of the PV system. In addition, the Bekkelund (2013) study found that the inverter contributes about 11% to freshwater eutrophication impacts, 10% to human toxicity impacts, and no more than 5.1% of other impacts (Kristine Bekkelund, 2013).

Given the useful life of the PV systems (about 20 to 40 years), limited data have been available to assess the end-of life stage – especially of thin film PV modules (NREL, 2013; SENSE, 2008; Kim et al., 2012). CIGS modules are currently in the early stages of development and hold a 2% market share (Solarbuzz, 2014). As a result, there is currently minimal recycling of CIGS modules taking place. However, CIGS recycling processes are being piloted and researched as the volume of CIGS cells that reach the end-of-life is anticipated to grow. In addition, the semiconductor materials and other materials used in the modules are considered valuable for use in other products (McDonald et al., 2010).

As described above, most prior LCA studies are based on dated pilot production data from Europe or secondary data sources. Limited data are also available to assess impacts from recycling and disposal of the modules, but this will become increasingly important as the PV modules reach the end of their useful life. **Accordingly, this study was designed to help fill this research gap by using primary data from manufacturers and suppliers from PVMC.** In addition, most prior LCA studies have focused on GHG emissions instead of also considering human health and other environmental impacts, which were evaluated for this study.

1.3 Product System

CIGS solar cells consist of nanometer to micrometer thick layers of materials, combining to create a semiconductor that converts light to energy (Eisenberg et al., 2013). As shown in Figure 1, CIGS cells generally consist of several layers including (from bottom to top): stainless steel or glass substrate, barrier layer, back metal contact, p-type absorber, buffer layer (junction partner), and n-type window. The thickness and type of material used in each layer may vary, resulting in multiple configurations of CIGS cells. Figure 1 lists the materials used by PVMC as well as the range in thickness in micrometers (μm).

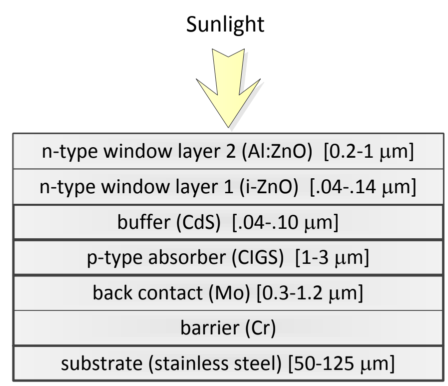

Figure 1. Cross-section of CIGS PV Cell
(Bekkelund, 2013; Eisenberg, 2013, PVMC, 2014)

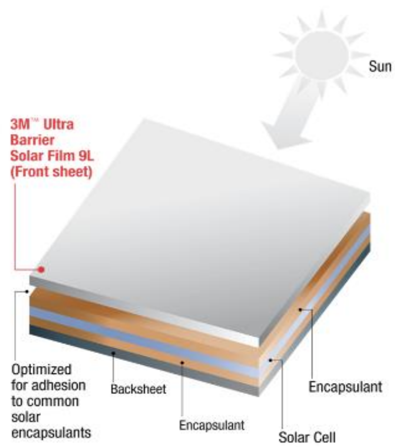

Figure 2. Cross-section of CIGS Module
(Source: 3M Website)

Once the discreet CIGS cells are formed, they are wired and glued together to form a solar module. The number of cells wired together depends on the end-use application. The solar module is then laminated together with a top and bottom sheet of polymer (to maintain flexibility) and encapsulant composed of ethylene vinyl acetate (that serves as the glue). A solar edge tape, composed of a desiccant (absorber) is also wrapped around the module. The polymer and solar edge tape serves to protect the module from weather and water damage (Bekkelund, 2013). Figure 2 illustrates the CIGS module layers.

Next, a junction box is attached to the module, which is composed of plastic and other electronic material. The module is then tested and installed using a mounting structure, cables, and an inverter - referred to as the balance of system (BOS). The BOS differs based how and where the modules are mounted for the consumer (use stage) (Bekkelund, 2013).

1.4 Functional Unit

In an LCA, the functional unit normalizes data based on equivalent use (or service provided to consumers) to provide a reference for relating process inputs and outputs, and impact categories for the LCA across product systems. Since the service provided by solar panels in the use phase is energy – consistent with prior LCA studies, we applied a functional unit of kilowatt-hours (kWh).

To derive the inventory amounts and impacts on a per kWh basis we estimated the total lifetime output (kWh) of the CIGS cell from one square meter using the following equation:

SI x PR x E x LT x DF x A= Lifetime Output (kWh)

Where,

- *SI = Solar irradiation level (kWh/m^2/year);*
- *PR = Performance ratio (%): ratio of the actual and theoretically possible energy output;*
- *E = Efficiency (%): percent of incoming solar irradiation converted into electricity;*
- *LT = Lifetime (years);*
- *DF = Degradation factor derived from degradation rate (DR) or (1-(1-DR)^L)/(1-(1-DR)); and*
- *A = Area of module (m^2).*

Table 1 presents the values assumed for each variable identified in the equation, which are based on the design of the CIGS cells by PVMC and assumes a rooftop installation in NYS.

Table 1. PVMC CIGS Performance Parameters

Factor	Value
Solar Irradiation (kWh/m^2/year)	*1409.7*
Performance ratio (%)	*89*
Efficiency (%)	*14*
Lifetime of Module (years)	*25*
Degradation Rate (%)	*1*
Area of Module (m^2)	*1*
Lifetime output (kWh) =	***3,902.5***

1.5 System Boundaries

As illustrated in Figure 3, LCAs evaluate the life-cycle environmental impacts from each of the major life-cycle stages: raw materials extraction, materials processing, product manufacture, product use, and end-of-life/final disposition. Also included are the activities that are required to affect movement between the stages (e.g., transportation). The inputs (e.g., resources and energy) and outputs (e.g., product and waste) within each life cycle stage, as well as the interaction between each stage (e.g., transportation), are evaluated to determine the environmental impacts.

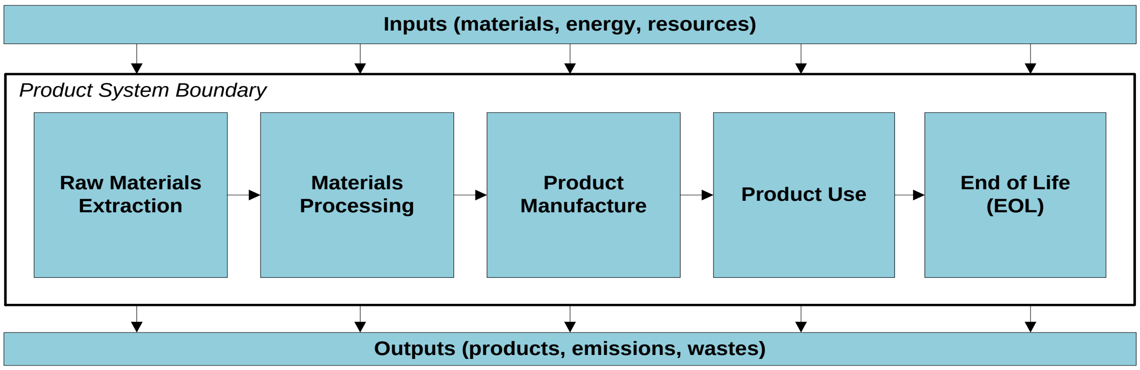

Figure 3. Life-Cycle Stages of the Product System

Figure 4 illustrates the process flow diagram of the CIGS cells manufactured by PVMC throughout the life-cycle. Below we describe key assessment boundaries and assumptions applied in this study:

- **Zinc oxysulfide alternative.** Because PVMC is researching different material and process choices for CIGS cells, the LCA study evaluated z*inc oxysulfide (Zn(O,S)) as an alternative for cadmium sulfide (CdS)* for the junction partner using a wet chemical bath deposition process. Although cadmium is the most common material used in a junction partner for CIGS cells, due to potential toxicity concerns in the manufacturing and end-of-life stages, alternative materials are being researched and used in CIGS cells (Eisenberg et al., 2013; Fthenakis, 2009). In fact, Solar Frontier (located in Japan) currently manufactures CIGS PV cells using a zinc alternative (Solar Frontier, 2015).

- **Balance of System.** Consistent with prior studies this study includes the balance of system (BOS), including the rooftop mounting structure, cabling, inverters, and other components needed to produce electricity from the PV modules. Due to limited resources, inventory data were not obtained on all of the BOS components, including the thermoplastic, printed circuit board and transformer, so these components were excluded from the study. In addition, PVMC's manufacturing processes have very limited influence on the BOS inventory with the exception of the rooftop mounting structure for which PVMC provided inventory data.

- **Use stage application.** Assumptions for the mounting structure needed for the BOS were based on a typical rooftop installation in NYS and based on data provided by PVMC. A lifetime of 25 years was assumed.

- **End-of-life stage**. Due to the lack of inventory data for the end-of-life stages, this stage was not modeled and assessed in the study. Recycling processes and options to recover the metals and hazardous materials in PV cells are still being piloted and investigated (Marwede et al., 2013). Accordingly, we provided a qualitative assessment of end-of-life impacts based on prior research.

- **Transportation.** This study focused on the manufacturing and use of these PV cells in NYS by PVMC. Accordingly, the study considered transportation distances of 98.2% (by mass) of the primary and ancillary materials used in the BOS and module.

- **Temporal boundaries.** Parameters that may change with time (e.g., availability of landfill space, recycling rates, recycling technologies) were assumed to be similar to current conditions and remain constant throughout the lifetime of the product system.
- **General exclusions.** Impacts from the infrastructure needed to support the manufacturing facilities (e.g., general maintenance of manufacturing plants and lighting) were beyond the scope of this study.

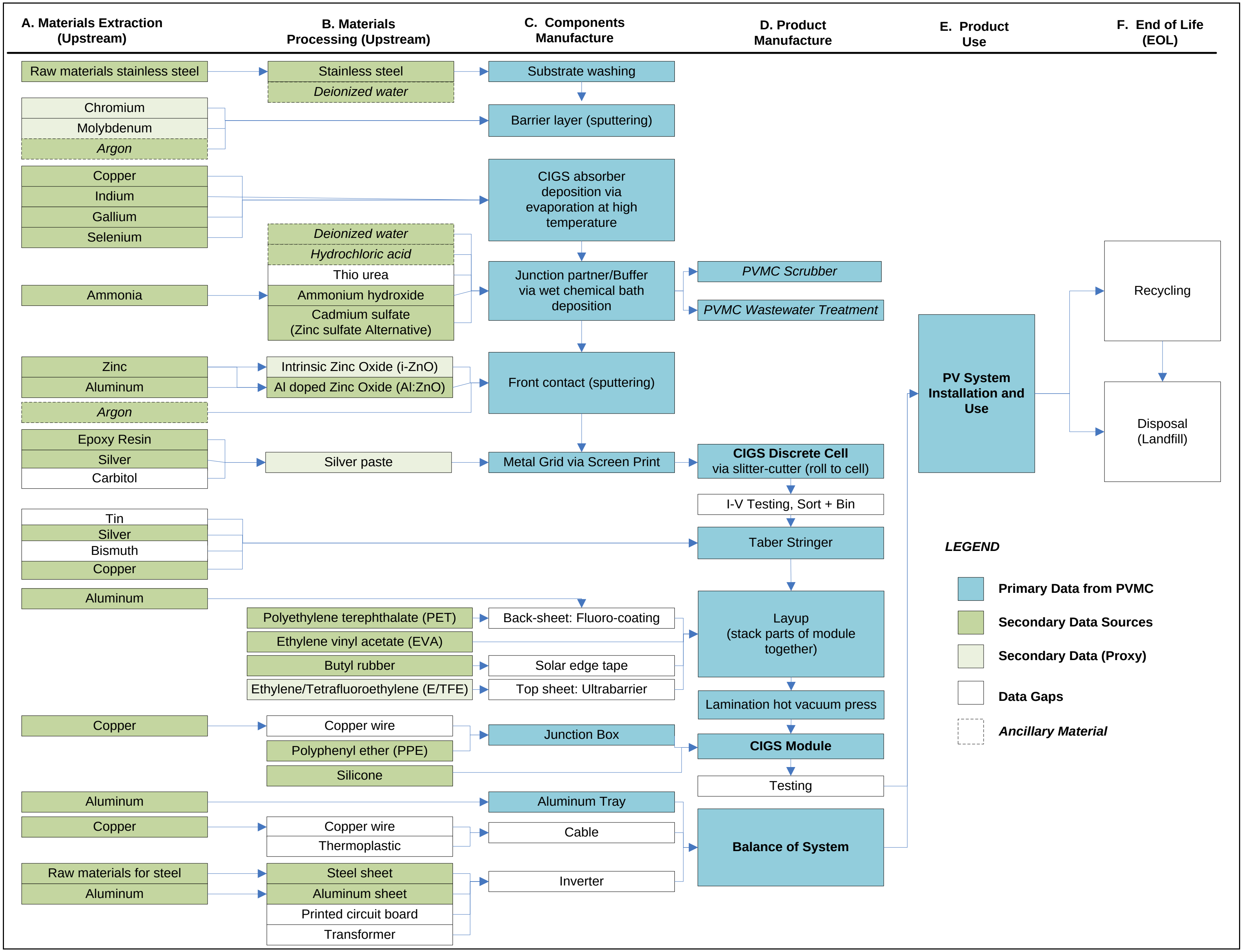

Figure 4. Process Flow Diagram of CIGS Cells Manufactured by PVMC

2 Methods and Data

Quantification of the life-cycle inventory (LCI) is conducted as part of the second phase of the LCA study. A product system is made up of multiple processes needed to produce, use, and dispose, recycle, or reuse the product. As presented in Figure 5, each process consists of an inventory of input and output flows.

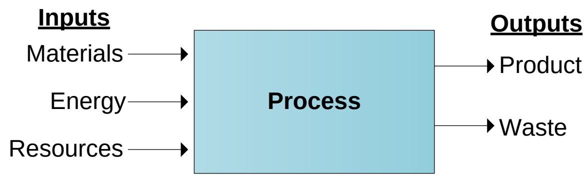

Figure 5. Process Input and Output Flows

Accordingly, an LCI of a product system consists of a set of inventories for processes throughout the life cycle of the product – from upstream materials extraction, to materials processing, product manufacture, product use, and then end-of-life. Below we describe the data sources used in the analysis (Section 2.1), assumptions (Section 2.2), and limitations (Section 2.3) of the study.

2.1 Data Sources

As shown in Figure 4, LCI data for the study were obtained from both primary and secondary data sources. Primary data are directly accessible, plan-specific, measured, modeled, or estimated data generated for the study. Secondary data are from literature, LCI databases, or other LCA studies. Primary data were obtained from PVMC's Research and Development (R&D) facility for the manufacture of the CIGS cell and module. Located in Halfmoon, New York, PVMC's R&D facility is led by the Colleges of Nanoscale Science and Engineering (CNSE) of SUNY Polytechnic Institute. The facility is used to develop prototypes, conduct testing, and pilot different CIGS thin film and PV manufacturing technologies (PVMC, 2014). The primary data covered the component and product manufacture stages. Secondary data were obtained for the upstream processes and materials from the GaBi6 LCA software tool and published literature. The GaBi software tool stores and organizes LCI data and calculates life-cycle impacts for a product profile. It is designed to allow flexibility in conducting life-cycle design and life-cycle assessment functions, and provides the means to organize the inventory data, investigate alternative scenarios, evaluate impacts, and assess data quality (Thinkstep, 2015).

2.1.1 Data Sources for Materials Used

LCI data were collected for materials included in the bill of materials (BOM) of the CIGS product system. Table 2 presents the BOM, which includes the materials and mass (on a per square meter basis) used for each component or layer of the PV module, provided by PVMC. The table includes both the materials used directly in the final product as well as ancillary materials (i.e., material needed for the manufacturing process, but not incorporated in the product).

As shown in the table, the CIGS module uses approximately 150kg of material per square meter. Of this, 98.6% is used as ancillary material, which primarily includes distilled water for the surface washing step (of the stainless steel substrate) and junction partner layer. Outside of the ancillary materials, the key materials by mass used in the CIGS module, include the stainless steel (20%), ethylene vinyl acetate (EVA) (46%), and polyethylene terephthalate (PET) (11.6%). The stainless steel, used for the substrate is the first layer of the CIGS cell (see Figure 1). The EVA and other plastics (PET and ETFE) in the layup process, where the components of the module are stacked together before lamination, are used to protect the cells from weather and other elements once installed.

Table 2. Bill of Materials for the CIGS module (Cadmium Sulfate option)

Material Inputs				Final Product			
Layer	**Material**	**Mass (g/m^2)**	**% of Non-Ancillary Inputs**	**Mass (g/m^2)**	**Mass (%)**	**Mass by Layer (g/m^2)**	**Mass by Layer (%)**
Surface	430 Stainless Steel	387.00	18.43%	387.00	20.25%	387.00	20.25%
	Water	122,000.00					
Barrier	Molybdenum	20.42	0.97%	10.13	0.53%	10.36	0.54%
	Chromium	0.45	0.02%	0.23	0.01%		
	Ancillary materials[b]	0.16					
CIGS	Copper	3.35	0.16%	1.84	0.10%	8.02	0.42%
	Indium	4.91	0.23%	2.70	0.14%		
	Gallium	0.95	0.04%		0.03%		
				0.52			
	Selenium	11.82	0.56%		0.15%		
				2.95			
Junction	Cadmium Sulfate	1.54	0.07%		0.03%	0.51	0.03%
Partner				0.51			
	Thiourea	22.84	1.09%		0.00%		
	Water	22,249.99					
	Ancillary materials	2,585.75					
TCO	Intrinsic ZnO	0.51	0.02%	0.25	0.013%	1.50	0.08%
	Al: ZnO	2.56	0.12%	1.25	0.065%		
	Ancillary materials	0.16					
Screen Printing	Silver paste	7.63	0.36%	7.10	0.37%	7.10	0.37%
Stringer	Copper	31.80	1.51%	31.80	1.66%	57.22	2.99%
	Bismuth	1.81	0.09%	1.81	0.09%		
	Tin	0.01	0.00%	0.01	0.001%		
	Silver	23.60	1.12%	23.60	1.23%		
Layup	Back Sheet (Al)	135.00	6.43%	133.65	6.99%	1,363.78	71.35%
	EVA (Ethylene Vinyl acetate)	888.81	42.32%	879.92	46.04%		
	Butyl rubber	48.60	2.31%	43.74	2.29%		
	ETFE (Ethylene tetrafluoroethylene)	85.00	4.05%	84.15	4.40%		
	PET (Polyethylene terephthalate)	345.00	16.43%	222.32	11.63%		
	Ancillary materials	119.23					
Lamination	None					0.00	
Module Assembly	Silicon	9.37	0.45%	8.43	0.44%	75.79	3.97%
	PPE	46.73	2.22%	46.73	2.44%		
	Copper wire	20.63	0.98%	20.63	1.08%		
TOTAL[a]	**All Materials**	**149,055.62**					
	***Excluding* Ancillary Materials**	**2,100.33**	**100.00%**	**1,911.27**	**100.00%**	**1,911.27**	**100.00%**

Note: [a] Figures may not sum to 100, due to rounding.
[b]Ancillary materials include argon, ammonium hydroxide, filters for water treatment, and PET plastic.

In some cases, proxy datasets and assumptions were applied for materials if the exact secondary dataset was not available or if costs for the dataset were outside the budget of this study. Table 3 provides a summary of the materials and processes for which proxy data were applied.

Table 3. Summary of Proxy Data Sources and Assumptions

Material	Proxy Dataset (Source)	Notes
Molybdenum (Barrier)	Ferro Manganese (Gabi6)	Similar production methods; may overstate health impacts from manganese versus molybdenum
Chromium (Barrier)	Ferro chrome (Gabi6)	Best available data set available from GaBi; Emissions associated with additional processing steps not captured
Indium; Gallium; Selenium (CIGS)	Nuss and Eckelman (2015)	Applies price data from 2006 to 2010 to allocate upstream environmental burden in multi-output processes, based on methods described in study.
Metal disposal	Landfill of ferro metals (Gabi6)	Best available dataset from GaBi.
Ion Exchange Resin (PVMC treatment plant)	Polystyrene (Gabi6)	Polystyrene is the primary component of resin
Zinc Oxide (Front Contact)	Zinc (Gabi6)	Extracted from the same ore
Silver paste (Screen printing)	Based on silver and resin amounts (Gabi6)	Primary component of silver paste. Missing carbitol and energy needed. (72% Ag, 16% Carbitol, 12% epoxy)
Ethylene tetrafluoroethylene (Layup)	Polytetrafluoroethylene (Gabi6)	Comparable plastics

In addition to the CIGS module, the study included the balance of system (BOS) for rooftop installations. LCI data for the BOS was obtained both from PVMC as well as a study by Fthenakis et al. (2011b). The study included LCI data for several PV systems as well as BOS for ground and roof-mount installations developed as part of the International Energy Agency (IEA), Task 12. For a rooftop installation, the BOS typically includes inverters, mounting structures, cables, and connectors. The Fthenakis et al. (2011b) study includes LCI data for the electrical cabling for roof top installations and a 2,500 W AC inverter. Based on data from PVMC regarding the number of inverters per CIGS module, we applied a factor of 6% to the LCI data for the inventor, which assumes that approximately 1 inverter is needed for about 16.7 m^2 of module area. The mass of mounting structure, composed of aluminum trays, was also obtained from PVMC (340 g/m^2).

2.1.2 Data Sources for Energy

During the data collection phase, we also collected energy use data for each process. As presented in Table 4, the CIGS layer and lamination process consume just over 50% of the energy needed to manufacture the PV module. This is due to the high-temperature processes needed for these layers. This percentage breakdown is consistent for both the cadmium sulfide and zinc oxysulfide alternative.

Table 4. Summary of Primary Energy Use of PV Module by Layer

Layer	Energy Input	
	By Layer (kWh/m2)	By Layer (%)
Surface	0.13	0.29%
Barrier Mo	5.20	11.62%
CIGS	11.08	24.77%
Junction Partner	6.39	14.27%
TCO	6.50	14.53%
Screen Printing	1.30	2.91%
Stringer	0.39	0.87%
Layup	0.26	0.58%
Lamination	12.00	26.82%
Module Assembly	1.50	3.35%
TOTAL	**44.75**	**100%** [a]

Note: [a] Figures may not sum to 100, due to rounding.

Because PVMC's facility is located in NYS the study assumed an average NYS based grid-mix. The New York State grid mix data are based on 2012 electricity production data from the U.S. EPA's Emissions and Generation Resource Integrated Database (eGRID), and accordingly does not account for electricity imports into or exports out of the region. As shown in Table 5, the NYS grid mix compared to the average U.S. grid mix, relies on approximately 37% less hard coal and 22% more hydropower.

Table 5: US. v. NY State Grid-Mix

Source [a]	US Grid (%)	NYS (%) (production mix)	Difference
Nuclear	20.24%	28.88%	8.64%
Lignite	2.00%	0.00%	-2.00%
Hard coal	42.51%	5.56%	-36.95%
Coal gases	0.06%	0.00%	-0.06%
Natural gas	23.45%	30.31%	6.86%
Heavy fuel oil (HFO)	1.08%	0.08%	-1.00%
Biomass solid	0.98%	0.79%	-0.19%
Biogas	0.20%	0.86%	0.66%
Waste-to-Energy	0.41%	0.67%	0.26%
Hydropower	6.81%	29.24%	22.43%
Wind	1.86%	3.60%	1.74%
Photovoltaics	0.02%	0.00%	-0.02%
Geothermal	0.38%	0.00%	-0.38%
Grid losses	6.54%	9.17%	2.63%
Output total	**100.00%**	**100.00%**	

Source: [a] eGRID (2012)

2.2 Assumptions

Due to data limitations, it was important to make key assumptions to model the CIGS PV cells, as described below:

- **Transportation.** In order to estimate transport distances and impacts, assumptions were made with respect to where the raw materials are likely obtained throughout the supply chain. The study included transport distances for higher volume and weight materials, which covers 98.2% (by mass) of the primary and ancillary materials used in the BOS and module. Upstream resource locations were determined by choosing locations with the highest yearly production in 2014, based primarily on U.S. Geological Survey data (USGS, 2015). For example, we assumed that steel for the substrate and inverter would be obtained from Japan and thiourea would be obtained from China. Transportation distances were estimated using SeaRates.com's online tool for distances by sea and Google Maps for distances by land. Impacts from transporting the modules from PVMC's manufacturing facility to the installation site were not included as the study assumed installation of the modules in NYS.

- **Allocation procedures** are typically required when multiple products or co-products are produced using the same process. Currently, PVMC manufactures only CIGS cells in its manufacturing development facility. Accordingly, allocation of the flows was not needed for the manufacturing stage.

  However, the study also uses many metals which are derived as co-products of other metals. For example, cadmium and indium are produced from further processing and refining of zinc mining residues. Consistent with ISO standards it is important to allocate the burdens of mining and processing metals co-products through mass or economic allocation. Using only mass allocation methods, however, may underestimate impacts especially when some metals are mined for their high-value co-products. Using only an economic allocation method instead also brings uncertainty given the volatility of metals prices. Following the zinc co-product example, although the concentration of the output from zinc mining is 53% zinc and 0.011% indium by mass, the values are $2.57/kg and $692.60/kg, respectively (based on average 2006-2010 prices). Accordingly, the Nuss et. al. (2014) study incorporates economic allocation of impacts of metals using a 5-year average market price to smooth out price variances. Drs. Nuss and Eckleman provided the study team with impact results for the CIGS metals, including indium, gallium, and selenium on a per mass basis based on the economic allocation method described in their study. These impacts were incorporated in our study results and converted to a per kWh basis.

2.3 Limitations

Although LCI data for most of the components and processes were identified through primary or secondary data sources, below we highlight key uncertainties, limitations, and assumptions with respect to the data:

- The inventory data provided by PVMC was based on pilot scale production data, and required some estimation of inventory data by PVMC. In addition, data on cells and modules that do not pass testing and quality control were not available.
- Inventory data were not available for thiourea (for the junction partner), and bismuth and tin (for the stringer). These materials comprise approximately 1.2% of the input materials (not including ancillary materials).
- The model did not include impacts for the granulated activated carbon (GAC) and resin filter materials or impacts from treating the filters once disposed due to limited data availability and resources.
- Data for the recovery of metals were limited. Some metals were sent for recovery by PVMC, including indium, aluminum zinc-oxide (Al:ZnO) and intrinsic zinc-oxide (i-ZnO), and silver. Accordingly, for these metals, we assumed metal landfilling using the GaBi6 dataset as a conservative assumption.
- Recovery of the PET in the layup process was not available. Similar to the metals, we assumed landfilling of PET in a plastics landfill as a conservative assumption.
- The model did not include energy resources needed to manufacture the Al:ZnO and Intrinsic ZnO.
- For the balance of system, data were not available for the thermoplastic polyurethane granules (TPC) for the cable and circuit board and transformer for the inverter.
- The energy grid data does not incorporate import or export energy sources in NYS.
- The location of the upstream datasets from GaBi6 may not reflect the actual location of PVMC's suppliers.
- Recycling of the CIGS cells is not included in the study as life cycle inventory data were not available.
- The performance and lifetime of the CIGS cells may vary due to weather and performance conditions once installed.

To account for some of these limitations, we conducted a sensitivity analysis on some of the key performance parameters and the grid mix assumptions. In addition, we included a comparison of thin film recycling technologies based on published literature.

3 Results

In its simplest form, life-cycle impact assessment (LCIA) is the evaluation of potential environmental, social, or economic impacts to a system as a result of some action. LCIAs generally use the material consumption and energy use data from the inventory stage to create a suite of estimates for various impact categories. Accordingly, below we present the overall material and primary energy input flows to the CIGS PV system (Section 3.1) followed by a summary of impact results, using established quantitative methods for a number of traditional categories, such as global warming, acidification, ozone depletion, and ecotoxicity and human health (Section 3.2).

3.1 Life Cycle Inventory Results

Upstream material and primary energy inputs are key drivers of the environmental and human health impacts. As a result, below we first present a summary of the energy and material input flows. Results are presented primarily on a functional unit basis (kWh) and where appropriate include results on a per square meter basis.

3.1.1 Primary Energy Use

"Primary" energy represents the system inputs from both raw fuels and other forms of energy. In other words, it is not the measure of energy "from the plug" at a plant, but rather the energy used originally to produce electricity for the grid. Table 6 presents a summary of the primary energy use from the upstream to manufacturing stages by key component for the cadmium sulfide alternative.

Table 6. Summary of Primary Energy Use

Component	kWh/kWh[a]	% of total
Surface Washing	0.0027	3.5%
Barrier Layer	0.0037	4.8%
CIGS Layer	0.0076	9.9%
Junction Partner	0.0099	12.9%
Front Contact	0.0044	5.8%
Screen Printing	0.0040	5.3%
Stringer	0.0139	18.1%
Layup	0.0135	17.7%
Lamination	0.0082	10.7%
Module Assembly	0.0017	2.2%
Mounting Structure	0.0043	5.6%
Balance of System	0.0027	3.6%
Total Primary Energy Demand	0.0766	100.0%[b]
Energy Payback Time	**1.91 years**	

Notes: [a] kWh of primary energy use per kWh of energy produced by CIGS modules. [b] Figures may not sum to 100, due to rounding.

Results indicate that the primary energy needed for the EVA and PET in the layup process and silver for the stringer process, which connects the individual cells together to form a module, consume significant amounts of energy. The CIGS layer and lamination processes are also key drivers of impacts due to the high temperature for these processes. In addition, the energy needed to run the treatment plant to address cadmium and other contaminants from the junction partner, also contributed to a higher primary energy use for this process.

The number of years estimated to generate the electricity used for the life-cycle of the CIGS module (from cradle-to-gate) is approximately 1.91 years. This is based on the benchmark efficiency, performance, life-time, and solar irradiation levels assumed (see Table 1).

3.1.2 Major Material Flows

Table 7 presents a breakdown of the largest material input flows to the CIGS PV system from the upstream extraction, processing, and manufacturing stages.

Table 7. Primary Material Inputs, including the PV Module and BOS (per kWh)

Input Material	Input (g/kWh)	% of Total	% of Total (non-ancillary)	Highest Contributor
Feedstocks				
Bauxite	0.84	0.002%	7.00%	Mounting Structure
Colemanite ore	0.11	0.000%	0.92%	Stringer
Iron Ore	0.34	0.001%	2.88%	Balance of System
Lead	0.43	0.001%	3.56%	Stringer
Lignite	0.42	0.001%	3.52%	Stringer
Limestone	1.43	0.004%	12.00%	Stringer
Ore Mined	1.13	0.003%	9.46%	Balance of System
Quartz sand	0.87	0.002%	7.27%	Stringer
Sodium Chloride	0.20	0.001%	1.68%	Surface Washing
Zinc	1.09	0.003%	9.12%	Stringer
Fuels				
Crude Oil	1.10	0.003%	9.21%	Stringer
Hard Coal	1.75	0.004%	14.62%	Stringer
Natural Gas	1.95	0.005%	16.35%	Layup
Ancillary Inputs				
Air	103.92	0.259%		Surface Washing
Carbon Dioxide	0.57	0.001%		Lamination
Inert Rock	31.68	0.079%		Stringer
Natural Aggregate	0.45	0.001%		Stringer
Soil	1.64	0.004%		Balance of System
Water	39,907.64	99.63%		Mounting Structure
Material accounted for	***40,057.57***	***100.00%***	***97.58%[a]***	

Note: [a] Material accounted for does not add up to 100% because some small quantity materials are not listed in this table.

As presented in the Table, water is the largest mass input. Not only does it comprise approximately 97% of the total material inputs (see Table 2), it is also used as a key energy source. Specifically, the NYS grid mix modeled in the study, which is based on eGRID data, assumes nearly 30% of energy is derived from hydropower. Accordingly, those processes that consume a larger quantity of energy (e.g., lamination process) also consume higher quantities of water. Surrounding air is also a key material input primarily used for the treatment of water following surface washing of the stainless steel substrate.

After water and air, the stringer process contributes significantly to the consumption of inert rock, crude oil, hard coal, limestone, quartz, zinc, and several other inputs. This is primarily due to the extraction and processing of silver, which comprises over 40% of the total mass input in the stringer process.

3.2 Life Cycle Impact Results

Consistent with established LCIA methods, to translate the inventory data into impacts, the data are first linked to impact categories to which they contribute. Next, characterization factors are applied to convert the inventory data to potential impacts and then aggregated for each impact category. For example, for the global warming potential impacts category greenhouse gases (e.g., methane) are sorted and then a characterization factor is applied to estimate impacts on an equivalent basis (e.g., CO_2-equivalents). An LCIA does not seek to determine actual impacts, but rather quantifies the relative magnitude of contribution to the impact category.

This study applies the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) to estimate impacts. TRACI, developed by the U.S. Environmental Protection Agency (EPA) was originally developed in 2003 for application within the U.S. The TRACI characterization factors have recently been updated (version 2.1), and these updated factors are used in this study (Ryberg et al., 2013). Below we present a summary of impact results reflecting PVMC's current process (Section 3.2.1). Next we discuss the results of replacing the cadmium sulfide with the zinc oxysulfide alternative for the junction partner (Section 3.2.2).

3.2.1 LCIA Results of PVMC's Current Process

Table 8 presents a summary of the LCIA results by impact category based on the TRACI 2.1 characterization factors. The results reflect PVMC's current process, which uses cadmium sulfide for the junction partner. .

Table 8. Summary of Life Cycle Impact Results

Impact Category	Units	Impact Quantity (per kWh)
Global Warming	kg CO_2-eq	1.264E-02
Acidification	kg SO_2-eq	2.098E-04
Ecotoxicity	CTUe [a]	3.340E-02
Eutrophication	kg N-eq [b]	5.252E-06
Human Health Particulate	$PM_{2.5}$-eq	6.008E-05
Human Toxicity, Cancer	CTUh	8.234E-11
Human Toxicity, Non-Cancer	CTUh	1.010E-08
Ozone Depletion	kg CFC 11-eq	6.239E-11
Smog	kg O_3-eq	4.869E-04

[a] CTUe: Comparative Toxicity Unit (ecotoxicity), measures relative toxicity based on the potentially affected fraction of a species due to a change in concentration per unit mass of a chemical emitted (USEtox, 2010)
[b] CTUh: Comparative Toxicity Unit (health) is based on the estimated increase in morbidity cases in the total human population per unit mass of a chemical emitted (USEtox, 2010)

Figure 6 presents the impact results by key component.

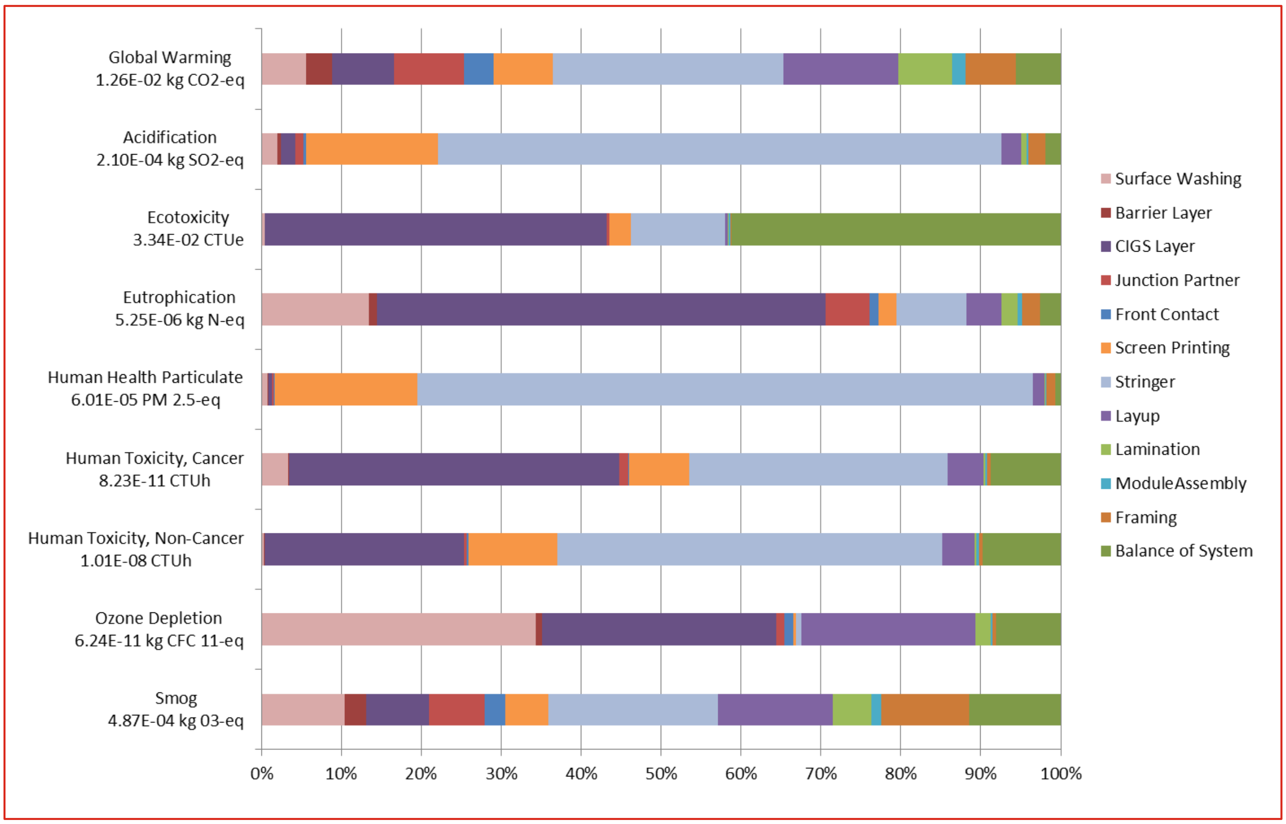

Figure 6. Summary of Life Cycle Impact Results of CIGS Cells by Component (per kWh)
Note: The mounting structure was treated separately from BOS for this figure.

Below we highlight key drivers of impacts based on the LCIA results:

- **Silver in stinger and screen printing.** The stringer is a key driver across most impact categories, including global warming, acidification, particular matter, and human toxicity (cancer and non-cancer). This is primarily due to impacts from the extraction and processing of silver used in the stringer, including high primary energy use. The screen printing processes also uses silver paste, although in a lower quantity than the stringer. The extraction and processing of silver is associated with the release of heavy metals including arsenic, lead and mercury which have high toxicity potential in regards to both cancer and non-cancer effects (U.S. EPA, 1998; U.S. EPA, 2004; U.S. EPA, 1995). These heavy metals likely contribute to the stringer and screen printing driving the human toxicity potential.
- **Metals in CIGS layer.** The impacts associated with the mining of copper, indium, gallium, and selenium contribute to high impacts for the ecotoxicity, human health (cancer and non-cancer), eutrophication, and ozone depletion. The mining and processing of these metals contributes to these impacts. Although selenium, gallium, and indium are not considered toxic metals, they are manufactured from copper refining and lead and zinc production, which contribute to higher toxicity impacts. Of the metals, copper exhibits higher potential toxicity impacts, including aquatic toxicity (U.S. EPA, 2011). Specifically, the mining of copper can lead to exposure of radioactive materials such as uranium, thorium and radium, which contributes to higher human health toxicity potential (U.S. EPA, 2014). Eutrophication and ozone depletion impacts are also attributable not only to the energy needed for the metal processing, but also the high-temperature co-evaporation process needed for to manufacture the CIGS layer.
- **Surface washing of stainless steel substrate.** The manufacture of the stainless steel substrate contributes to higher ozone depletion potential. In addition, the treatment of water used to wash the substrate, contributes to higher eutrophication impacts, as a result of emissions to freshwater.
- **Copper in balance of system.** Across most impact categories, the BOS, including the aluminum mounting structure, does not contribute significantly to impacts. The exception is the copper used in cabling, which leads to higher ecotoxicity potential and also contributes to human health toxicity. As explained previously the mining and processing of copper is highly toxic to aquatic organisms and contributes to human health impacts (U.S. EPA, 2011; U.S. EPA, 2014).

Other notable drivers of impacts include the **treatment plant for the junction partner process** and **EVA and PET used in the layup process**, which contributes to global warming impacts, and **PTFE in the layup process**, which contributes to ozone depletion potential impacts.

3.2.2 Cadmium Sulfide vs. Zinc Oxysulfide Results

PVMC is currently researching zinc oxysulfide as an alternative to the cadmium sulfide currently used in the junction partner layer. Cadmium is known to have a higher toxicity than zinc, particularly in the end-of-life stage, raising concerns about the use of cadmium in CIGS and CdTe PV technologies. The cadmium sulfide is derived from a cadmium sulfate ($CdSO_4$) input material and the zinc oxysulfide is derived from a zinc sulfate ($ZnSO_4$) input material. Figure 7 presents the impacts of producing both input materials (from upstream extraction to processing) on a per area of CIGS cell (sqm) basis and per mass (kg) basis. As shown in the figure, when comparing the alternatives on a per mass basis (right of the figure), the production impacts favor either cadmium sulfate or zinc sulfate depending on the impact category. However, PVMC uses nearly 9 times more cadmium sulfate for the cadmium sulfide alternative versus zinc sulfate for the zinc oxysulfide alternative on a per sqm basis, resulting in significantly higher impacts for the cadmium sulfide option across all impact categories.

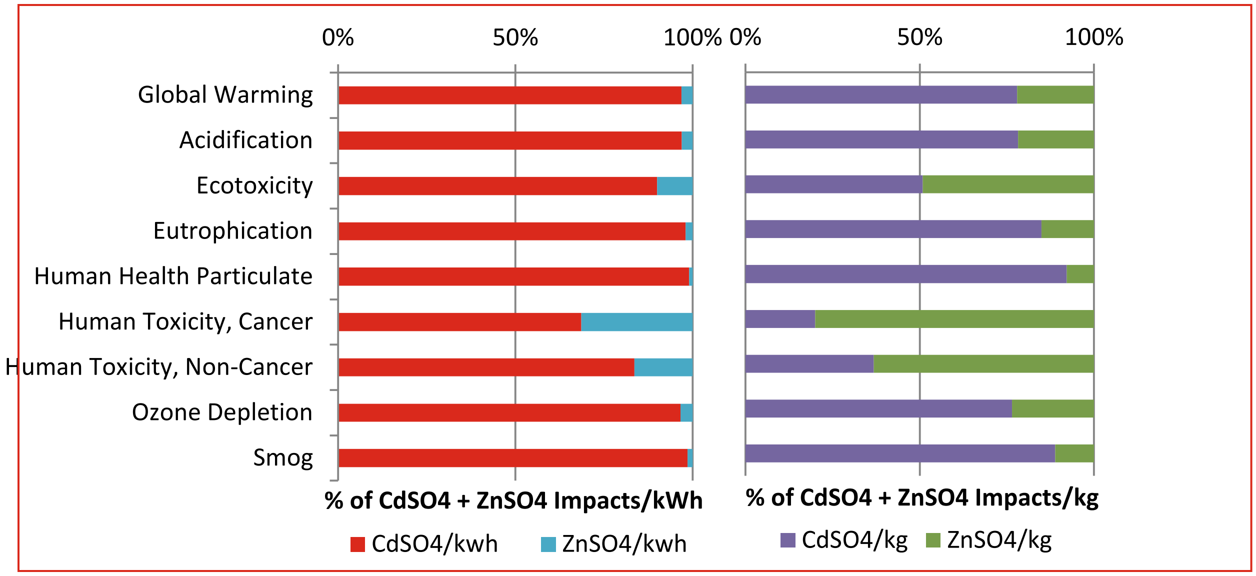

Figure 7. Production Impacts of Cadmium Sulfate Versus Zinc Sulfate Materials

As shown in Table 9, however, in comparing the *total* life cycle impacts of PV production using the cadmium sulfide versus zinc oxysulfide alternatives**,** no significant differences were identified even though cadmium is known to have higher toxicity impacts. This is primarily due to the smaller quantity of these materials used compared to the total product system inputs (.07% of non-ancillary inputs for Cadmium and .008% of non-ancillary inputs for Zinc). In addition, due to the lack of data, the study did not include impacts from (a) the disposal of the filters that captured the cadmium residues in the junction partner process and (b) end-of-life disposition of the cells.

Table 9. Life Cycle Impacts of Cadmium Sulfide Versus Zinc Oxysulfide Junction Partner

Impact Category	% Difference for Zinc Oxysulfide Alternative
Global Warming	0.00%
Acidification	0.05%
Ecotoxicity	0.09%
Eutrophication	0.00%
Human Health Particulate	0.00%
Human Toxicity, Cancer	0.02%
Human Toxicity, Non-Cancer	0.00%
Ozone Depletion	0.02%
Smog	0.02%

3.3 Sensitivity Analysis

We undertook an analysis to assess the sensitivity of the impacts to (i) differences in the performance parameters assumed in the use-stage, and (ii) the underlying grid mix assumptions to better assess the study results against published research (discussed in the Section 3.4).

3.3.1 Use-Stage Parameter Assumptions

In order to assess the impact results on a per kilowatt hour basis (functional unit) the study assumed a total lifetime energy output based on the performance parameters provided by PVMC of the product system. However, because these parameters may vary depending on external factors, such as weather and other conditions, PVMC provided a range of best and worst case scenarios (see Table 10).

Table 10. Differences in CIGS Performance Parameters

Factor	Worst Case	Benchmark	Best Case
Solar Irradiation (kWh/m^2/year)	*763*	*1409.7*	*2,180*
Performance ratio (%)	*85*	*89*	*95*
Efficiency (%)	*13*	*14*	*17*
Lifetime of Module (years)	*20*	*25*	*30*
Degradation Rate (%)	*1.5*	*1*	*0.5*
Lifetime output (kWh/m^2)	***1,466.3***	***3,902.5***	***9,830.9***

Based on the range in performance parameters, we conducted an analysis to determine the range in potential impacts for the cadmium sulfide alternative. Overall, the impacts decreased by 60% under the best case scenario and increased by 166% under the worst case scenario across all impact categories. Figure 8 illustrates this range for global warming potential.

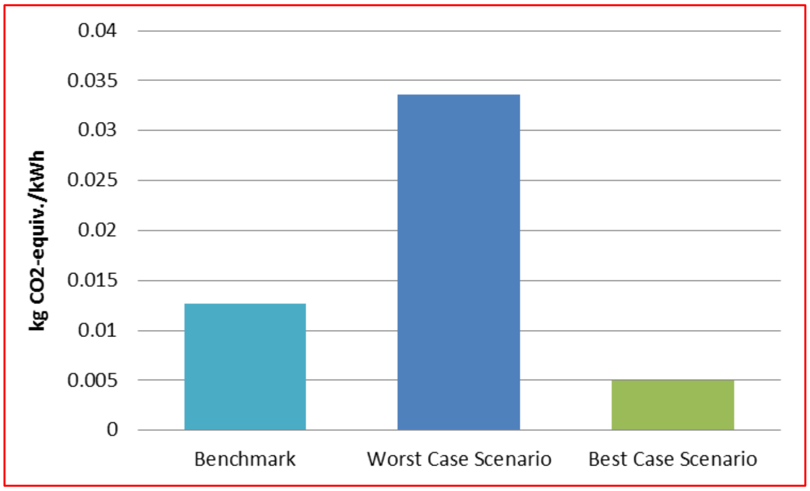

Figure 8. Summary of Best and Worst Case Scenario for Global Warming Potential

3.3.2 Grid-mix Assumptions

Given the high energy needed to manufacture the CIGS cells and reliance on eGRID data, it was also important to assess the grid-mix assumptions. Table 11 presents a summary of the life cycle impacts for an average U.S. based versus NYS grid mix. As noted above, the NY grid mix relies more upon renewable energy sources, such as hydropower versus coal. Accordingly, the production of PVMC's CIGS cells in NYS presents significant benefits across most of the impact categories. For example, global warming potential is reduced by 36% by production in NYS compared to a typical U.S. grid mix. However, for ozone depletion slightly higher impacts are observed due to lower emissions of halogenated compounds like R11 and R12, in comparison to grids dependent on more renewable energy sources.

Table 11. Summary of Life Cycle Impact for Cadmium Sulfate Alternative by Grid Mix

Impact Category	Units	NY State Grid (per kWh)	U.S. Grid (per kWh)	Difference
Global Warming	kg CO_2-eq	1.26E-02	1.71E-02	35%
Acidification	kg SO_2-eq	2.10E-04	2.26E-04	8%
Ecotoxicity	CTUe	3.26E-02	3.27E-02	0%
Eutrophication	kg N-eq	5.09E-06	5.68E-06	12%
Human Health Particulate	$PM_{2.5}$-eq	6.01E-05	6.14E-05	2%
Human Toxicity, Cancer	CTUh	8.04E-11	8.11E-11	1%
Human Toxicity, Non-Cancer	CTUh	9.96E-09	1.00E-08	1%
Ozone Depletion	kg CFC 11-eq	6.14E-11	6.00E-11	-2%
Smog	kg O_3-eq	4.86E-04	6.08E-04	25%

3.4 Comparison of Results to Literature

As noted previously, there is a range in impacts of thin film PV cells from prior studies due largely to differences in the product system (CIGS technology) and different assumptions regarding performance parameters. Accordingly, several studies have sought to harmonize the study results against a consistent set of parameters so the results are more comparable (e.g., Peng et al. (2013) and Kim et al. (2012)). We carried out a similar harmonization of global warming impacts based on CIGS LCA studies, with a focus on roof-top installations. We applied the parameters provided by PVMC (see Table 10), namely a solar irradiation of 1,409.7 kWh/m^2/year, performance ratio of 89%, efficiency of 14%, and lifetime of 25 years. Table 12 presents the results of this harmonization.

Table 12. Harmonization of CIGS LCA studies

Author (year)	Harmonized GWP by E,PR, LT, and I [a]	From Literature (Not Harmonized) [b]					Notes [c]
		GWP	E	PR	LT	I	
Ito et al. (2008)	12.41	10.5	0.11	.78 [d]	30	2017	Gobi Desert, 100 MW system
Bekkelund (2013)	19.74	20.6	0.11	0.75	30	1700	Europe
de Wild-Scholten (2013)	22.39	21.4	0.117	0.77	30	1700	Europe, 0.02% degradation/year
Frankl et al. (2004)	19.97	32	0.09	0.875	20	1740	Integrated skylight roof, Rome
Dominguez-Ramos (2010)	30.15	31	0.1	0.78	30	1825	Spain, 0.5% degradation/year
SENSE (2008)	34.92	43	0.115	0.912	20	1700	Germany, ground-mounted
Ito et al. (2010)	45.89	46	0.11	0.78	30 [e]	1702	Gobi Desert, 1 GW system including transmission lines
Ito et al. (2009)	63.83	58.8	10.1	0.78	30 [e]	2017	Gobi Desert, 1 GW system
Cucchiella & D'Adamo (2012)	46.12	83	0.095	0.85	20	1511	Rome
Raugei et al. (2007)	60.68	95	0.11	0.75	20	1700	Southern Europe
Average	**35.61**	**44.13**	**0.11**	**0.81**	**25**	**1761**	

[a] Harmonized by an E of 0.14, PR of 0.89, LT of 25 years, and an I of 1409.7
[b] GWP – global warming potential, g CO_2/kWh; E – cell conversion efficiency; PR – performance ratio; LT – module lifetime, years; I – solar irradiation, kWh/m^2/year)
[c] Studies use roof-mounted modules unless otherwise stated, all technologies use a glass substrate
[d] Assumed PR of .78 as used in other studies by Ito et al.(2008)
[e] Assumed LT of 30 as provided in Ito et al. (2008)

As shown in Figure 9, the non-harmonized LCA results range from approximately 10 to over 90 g CO_2/kWh, with a median value of approximately 39 g CO_2/kWh. Once harmonized using the parameters applied in this study, the range narrows to approixmately 12 to 64 g CO_2/kWh, with a median value of approximately 32 g CO_2/kWh. In addition, the energy payback time (EPBT) for CIGS cells of 1.91 years was in the range of 1.45 to 2.2 years reported in another harmonization study by Peng et al. (2013). The EPBT of PVMC CIGS technology is comparable to other technologies ranging from 1.5 to 3.5 years for silicon based cells (e.g., a-Si, mono-Si, and multi-Si), and 0.75 to 2.1 years for CdTe systems (Peng, 2013).[1]

[1] Note that the Peng study reports different ranges for EPBT in their report text versus a figure where they summarize the data. We present the ranges illustrated in Figure 5 of the Peng et. al. study (2013).

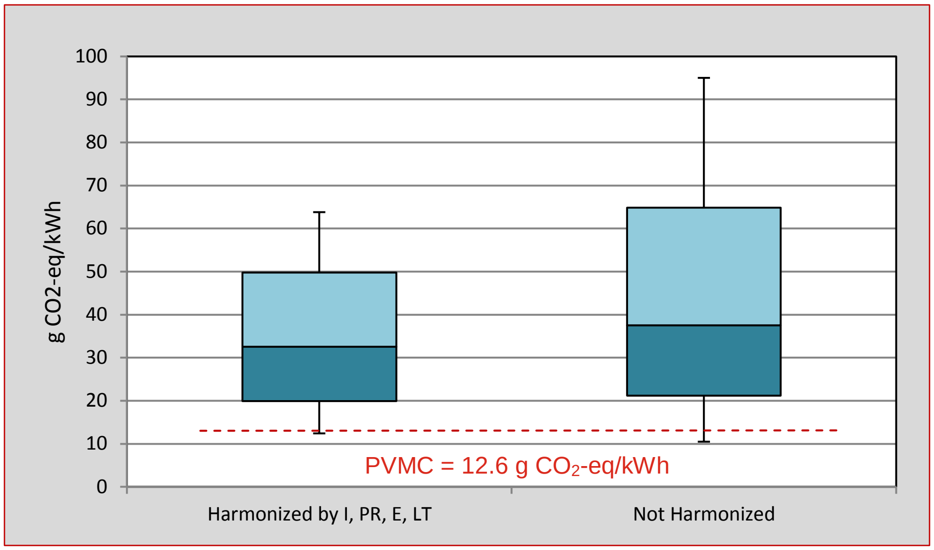

Figure 9. Summary of Harmonized and Non-Harmonized LCA Literature Values

Note: Statistics are displayed by minimum (lower outlier), 2nd quartile (dark), median (center line), 3rd quartile (light), and maximum (upper outlier).

As illustrated in Figure 9, the results from the LCA study of PVMC's CIGS cells fall in the lower end of the range of published impacts. Key reasons for this may include differences in the materials used, grid-mix assumptions, as well as data limitations and assumptions. Specifically, most studies use a glass substrate, which comprises approximately 16 kg/m^2 of a PV cell (Fthenakis, 2011b; de Wild-Scholten, 2013; Jungbluth et al., 2012). PVMC uses a very thin stainless steel substrate accounting for only 0.387 kg/m^2. Although glass has a lower GWP than stainless steel (1.13 kg CO_2-eq/kg versus 5.07 kg CO_2-eq/kg), the glass requires a much thicker layer, resulting in a GWP of 11 kg CO_2-eq /m^2 of solar cell compared to 2 kg CO_2-eq /m^2 for stainless steel. This LCA study also assumed that the module will be protected using various polymers, including EVA, PET, and PTFE, while other studies assume glass will be used instead to protect the modules. The use of these lighter weight materials in turn reduces the amount of mounting structure needed to secure the modules in place, also contributing to overall lower life cycle impacts. Finally, as described in the sensitivity analysis, differences in grid-mix assumptions (depending on the location of the manufacturing facility and upstream suppliers) also significantly impact results. The fact that PVMC's manufacturing facility is located in NY State, which relies more on renewable energy sources, contributes to lower impacts.

3.5 Review of End-of-Life Impacts

As thin-film cells continue to expand, recovery of the rare and critical metals (e.g., In and Ga) and hazardous materials (e.g., Cd) employed in the cells will become increasingly important to both ensure the adequate supply of important materials and reduce environmental impacts (Marwede, 2013; Gustafsson, 2014). Since there are currently no established practices for recycling CIGS on stainless steel, our study does not include impacts from the end-of-life stage. Accordingly, we conducted a review of data from published studies.

Our research found limited published data on impacts from recycling of CIGS cells. Most studies focused on the economic or technological feasibility of CIGS recycling, but did not quantify the environmental impacts using a life cycle approach. For example, a study by Marwede et al. (2013) identified three key steps for recovery of CIGS modules with a glass substrate. These steps are (1) delamination, (2) de-coating and separation of non-metals, and (3) metal extraction and purification. For each step, the study identified different processes that may be used, including some that are commercially available and for which life cycle inventory data may be available (e.g., hydrometallurgical processes for metal recovery).While a high purity of extracted metals can be achieved, process challenges include high energy demands, long process times, and high use of chemicals. Potential sources of pollution include cadmium leaching to wastewater and emission of dust containing heavy metals.

In addition, a study by SENSE (2008) used laboratory experiments and data to estimate impacts of recycling a variety of thin film cells, including CIGS. The study found that despite the challenges associated with the recovery of the cells, the environmental impacts of recycling CIGS modules with a glass substrate were less than 4.5% of the overall life cycle impacts (Shibasaki et al., 2006; SENSE, 2008). In addition, McDonald et al. (2010) quantified the costs and benefits of recycling CIGS, CdTe and silicon-based PV modules and determined that CIGS is the only technology for which recycling would be profitable. Specifically, the study found that recycling a CIGS module could generate $22.25 for modules with a nominal power of 160 W.

Rocchetti et al. (2014) recently published a more quantitative study on the impacts of recycling thin film PV modules with a glass substrate. They proposed the following options: landfill, conventional recycling (glass and plastic), and innovative recycling (glass, plastic, metals). Conventional recycling includes the recovery of ethylene-vinyl acetate (EVA) and glass, while the innovative recycling also includes recovery of critical metals: selenium, indium, gallium for CIGS and tellurium from CdTe. The impacts presented by the study are presented in Table 13.

Table 13. Summary of EOL Impacts of Thin Film Modules (Rochetti et al., 2014)

EOL Plan	Impact Category	CIGS Impact	CdTe Impact	Units
Landfill CIGS/CdTe	abiotic depletion	1.7E-08	1.7E-08	kg Sb-eq/sqm
	acidification potential	4.8E-03	4.8E-03	kg SO_2-eq/sqm
	eutrophication potential	2.2E-02	2.2E-02	kg PO_4^{3-} eq/sqm
	global warming potential	1.3E+01	1.3E+01	kg CO_2-eq/sqm
	ozone layer depletion	2.2E-08	2.2E-08	kg R11-eq/sqm
	photochemical ozone reaction	3.0E-03	3.0E-03	kg C_2H_4-eq/sqm
Conventional Recycling	abiotic depletion	-1.4E-06	-1.6E-06	kg Sb-eq/sqm
	acidification potential	3.4E-03	1.9E-03	kg SO_2-eq/sqm
	eutrophication potential	8.4E-04	4.6E-04	kg PO_4^{3-} eq/sqm
	global warming potential	7.3E-01	7.3E-01	kg CO_2-eq/sqm
	ozone layer depletion	-4.2E-08	-7.2E-08	kg R11-eq/sqm
	photochemical ozone reaction	8.5E-05	-1.0E-04	kg C_2H_4-eq/sqm
Innovative Recycling	abiotic depletion	-3.8E-04	-5.0E-03	kg Sb-eq/sqm
	acidification potential	1.6E-02	-1.2E-03	kg SO_2-eq/sqm
	eutrophication potential	1.4E-03	-3.2E-04	kg PO_4^{3-} eq/sqm
	global warming potential	2.5E+00	6.7E-01	kg CO_2-eq/sqm
	ozone layer depletion	-9.8E-08	-7.8E-08	kg R11-eq/sqm
	photochemical ozone reaction	5.6E-04	-2.4E-04	kg C_2H_4-eq/sqm

In order to more easily compare impacts between EOL disposition options, each impact category was rated high (red), medium (yellow), or low (green) for both the CIGS and CdTe cells. For example, acidification potential from CIGS innovative recycling was marked red because it had the highest impact value compared to the acidification potential from CIGS landfilling and conventional recycling. Negative impacts denote a reduction in impacts (or credit) as a result of the reuse of materials.

Although the study did not specify what the recycled materials were used for, it did account for the environmental credits resulting from the avoided use of virgin materials. Based on this comparison, recycling is found to yield lower impacts versus landfilling across most impact categories. In addition, the innovative recycling process is found to be more favorable than the conventional recycling process for CdTe cells. However, for the CIGS cell, both recycling options offer benefits across different impact categories. For example, ozone depletion impacts are more favorable under innovative recycling while global warming impacts are more favorable for the conventional recycling method. This is due to materials and energy required for stripping and separating the indium, gallium, and selenium from the rest of the cell material (Rocchetti et al., 2014).

4 Conclusions

The objective of this LCA study was to assess CIGS PV systems manufactured by PVMC. Specifically, the study sought to identify opportunities to reduce human health and environmental impacts of the product system throughout the life-cycle, to support the development of a more sustainable product system before it is produced on a larger scale. Below we summarize the key results and conclusions from the study, including additional research and next steps to consider.

Overall, the study found that in comparison to prior LCA studies of thin film cells, which focused on global warming impacts, the CIGS PV cells produced by PVMC fall in the lower end of the range of published data compared to the published results on other types of thin film cells. After harmonizing the results of the prior studies to reflect the use-stage parameters provided by PVMC (solar irradiation of 1,409.7 kWh/m^2/year, performance ratio of 89%, efficiency of 14%, and lifetime of 25 years), PVMC's CIGS cells are estimated to produce 12.6 g of CO_2-eq/kWh compared to a range of approximately 12 to 64 g CO_2-eq/kWh reported in the published studies reviewed. In addition, the energy payback time (EPBT) for CIGS cells of 1.91 years is in the range of 1.45 to 2.2 years reported in another harmonization study by Peng et al. (2013). Key factors that likely contribute to PVMC's CIGS lower global warming impacts compared to other CIGS systems include:

- **Use of stainless steel substrate.** One likely factor is the very thin stainless steel substrate used as the base layer of the cells by PVMC versus a glass substrate used in many of the other product systems assessed in prior studies. In addition, this study assumed high-tech plastics, including EVA, PET, and PTFE are used in place of glass for the outside protective layer. The use of these lighter weight materials also reduces the amount of mounting structure needed to mount the CIGS PV system for rooftop installations, further reducing impacts.
- **Reliance on more renewables-based grid-mix.** Another key factor that may contribute to lower global warming impacts includes differences in the grid-mix assumptions. The fact that PVMC's manufacturing facility is located in NY State, which relies more on renewable energy sources, including hydropower versus coal, contributes to lower global warming impacts. In fact, a sensitivity analysis indicates that global warming is reduced by 36% when assuming a NY based grid versus U.S. grid mix.

The study also identifies other key contributors across all impact categories, including ecotoxicity, human health, ozone depletion potential, eutrophication, and others. Specifically, the **silver used in the stringer and screen printing processes** contributes significantly across most impact categories, including global warming, acidification, particular matter, and human toxicity (cancer and non-cancer). This is primarily due to impacts from the extraction and processing of silver used in the stringer, including high primary energy use. Other metals used in the CIGS layer, including the **copper, indium, gallium, and selenium in the CIGS layer** and **copper used in the cabling for the balance of system** also contribute strongly to ecotoxicity, human health (cancer and non-cancer), eutrophication, and ozone depletion mainly due to the mining processes associated with these metals. In addition, the **manufacture of the stainless steel substrate** and **treatment of water used to wash the substrate** contributes to higher ozone depletion and eutrophication impacts, respectively.

Although the use of cadmium sulfide did not appear to be a key contributor to total life cycle impacts of the product system, this was primarily due to the small quantity used in PVMC's CIGS cells (.07% of non-ancillary inputs). Closer examination reveals, however, that compared to the zinc oxysulfide alternative **cadmium sulfide has higher impacts across all impact categories on a per sqm basis**. This is primarily due to the fact that PVMC uses nearly 9 times more cadmium sulfate for the cadmium sulfide alternative versus zinc sulfate for the zinc oxysulfide alternative on a per sqm basis, and cadmium has higher overall impacts versus zinc. However, as described below, we recommend additional research to better assess life-cycle impacts of these alternatives.

A number of opportunities for improving the environmental profile of the CIGS PV system are identified based on the results of the study. Figure 10 summarizes these potential opportunities for improvement in order of the key components/layers of the CIGS manufacturing process.

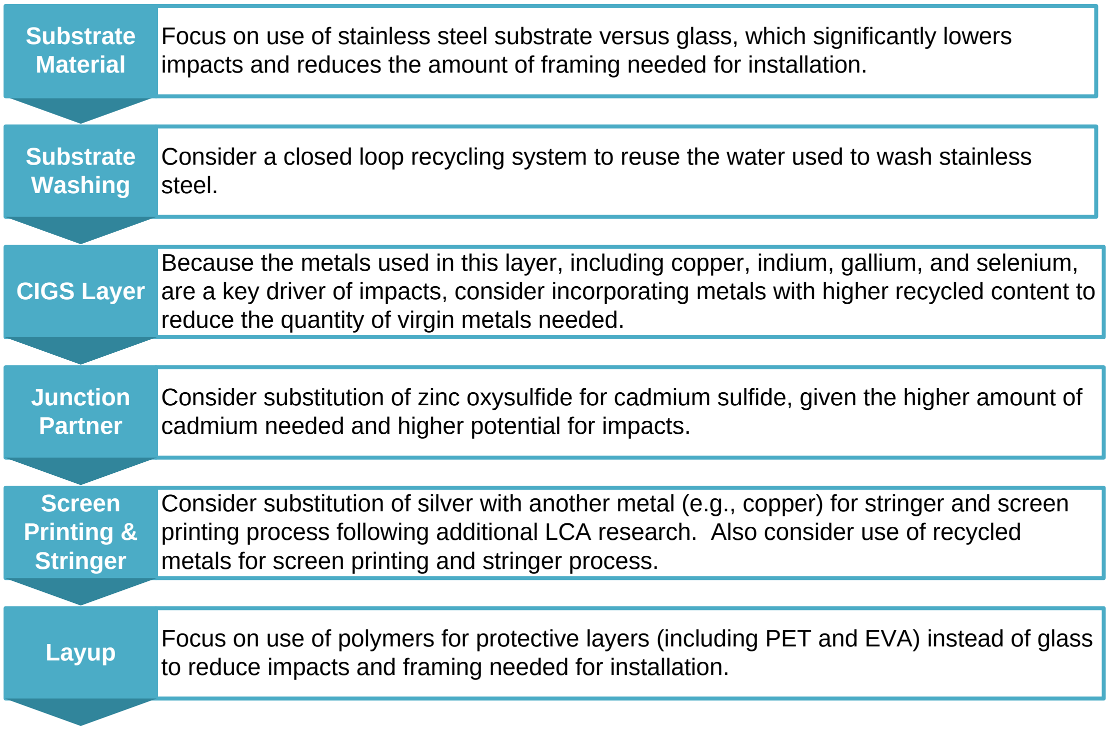

Figure 10. Summary of Opportunities for Improvement by Layer/Process

Finally, given some of the limitations of the study, we propose further areas of research that may serve to inform the results and identify additional opportunities for improvement, as follows:

- **Conduct additional research on the cadmium sulfide versus zinc oxysulfide alternative.** Although minimal differences were observed in comparing the cadmium sulfide versus zinc oxysulfide alternatives, further research should be conducted to more fully assess impacts. For example, the study did not address impacts from the disposal of the filters that captured the cadmium residues in the junction partner process. Further study of impacts of using cadmium versus zinc for the end-of-life stage, including a better understanding of the upstream and downstream impacts of the filter materials would inform the study results.

- **Research the impacts of an alternative to the silver used in the stringer process.** Copper has been identified by PVMC as a potential substitute for silver in the stringer process. However, copper also has impacts associated with upstream extraction and processing. Accordingly, it would be prudent to conduct a life cycle assessment substituting copper in place of the silver to fully weigh trade-off between the metal choices.

- **Conduct a life cycle costing of CIGS cells produced by PVMC.** Although many materials have been identified as drivers of impacts, material selection decisions are often influenced by cost. For example, although EVA and other plastics may be preferable for the layup process instead of glass, these materials are also more expensive. A study conducted by Fthenakis (2009) emphasized the importance of investigating cost, resource availability, and environmental impacts of thin-film solar cells to ensure long-term sustainability of the technology.

As noted above, there are many opportunities for further research on the potential impacts of CIGS PV systems, especially given that it is an emerging and growing technology. This study provides a benchmark for future research of this technology, and for identifying additional opportunities for reducing environmental and human health impacts throughout the life cycle of the PV system.

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