Addressing Hotspots in the Product Environmental Footprint of CdTe Photovoltaics

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***Abstract* — A pilot study within the European Commission's "Single Market for Green Products" initiative has been developing standardized methods for measuring, verifying, and communicating a product's environmental performance. These methods provide the basis for identifying and then addressing hotspots in the product environmental footprint of photovoltaics. In the case of CdTe PV, hotspots related to electricity usage in manufacturing, glass content in PV modules, and metal content in modules and balance of systems can be addressed through technology innovation. Transitioning to a larger, lighter (per unit area), more efficient, and still recyclable version of current thin film modules is expected to reduce the product environmental footprint of CdTe PV to a factor of 3.5-4 below that of an average PV module.**

***Index Terms* — environmental management, product life cycle management, thin films.**

I. Introduction

Since 2013, the European Commission has been conducting a pilot study within its "Single Market for Green Products" initiative. The pilot study has been testing rules, verification approaches, and communication vehicles for measuring a product's environmental performance. The product group "photovoltaic electricity generation" has been part of the pilot study since 2014, including development of product environmental footprint (PEF) category rules for conducting life cycle assessment of photovoltaic (PV) modules [1], a screening study implementing these rules on different photovoltaic technologies [2], and supporting studies by PV manufacturers [3] testing those rules on their own products. The objective of this study is to evaluate how hotspots identified in the product environmental footprint of CdTe PV may be addressed with technology innovation.

II. Methods

Life cycle assessment (LCA) has been conducted with Simapro (V. 8.2.0) software and Ecoinvent (V. 2.2+) unit processes [4]. Life cycle impacts for PV modules were assessed in accordance with ISO 14040/14044, the PEF category rules [1], and the PEF guide [5]. The environmental footprint was quantified using the 15 environmental indicators proposed by the European Union [5] as implemented in the ILCD 2011 Midpoint V. 1.09 impact method (long term emissions excluded [1]) with equal weight assigned to the factors. Carbon footprint was estimated with 100-yr global warming potentials (GWP-100), including a GWP-100 of 25 for methane. In addition to the default 15 indicators, three additional indicators have been evaluated (cumulative energy demand non-renewable, cumulative energy demand renewable, and nuclear waste), with long term emissions excluded [1]. Normalization factors from Benini et al. [6] were the basis to determine the environmental relevance of the different environmental impacts.

The functional unit is 1 kWh of DC electricity generated by a photovoltaic module given an average European irradiation. A product lifetime of 30 years is assumed [1]. Based upon average irradiation conditions of optimally oriented PV modules in Europe and a default 0.70%/yr module degradation rate, an average annual energy yield of 975 kWh/kWp is assumed [1].

The product system of the electricity production with a PV module consists of the three stages of manufacturing, use, and end-of-life (Fig. 1). The manufacturing of PV modules includes the supply chain of raw materials as well as the manufacturing process. The product system also includes the mounting system required for a 3 kWp roof mount PV plant. The inverter and the AC cabling are not part of the product system. Although the predominant application of CdTe PV modules is in large commercial and utility scale power plants, the analysis of 3 kWp roof mount systems was included in this study to ensure comparability with the PEF screening study [2] and the representative product portrayed in that study. The use phase includes electricity production and maintenance.

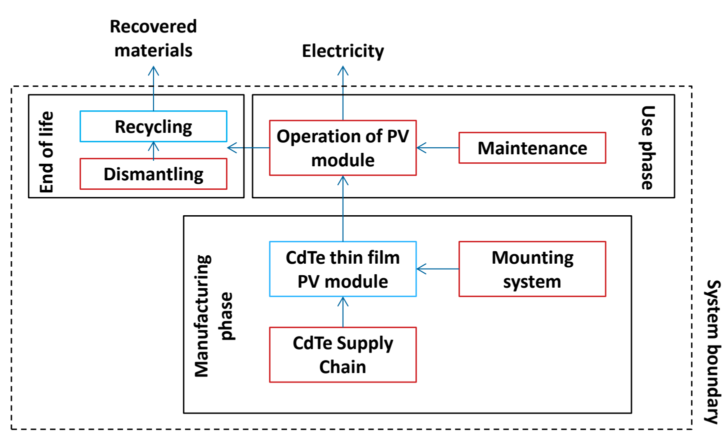

Fig. 1. Product system of electricity produced with a CdTe photovoltaic module, with processes of the foreground (product specific) and background [4] system marked with blue and red color, respectively.

TABLE I

LIFE CYCLE INVENTORY OF CDTE PV MODULE MANUFACTURING FOR SERIES 6 (2017-2018) MODULES

Explanations	Name	Location	Infrastructure-Process	Unit	photovoltaic laminate, CdTe, at plant (2017-2018 estimated)		uncertaintyType	StandardDeviation 95%	GeneralComment (Pedigree Matrix)
	Location				MY	US			
	InfrastructureProcess				1	1			
	Unit				m2	m2			
prod-uct	photovoltaic laminate, CdTe, at plant	MY	1	m2	1				
	photovoltaic laminate, CdTe, at plant	US	1	m2		1			
energy	electricity, medium voltage, at grid	MY	0	kWh	3.34E+1	-	1	1.07	(1,1,1,1,1,3,BU:1.05)
	electricity, medium voltage, at grid	US	0	kWh	-	3.48E+1	1	1.07	(1,1,1,1,1,3,BU:1.05)
	natural gas, burned in boiler modulating >100kW	RER	0	MJ	-	2.08E+1	1	1.07	(1,1,1,1,1,3,BU:1.05)
infra-struct.	Photovoltaic panel factory CdTe	US	1	unit	-	4.00E-6	1	3.04	(2,2,1,1,1,3,BU:3)
	Photovoltaic panel factory CdTe	MY	1	unit	4.00E-6	-	1	3.04	(2,2,1,1,1,3,BU:3)
materials	tap water, at user	RER	0	kg	2.07E+2	1.93E+2	1	1.07	(1,1,1,1,1,3,BU:1.05)
	copper, at regional storage	RER	0	kg	3.22E-3	3.27E-3	1	1.07	(1,1,1,1,1,3,BU:1.05)
	silicone product, at plant	RER	0	kg	1.17E-1	1.19E-1	1	1.08	(1,1,1,1,1,3,BU:1.05)
	solar glass, low-iron, at regional storage	RER	0	kg	6.94E+0	7.18E+0	1	1.07	(1,1,1,1,1,3,BU:1.05)
	flat glass, uncoated, at plant	RER	0	kg	5.34E+0	5.42E+0	1	1.07	(1,1,1,1,1,3,BU:1.05)
	glass fibre reinforced plastic, polyamide, injection moulding, at	RER	0	kg	1.08E-1	1.08E-1	1	1.16	(1,4,3,3,1,3,BU:1.05)
	ethylvinylacetate, foil, at plant	RER	0	kg	3.85E-1	3.91E-1	1	1.07	(1,1,1,1,1,3,BU:1.05)
	cadmium telluride, semiconductor-grade, at plant	US	0	kg	2.21E-2	2.29E-2	1	1.07	(1,1,1,1,1,3,BU:1.05)
	nitric acid, 50% in H2O, at plant	RER	0	kg	5.72E-2	5.72E-2	1	1.16	(1,4,3,3,1,3,BU:1.05)
	sulphuric acid, liquid, at plant	RER	0	kg	3.93E-2	3.93E-2	1	1.16	(1,4,3,3,1,3,BU:1.05)
	sodium chloride, powder, at plant	RER	0	kg	4.53E-2	4.53E-2	1	1.16	(1,4,3,3,1,3,BU:1.05)
	hydrogen peroxide, 50% in H2O, at plant	RER	0	kg	1.67E-2	1.67E-2	1	1.16	(1,4,3,3,1,3,BU:1.05)
	isopropanol, at plant	RER	0	kg	2.08E-3	2.08E-3	1	1.16	(1,4,3,3,1,3,BU:1.05)
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	0	kg	4.93E-2	4.93E-2	1	1.16	(1,4,3,3,1,3,BU:1.05)
	chemicals inorganic, at plant	GLO	0	kg	9.26E-3	1.06E-2	1	1.07	(1,1,1,1,1,3,BU:1.05)
	chemicals organic, at plant	GLO	0	kg	2.68E-2	3.35E-2	1	1.16	(1,1,1,1,1,3,BU:1.05)
	nitrogen, liquid, at plant	RER	0	kg	7.32E-2	7.32E-2	1	1.16	(1,4,3,3,1,3,BU:1.05)
	aluminium alloy, AlMg3, at plant	RER	0	kg	1.67E+0	1.69E+0	1	1.07	(1,1,1,1,1,3,BU:1.05)
	chromium steel 18/8, at plant	RER	0	kg	1.11E-2	1.13E-2	1	1.07	(1,1,1,1,1,3,BU:1.05)
	EUR flat pallet	RER	0	p	1.45E-2	1.45E-2	1	1.07	(1,1,1,1,1,3,BU:1.05)
trans-port	transport, lorry >16t, fleet average	RER	0	tkm	1.02E-1	6.95E+0	1	2.00	(1,1,1,1,1,3,BU:2)
	transport, freight, rail	RER	0	tkm	2.11E+0	-	1	2.00	(1,1,1,1,1,3,BU:2)
	transport, transoceanic freight ship	OCE	0	tkm	3.12E+1	-	1	2.00	(1,1,1,1,1,3,BU:2)
disp-osal	disposal, municipal solid waste, 22.9% water, to sanitary landfill	CH	0	kg	2.52E-1	4.75E-1	1	1.16	(1,1,1,1,1,3,BU:1.05)
	treatment, sewage, unpolluted, to wastewater treatment, class 3	CH	0	m3	-	8.63E-2	1	1.07	(1,1,1,1,1,3,BU:1.05)
emissions air	Heat, waste	-	-	MJ	1.20E+2	1.25E+2	1	1.29	(3,4,3,3,1,5,BU:1.05)
	Cadmium	-	-	kg	9.56E-9	9.56E-9	1	5.00	(1,1,1,1,1,3,BU:5)
	Copper	-	-	kg	7.39E-9	7.39E-9	1	5.00	(1,1,1,1,1,3,BU:5)
	Lead	-	-	kg	4.35E-9	4.35E-9	1	5.00	(1,1,1,1,1,3,BU:5)
	Nitric acid	-	-	kg	3.00E-4	3.00E-4	1	5.00	(1,1,1,1,1,3,BU:5)
emissions water	Cadmium, ion	-	-	kg	3.62E-8	3.62E-8	1	3.00	(1,1,1,1,1,3,BU:3)
	Copper	-	-	kg	1.76E-7	1.76E-7	1	3.00	(1,1,1,1,1,3,BU:3)
	Lead	-	-	kg	2.58E-8	2.58E-8	1	3.00	(1,1,1,1,1,3,BU:3)
	Nitrate	-	-	kg	2.59E-2	2.59E-2	1	3.00	(1,1,1,1,1,3,BU:3)
	Zinc	-	-	kg	1.34E-7	1.34E-7	1	3.00	(1,1,1,1,1,3,BU:3)

TABLE II

LIFE CYCLE INVENTORY OF SERIES 6 CDTE PV SYSTEM RECYCLING (MODULES, CABLING, AND MOUNTING STRUCTURES)

	Name	Location	Infrastructure Process	Unit	CdTe PV module takeback + recycling	Avoided burden from recycling, CdTe PV module, mounted construction	UncertaintyType	StandardDeviation9	General Comment (Pedigree Matrix)
					2017-2018 (estimated)				
	Location				RER	RER			
	InfrastructureProcess				0	0			
	Unit				m2	m2			
product	CdTe PV module takeback + recycling	RER	0	m2	1.00E+0				
	Avoided burden from recycling, CdTe PV module, mounted construction	RER	0	m2		1.00E+0			
energy	Electricity, medium voltage, at grid	DE	0	kWh	4.38E+0		1	1.07	(2,4,1,1,1,3)
auxiliaries	Water, deionised, at plant/CH U	CH	0	kg	5.42E+0		1	1.07	(2,4,1,1,1,3)
	Sulphuric acid, liquid, at plant	RER	0	kg	8.33E-2		1	1.07	(2,4,1,1,1,3)
	Hydrogen peroxide, 50% in H2O, at plant	RER	0	kg	5.71E-1		1	1.07	(2,4,1,1,1,3)
	Sodium hydroxide, 50% in H2O, production mix, at plant	RER	0	kg	1.04E-1		1	1.07	(2,4,1,1,1,3)
transport	Transport, lorry >16t, fleet average	RER	0	tkm	1.25E+1		1	2.00	(2,4,1,1,1,3)
disposal	Treatment, PV cell production effluent, to wastewater treatment, class 3	CH	0	m3	4.79E-3		1	1.23	(2,4,1,1,1,3)
	Disposal, plastics, mixture, 15.3% water, to municipal incineration	CH	0	kg	6.16E-1		1	1.23	(2,4,1,1,1,3)
	Disposal, inert waste, 5% water, to inert material landfill	CH	0	kg	1.28E-1		1	1.23	(2,4,1,1,1,3)
emissions air	Cadmium	-	-	kg	5.89E-9		1	1.28	(2,4,1,1,1,3)
emissions water	Cadmium, ion	-	-	kg	8.92E-8		1	2.09	(2,4,1,1,1,3)
avoided energy	Natural gas, high pressure, at consumer	RER	0	MJ		-1.49E+01	1	2.00	(2,4,1,1,1,3)
	Heavy fuel oil, at regional storage	RER	0	MJ		-9.64E+00	1	2.00	(2,4,1,1,1,3)
avoided materials	copper, at regional storage	RER	0	kg		-3.84E-01	1	2.00	(2,4,1,1,1,3)
	copper, secondary, at refinery	RER	0	kg		3.84E+00	1	2.00	(2,4,1,1,1,3)
	aluminium, primary, at plant	RER	0	kg		-3.05E+00	1	2.00	(2,4,1,1,1,3)
	aluminium, secondary, from old scrap, at plant	RER	0	kg		3.05E+00	1	2.00	(2,4,1,1,1,3)
	pig iron, at plant	GLO	0	kg		-9.70E-01	1	2.00	(2,4,1,1,1,3)
	Cadmium sludge, from zinc electrolysis, at plant	GLO	0	kg		-2.84E-02	1	2.00	(2,4,1,1,1,3)
	Copper telluride cement, from copper production	GLO	0	kg		-3.22E-02	1	2.00	(2,4,1,1,1,3)
	Silica sand	DE	0	kg		-6.28E+00	1	2.00	(2,4,1,1,1,3)
	Soda, powder, at plant	RER	0	kg		-2.49E+00	1	2.00	(2,4,1,1,1,3)
	Limestone,milled, packed, at plant	CH	0	kg		-4.34E+00	1	2.00	(2,4,1,1,1,3)
avoided emissions air	Carbon dioxide	-	-	kg		-2.26E+0	1	2.00	(2,4,1,1,1,3)

The end-of-life covers the dismantling of the modules including transport to a recycling facility and the recycling process itself. Potential benefits for recycling are quantified and allocated 50:50 to the electricity production and the products made of recycled material, respectively [1]. Recycling of aluminum, steel, and copper in the balance of system (BOS) is evaluated, with benefits estimated after subtracting existing recycled content in those metals (32%, 37%, and 44 %, respectively [4]).

Life cycle inventory (LCI) data for Series 6 CdTe PV module manufacturing and end-of-life recycling are shown in Tables I and II. BOS and Series 4 CdTe PV LCI data are from [3]. PV modules are manufactured in the United States (US) and Malaysia (MY) with relative production capacities of 13.8% and 86.2%, respectively. PV module characteristics are shown in Table III, with average module efficiency of 15.5% based on 2015 production of the Series 4 module [7], and 17.0-18.0% based on 2017-2018 production of the Series 6 module [8].

III. RESULTS AND DISCUSSION

The environmental performance of CdTe PV modules is summarized in Table IV and Fig. 2 for a wide variety of impact categories, including those related to ecosystems, human health, and natural resources. Life cycle environmental impacts for Series 6 systems are lower than those for Series 4 systems with the exception of human toxicity, non-cancer effects and ozone depletion, where slight increases for Series 6 are due to the addition of a module frame.

Total life cycle environmental impacts for Series 4 and Series 6 systems are mainly driven by mineral, fossil and renewable resource depletion (34-37%), human toxicity cancer effects (20-22%), human toxicity non-cancer effects (11-13%), and by freshwater ecotoxicity (11-12%) (Fig. 2). Within the impact category mineral, fossil and renewable resource depletion, the extraction of cadmium and tellurium are the main contributors.

Table III. Characteristics of CdTe PV modules

	Unit	First Solar Series 4 (2015)	First Solar Series 6 (2017-2018)
Length |width| thickness	mm	1200|600|6.8	2005|1230|5.4
Area	m^2/module	0.72	2.47
Weight	kg/module	12	35
	kg/m^2 module	16.67	14.17
Front glass	kg/module	5.7	16.6
Back glass	kg/module	5.7 (tempered)	13.0 (heat strengthened)
Encapsulation	-	Laminate material with edge seal	
Frame material	-	None (frameless)	Aluminum
Efficiency	%	15.5	17.0-18.0

Table IV. Characterized environmental impact results (based on European deployment, average annual energy yield of 975 kWh/kWp, and 30 year lifetime).

3kWp installation, roof mounted (total all life stages, recycling benefits included)			
Impact category	Unit per kWh DC electricity	First Solar Series 4	First Solar Series 6
Climate change	kg CO2 eq	1.94E-02	1.66E-02
Ozone depletion	kg CFC-11 eq	8.78E-10	9.47E-10
Human toxicity, non-cancer effects	CTUh	4.95E-09	5.11E-09
Human toxicity, cancer effects	CTUh	5.97E-10	5.16E-10
Particulate matter	kg PM2.5 eq	9.95E-06	7.72E-06
Ionizing radiation HH	kBq U235 eq	9.06E-04	7.83E-04
Photochemical ozone formation	kg NMVOC eq	7.43E-05	5.62E-05
Acidification	molc H+ eq	1.46E-04	1.10E-04
Terrestrial eutrophication	molc N eq	2.76E-04	2.07E-04
Freshwater eutrophication	kg P eq	3.60E-06	3.51E-06
Marine eutrophication	kg N eq	2.54E-05	1.91E-05
Freshwater ecotoxicity	CTUe	7.63E-02	7.50E-02
Land use	kg C deficit	1.19E-02	8.61E-03
Water resource depletion	m3 water eq	7.83E-05	6.07E-05
Mineral, fossil & ren resource depletion	kg Sb eq	3.09E-06	2.58E-06
Cumulative energy demand non renewable	MJ	2.90E-01	2.47E-01
Cumulative energy demand renewable	MJ	3.63E+00	3.62E+00
Nuclear waste	m3 HAA eq	2.12E-11	1.84E-11

Human toxicity cancer effects and human toxicity non-cancer effects are dominated by the installation and mounting system and the supply chains of aluminum, copper and steel therein, including the addition of an aluminum frame for the Series 6 module. The freshwater ecotoxicity impacts are also mainly caused by the installation and mounting system and the supply chain of copper therein, as well as the disposal of plastics from industrial electronic waste, which is associated with the production of the electric installation.

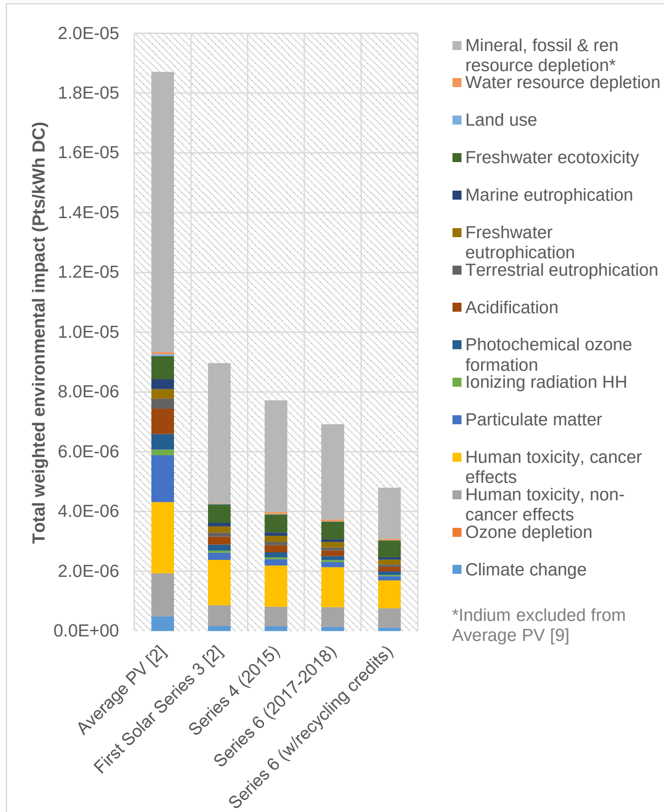

Fig. 2. Total environmental impact results (normalized [6] and equally weighted) of 1 kWh of DC electricity produced with a 3 kWp roof mounted installation (based on European deployment, average annual energy yield of 975 kWh/kWp, and 30 year lifetime), with recycling benefits excluded except where indicated.

Excluding recycling benefits, the total weighted environmental impacts of the First Solar Series 6 module are about 10% lower than the Series 4 module, about 20% lower than the Series 3 module, and about three times lower than the average PV module (with indium contribution to mineral, fossil, and non-renewable resource depletion excluded due to anomalous results [9]) (Fig. 2). When recycling benefits are included, the total weighted environmental impacts of the First Solar Series 6 module are about four times lower than the average PV module (Fig. 2). The latter is a representative (virtual) product composed of market-share weighted averages of different PV technologies in 2012 and based on global supply chain data from 2011 and module efficiencies shown in Table V [2]. From 2011 to 2015, the global supply chain of module production by region has remained reasonably consistent, with an increase of production in China and Taiwan from about 65% in 2011 to about 70% in 2015 [10].

Table V. Assumptions related to representative product

	Average PV [2]		Average PV (2015)	
	Market share	Module efficiency	Market share [10]	Module efficiency [10]
CdTe	6.3%	14.0%	4.0%	15.6%
CIS	3.5%	10.8%	1.7%	13.8%
micromorph -Si	4.5%	10.0%	-	-
multi-c-Si	45.2%	14.7%	69.5%	~16%
mono-c-Si	40.5%	15.1%	23.9%	~17%

Accounting for the technology market shares and increased module efficiencies in 2015, the environmental impacts of the average PV module shown in Fig. 2 may be reduced by about 10%. Accordingly, the total weighted environmental impacts of the First Solar Series 6 module (recycling benefits included) are about 3.5 times lower than the average PV module (2015).

As shown in Fig. 3, the most important contributors (hotspots) to CdTe PV environmental impacts are the supply chain of electricity consumed in various stages of the life cycle of PV electricity, the supply chain of aluminum and steel required in the mounting structure and module frame, the supply chain of copper required mainly in the electric installations of the PV systems, flat glass production, the supply chains of cadmium, and tellurium as abiotic resource hotspots, and transport services provided by transoceanic ships. These hotspots are discussed in turn, with respect to how they may be addressed by Series 6 technology.

A. *Supply chain of electricity*

In 2011, First Solar developed a sustainability target of reducing its corporate carbon footprint (metric tons CO2-eq per MW produced) by 35% by 2016 relative to a 2008 base year. The single largest contributor to First Solar's corporate carbon footprint is purchased electricity for PV module manufacturing. By end of 2015, the target has been surpassed [11], and a future 2021 target of 45% below base year emissions has been established. The latter includes a targeted 10% reduction in electricity usage per m^2 of module produced for Series 6 compared with Series 4 [12]. Since these reductions are based on equipment design loads and have not been confirmed with operational data, no reductions in electricity usage per module produced are considered in this study.

In addition to a series of energy efficiency projects involving facilities management (e.g., lighting, HVAC controls, compressed air), sub-metering has been installed on manufacturing tools to enable comparative monitoring of manufacturing lines and continuous improvement. In 2014-2015, the electric utility serving First Solar's Kulim, Malaysia facility has also transitioned from a mix of fossil fuel generation to 100% combined cycle natural gas generation, thereby lowering the carbon intensity of the electricity supply [11].

Leading contributors to impact categories (electricity, 3kWp installation, roof mounted with CdTe PV technology, characterized)	Aluminium, copper, and/or steel consumption in mounting system and electrical installation	Copper consumption in PV panel production	Electricity consumption in PV panel production	Electricity consumption in PV panel recycling	Flat and solar glass production	Harvested solar energy	Semiconductor materials in PV panel production	Transoceanic transport of PV panels	Water use in PV panel production
Climate change	X		X		X				
Ozone depletion	X		X						
Human toxicity, non-cancer effects	X								
Human toxicity, cancer effects	X	X							
Particulate matter	X		X		X			X	
Ionizing radiation HH	X		X					X	
Photochemical ozone formation	X		X		X			X	
Acidification	X				X			X	
Terrestrial eutrophication	X				X			X	
Freshwater eutrophication	X		X						
Marine eutrophication	X				X			X	
Freshwater ecotoxicity	X								
Land use	X		X						
Water resource depletion	X		X	X					X
Mineral, fossil & ren resource depletion							X		
Cumulative energy demand non renewable	X		X						
Cumulative energy demand renewable						X			
Nuclear waste	X		X						

Fig. 3. Environmental hotspots for 1 kWh of DC electricity produced with a 3 kWp CdTe PV roof mounted system (based on European deployment, average annual energy yield of 975 kWh/kWp, and 30 year lifetime).

B. *Aluminum, Steel, and Copper in BOS*

The demand for metals (aluminum and steel) in mounting structures per MWp installed will decrease with the larger, more efficient, framed Series 6 module. This module will be the same length as a 72-cell c-Si PV module (~2 m) but will be wider (~1.2 m), enabling more rapid installation of arrays with fewer mounting materials required per unit area.

C. *Flat glass production*

The Series 6 module will involve a reduction in thickness of front and back glass (from 3.2 to 2.8 mm and 3.2 to 2.2

mm, respectively) relative to the current Series 4 module, thereby reducing the demand for flat glass. The reduced glass weight will also lower the environmental impact of transport services per unit area of module.

D. Supply chain of cadmium and tellurium

Demand side management strategies have led to about a 50% reduction in the semiconductor intensity (usage per Watt) of CdTe PV modules since 2009 [13]. PV recycling also largely addresses the resource depletion hotspot and provides an additional source of semiconductor material for new PV modules. As of 2016, First Solar PV modules had approximately 8% recycled semiconductor content, which will likely increase as greater volumes of end-of-life modules return from the field [14].

E. Module efficiency

Improvements in module efficiency proportionally lower all of the above hotspots. Series 6 module efficiency is planned for 17-18% in the near term [8] and >19% in the medium term, with research cells already exceeding 22% efficiency [15].

IV. Conclusion

Life cycle environmental impact hotspots for CdTe PV technology have been identified through use of the PEF category rules within the European Commission's "Single Market for Green Products" initiative. These hotspots include the supply chains of electricity, aluminum, steel, and copper, flat glass production, transoceanic transport, and the supply chains of cadmium and tellurium as abiotic resource hotspots. Technology innovation for CdTe PV related to Series 6 technology will address hotspots through larger area modules with higher efficiency, reduced glass thickness, and continued recyclability. As a result, the total weighted environmental impacts of the Series 6 module are about 3.5-4 times lower than an average PV module.

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