ENVIRONMENTAL BENEFITS OF SOLAR PHOTOVOLTAICS IN SOUTH AFRICA

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ABSTRACT: With extensive coal supplies, South Africa currently meets over 90% of its electricity needs through coal. However, the South African government has committed to diversifying its energy portfolio, including reducing dependence on coal by 2030 to 65% (from the current 93%) which will result in a new non-coal capacity of ~28 GW. In addition, the 2010 Integrated Resource Plan lists the intention of installing 300 MW per year of solar power from 2012 onwards. International Reference Life Cycle Data System (ILCD) methods have been used to compare life cycle environmental impacts of grid electricity in South Africa with electricity from photovoltaics (PV). While a variety of life cycle environmental impact assessment methods are currently available, there has been a recent effort within the Joint Research Center of the European Commission to develop consensus impact methods through the ILCD. In the case of ground-mounted CdTe PV systems and roof-mounted crystalline Si PV systems, displacement of South African grid electricity results in over two-thirds reductions in a variety of impact categories for ecosystems, human health, and natural resources. The only impact category where PV does not provide a comparative benefit is with respect to the ILCD mineral, fossil, and renewable resource depletion category. This is primarily due to the use of valuable metals in PV modules and balance of systems. The impacts of resource depletion by PV may be mitigated by high-value end-of-life product recycling that recovers both bulk materials (e.g., glass, aluminum, copper) and semiconductor and rare materials in PV modules, and recovers recyclable materials (e.g., steel, aluminum, and copper) in balance of systems. In the case of ground-mount PV systems, potential land use impacts may be reduced by responsible land use practices that include careful site selection, minimal soil grading techniques, and project decommissioning that includes end-of-life recycling.
Keywords: PV system, PV market, Thin film, Crystalline Silicon, ILCD, LCA

1 INTRODUCTION

South Africa is an excellent candidate for a sustainable PV market as it enjoys high solar irradiation and a long-term growing demand for electricity. With extensive coal supplies, South Africa currently meets over 90% of its electricity needs through coal (Table 1). Assisted by low electricity prices, South Africa has historically developed energy-intensive metallurgical industries. However, rising demand for metals and stagnating electricity supply has resulted in recent energy shortfalls. In addition to growing demand and energy shortfalls, another driver for renewable energy in South Africa is climate change. South Africa has been an active participant in the UN Climate Change Conference (COP 17) in Durban and the COP18 in Doha, Qatar. South Africa has made long-term commitments to diversifying its energy portfolio, including reducing dependence on coal by 2030 to 65% (from the current 93%) which will result in a new non-coal capacity of ~28 GW. In addition, the 2010-2030 Integrated Resource Plan (http://www.energy.gov.za/files/irp_frame.html) lists the intention of installing 300 MW per year of solar power from 2012 onwards.

Table I: Electricity production in South Africa in 2009 [1]

Fuel	Percentage	Fuel	Percentage
Coal	93.04%	Oil	0.02%
Nuclear	5.13%	Wind	0.01%
Hydro	1.68%	Solar PV	0.01%
Biofuels	0.10%		

The coal-fired power plants in South Africa routinely emit per MWh of electricity output about 999 kg of CO_2, 10 kg of SO_2, 4 kg of NO_x, and 0.7 kg of particulates including emissions of the heavy metals that are in the coal [2]. Table 2 lists the concentrations of heavy metals in the type of coal used in South Africa [3]. For example, coal-fired power plants are the largest contributors to Hg emissions to the South African environment, accounting for 72% to 78% of atmospheric Hg emissions, and 54 to 63% of general Hg waste releases in the country [4]. Based on the existing impacts of electricity from coal in South Africa, displacement with PV is expected to result in environmental benefits.

2 METHODS

Life cycle assessment (LCA) has been conducted with Simapro (V. 8.0.1) software and Ecoinvent (V. 2.2) unit processes. Life cycle impacts for PV systems were assessed in accordance with International Energy Agency Photovoltaic Power Systems Program (IEA PVPS) Task 12 guidelines for LCA of PV [5]. Life cycle inventory (LCI) data for cadmium telluride (CdTe) PV is based on publicly available sources for module manufacturing in First Solar's U.S. facility [6], fixed-tilt ground-mount balance of systems (BOS) [7], and collection and recycling in First Solar's U.S. facility [8]. These public life cycle inventories have been updated with additional data on emissions from manufacturing, land use in manufacturing and deployment, transoceanic freight shipping of modules from U.S. to South Africa, and use of local electricity mixes for manufacturing (U.S. EPA RFCW eGRID subregion) and project construction (South Africa grid electricity).

LCI data for mono and multi-crystalline silicon (mono-c-Si and multi-c-Si) PV [9] includes polysilicon,

Table II. Average trace element concentrations (ppm) for coal used at Eskom power stations in South Africa [3].

	Hg	V	Cr	Mn	Co	Ni	Cu	Zn	Ga	Ge	As	Rb	Sr	Y	Zr	Ba	Pb	U
Eskom–Arnot	0.17	44.4	114.9	131.1	3.7	62.4	10.7	40.2	11.3	2.3	4.8	6.1	284	17.3	90	276	15.7	2.4
Eskom–Duvha	0.23	39.2	49.4	106.3	5.8	20.2	24.6	38.6	13.9	2.1	3.4	11.8	415	22.4	118	378	20.2	3.5
Eskom–Hendrina	0.21	36.4	84.4	57	7.4	40.2	12.2	68.8	12	3.4	12.9	9.6	251	21.3	112	362	19.2	3.6
Eskom–Kendal	0.44	41.6	58.3	78.2	4.8	25.6	15.7	18.6	16.9	2	3	14.8	498	24.4	140	500	20.5	3
Eskom–KrielO/C	0.29	32.7	51.8	87.8	2.5	23.9	13.4	30.3	11.8	1.6	3.7	4.9	682	17.9	94	524	17.4	1.3
Eskom–KrielU/G	0.38	37.4	49.7	77.5	4.8	19.9	15.1	18.9	14.1	1.5	3	10.9	562	20.6	116	346	20.8	2
Eskom–Lethabo	0.36	57.5	81.7	115	6.9	36.9	22.8	30.4	17.9	1.2	2.4	17.1	361	27.2	171	428	23.8	5.3
Eskom–Majuba	0.29	35.6	55.2	88.4	6.9	27.6	16.4	30.1	13.6	1	5.1	10.7	320	23.7	145	357	24.9	3.3
Eskom–Matimba	0.45	57.6	48.9	156.4	8.1	26.1	18	45.3	16.9	1.8	3.8	21.1	186	26	164	347	23.3	4.5
Eskom–Matla	0.29	34.7	53.1	77.4	3.9	23.3	14.9	15.9	12.6	1.8	4.2	7.9	749	19.2	71	637	17.5	1.2
Eskom–Tutuka	0.29	41.2	69.9	97.7	11.1	38.9	12.2	34.1	13.3	2.6	4.9	7.9	430	29.7	90	285	22.4	2
SARM18(Witbank)	-	23	16	22	6.7	10.8	5.9	5.5	-	-	-	8.1	44	-	67	78	-	1.5
SARM19(FreeState)	-	35	50	157	5.6	16	13	12	14	13	-	9	126	-	351	304	20	5
SARM20(Sasolburg)	0.25	47	-	80	8.3	25	18	17	16	-	-	10	330	29	-	372	26	4

ingot, wafer, cell and module produced with electricity mixes of the countries where the polysilicon, ingots, wafers, cells and modules are produced. BOS data is based on Schletter Eco05/EcoG on-roof support structure and roof cabling. The inverter is based on the Ecoinvent unit process "inverter, 2500W, at plant/RER/I U" assuming 15 yr life and inverter sizing ratio of 0.89 kW/kWp [10]. End-of-life collection and recycling for c-Si PV systems is not considered because LCI data is not available.

CdTe PV represents a fixed-tilt utility-scale installation in South Africa with 2012 average module conversion efficiency of 12.7% [9], performance ratio of 0.80, 0.67%/yr module degradation rate, 30 year lifetime [5], and population-weighted plane-of-array irradiation of 2166 kWh/m^2/yr [11]. c-Si PV represents a fixed-tilt rooftop installation in South Africa with 2012 average module conversion efficiency of 14.7% for multi-c-Si and 15.1% for mono-c-Si [9], performance ratio of 0.75, 0.67%/yr module degradation rate, and 30 year lifetime [5], and population-weighted plane-of-array irradiation of 2166 kWh/m^2/yr [11].

While a variety of life cycle impact assessment methods are currently available (e.g., Recipe, Eco-indicator, CML, etc.), there has been a recent effort within the Joint Research Center of the European Commission to develop consensus methods through the ILCD (2011 Midpoint Method V. 1.02) [12]. These new methods are used in this study to evaluate environmental benefits of displacing South African grid electricity [13] with PV, with additional consideration of environmental policies that could further improve the environmental profile of PV. Note that water usage in this study reflects life cycle off-stream water withdrawal (excluding water used in running hydroelectric turbines).

3 RESULTS AND DISCUSSION

Ground-mount CdTe PV and roof-mount c-Si PV systems provide over two-thirds reductions in environmental impacts for a wide variety of impact categories, including ecosystems, human health, and natural resources (Table 3 and 4).

3.1 Mineral, fossil, and renewable resource depletion

The only ILCD impact category where PV does not provide a comparative benefit is with respect to mineral, fossil, and renewable resource depletion. While solar resources are abundant, the materials used to manufacture and deploy PV systems are finite. For example, the resource depletion estimate for CdTe PV systems is primarily due to depletion of the raw materials in the PV module semiconductor layer and the zinc coating in the galvanized steel used in ground-mount BOS mounting systems.

The impacts of resource depletion by PV modules may be mitigated by high-value end-of-life product recycling that recovers both bulk materials (glass, aluminum, copper) and semiconductor and rare materials for reuse in new products (Figure 1). For example, CdTe PV recycling technologies currently provide approximately 90% recovery of glass and 95% recovery of semiconductor material [8]. As large quantities of modules reach end-of-life in coming decades and module efficiency is improved, the CdTe PV industry has the potential to fully rely on Te from recycled end-of-life modules by 2038 [14]. As this case illustrates, widespread recycling practices may significantly mitigate the potential resource depletion impacts of PV.

Table III: ILCD environmental impacts relative to South African grid electricity (green: <33%; yellow: <100%; red: ≥100%)

		Mono-Si PV	Multi-Si PV	CdTe PV	CdTe PV (local)
Ecosystems	Climate change	🟢	🟢	🟢	🟢
	Terrestrial eutrophication	🟢	🟢	🟢	🟢
	Freshwater eutrophication	🟢	🟢	🟢	🟢
	Marine eutrophication	🟢	🟢	🟢	🟢
	Acidification	🟢	🟢	🟢	🟢
	Photochemical ozone formation	🟢	🟢	🟢	🟢
	Ozone depletion	🟢	🟢	🟢	🟢
	Ionizing radiation E (interim)	🟢	🟢	🟢	🟢
	Freshwater ecotoxicity	🟢	🟢	🟢	🟢
Human Health	Human toxicity, cancer effects	🟢	🟢	🟢	🟢
	Human toxicity, non-cancer effects	🟢	🟢	🟢	🟢
	Ionizing radiation HH	🟢	🟢	🟢	🟢
	Particulate matter	🟢	🟢	🟢	🟢
Natural Resources	Water resource depletion	🟢	🟢	🟢	🟢
	Land use	🟢	🟢	🟢	🟢
	Mineral, fossil & renewable resource depletion	🔴	🔴	🔴	🔴

An example of proactive recycling policy is in the European Union which has mandated the recycling of waste electrical and electronic equipment (WEEE) since 2003. End-of-life collection and recycling of PV modules has recently been included within the scope of the recast WEEE Directive [15]. Whereas the text of the Directive depicts a mass-based recovery quota which could be obtained by recycling of PV module glass and aluminum frames only, the European Commission also saw the need to develop high value recycling standards (which can include recycling of PV semiconductor and rare materials) and mandated the European

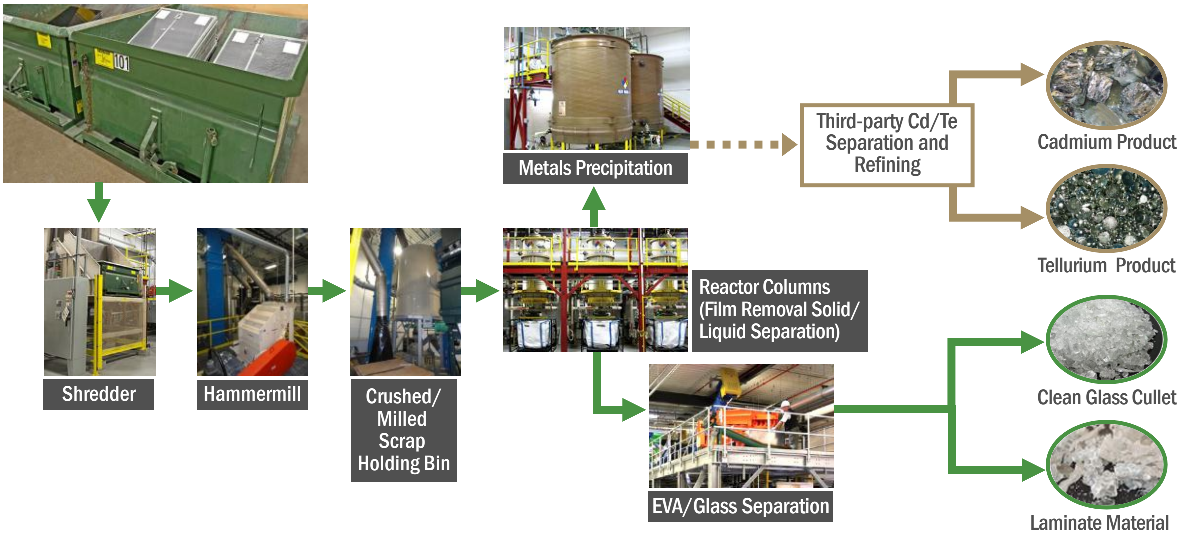

Figure 1: CdTe PV module recycling with approximately 90% recovery of glass and 95% recovery of semiconductor material.

Standardization Organization CENELEC to develop these standards [16].

Figure 2 shows the relative benefits of bulk and high value recycling with regard to mitigating mineral, fossil, and renewable resource depletion. High value recycling provides greater resource recovery benefits than bulk recycling by over an order of magnitude for CdTe PV systems. In general, depletion can be resolved with recycling and/or use of more abundant materials. For example, trends in c-Si solar cell manufacturing include the development of silver replacement with copper [17].

For PV BOS, the impacts of resource depletion may be reduced through a combination of reuse and recycling. Although PV modules have a lifetime of approximately 30 years, PV BOS can have a lifetime of up to 60 years [5]. Extending the useful life of BOS structures would reduce the impacts of resource depletion, as would recovery of recyclable materials (e.g., steel, aluminum, and copper) at end of project life.

In the case of grid electricity in South Africa, approximately three-quarters of the mineral, fossil, and renewable resource depletion is due to depletion of coal and uranium. Unlike PV systems, coal is not recyclable, though it could have non-energetic uses if not combusted. Kroll [18] developed an approach to calculate the opportunity costs incurred when the use of a free and abundant commodity (solar radiation) is supplanted by the use of a finite commodity (fossil fuels), which is destroyed and thus unusable in the future. Through substitution of fossil fuel energy generation, the value of the finite resource is preserved for future non-energetic uses. For example in Germany, approximately 1-15% of fossil fuel resources such as hard coal, oil, and natural gas have non-energetic uses [19].

3.2 Land use

In the case of land use impacts, roof-mount PV systems would be expected to have lower impacts than ground-mount systems. However, ILCD analysis indicates a negative impact (benefit) for ground-mount CdTe PV systems. In this case, the ground-mount BOS LCI data is based on a PV system constructed in degraded agricultural land which has been converted to grassland. Because the land's ecological value has been improved, the land use impact has been assessed as beneficial.

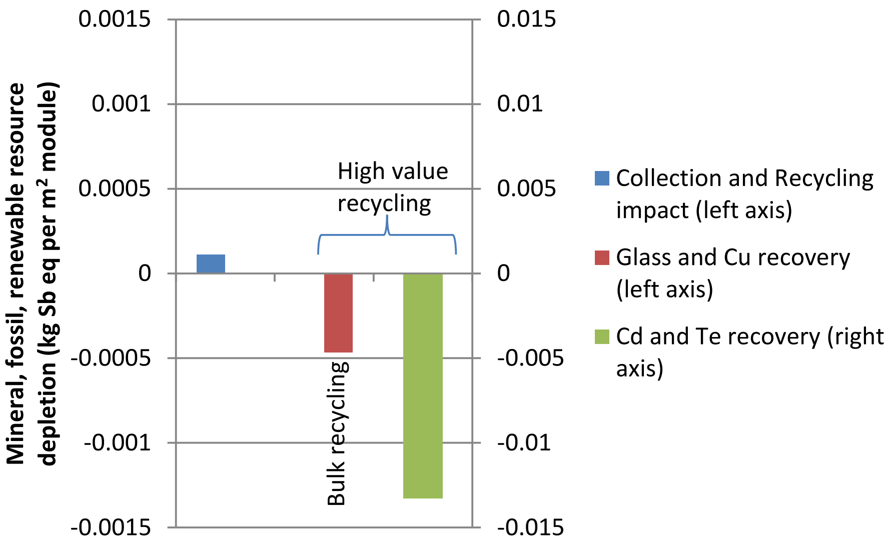

Figure 2: Relative benefits of bulk and high value recycling with respect to mineral, fossil, and renewable resource depletion for CdTe PV modules. Negative impacts represent a credit for resource recovery from recycling.

Although there is currently no international standard for responsible large-scale PV development, the World Wildlife Fund has collaborated with the PV industry to develop responsible land use guidelines [20]. In addition to careful site selection, soil grading techniques that minimize disturbance to topsoil will reduce impacts to ecosystems and the need for water to manage dust emissions. In addition, project decommissioning needs to be considered when developing PV projects to facilitate end-of-life recycling.

3.3 Local content

In support of South Africa's Renewable Energy Independent Power Producer Procurement Program (REIPPP) local content requirements, manufacturers are considering local assembly lines for PV module manufacturing, local manufacturing of inverters, and local sourcing of BOS cables and mounting structures. A limited analysis has been performed in which electricity-intensive processes (PV module and inverter manufacturing) have been evaluated with use of South African grid electricity. For the CdTe PV system, the environmental impact of this local content is minimal and maintains the over two-thirds reductions in ILCD impacts relative to grid electricity (Table 3 and 4; "local" column).

3.4 Use of ILCD methods

Because of the wide range of impact indicators in the the ILCD Midpoint Method, it is important to obtain complete life cycle inventory data prior to using the method. For example, impact assessments focused on metrics such as carbon footprint and energy payback time have primarily relied on material and energy usage life cycle inventory data. Life cycle inventories need to also include data on emissions, land use, water use, and waste to treatment over the product life cycle in order to improve the accuracy of the ILCD impact assessments.

4 CONCLUSIONS

Displacing grid electricity with PV in South Africa can provide a wide variety of benefits to ecosystems, human health, and natural resources, and use of high-value PV recycling and responsible land use practices can further improve the environmental profile of PV.

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