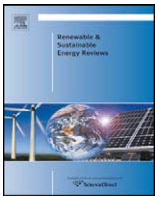
Renewable and Sustainable Energy Reviews 13 (2009) 2746–2750

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Sustainability of photovoltaics: The case for thin-film solar cells

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ARTICLE INFO

Article history:
Received 21 April 2009
Received in revised form 29 April 2009
Accepted 12 May 2009

Keywords:
Photovoltaics
Tellurium
Indium
Germanium
Availability
Resources
Recycling

ABSTRACT

To ensure photovoltaics become a major sustainable player in a competitive power-generation market, they must provide abundant, affordable electricity, with environmental impacts drastically lower than those from conventional power generation. The recent reduction in the cost of 2nd generation thin-film PV is remarkable, meeting the production milestone of $1 per watt in the fourth quarter of 2008. This achievement holds great promise for the future. However, the questions remaining are whether the expense of PV modules can be lowered further, and if there are resource- and environmental-impact constraints to growth. I examine the potential of thin-films in a prospective life-cycle analysis, focusing on direct costs, resource availability, and environmental impacts. These three aspects are closely related; developing thinner solar cells and recycling spent modules will become increasingly important in resolving cost, resource, and environmental constraints to large scales of sustainable growth.

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1. Introduction

A sustainable development is one that meets the needs of the present while maintaining the ability of future generations to sustain their own needs [1]. Photovoltaics as fuel-free energy sources inherently will be sustainable unless they are too expensive to produce, the materials required for their manufacture are depletable, or they are environmentally unsafe. Clearly specifying the sustainability of the 2nd generation of photovoltaics, i.e., thin-film-silicon, cadmium telluride (CdTe), and copper indium gallium selenide (CIGS), demands investigations of three measurable aspects: cost, resource availability, and environmental impact. Improving them directly relates to the desired human empirical sustainability outcomes of security, opportunity, and health from affordable, abundant clean energy, which have cross-societal, multi-regional, and transgenerational dimensions [2].

The question of cost concerns the affordability of energy in both rich- and poor-countries. Resource availability, viz., land- and material-requirements, matters to current and future generations under the constraint of affordability. The deliberation on environmental impacts includes local-, regional-, and global-effects, and has a long time-horizon. Straightforwardly, these issues condense into the following: thin-film photovoltaics are required to meet the

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doi:10.1016/j.rser.2009.05.001

need for abundant electricity generation at competitive costs, while conserving resources for future generations, and having environmental impacts lower than those of current modes of power generation, preferably less than those of alternative future energy-options. The costs of producing thin-film photovoltaics are the lowest among current commercial technologies, but there are concerns about the availability and toxicity of materials used in their manufacture (e.g., Te, In, Ge, Cd and Se), and the greenhouse potential of gases used in some reactor-cleaning operations (e.g., NF_3, SF_6).

2. Affordability

Photovoltaics now enjoy rapid growth in a subsidized market. However, such funding will not last forever, and unless the external costs of electricity generation are accounted for in the cost equation, the expense of PV power must reach parity with the direct cost of grid electricity, to be sustainable. The expenditure of producing thin-film solar cells is lower by a factor of two than that for multi-crystalline silicon-based modules, currently the dominant technology in the market. In the fourth quarter of 2008, the cost of manufacturing the module of the least expensive of the thin-film photovoltaics (i.e., CdTe) was $0.98/$W_p$. Meeting the $1/$W_p$(dc) benchmark has opened long-sought market opportunities. With such inexpensive modules, total installed systems prices of ~$4/$W_p$ are likely, corresponding to electricity prices generated under South West (SW) irradiation of ~14–15 ¢/kWh(ac). These prices already are competitive with the peak rates for grid electricity in California.

Forecasts suggest that the expense of producing modules for thin-film PV will fall to $0.50–0.70/$W_p$ with system prices of $1.5–$2.5/W_p by 2020, assuming sufficient market incentives to maintain technology progress throughout this period. These reductions will be driven by the economics of scale, improved production, and higher module efficiencies [3,4]. However, these scales will be attained only by the maintenance of, and expansion in new regions of current financial incentives. At a cost of $2.50/$W_p$ per system, the price of electricity from the US-SW is ~8 ¢/kWh, in parity with global averages of utility-scale electrical-power generation without carbon mitigation [5]. Further reductions towards $1.50/$W_p$ would cover the expenses of adding storage of electricity, and so transforming PV to a continuous, dispatchable source of electricity [6,3,4].

3. Resource availability and cost

Concerns have been raised about the availability of land for installing photovoltaic systems, and the obtainability of some materials needed in 2nd generation technologies. The former are unjustified as PV plants often use less land during their life cycle than does coal during its life cycle [7], and there are plenty of desert lands and roof-tops that can support many TWs of PV installations. PV have advantages for distributed power generation, and roof-top installations represent 66% of the world market today. However, uneasiness is justified about the availableness of materials for very large scales of growth. The supply of some materials used in fabricating thin-film photovoltaics (e.g., Te, In, and Ge) is limited as they are minor byproducts of copper, zinc and lead production, and, as such, their generation is inherently linked to that of the base metals' production. Thus, their annual availability must be examined.

3.1. Tellurium

The main sources of tellurium (and selenium) are the anode slimes from copper electrorefining operations. Green [8] reviewed surveys of Cu refineries and estimated that 430- and 2600-tonnes of Te and Se, respectively, were available in 2005, based on 33% and 52% recovery rates from the 1300 tonnes of Te, and the 5000 tonnes of Se in the slimes. Ojebuoboh [9] investigated details of production and determined the respective recovery rates as 40% and 80% for Te and Se from slightly lower amounts of the metals in the slimes (i.e., 1200 tonnes of Te, 4600 tonnes of Se). He argued that the recovery rate of Te is lower simply because the market for Te is very small and many smelters do not bother to recoup it; he suggests that an 80% Te recovery from anode slimes is feasible with current technology. Most importantly, Ojebuoboh details the flow of minor metals from the Cu ores to the Cu-production circuit, and points out that most Te and Se is left in the mine tailings because they interfere with the production of Cu and the refineries do not want them. Only the fractions of Se and Te that is associated with copper and precious metals (e.g., the selenides and tellurides of Au, Ag, Cu, Pt, and Pd) are extracted from the ores, and the amounts were only about 12% according to data from 1970 and earlier [9]. This low level contrasts with the recovery rate of copper from the same ores of 80% or better, and a 95+% recovery of gold. However, there are indications that the reclamation of Te from Cu ores in some operations now is up to 50% in anticipation of significant markets for it. Evidently, the market drives the rate of recovery, and higher demand and price justifies additional processing. There is nothing inherently preventing recovery rates for Se and Te as high as those for Au provided the price is sufficiently high; I note that the concentration of Au in anode slimes typically is lower than that of Te. However, there is a limit to the price of Te that will sustain affordable CdTe PV. For decades, Te prices were about $10/kg; then, during 2005–2008, they climbed into the $82–215 range. At $200/kg, the Te currently used in CdTe modules is ~3 ¢/W_p; it will fall to 1 ¢/W when the module's efficiency increases to 13.2%, and the thickness of the CdTe layer drops to 1.5 μm. Thus, Te prices up to 5–10 times higher than current levels may not affect the module production goal of $0.50–0.70/$W_p$.

Several scenarios are possible for estimating the future availability of Se and Te, all related to projected Cu production because, with very few exemptions, the quantities and price of the minor metals do not warrant economic extraction and processing of ores without recovering copper. Estimates of global demand for copper through the end of the century are based on scenarios accounting for population- and economic-growth, intensity of copper consumption, and recycling performance. The US Geological Survey [10,11] predicted a global demand growth rate for copper of 3.1% per year between 2000 and 2020; so far, their predictions have been correct (2000–2006). Although primary production in the world's metal smelters fluctuates highly [12], the average production is in line with the average demand. Forecasts beyond 2020 are less certain. Kapur [13] presents three scenarios of copper use; two of his scenarios show a continuous growth to the end of the century, whereas one shows a peak of about 60 million tonnes/yr of global copper use in 2050. Ayres et al. [14] developed eight scenarios of future demand and growth rates for both primary and secondary production of copper until 2100, based on the economic growth models of the International Panel on Climate Change (IPCC). Their model predicts that the world will use 26.5–30.5 million tonnes of copper from primary production in 2025 (from 15.7 million tonnes in 2008), and 40.2–53.3 million tonnes in 2050; thereafter, demand will gradually decrease or remain about constant during the rest of the 21st century. However, the authors expressed skepticism about the model predictions and stated that a peak could possibly occur earlier (in about 15 yr) with production at about two-times current levels. It is possible that Ayres et al (2002) constraints are outdated, since in 2006 USGS revised upwards their estimates of Cu resources from 1.6 billion to 3 billion tonnes. To capture ongoing debates about copper resources [15,16], I assumed a primary Cu production peak

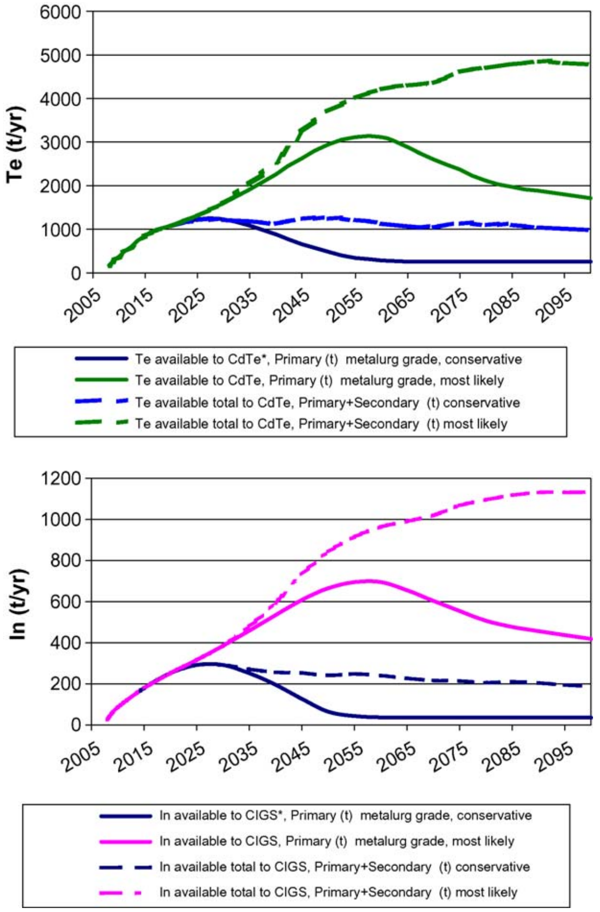

Fig. 1. Estimates of Te and indium availability for PV (after subtracting competitive uses); secondary source is from recycling of spent modules.

in 2025 in a conservative scenario, and peaks in 2055–2060 in most-likely and optimistic scenarios.

Taking the average ratio of Te to Cu concentrations of 1.5/5000 in typical land ores, 3 billion tonnes of Cu resources correspond to 900,000 tonnes of Te. However, comparing total resources is an academic exercise since the economic production of Te can occur only in conjunction with the production of the base metal. An 80% recovery of Te from Cu anodes is likely in the next 5–10 yr, and additional Te may become available in the longer term, if the losses in ore concentration are reduced. Starting with Te content in Cu anodes of 1250 tonnes/yr (average of the values reported by Green and Ojebuoboh), and applying a 3.1%/yr growth and recovery from anode slimes gradually increasing to 80%, then the annual primary production of metallurgical-grade Te would be 1450 tonnes/yr in 2020. In addition, there are two Te-rich mineral deposits in China and Mexico from which direct mining of Te is economically feasible [23]; lacking information we did not include such in the current long-term analysis. It is also noted that massive resources of Te exist in ocean-floor ferromanganese nodules; reportedly 9 million tonnes of Te at mean concentrations of 50 ppm [17]. However, since cost efficient recovery of metals from deep ocean is not currently practiced, we did not include this resource in the current analysis.

About 42% of the 2006 production of Te is currently used in iron and steel and 23% in chemicals. The demand in these uses is expected to be flat ($\sim$322 tonnes/yr), and so the growth in Te supply is assigned exclusively to PV.

3.2. Secondary Te resource availability

The Te content in CdTe modules is around 500 ppm, so that end-of-life modules are the obvious choice for extracting scarce metals. The technical- and economic-feasibility of recycling CdTe solar cells is proven. Small-scale operations achieved a 99.99% separation of Te and Cd from end-of-life modules at an estimated cost of 2 ¢/Wp [18]. On an industrial scale, I expect a 90% overall recovery rate. With economic incentives and laws regulating disposal, the collection of spent modules from large utility installations expectedly is 100%, and 80% from residential installations. Accordingly, recycling will become an increasingly significant source of secondary Te after 2045 (Fig. 1). This evaluation is incorporated into material constraints to CdTe PV growth. I consider conservative, most-likely, and optimistic scenarios with different efficiency and thickness targets (Table 1). The most-likely scenarios in this table correspond to module efficiencies in 2020 equal to 80% of the current record cell efficiencies for each of the thin-film technologies [19]. The Te growth scenarios are based on a 3.1%/yr growth rate for primary Cu production, Te recovery from copper anode slimes gradually increasing to 80%, losses during Te purification, CdTe synthesis, and utilization totaling 54% in 2008 and falling to 25% from 2015 onwards. For secondary Te availability from module recycling, I assume a 30-yr life, an average 10% loss of Te in module collection, and 10% loss in separations.

3.3. CdTe PV production

Under these assumptions, the total annual production of CdTe PV that can be supported by Te availability in Cu smelting is constrained between 14–38 GW_p in 2020, 19–149 GW_p in 2050, and 20–211 GW_p in 2075 (Table 2 and Fig. 2). These limits are strictly based on Te co-production in Cu production from known resources, and do not include the potential for direct mining and additional resource discovery. Accordingly, the primary annual Cu and Te supplies reach a peak in 2025 in the conservative scenario, and in 2055 in the most-likely and optimistic scenarios. The total supply, thus the sum of primary and secondary Te from recycled modules, remains flat in the conservative scenario and keeps growing in the other two scenarios. The Te-based limit of cumulative global production of CdTe PV by 2020 is 98–205 GW_p, rising to 0.6–2.7 TW_p by 2050, and 1.6–13 TW_p by 2100 (Table 2).

For CdTe PV to continue growing by 40%/yr, Te recovery from anode slimes must increase to 80% and the CdTe film thickness has to decrease by a factor of two from current thickness of films formed by vapor transport deposition. The technological basis

Table 1
Basic assumptions for thin-film PV growth.

PV type	Efficiency (%)				Layer thickness (μm)			
	2008	2020			2008	2020+		
		Conservative	Most likely	Optimistic		Conservative	Most likely	Optimistic
CdTe	10.8	13	13.2	14	3.3	2.5	1.5	1
CIGS	11.2	14	15.9	16.3	1.6	1.2	1.	0.8
a-SiGe	6.7	9	9.7	10	1.2	1.2	1.1	1

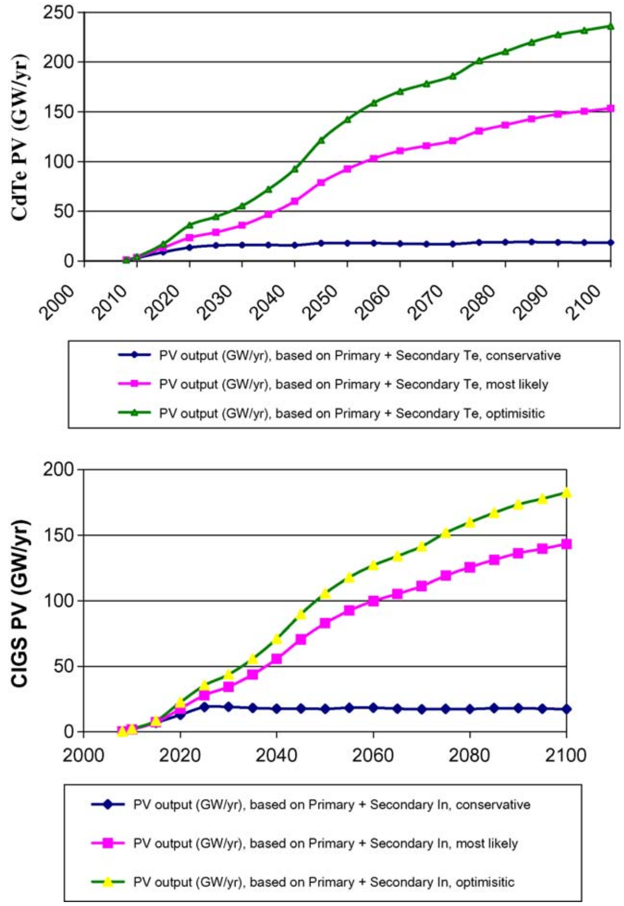

Fig. 2. PV growth rate limits based on material availability (a) CdTe PV; (b) CIGS PV. Increases are due to growth in the extraction of the primary ore, better byproduct recovery, reduced refining losses, thinner layers, improved efficiencies, and recycling of spent modules.

exists for increased recovery of Te in the near term; additional R&D will be required to accomplish the layer thickness reductions.

3.4. *Indium and germanium*

Zinc mineral deposits are the main sources of indium and germanium. The supply of indium is subject to the production of zinc, and likely to remain so in future. Zinc extraction grew by 3.2% annually between 1910 and 2002, and growth in the last 10–20 yr is consistent with this historical trend [20,21]. Since the ratio of the current production of Zn (11 million tonnes/yr) to the reserves (~1.9 billion) is about the same with that of copper, I use the same scenarios for Zn peaking as those for Cu peaking. The extraction-efficiency of indium is 70–80%. The average refinery production of indium in 2007–2008 was 545 tonnes, and that of germanium about 95 tonnes. The prices of the two metals have reached a high of ~$1000/kg.

The current thickness of CIGS thin-films, about 1.6 μm, is expected soon to decrease to 1.2 μm [22], and to 0.8 μm over the longer term (Table 1). Currently, the material utilization rate of In in co-evaporation commercial processes is a relatively low 34%, corresponding to ~10 ¢/W_p cost for In at $1000/kg. With material utilization of 90% (via electrodeposition and/or recycling of residuals in vapor deposition), a module efficiency of 15.9%, and 0.8 μm thick layers, this cost will plunge to 1 ¢/W_p. However, even in the optimistic scenarios, neither CIGS- nor CdTe-PV would be sustainable in very large growth scenarios if the prices of In and Te increase more than about ten times above maximum prices. Competing applications of In pose further restrictions. The main use of indium today is in liquid crystal displays (LCDs), accounting for 65% of current consumption; photovoltaics use an estimated 5% of the primary In production. Since expanding use of In is anticipated in LCDs, computers, cell phones, and other display components [23], in this forecast I assign to PV usage an arbitrary 50% of the growth in indium availability. The In-constrained growth potential of CIGS PV is estimated to be 13–22 GW_p/yr in 2020, 17–106 GW_p/yr in 2050, and 17–152 GW_p/yr in 2075. The Ge-related constraints of a-SiGe PV are estimated to be 3–11 GW_p/yr in 2020, 5–49 GW_p/yr in 2050 and 10–120 GW_p/yr in 2075 (Table 2 and Fig. 2). The Ge availability estimates carry higher uncertainty than those of indium, because resource data on the former are missing.

An earlier study [24] forecasted future respective capacity constraints of 20-, 70-, and 200-GW_p/yr, for CdTe, CIGS, and a-SiGe. However, the authors assumed a 100% use of the minor metal resources for PV, 100% material utilizations, and did not correlate resources with the annual production of Cu and Zn and competitive uses of Te, In and Ge.

Te and In cannot be replaced in the current technologies because of their particular functions. However, germanium can be superseded by nano-structured layers of crystalline silicon and in tandem a-Si/mc-Si cascade thin-film modules. The latter is one of the fastest growing silicon-film technologies today; with a transition to nanocrystalline or microcrystalline films, silicon technology lifts the restrictions of Ge-related material.

Each of the thin-film technologies has the potential to satisfy a 30–40%/yr overall PV growth till 2020. Future approaches may have different characteristics, some better than those discussed herein. Aggressive scenarios of continuing high growth rates to mid century prescribe for the United States 2.8 TW by 2050, to support 70% electricity generation from renewable energy for current uses and hybrid-plug-in electric cars [3,4]. At least three times more capacity will be needed for a global plan of the same proportions. This may not be achieved by a single thin-film PV technology, but can be supported by these technologies together.

4. Environmental impacts

The operation of fossil-fuel-burning power plants has caused health effects and increased atmospheric carbon-dioxide concentrations. Although operating photovoltaic systems do not generate any toxic- or greenhouse-gases, in common with other products, such gases may be emitted during the production of the materials

Table 2
PV growth constraints due to material availability.

PV type	Restricted metal	Baseline-2008		Expected-2020			2050	2075
		Metal requirement (tonnes/GW)	Refinery production (tonnes)	Metal requirement (tonnes/GW)	Refinery production (tonnes)	PV production (GW/yr)	PV production (GW/yr)	PV production (GW/yr)
CdTe*	Te	176	480	30–80	1412	14–38	19–149	20–211
CIGS^{+}	In	83	545	11–20	797	13–22	17–106	17–152
a-SiGe$^{\#}$	Ge	73	95	36–48	153	3–11	5–49	10–120

used for solar cells and systems. Therefore, their potential for adverse effects must be examined in a comparative life-cycle framework. Recent studies of the life-cycle emissions from photovoltaics showed that CdTe thin-film photovoltaics emit, under average US conditions, about 20 g CO_2/kWh, in comparison to 500–1000 g CO_2/kWh from fossil-fuel plants. Some facilities producing tandem a-Si/mc-Si cascade thin-film modules use potent greenhouse gases, like SF_6 or NF_3, as reactor cleaning agents, but they can be replaced, or their emissions abated. Releases of priority pollutants (e.g., SO_2, NO_X, particulates) from photovoltaic life-cycles comprise, like their GHG emissions, only 2–4% of those from fossil-fuel plants. Heavy-metal emissions deserve special consideration as certain thin-film solar cells use such metals (e.g., Cd in CdTe and CdS, Se in CIGS). An experimental investigation of the potential for liberating Cd during residential fires demonstrated that 99.5–99.96% of Cd is safely encapsulated in the molten glass [25]. The direct cadmium emissions in the life cycle of CdTe solar cells amount to 0.02 g per GWh of energy produced under average US conditions [26]. On the other hand, a typical coal-burning plant in the United States, equipped with electrostatic precipitators (ESPs) or baghouses operating at 98.6% Cd removal efficiency, emits 2 g Cd per GWh [25]. Replacing grid electricity with thin-film PV systems, results in 89–98% reductions in the emissions of GHGs, criteria pollutants, heavy metals and radioactive species [27]. Thus, photovoltaics, in concert with other renewable energy sources, can reduce CO_2 emissions in 2050 by 62% below the 2005 level [4].

While these results offer a comparative picture of the environmental benefits from employing thin-film photovoltaics, the question of potential risks from PV modules at the end of their useful life merits further discussion. There are concerns about the cadmium components in CdTe- and CIGS/CdS-thin-film solar cells. However, the potential for harm is not related to the quantity of toxic compounds in a module, but rather to their potential for leaking out. Release scenarios include leaching from modules abandoned in landfills, and emissions of those compounds during fires. The first problem, addressed by the Toxic Characteristic Leaching Procedure (TCLP) that simulates leaching of wastes, has substantiated their safety under controlled conditions. Current vintage photovoltaics reportedly passed the TCLP, and Cd was shown to be retained in the glass matrix during fires. However, there may be other plausible accident scenarios, and, therefore, every effort should be made to collect the modules, and recycle the contained metals at the end of their useful life. The greatest challenge may lie in ensuring a high recovery rate of spent modules from dispersed residential installations. Estimates of residual risks should be compared with the risks inherent in the life cycle of alternative systems and the conventional power-generation systems that photovoltaics would replace. Toxic emissions are much lower in the life cycle of thin-film photovoltaics than in the life cycles of alternative photovoltaic- and conventional-power systems [27].

5. Conclusion

Thin-film photovoltaics currently are the most inexpensive technologies for harnessing sunlight for electricity generation; it appears that their affordability can improve to cost-parity with grid electricity in the United States and other parts of the world that enjoy high insolation. These technologies use minor metals, the availability of which is constrained by the annual production of base metals. Although some technological- and economic-challenges remain, a cumulative production of several TW is possible by mid century, supporting the most aggressive scenarios for renewable-energy and reductions in CO_2-emissions. Material-related sustainability deficits will be eased with enhanced recovery during primary production, reducing the thickness of the semiconductor layers, and efficient recycling of spent modules. Especially needed is R&D on developing thinner layers, an area that has not been sufficiently studied so far. Resolution of the issues of resource availability and environmental impact is likely to follow the effective collection and recycling of the modules at the end of their useful life.

Acknowledgments

Many people contributed to this work with helpful discussions; we would like especially to acknowledge H. Kim, Columbia U., K. Zweibel, GWU, F. Ojebuoboh and A. Meader, FirstSolar, B. Stanbery, HelioVolt, J. Britt, GlobalSolar, S. Guha, Uni-Solar, X. Deng, Xunlight, J. Sites, Colorado State U. and B. von Roedern, NREL. This work was supported by the Solar Technologies Program, US Department of Energy, under Contract DE-AC02-76CH000016 with the US-DOE.

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