Solar Energy Materials & Solar Cells 138 (2015) 58–71

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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

Evaluating the availability of gallium, indium, and tellurium from recycled photovoltaic modules ☆

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ARTICLE INFO

Article history:
Received 29 October 2014
Received in revised form
17 February 2015
Accepted 23 February 2015
Available online 18 March 2015

Keywords:
Recycling
Thin-films
Photovoltaic
PV
Solar module
Mineral availability
Tellurium
Indium
Gallium

ABSTRACT

The use of thin-film copper indium gallium (di)selenide (CIGS) and cadmium-telluride (CdTe) in solar technologies has grown rapidly in recent years, leading to an increased demand for gallium, indium, and tellurium. In the coming years, recycling these elements from end-of-life photovoltaic (PV) modules may be an important part of their overall supply, but little is known about the economic feasibility and the potential quantities available. This article investigates the future role of PV recycling in supplying gallium, indium, and tellurium. The authors evaluate both the quantities available from recycling over the next century and the associated costs for recycling modules and reusing each element in PV manufacturing. The findings indicate that, in terms of technical potential, there may be significant quantities of each element available from recycling CIGS and CdTe modules. The estimated cost of recovering each element from end-of-life PV modules and reusing it in PV manufacturing is higher than current raw mineral costs; however, learning and economies of scale may reduce the reported early estimates of recycling costs. These findings help improve the understanding of recycling's role in enabling higher levels of CIGS and CdTe module production.

1. Introduction

Although thin-film photovoltaic (PV) technologies cadmium-telluride (CdTe) and copper indium gallium (di)selenide (CIGS) comprise only about 10% of the current PV market [1] their production has grown rapidly in recent years. The strong light absorption characteristics and low manufacturing cost of CdTe [2] and CIGS [3] modules may increase the contribution of these technologies to the total PV growth in the coming decades.

These technologies, however, require the use of the elements gallium (Ga), indium (In), selenium (Se), and tellurium (Te)—each of which has a relatively fragile supply. Lokanc et al. [4] discuss the reasons why supplies of these minerals are so considered. First, current production of each is small and these markets are susceptible to abrupt demand shocks from new end uses, such as the surge in demand for indium for flat-panel displays in the early 2000s. Next, the primary supply (i.e. production from ores) of each mineral comes as a by-product of another mineral, which is the associated main product (e.g., copper, in the case of tellurium). As by-products, each mineral's supply is vulnerable to changes in main-product supply. Moreover, producers have optimized their operations to efficiently produce the main product, and recovery of any by-products is of secondary importance. Finally, these minerals are relatively rare in the earth's crust. The average crustal abundances of only 0.002 and 0.05 ppm (ppm) place tellurium and indium among the rarest elements [5,6]. Gallium is relatively more abundant, with an average crustal abundance of about 17 ppm (comparable to lead) [7], but none of these minerals are found in high-enough concentrations to be the principal mineral of an ore body. This is why it can be cost prohibitive to mine any one of these elements as the mineral of primary economic interest.

Due to these factors, the supply of each mineral from end-of-life products—commonly referred to as supply from “old scrap”—could be important in meeting total demand and enabling wider adoption of these thin-film PV technologies. While recycling is not expected to contribute much to total mineral supply for many years, understanding the potential for recycling is critical to evaluating the long-term constraints on CdTe and CIGS module deployment and has received recent attention in the literature on mineral availability for thin films [8,9]. The purpose of this article is to determine the potential for recovering these elements from

☆This research was supported by the National Renewable Energy Laboratory, Office of Energy Efficiency and Renewable Energy under Agreement no. UGA-0-41025-66.

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http://dx.doi.org/10.1016/j.solmat.2015.02.027
0927-0248/

end-of-life PV modules for reuse in CIGS and CdTe cell manufacturing.[3] The analysis examines the technical potential for PV deployment from old scrap mineral supply in terms of the quantity of PV production possible from gallium, indium, and tellurium old-scrap supplies and the cost of recycling modules and reusing each element in PV cell manufacturing. In particular, it evaluates the gigawatts of CdTe cells that can be produced annually from tellurium recovered from end-of-life modules, and the contribution recovered tellurium makes to PV module manufacturing cost (measured in U.S. dollars per watt produced). This article also assesses the same factors for indium and gallium in CIGS cell production.

Section 2 describes the existing literature on availability of these minerals and PV recycling costs. Section 3 presents the model and model inputs employed in the analysis. Section 4 discusses the results and provides some sensitivity analysis. Section 5 states the conclusions of the research, remarks on the implications of the results, and gives suggestions for future work.

2. Literature review

This section reviews existing literature and divides it into two types. The first type discusses the quantity of CdTe or CIGS modules that can be produced from recycling end-of-life modules, within the context of overall availability, and includes Fthenakis [8] and Hourai et al. [9]. The second type considers the cost of recycling CIGS and CdTe PV modules, and includes Fthenakis et al. [10], Choi and Fthenakis [11], and McDonald and Pearce [12].

Fthenakis [8] assesses the amount of CdTe and CIGS modules producible based on the availability of tellurium and indium from primary sources (from ores) and secondary sources (from recycling). In the low case, he finds that, while holding demand from other applications constant, the amount of primary and secondary tellurium production available for PV in 2100 could be on the order of about 1000 and 2500 t, respectively. In the high case, annual tellurium production available for PV is 5000 t. The low and high cases translate to CdTe production in 2100 of 75 and 100 gigawatts (GW), respectively if the modules are competitive in the market. Annual CIGS production could be 17–106 GW/year and 17–152 GW/year in 2050 and 2075, respectively.

Hourai et al. [9] use system dynamics modeling to assess the availability of tellurium for use in CdTe cells. In the analysis, Hourai et al. incorporate primary tellurium by-product production from copper, main-product mining of tellurium, and recovery of tellurium from post-consumer waste. Copper production is modeled using a logistic function, with peak copper production occurring in approximately 2050 at up to nearly 40 million tons per year. Main-product tellurium mining comes from two known deposits totaling 2700 t, and also is modeled with a logistic function. In tellurium recycling from end-of-life PV modules, the authors assume 10% tellurium loss in module collection, 10% loss in tellurium separation, and a 30-year cell life. Hourai et al. present three cases (business as usual, dynamic, and optimistic), and find that tellurium available for PV in the year 2050 could be approximately 1000 t, 2500 t, and 3500 t in the three respective cases, which could result in annual CdTe module production of ~5 GW, 150 GW, and 250 GW, if economic.

Fthenakis et al. [10] estimate the cost manufacturers could pay to recycle $CuInSe_2$ modules to be \$0.08/W (in 1996 dollar terms) using a system of reverse recycling. Choi and Fthenakis [11] evaluate the profitability of CdTe module recycling using First Solar's recycling process as a case study. The findings indicate that, although base case recycling is not profitable, there are many cases in which recycling could become profitable; profitability greatly depends on the incoming module cost and the price of glass cullet. McDonald and Pearce [12] examine the profitability of recycling five different PV technologies, including CdTe and CIGS modules. They account for recycling cost, avoided disposal cost, credit for glass cullet, and the price of recovered semiconductor material. The research determined that CdTe module recycling would not be profitable but CIGS module recycling might be profitable.

The present analysis contributes to the current literature in three respects. One is that, to our knowledge, this is the first study that evaluates potential CIGS deployment from both gallium and indium available in end-of-life modules. Second, whereas previously published literature has estimated recycling cost or profitability, this article estimates both the recycling and reuse costs of each element and how these costs evolve over time. Finally, whereas prior literature focused on either the quantity of PV deployed or the recycling cost, this research estimates both quantity of deployment and element cost, to provide a more thorough assessment of potential PV deployment from end-of-life modules.

3. Model and inputs

This section discusses the model and model inputs used in this analysis. The model has two main outputs. The first is the amount of annual PV production technically feasible from old scrap mineral supply (e.g., the gigawatts of CdTe modules that can be deployed with tellurium available from recycled modules). The second is the cost of recovering an element from end-of-life modules and reusing it in PV manufacturing. This is measured in U.S. dollars-per-watt peak (direct current), and herein is referred to as the recycled mineral's contribution to PV manufacturing cost. The following sections discuss how these two outputs are calculated within the model.

3.1. Photovoltaic production from old scrap supply

Photovoltaic production or deployment measured in gigawatts peak (GWp) from old scrap supply in year t is denoted by D_t and calculated as

$$D_t = \frac{R_t \times m}{I_t}, \tag{1}$$

where

R_t is the old scrap supply of an element from recycled modules in year t (tons);
m is the PV technology's proportional share of mineral consumption among all end uses;
I_t is the material intensity of the element in either CdTe or CIGS modules (tons/GW).
Old scrap supply in year t (R_t) is equal to use or consumption by the PV technology in year $t-L$ that is in turn recovered from recycled modules in year t: $R_t = r \times C_{t-L}$, where r is the efficiency in which the element is recovered from end-of-life modules, L is the length of module life, and C_{t-L} is consumption of the mineral by the PV technology in year t–L. For simplicity, we assume that module life is constant over time. The initial year used in this model (year $t = 0$) represents the year 2005, the first year in which data on CdTe module deployment are available. For years $t < L$, where L is the life of the module in years, no modules are recycled and there is no old scrap supply,

[3] Recycling gallium arsenide (GaAs) modules is not evaluated in this analysis, but the methodology applied here can be extended to GaAs.